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Executive Summary

A team composed of scientists from Michigan State University (MSU) and Michigan Technological University (MTU) assembled to better understand, document, and improve systems for using forest-based biomass feedstocks in the production of energy products within Michigan. Work was funded by a grant (DE-EE-0000280) from the U.S. Department of Energy (DOE) and was administered by the Michigan Economic Development Corporation (MEDC).

The goal of the project was to improve the forest feedstock supply infrastructure to sustainably provide woody biomass for biofuel production in Michigan over the long-term. Work was divided into four broad areas with associated objectives:

- **TASK A:** Develop a Forest-Based Biomass Assessment for Michigan – Define forest-based feedstock inventory, availability, and the potential of forest-based feedstock to support state and federal renewable energy goals while maintaining current uses.
- **TASK B:** Improve Harvesting, Processing and Transportation Systems – Identify and develop cost, energy, and carbon efficient harvesting, processing and transportation systems.
- **TASK C:** Improve Forest Feedstock Productivity and Sustainability – Identify and develop sustainable feedstock production systems through the establishment and monitoring of a statewide network of field trials in forests and energy plantations.
- **TASK D:** Engage Stakeholders – Increase understanding of forest biomass production systems for biofuels by a broad range of stakeholders.

The goal and objectives of this research and development project were fulfilled with key model deliverables including: 1) The Forest Biomass Inventory System (Sub-task A1) of feedstock inventory and availability and, 2) The Supply Chain Model (Sub-task B2). Both models are vital to Michigan's forest biomass industry and support forecasting delivered cost, as well as carbon and energy balance. All of these elements are important to facilitate investor, operational and policy decisions. All other sub-tasks supported the development of these two tools either directly or by building out supporting information in the forest biomass supply chain.

Outreach efforts have, and are continuing to get these user friendly models and information to decision makers to support biomass feedstock supply chain decisions across the areas of biomass inventory and availability, procurement, harvest, forwarding, transportation and processing. Outreach will continue on the project website at <http://www.michiganforestbiofuels.org/> and <http://www.michiganwoodbiofuels.org/>

Executive summaries for each subtask follow, and where applicable address technical effectiveness and economic feasibility of the methods or techniques investigated or demonstrated. Full final reports for each sub-task also follow and identify associated publications, conference papers, technology transfer activities and other developed products.

SUB-TASK A1: Geospatial Forest Inventory Models for Michigan

Strategic decisions concerning the timing and location of forest operations require accurate information about the state and rate of change of forest growing stock. Regional forest management would benefit from spatially explicit inventory data across the entire forest area. Due to cost considerations in detailed field inventories, remotely sensed data have often been employed to extend forest inventories through both space and time. The purpose of this study was to generate spatially explicit predictions of growing stock inventory, growth, mortality and removals of above ground biomass across the entire state of Michigan, U.S.A. This is achieved by coupling spectral information from Landsat TM images and other geospatial layers with the inventory data from Forest Inventory and Analysis (FIA) program of U.S. Forest Service in a kNN imputation procedure. The predictor layers in the imputation process included normalized difference vegetation index (NDVI), land cover classes, basal area weighted height (BAWHT), and digital elevation model (DEM) while volume, growth, mortality and removal data from 6,702 sample plots of FIA were utilized for both model calibration and validation. A Random Forest imputation algorithm was implemented to develop spatially explicit forest inventory information across the Entire State of Michigan via the integration of geospatial data with forest inventory plot measurements. Generally, state wide spatial inventory was unbiased but demonstrated relatively low precision. Inclusion of BAWHT as an explanatory variable was found to significantly improve the prediction accuracy. Three levels of comparison were made to evaluate the accuracy of the inventory estimates: at the plot, stand and county levels. The validation procedure confirmed that county level estimates were better than stand level which in turn was better than plot level estimates. The statistical modeling approach employed (imputation) achieved acceptable accuracies when compared to other studies.

SUB-TASK A2: Forest Biomass Information System for Michigan

Very high quality forest inventory data are available from the USDA Forest Service Forest Inventory and Analysis Program, for forests under all ownerships in the United States. These data span multiple owners in time and space and are known to be very accurate and of exceptionally high quality. Unfortunately, systems for non-technical users to access these data are not available, and furthermore, spatial analyses especially at small scales are difficult with extant public FIA database tools. In this project, a user-friendly, cross-platform interface to FIA data was developed based on ESRI ArcGIS server software. Non-technical users, Mac, PC, Linux or other platform, can access the server system using a standard web browser. Both fixed-radius and irregular user-defined query areas are possible for users to define, and the web system presents both graphical and tabular summaries of forest inventory, growth, mortality, removals, net growth after removals, and potential logging residues associated with timber harvest. The new system is robust, stable, and effective at making dense and sparse inventory data available to non-technical users with continuous, 30 m resolution raster coverage for the entire state of Michigan. Analysis of accuracy of the underlying data is presented elsewhere. This report summarizes the functionality of the Forest Biomass Information System (FBIS), the WebGIS software environment and extensions that make the underlying data, developed recently and revised in the future, available to non-technical users (FBIS is accessible at the URL <http://fbis.mtu.edu>).

SUB-TASK A3: Assessment of forest-based biomass availability.

Forest biomass inventory figures derived elsewhere in the project do not accurately predict the amount of material that may be “*available*” for use in bioenergy facilities. This sub-task established forest growth, removals, and availability multipliers to be combined with forest biomass inventory figures in the Forest Based Information System (FBIS) developed under sub-task A2. These multipliers were developed to reflect the distribution of forest resources in the state, existing users of the resource, and landowner patterns and behaviors among other things. Forest biomass availability estimates from the FBIS will provide a critical planning tool for bioenergy project developers, policy makers, communities, and other stakeholders.

SUB-TASK A4: Spatial Forest-Based Biomass Availability

Geospatial models were developed for the amount of growth in Michigan’s forests that is net of both natural mortality and harvest removals. This metric, called *net growth after removals* (or NGAR) represents the relative accumulation or depletion of forest inventory at any given spatial location in Michigan. Where NGAR is positive there may be opportunities for additional biomass harvest, though ultimately many factors conspire to constrain the amount of NGAR that is actually available to a suitably motivated marketplace. Ultimately, if accurate data on availability and drain (current consumption) could be developed and combined with NGAR, an informative picture of opportunities for new industrial development, as well as areas where competition is already constraining current use would be possible.

SUB-TASK B1: Forest Biomass Information System for Michigan

Minimizing transportation costs is essential in the forest products industry, as the relatively low value and high weight of the products causes transportation to account for exceptionally high portion of the overall cost. The forest products such as logs, chips, and residues (woody biomass) are one of the major business sources in Michigan especially in Upper Peninsula, with different constraints in terms of transportation and handling requirements.

This report details the transportation-related investigations conducted as part of the Forestry Biofuels Statewide Collaboration Center (FBSCC) project for the state of Michigan, supported by the U.S. Department of Energy (DOE) and the Michigan Economic Development Corporation (MEDC). The main objective of the transportation systems evaluation under the FBSCC project framework was to identify and evaluate the capabilities of the Michigan transportation system to deliver woody biomass in general and especially to nine biomass plants proposed through other parts of the study. The report concentrates on in-state movements only and uses road (truck) transportation as the only alternative for single mode transportation and a combination of road with rail and marine transportation as the multimodal supply chain alternatives.

The transportation analyses were divided to three main categories:

- **Infrastructure:** Inventory and assessment of current road, rail and marine transportation infrastructure in forest regions of Michigan with main concentration to the northern part of Lower Peninsula.
- **Equipment:** Identification of most suitable types of equipment for forest biomass transportation and evaluation of their availability in the State of Michigan.

- **Operations:** Operational and economic considerations for each modal and for multimodal transportation alternative. This section also included developing general level estimates for delivery of woody biomass to the nine proposed facilities and review of the formation of transportation costs.

The research methods applied through this report included literature searches, interviews, database searches, field visits, surveys, and limited modeling of different transportation scenarios.

SUB-TASK B2: Analyze woody biomass harvesting, forwarding, and processing systems.

Feedstock harvesting, forwarding, and processing (HFP) represents the largest portion of the cost of delivered feedstocks at bioenergy plants. This sub-task took inventory of the available HFP systems in Michigan, examined the operating costs of various components, and created a decision-support model to assist operators optimize their operations. A detailed examination of wood torrefaction (a mild pyrolysis producing a solid, friable, energy-dense intermediate feedstock) was also undertaken to understand how pre-processing raw wood in this way in local depots would impact the long-range distribution and use of biomass within the energy economy.

SUB-TASK B3: Evaluation of biomass processability.

Reasons for renewed interest in biofuels production include new policy and legislation such as sustainable biofuel targets in the US Energy Policy Act (EPC, 2005), foreign oil dependence reduction, reduction in harmful environmental impacts, and the ability to create a more diverse product industry. This study provides a technical screening of biofuels production feasibility from forest-based feedstock that can be implemented in Michigan. Feedstocks studied include poplar, willow, aspen, switchgrass, red maple, and balsam.

Two conversion pathways were considered within this work: dilute acid hydrolysis followed by enzymatic hydrolysis (biochemical mechanisms), and pyrolysis (thermal degradation mechanisms). These processes were evaluated on their production of valuable bio-fuels intermediates. The dilute acid pretreatment and enzymatic hydrolysis was evaluated on the production of sugars that can be fermented into fuels, such as ethanol. Pyrolysis was evaluated based on the yield of liquid and gaseous phase products.

From study, we found that our results agree well with existing literature, indicating that Michigan grown woody feedstocks can be processed to valuable product through either investigated method. This work found that yields of greater than 50% of biomass-embodied sugars can be extracted when processing woods such as poplar and willow through dilute acid pretreatment and enzyme hydrolysis. Additionally, this study found that combined bio-oil and gas phase yields of greater than 50% mass can be obtained from fast pyrolysis, within a 500-700 °C range.

SUB-TASK B4: Extended Supply Chain Model and Access Economic Business Viability Project.

The supply chain models were developed in conjunction with the Forestry Biofuel Statewide Collaboration Center exploring the option of a biorefinery in the upper portion of the Lower Peninsula of Michigan. The models integrated information from several of the project tasks and

allowed for an evaluation of cost, emissions, and energy consumption impacts of forest resources as feedstocks for potential biofuels facilities in Michigan. The initial project intent was to apply the models in relation to biorefineries only. In reality, the feedstock supply chain would be the same for biomass supplied to a biorefinery, biomass fired or co-fired power plant, or torrefaction/pelletization operations.

SUB-TASK B5: Understand Life Cycle Environmental Impacts of System Alternatives from Forest to Factory Gate.

The goal of Project B5 was to develop measures of the environmental footprint for the main forest products supply chain activities (harvesting and hauling wood) within the state of Michigan. A clear understanding of the environmental impacts of these two activities will help policy makers and investors have a better understanding of how current forest biomass supply operations in Michigan will add to the footprint of their proposed bioenergy/biofuels facilities, giving them more certainty about the entire life cycle of their proposed product. This type of environmental data is critical to businesses hoping to qualify for federal and state incentives to produce fuels or energy that is verifiably lower in environmental burdens than our current fuels or energy.

We detail a life-cycle assessment procedure to collect this environmental impact data, relying on a combination of peer-reviewed literature, national databases, and primary data collected from loggers and truckers within the study area. Several different equipment configurations and operating scenarios for roundwood harvesting are considered. Greenhouse gas emissions and fossil energy demand per green ton of wood are calculated with the assistance of SimaPro 7.2 LCA software. Greenhouse gas emissions and fossil energy demand for wood harvesting were highly dependent on the equipment configuration used and the intensity of the harvest scenario. Results indicated that a full processor / forwarder is the best choice of harvesting equipment configuration due to relatively low inputs and high reported productivity, although the burdens of harvesting depend strongly on the intensity of the particular harvest scenario. Rail transport had 4-5X lower environmental burdens than typical log truck transport, which was directly related to the fuel efficiency of the two transport modes. Calculated environmental burdens for a default harvest and transport supply chain in MI were within the range of values reported for similar operations in the literature. We hope that a detailed summary of our approach to arriving at these values will allow policy makers, business developers, and other stakeholders in the forest biomass industry to utilize these values with some degree of confidence when considering the environmental burdens of the forest biomass supply chain for planned biofuels and bioenergy facilities, or highlight areas where more location-specific data would improve the accuracy of a particular assessment.

SUB-TASK C1: Genetic improvement of planting stock.

Clones of poplar (*Populus* spp.) and shrub willows (*Salix* spp.) have shown great promise as energy plantation crops, producing dry matter yields that are more than eight times greater than the natural forests of the Great Lakes region. Silver maple (*Acer saccharinum*) has shown promise on wet sites in the region. Test plantations were established under this sub-task to screen new clones and half-sib families of these taxa and match the correct varieties of each taxa to the range of sites available for energy plantations in Michigan. Final results of these trials will be available in the future, after the trees have grown for three to eight years.

SUB-TASK C2: Determine yield of poplar and willow clones.

The most promising clones and seedlots from regional breeding and screening programs (like those mentioned in C1 above) need to be tested on a range of sites in large plot plantings in order to establish reliable estimates of yield and produce sufficient material for testing of feedstock physical and chemical properties. Under this sub-task, twenty promising willow clones and ten promising poplar clones were planted in large-plot trials on five sites across Michigan. We will continue to collect data from these field trials for many years to come.

SUB-TASK C3: Improve energy plantation cultural systems.

Sustainability and profitability of energy plantation systems will rely on balancing energy and cost inputs with yields. Choosing optimal planting densities, weed control methods, and fertilizer regimes will determine the success or failure of these systems. This sub-task built on work begun in Escanaba, MI by establishing additional spacing, fertilizer, and herbicide trials for poplar and willow energy crops.

SUB-TASK C4: Commercial plantations of tree energy crops.

Little experience is available in the establishment and management of tree energy plantations in Michigan, despite conceptual appeal. A particular need is for the availability of established, commercial-scale (i.e., greater than 10 acre) trials that would facilitate research on operational-scale management. In this project, two commercial scale tree energy plantations were established in the western Upper Peninsula of Michigan. These plantations complement small-scale test plot networks and a commercial scale plantation established in the northern Lower Peninsula. In the spring and summer of 2010, the two retired agriculture fields were cultivated and hand-planted with hybrid poplar (mostly *Populus nigra x maximowiczii*) cuttings. Early results were positive, with high survival and acceptable growth. Some browse from native white-tailed deer was observed, and limited through the building of temporary fencing.

SUB-TASK C5: Evaluate carbon and nutrient cycling.

The potential environmental benefits and long-term sustainability of biofuels production remains controversial, with uncertainty over what net reductions in greenhouse gas emissions are actually achievable, as well as concerns about the environmental consequences of planting large areas with biofuel crops. The purpose of this sub-task was to develop a better understanding of the environmental impacts associated with conversion of retired agricultural lands to woody biofuels production, including: 1) soil C loss/gain, 2) emissions of greenhouse gases (CO₂, N₂O and CH₄) to the atmosphere, and 3) nutrient leaching and eutrophication of ground and surface waters. Work has quantified the greenhouse gas deficit incurred when land use changes from old-fields to energy plantations.

SUB-TASK C6: Characterize wood properties of poplar and willow clones.

Physical and chemical properties of biomass feedstocks vary among different parts of the tree and with taxa, age, and management system. It will be important to understand this variation in order to characterize various feedstocks' suitability for use by different consumers, such as electric power producers or ethanol manufacturers. This sub-task characterized samples of five poplar and twelve willow clones grown at MSU's Forest Biomass Innovation Center in

Escanaba, MI. Differences among cellulose, hemicellulose, lignin, ash, extractives, and calorific values were measured and reported.

SUB-TASK C7: Commercial plantations of tree energy crops.

Forest residue products are those typically left after timber harvest and include tree tops, branches, standing dead wood, downed dead wood, and non-merchantable trees. Removing residues from forests represents a substantial source of biomass feedstock for biofuel applications. This scale of removal calls for research to understand the sustainability of residue removal from forests. The scope of the research objective is to address the efflux of carbon (C) and nutrients released from forest residue products, which would otherwise be left on site, and to address recovery of forests' productivity following harvest operations when residue removal is increased. Recovery of soil productivity after harvesting is directly affected by forest management and there is a need to identify the level of organic matter that can be sustainably harvested. Results from previous studies indicate that C and nutrient pools and fluxes are extremely sensitive to site specific conditions and require site specific models to be built. Quantifying the pools and fluctuation of C and nutrients in organic material within the Northern Hardwood Forest Ecosystems is crucial to understanding the sustainability of residue harvesting in Michigan and the neighboring states. An assessment of Biomass Harvesting Guidelines and literature review is used as a baseline to discuss potential impacts of residue removal.

SUB-TASK D1: Engage supply chain partners in producing biofeedstocks.

The purpose of this sub-task was to design a landowner engagement process, including the optional design of the contracting relationships with the landowners who are the ultimate source of access to the woody biomass supply. The approach involved five steps: (1) identify and categorize landowners in the affected area; (2) develop options for optimal contracting (e.g., individual performance contracts, landowner cooperative/joint ventures) based on the anticipated supply chain structure with emphasis on incentives, prices/costs/investments, and supply specifications; (3) develop and analyze a landowner survey to assess landowner interests and concerns and to gather reactions to the possible contractual relationships; (4) develop and document a final form for the optimal contract recommendations; and, (5) develop outreach material consistent with the learning from the analysis and survey work.

SUB-TASK D2: Engage communities in producing biofeedstocks.

The purpose of this sub-task was to design a community stakeholder engagement process that will enhance the local community's acceptance of the planned biomass processing facility and its related supply chain. The approach involved three steps. First, an Issue Guide was developed that presents an overview of the issues raised by the biomass project and possible approaches to change. The guide was prepared with input from biofuels and general community stakeholders in the area based on a one-day framing workshop to access public opinion and reactions. Second, a training module was developed for Extension Educators on Community Engagement in Biofuels. Educators were trained in strategies for fostering community dialogue around biofuels and, once trained; they conducted forums in their community to catalyze robust dialogue. The module included a two-day workshop for Extension Educators in the affected region, the Issue Guide (from the first step), a moderators guide to help Educators lead forums, and a brief video documentary to be used at the start of community forums to crystallize issues at hand. Third, we assigned researchers to document and analyze this process with the expectation that scholarship will emerge to inform other communities regarding strategies for meaningful engagement of diverse stakeholders in cellulosic supply chain development.

SUB-TASK D3: Communicate to stakeholders through multiple avenues.

A key objective of the Forestry Biofuel Statewide Collaboration Center (FBSCC) is to increase understanding of forest biomass production systems for biofuels among a broad range of stakeholders. Sub-task D.3 of this project engaged stakeholders by developing a website to house information on the multiple components of the FBSCC, thus providing a forum for distributing publications, event announcements and research results to varied user groups. The website was developed with a range of stakeholder groups in mind, and structured with non-technical language at the higher levels leading to more in-depth and technical information with further exploration of the site. In addition, a seminar series was recorded and distributed online, giving project investigators the opportunity to present research outcomes to targeted stakeholder groups. This video seminar series is hosted through the project website, and provides opportunities for viewer interaction by allowing comments on presentations and the submission of questions for speakers. Throughout the duration of the project, potential website users have been informed of the resources available and new postings through electronic mail and existing mailing lists, linkages with cooperating websites, and outreach and extension personnel. The website is available at <http://www.michiganforestbiofuels.org/> and <http://www.michiganwoodbiofuels.org/>.

Sub-Task A1: Geospatial Forest Inventory Models for Michigan

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Executive Summary

Strategic decisions concerning the timing and location of forest operations require accurate information about the state and rate of change of forest growing stock. Regional forest management would benefit from spatially explicit inventory data across the entire forest area. Due to cost considerations in detailed field inventories, remotely sensed data have often been employed to extend forest inventories through both space and time. The purpose of this study was to generate spatially explicit predictions of growing stock inventory, growth, mortality and removals of above ground biomass across the entire state of Michigan, U.S.A. This is achieved by coupling spectral information from Landsat TM images and other geospatial layers with the inventory data from Forest Inventory and Analysis (FIA) program of U.S. Forest Service in a kNN imputation procedure. The predictor layers in the imputation process included normalized difference vegetation index (NDVI), land cover classes, basal area weighted height (BAWHT), and digital elevation model (DEM) while volume, growth, mortality and removal data from 6,702 sample plots of FIA were utilized for both model calibration and validation. A Random Forest imputation algorithm was implemented to develop spatially explicit forest inventory information across the Entire State of Michigan via the integration of geospatial data with forest inventory plot measurements. Generally, state wide spatial inventory was unbiased but demonstrated relatively low precision. Inclusion of BAWHT as an explanatory variable was found to significantly improve the prediction accuracy. Three levels of comparison were made to evaluate the accuracy of the inventory estimates: at the plot, stand and county levels. The validation procedure confirmed that county level estimates were better than stand level which in turn was better than plot level estimates. The statistical modeling approach employed (imputation) achieved acceptable accuracies when compared to other studies.

Introduction

Forest inventory and monitoring are crucial to develop sound forest management plans, which in turn help in achieving desired ecological, economic, and social objectives. The strategic decisions concerning the timing and location of forest operations are typically dependent on assessment and mapping of forest variables. Two types of forest inventories can be distinguished based on the extent of survey: strategic inventories focus on large area estimates for a large number of attributes while management inventories focus on small area estimates to guide operational forest management (McRoberts *et.al.*, 2007). The number of variables measured during forest inventory is usually high, and new variables are further derived through computations (Tomppo *et.al.*, 2002). Regional forest planning requires spatially explicit inventory of forest attributes across the entire area of interest. Since exhaustive field measurements at the landscape or regional level are prohibitively expensive, remotely sensed data are often coupled with limited forest inventory data to extend the measurements through both space and time.

Imputation Methods

K nearest neighbor (kNN) imputation can be used to develop spatially explicit inventories by coupling sparse sample plot data with continuous scale remote sensing data partitioned into pixel units. The kNN imputation is often applied to (i) supply missing data to complete a data set for subsequent analyses or (ii) to estimate sub-population totals (Reese *et.al.*, 2002; Stage and Crookston, 2007). The idea that motivates kNN imputation methods is that two records with similar X-values (predictor variables) should have similar Y-values (dependent variables) (Eskelson *et.al.*, 2009). The kNN imputation is an approach commonly used to extrapolate forest inventory data collected at discrete sampling locations to progressively larger spatial extents. The value imputed to a location can be a value measured at another sample plot location, or an average value computed from multiple sample plot locations (Eskelson *et.al.*, 2009). In a forestry context, the kNN imputation exploits the association between auxiliary variables that are inexpensive to measure over the entire area of interest (such as remote sensing and geospatial data), and forest attributes (which are expensive to measure) of interest measured at discrete sampling locations within the area of interest (Crookston and Finley, 2008). The process involves integrating forest plot inventory data with spatially explicit geo-information on land cover, topography, climate, among others, which are often derived from remote sensing data. The kNN imputation is a two phase sampling procedure in which the first phase involves identifying and obtaining spatially explicit auxiliary layers (geospatial predictors) and the second phase involves a detailed sample plot inventory for the required forest parameters (Falkowski *et.al.*, 2010; Falkowski, 2008; Moeur and Stage, 1995). In the procedure, a reference dataset is first produced to generate a model which is then generalized over a continuous target dataset to predict attributes of interest in un-inventoried areas (Hudak *et.al.*, 2008). The reference set consists of field measured sample plot data and corresponding pixel values from geo-referenced raster layers while target set is comprised of only the predictor variables for the total area of interest in the form of pixel values (Bernier *et.al.*, 2010; Hudak *et.al.*, 2008). The kNN imputation algorithm associates one or more of the sample plot data in the reference set to unsampled areas based on the spectral similarity between sampled and unsampled areas. The spectral similarity between a target and reference pixels can be determined by calculating spectral space distance based on covariate (auxiliary variables) characteristics available from geospatial layers for both target and reference sets (Falkowski, *et.al.*, 2010; LeMay and

Temesgen, 2005; McRoberts *et.al.*, 2007). The spectral distance (i.e. nearness of a target and reference pixels) can be measured through several algorithms such as Euclidian distance, Mahalanobis distance, and random forest proximity and target locations can then be imputed with response variables from the nearest neighbors in the reference dataset.

Imputation mapping is a promising technique, with potential for generating spatially explicit, border-to-border information on forest composition (Grossmann, *et.al.*, 2009). The kNN method is non-parametric (i.e. there is no assumption of distributional characteristics of the variables) and can estimate multiple forest variables simultaneously and is a simple but powerful tool to extend a wide range of field data to landscapes (Haapanen *et.al.*, 2002; LeMay and Temesgen, 2005; Katila and Tomppo, 2002). The method can also preserve the covariance structure of forest variables and thus produce maps that appear very realistic in terms of their spatial pattern (Haapanen *et.al.*, 2002; Holmstrom, 2003; LeMay and Temesgen, 2005; Moeur and Stage, 1995). Nearest neighbors techniques have been shown to be useful for predicting multiple forest attributes from forest inventory and remote sensing data such as Landsat imagery (McRoberts, 2009).

Imputation mapping is impacted by a wide array of factors including the selection of explanatory variables. Examples of such factors include raster images from satellite sensors as explanatory layers, type of distance metric (for finding nearest neighbors), and the number of nearest neighbors (i.e. value of k) from a reference set to be considered in the imputation (Kalila and Tomppo, 2001). The type of distance metric and the number of neighbors (k) used in imputation mapping vary among applications (LeMay and Temesgen, 2005). When a single nearest neighbor is considered for imputing target locations, then simply the response variables of the nearest neighbor is assigned to the target points (Crookston and Finley, 2008; Falkowski, 2010; Hudak *et.al.*, 2008), and in such a case the natural variation of the forest variables is retained in the prediction but accuracy of prediction reduces (Katila and Tomppo, 2001; Makela and Pekkarinen, 2004). When more than one nearest neighbors are used to impute missing parameters at target locations, the prediction accuracy improves but more bias is introduced (McRoberts *et.al.*, 2002). The bias introduced with increasing values of k can be reduced to some extent by undertaking weighted average of the k neighbors (Kalila and Tomppo, 2001).

The pixel-wise estimates of any forest parameter can be made as the weighted average of the parameter (v) measured in k nearest sample plots (j). For any target pixel (p) in a feature space, the value of a parameter (v) can be expressed as in the equation 1. The weights assigned to each of the k samples are generally proportional to the inverse squared Euclidean distance (d) between the pixel to be estimated (p) and the reference plot-pixel, j (see equation 2) (Haapanen, *et.al.*, 2002; Nilsson, 2002; Reese *et.al.*, 2002; Tomppo *et.al.*, 2002). The estimate of variable (v) for pixel p is

$$\hat{v}_p = \sum_{j=1}^k w_{j,p} \times v_{j,p} \dots\dots\dots 1$$

Where

$$w_{j,p} = \frac{1}{d_{j,p}^2} \bigg/ \sum_{i=1}^k \frac{1}{d_{i,p}^2} \dots\dots\dots 2$$

such that $d_{1,p} \leq d_{2,p} \leq \dots\dots \leq d_{k,p}$ and

$d_{j,p}$ = feature space distance from pixel p to plot j and

$v_{j,p}$ = variables for the plot with distance $d_{j,p}$

Haapanen and Ek (2001) have described the kNN algorithm in a straightforward way as:

1. For each target pixel calculate the Euclidean distance to all reference pixels
2. Rank the k nearest plots based on the Euclidean distance
3. Calculate weighted average of the desired forest parameters of the k nearest plots
4. Proceed to the next target pixel.

The kNN imputation simultaneously gives estimates for more than one response variables (Bernier, *et.al.*, 2010); in fact, the plot identifiers (IDs) of reference set are imputed to the missing locations based on the similarity of explanatory variables and the values of the response variables corresponding to the IDs are assigned to that location (Falkowski, 2010). The imputation with a single nearest neighbor produces output with similar variance structure to that of the sample plots measurements. Imputation error is evidently greater than ordinary least square regression because values assigned to each target unit using single neighbor imputation are the original values from reference plot data (Hudak *et.al.*, 2008). The root mean square difference (RMSE) calculated from the difference between imputed and observed values provide a measure of model error.

The plot level accuracy of imputation estimates are found to increase somewhat with higher values of k but also leads to over-prediction of forest growing stock (and hence bias) in areas having low stock and vice versa (Grossmann *et.al.*, 2009). Depending on the purpose of imputation, a lower value of k is set to retain the variation of field variables in the estimation and mapping while a higher value of k selected to minimize pixel level RMSE (Kalila and Tomppo, 2001; McRoberts *et.al.*, 2002). The errors of omission are found to decrease with increasing levels of k , but errors of commission increase for forest type predictions (Grossmann *et.al.*, 2009; Haapanen *et.al.*, 2002). Also by increasing the number of sample plots in the reference set, the prediction accuracy can be expected to improve as better matches, in terms of predictor variables (X-values), would be found for the un-sampled areas (LeMay and Temesgen, 2005). Thus, to obtain a reliable estimate with the kNN method, it is important to have a practically large sample of field inventory plots representing all forest conditions available in the area of interest (Haapanen *et.al.*, 2002; Tomppo, 2006). The sample plots in the reference set are assumed to characterize the entire range of variability in the predictor variables i.e. the field plots and the corresponding geospatial data should characterize the entire area of study (Hudak *et.al.*, 2008). Choice of X and Y variables, distance measure and k all contribute to error, but no single choice gives best result for all applications, nor for all response variables within a given application, and models must be developed on a case-by-case basis (Eskelson *et.al.* 2009; Ohmann *et.al.*, 2011). There are several popular variants of kNN and most of these methods define nearness in terms of weighted Euclidean distance. Previous researches suggest that Random Forest (RF) NN outperforms other NN methods for mapping forest attributes (Ohmann *et.al.* 2011). The RF algorithm offers a novel nearest neighbor distance metric for imputation problems and can handle both categorical and continuous data simultaneously (Breiman, 2001). The algorithm is based on classification and regression tree (CART) technique that has achieved excellent results in classifying remotely sensed data (Falkowski *et.al.* 2009).

RF is a type of ‘ensemble learning’ that generates many trees and aggregates their results. The two well-known methods of ensemble learning are boosting and bagging. In boosting, successive trees give extra weights to elements incorrectly predicted by earlier trees and final prediction is based on weighted voting of each. In bagging, each tree is independently constructed using a bootstrap sample of the data set and final prediction is based on a simple majority vote of prediction (Liaw and Wiener, 2002). The RF algorithm begins with the selection of many bootstrap samples and a classification tree is fitted to each of the bootstrap samples (see Figure 1) such that each node of a tree is split using the best among a subset of predictor variables selected randomly at that node for the binary partitioning (Breiman and Cutler, 2004; Cutler *et.al.*, 2007; Liaw and Wiener, 2002). RF can be thought of as a special case of bagging: in the case of bagging, best split at a node is chosen from among all predictors but in case of RF the best split is chosen from a random sample (subset) of predictors (Liaw and Wiener, 2002). Hence, every tree is different owing to two factors: first, at each node, a best split is chosen from a random subset of the predictors rather than all of them; second, every tree is build using a bootstrap sample. At each step in fitting a classification tree, an optimization is carried out to select a node, a predictor variable, and a cut-off value (for numerical variables) that result in the most homogeneous subgroups for the data, as measured by the Gini index (Falkowski *et.al.*, 2009). The splitting process continues until further subdivision no longer reduces the Gini index. Every time a split of a node is made on variable m the Gini impurity criterion for the two descendent nodes is less than the parent node. After the trees are fully-grown, each is used to predict the OoB observations (about one-third of the cases are left out of the bootstrap sample). The predicted class of an observation is calculated by majority vote of the OoB predictions for that observation (Cutler *et.al.*, 2007). The error rates are computed for each observation using the OoB predictions and then averaged over all observations. Thus out-of-bag (OoB) observations are used to estimate the prediction accuracy and variable importance for an element, and there is no need for cross-validation or a separate test set to get an unbiased estimate of error (Breiman and Cutler, 2004; Cutler *et.al.*, 2007; Falkowski *et.al.*, 2009; Liaw and Wiener, 2002; Pang *et.al.*, 2006). The RF algorithm is strictly non-parametric, flexible and robust with respect to non-linear and noisy relations among input features and class labels (Breiman, 2001; Cutler *et.al.*, 2007; Falkowski *et.al.*, 2009).

Figure 1. A simple schematic of random forest algorithm (adapted from Yang *et.al.* 2008)

In RF, nearness is defined by one minus the proportion of trees where target observation is in the same terminal node as a reference observation (Breiman, 2001; Crookston and Finley, 2008; Liaw and Wiener, 2002). The intuition is that similar observations should be in the same terminal nodes more often than dissimilar ones (Liaw and Wiener, 2002).

The RF described by Breiman (2001) has following characteristics:

- Its accuracy is as good as Adaboost and sometimes better
- It's relatively robust to outliers and noise
- It's faster than bagging and boosting
- It gives useful internal estimates of error, strength, correlation and variable importance
- It's simple and easily parallelized.

Data Sources

Forest Inventory and Analysis Program

The Forest Inventory and Analysis (FIA) program of the US Forest Service has a nationwide periodic inventory system for national, regional, and state-level assessment of forest resources to describe status and change in forest resources (McRoberts, 2000). The FIA program has

collected and compiled data for several attributes under the permanent plot design, established especially after 1999 when FIA program shifted from a periodic inventory to an annual inventory system (Woudenberg *et.al.* 2010). FIA permanent ground plots are designed to cover 1-acre sample area (however, not all trees on the acre are measured) such that each plot is representative of 6,000 acre hexagonal area on ground and consists of a national standard fixed radius four subplots as shown in Figure 2 (Woudenberg *et.al.* 2010; Burkman, 2005). The annual inventory scheme of FIA program covers upto 20 percent of the total plots (called panel) in a state each year (hence, generally all plots in a state are visited once in five years and have five panels). The sampling intensity of this program is obviously designed for large area estimation such as entire states or regions.

Figure 2. Distribution of one FIA sample plot per hexagon of 6,000 acre on ground (left) and standard plot design for the measurement of different forest components

Remote Sensing Products

The development of remote sensing sensor systems, both satellite-borne and airborne, and GPS devices are facilitating the enhanced use of remotely sensed data in forest inventories. Landsat Thematic Mapper (TM) has archived the longest data record since 1972 and has a long history of widespread use and acceptance (Powell *et.al.*, 2010). These data products are available for free at the global archive of U.S. Geological Survey online server (<http://glovis.usgs.gov/>) in a standard processing format at a spatial resolution compatible to the size of FIA field inventory plots (see Figure 3).

Figure 3. The FIA ground plot geometry versus 30 m TM pixels. The dark grey circles represent the area of locational error due to GPS errors. The larger grey circles represent the potential locational error due to image registration (Hoppus *et.al.* 2000).

Objectives

In this study we mapped regional scale growing stock woody volume and net-growth by coupling four geospatial layers (auxiliary variables), namely normalized difference vegetation index (NDVI) derived from Landsat TM imageries, Digital Elevation Model (DEM), land-cover types (IFMAP) and Basal Area Weighted Height (BAWHT), with forest inventory data of US Forest Service's Forest Inventory and Analysis (FIA) program. We applied the RF method of k-NN imputation to predict forest inventory information of interest across the entire State of Michigan. The RF technique was chosen because it has shown better performance in the prediction of forest inventory parameters as compared to other methods (Breidenbach *et.al.*, 2010; Hudak *et.al.* 2008). The technique is intended to create detailed maps of volume and net-growth with useful precision and a high degree of automation.

The purpose of this study was to generate spatially explicit predictions of growing stock volume, and growth across 47 counties in the northern parts of Michigan, USA. The specific research questions were:

1. How can geospatial and FIA data be efficiently integrated to predict the distribution of the desired forest inventory parameters at a regional scale in a spatially explicit manner?
2. How does the accuracy of forest attribute estimates from imputation technique vary from plot to stand to county level?
3. How reliable are the geospatial data for estimation of the inventory parameters of interest?

Methods

Study Area

The northern Lower Peninsula and entire Upper Peninsula of Michigan, comprising 47 counties, was the area of interest for this research (see Figure 4). The study area was delineated so as to avoid the counties with sparse forest distribution in terms of canopy density, particularly from the southern Michigan. The growing stock volume, growth, mortality and removal data (in standard format) from the extensive FIA data base were the basic response variables considered in the analysis for estimation and mapping purpose in this study. The FIA database has inventory records available at both plot and county level.

Figure 4. Study area in Michigan, U.S.A.

The geospatial predictor layers considered in the study were Landsat TM derived NDVI, Land Cover data from 2001, digital elevation model (DEM), and basal area weighted canopy height (BAWHT). All these data layers are publicly available and have the same spatial resolution of 30 m. An independent inventory dataset across Michigan Tech's forestland holdings (1,840 ha at Ford Forestry Centre) was also utilized in this study to compare the results of estimates at the plot and stand-level via field inventory and imputation techniques.

Geospatial Data Preparation

NDVI raster

The following Landsat 5 Thematic Mapper (TM) images as in Table 1 were downloaded from the Global Visualization Viewer (<http://glovis.usgs.gov/>) operated by the Earth Resource Observation and Science Centre (EROS) of the USGS. The images are already processed at the source to Level 1T (L1T) that provides systematic radiometric and geometric accuracy by

incorporating ground control points and also employing a Digital Elevation Model (DEM) for topographic accuracy

(http://edcsns17.cr.usgs.gov/helpdocs/landsat/product_descriptions.html#terrain_15_11t).

Table 1: Landsat imageries used in the study for the derivation of NDVI raster

SN	WRS-2 Path/ Row	Lat/ Long	Acquisition Date	Scan Time	UTM Zone	Sun elevation	Earth-Sun Distance* (d)
1.	20/ 29	44.6/ - 82.7	2007-06-11	16:09:52	17	62.86	1.01536
2.	20/ 30	43.2/ - 83.2	2008-05-28	16:04:19	17	61.93	1.01355
3.	20/ 31	41.8/ - 83.7	2008-07-15	16:03:22	17	61.07	1.01646
4.	21/ 28	46.0/ - 83.8	2008-07-06	16:08:37	17	60.11	1.01670
5.	21/ 29	44.6/ - 84.3	2008-07-06	16:09:01	16	60.86	1.01670
6.	21/ 30	43.2/ - 84.8	2006-06-15	16:15:11	16	63.57	1.01577
7.	21/ 31	41.8/ - 85.3	2007-07-20	16:16:21	16	61.46	1.01616
8.	22/ 28	46.0/ - 85.3	2007-06-25	16:21:35	16	61.91	1.01652
9.	22/ 29	44.6/ - 85.8	2007-06-09	16:22:16	16	62.78	1.01513
10.	22/ 30	43.2/ - 86.3	2007-06-09	16:22:40	16	63.59	1.01513
11.	22/ 31	41.8/ - 86.8	2008-07-13	16:15:47	16	61.35	1.01655
12.	23/ 28	46.0/ - 86.9	2006-07-15	16:27:24	16	59.79	1.01646
13.	23/ 29	44.6/ - 87.4	2007-08-03	16:27:47	16	57.21	1.01471
14.	23/ 30	43.2/ - 87.9	2007-08-03	16:28:11	16	58.08	1.01471
15.	24/ 27	47.4/ - 87.9	2009-08-31	16:29:14	16	47.23	1.00946
16.	24/ 28	46.0/ - 88.4	2007-06-23	16:33:59	16	62.00	1.01642
17.	24/ 29	44.6/ - 88.9	2010-07-17	16:30:58	16	59.95	1.01635
18.	24/ 30	43.2/ - 89.4	2010-07-01	16:31:25	16	62.61	1.01667
19.	25/ 27	47.4/ - 89.4	2009-06-03	16:33:57	16	60.05	1.01433

20.	25/ 28	46.0/ - 89.9	2009-06-03	16:34:21	16	60.92	1.01433
21.	25/ 29	44.6/ - 90.5	2007-08-17	16:39:59	15	53.81	1.01244
22.	26/ 28	46.0/ - 91.5	2007-07-07	16:46:10	15	60.93	1.01669

(* earth-sun distance in astronomical units for Day of the Year).

The images used were captured in between the years 2006 and 2010, ranging from June to August, in the peak of growing season of tree species; only the images from June-Aug were considered to reduce the impact of seasonal and phenological variation. The best quality images with zero percent cloud cover were selected for each scene and area of interest (AOI) were determined for each based on visual inspection of false color composite (FCC) in Erdas Imagine 2010 software. The procedure and parameters suggested by Chander *et.al.* (2009) were applied for the conversion of calibrated digital numbers (DNs) to absolute units of at-sensor spectral radiance and top-of-atmosphere (TOA) reflectance. The models for this conversion were built in Erdas Imagine's Modeler. Thus reflectance images were generated and the red and near infrared bands (namely band 3 and 4) were used for the computation of Normalized Difference Vegetation Index (NDVI) for each of the scenes using model builder in Erdas Imagine 2010. The individual NDVI images were then mosaicked using MosaicPro tool in Erdas Imagine 2010. The overlap function was set to 'feather' and color correction across the NDVI images was made using illumination equalization and image dodging across images (ERDAS Desktop 2010, online help).

Land Cover Raster

The land cover 2001 raster, product of Integrated Forest Monitoring Assessment and Prescription (IFMAP) Project, was downloaded from MI Geographic Data Library <<http://www.mcgi.state.mi.us/mgdl/?action=thm>>. The land cover was derived by the IFMAP project via the classification of Landsat TM imageries collected between 1997-2001 over three seasons, spring (leaf-off), summer, and fall (senescence), to produce a dataset that can serve multiple functions. The land-cover rasters were available separately for the upper and lower peninsula of Michigan. The original raster had 32 classes; however, it was further reclassified into four broad categories (broadleaved forests, conifer forests, mixed forests and non-forest) for the purpose of this study.

DEM Raster

The digital elevation model (DEM) at 30 m spatial resolution (1 arc second) was downloaded for the study area from the National Map Seamless Server (URL: <http://seamless.usgs.gov/website/seamless/viewer.htm>) of USGS, Seamless Data Warehouse. The DEM rasters (in .tiff format) were downloaded in tiles and then mosaicked in the Erdas Imagine using NN resampling and overlay function.

BAWHT Raster

The basal area weighted height (BAWHT) in a raster format is developed by the Wood Hole Research Centre as a part of the National Biomass and Carbon Dataset (NBCD) 2000. The BAWHT raster (as .tif file) is freely available for download from

<http://atlas.whrc.org/NBCD2000>. The raster is produced based on a mapping zone approach in which the conterminous U.S. is split into 66 eco-regionally distinct mapping zones and our study area is labeled as the zone 51. Digital numbers (DN) of the raster represent the average basal area weighted height in meters multiplied by 10. Thus, the average basal area weighted height in meters is DN/10. Development of the dataset is based on an empirical modeling approach that combined FIA sample plot data with high-resolution InSAR data acquired from the 2000 Shuttle Radar Topography Mission (SRTM) and optical remote sensing data acquired from the Landsat ETM+ sensor (Walker *et.al.*, 2007). The BAWHT for an FIA plot is calculated according to:

$$BAWHT = \frac{1}{BA_{plot}} \sum_{i=1}^n (BA_i \times ACTUALHT_i)$$

Where BA_i is the basal area (m^2) of the i th tree in the plot and is calculated according to:

$$BA = 0.00007854 \times DBH^2$$

(DBH is the diameter at breast height (cm) and $ACTUALHT_i$ is actual height of i th tree) and BA_{plot} is the total basal area (m^2) for the plot and is calculated according to:

$$BA_{plot} = \sum_{i=1}^n BA_i$$

The plot level BAWHT of the FIA database is integrated with the predictor rasters using regression tree modeling approach to derive spatially explicit basal area weighted height raster (Walker *et.al.*, 2007).

All the four predictor rasters and GIS layers used in the study were projected to Michigan GeoRef spatial reference (NAD_1983_Michigan_GeoRef_Meters; UTM_Zone_16N).

Mapping Model Development

Joining Geospatial Predictors to Field Inventory Data

The imputation procedure was implemented with a large number of FIA field sample plots in the reference set. The reason for including a large number of sample plots in the imputation process was to find a better match of nearest neighbors for the un-sampled areas based on the similarity of X values of the selected reference and the target pixels as suggested by LeMay and Temesgen (2005) and also with the hope that bigger sample size would better represent available forest conditions in the area of interest. Altogether 6,702 FIA inventory plots data (throughout the Michigan) were obtained for the reference set that included response variables such as growing stock volume, growth, mortality and removals on per acre basis (also by species group code). In order to increase the sample size a compromise was needed in order to pass FIS security clearances. This was achieved by regrouping the NDVI and Land Cover rasters into broad classes instead of using in a continuous format. Because of the privacy and security restrictions of FIA, it was not possible to obtain field coordinates of the FIA plots. However, the generosity of FIA unit at the Northern Research Station made our life easy by attaching the pixel values of each predictor raster layers to the FIA field plots. But this task of linking the FIA field plot attributes to the raster values was possible only after retaining a limited number of unique values for the combinations of the raster layers and that needed grouping (classification) of the NDVI and Land Cover rasters. Since users of FIA data are could track an individual FIA plot on the ground (which is against the privacy requirements specified in the amendments to the U.S. Food

Security Act of 1985) if each of the plots have a unique combination of raster values, we had to group the NDVI and land cover rasters into broader classes.

The continuous NDVI raster was classified into 20 classes (using natural breaks in Arc Map 9.3) and the land-cover raster was reclassified into four broader classes namely broadleaved, conifers, mixed and non-forests. The predictor raster layers were then sent to the FIA unit at the Northern Research Station where the plot coordinates were intersected with the spatially referenced predictor rasters and the corresponding raster values were associated with each of the sample plots. In fact, we sent only the classified NDVI and land-cover rasters to the FIA unit in an anticipation to obtain as many sample plots data as possible after passing the security restrictions of FIA; the ground elevation and BAWHT data assigned to the plots were the direct values as measured by FIA. That means the elevation and BAWHT used in the training (reference) set for model building were from FIA while the values of target points for spatially extending the model for the study area were from the rasters. We simply assumed that the plot elevation and BAWHT values provided by FIA were the same as the corresponding values in the spatially referenced raster layers. We do acknowledge that since plot level elevation and BAWHT from FIA data may not exactly match with the corresponding values in the geo-referenced rasters, there is likely bias associated at this stage. A simple flow diagram of the methods employed in the study is described in the Figure 5 below.

Figure 5: Flow diagram of the methods of study

Model Training and Prediction

The sample plots in the reference set are assumed to characterize the entire range of variability in the predictor layers, though the used predictor layers itself were not sufficient to fully describe the heterogeneous forest conditions of this regional study. Since imputation with a single nearest neighbor produces output with similar variance structure to that of the observations, the value of k (number of nearest neighbors) was set equal to one to maintain the variance structure of forest attributes in the imputation process.

To scale the plot level FIA data to maps, we developed RF imputation models relating field-measured response variables to plot level raster value as the predictor variables. As already mentioned NDVI, DEM, land-cover and BAWHT were the predictor variables, however the latter was not included while producing forest attributes distribution map because BAWHT data was available only for limited number of plots. The yaImpute package in R statistical software (www.r-project.org) was used to implement the random forest algorithm (Crookston and Finley, 2008) to impute growing stock volume, growth, mortality and removal for whole of the study area. The yaImpute works with .csv file format of the reference data matrix and determines nearest neighbors for each of the target points based on spectral space distance using auxiliary variables of the reference and target points. The feature space distance considered in this study was based on random forest method. The random forest mode was set to regression, number of trees was fixed at 2000 and $k = 1$. After determining the best random forest model based on least statistical errors, the model was extended spatially using the Ascii Grids of the predictor layers for target area. Since the AsciiGridImpute function takes long time to generate spatial prediction, the imputation process was carried out by splitting the predictor rasters into a dozen tiles and running the imputation model separately for each tile. In this step, each of the target pixels are assigned an identifier from the reference data set and the response variable for the target pixel will be the same as of the assigned identifier.

Model Validation

For validation purpose of the imputation results, a set of data for growing stock volume, growth, mortality and removal was retrieved from the FIA database (FIADB) using EVALIDator program where these data are available for forestland at county-level. This reference set was used for validation of the imputation results for each of the 47 counties. In order to compare the estimates of the forest attributes (particularly volume) at plot and stand level, the growing stock volume data from the Capstone Forestry Project of Michigan Tech was utilized. The Capstone dataset has inventory records, only for the growing stock volume, for 358 permanent plots and 50 stands.

We have used the RMSE and biases (calculated from the difference between imputed and observed values) as a measure of predictive performance of yaImpute i.e. prediction accuracy of the RF imputation, in this study.

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (\hat{y}_i - y_i)^2}$$
$$Bias = \frac{\sum_{i=1}^n (\hat{y}_i - y_i)}{n}$$

Results

Three RF models were developed with the common predictors NDVI, DEM and land-cover. The root-mean square errors (RMSE) with and without BAWHT as an additional predictor in the three models, are given in the Tables 2, 3 and 4. The first model predicts volume and % hardwood; second model predicts volume, %hardwood and growth; and the third model predicts volume, %hardwood, growth and mortality. These model errors are comparable to the estimation error reported by Holmstrom and Fransson (2003), Tomppo *et.al.* (2002) and Nellson (1997) for wood volume using kNN technique (RMSEs of 50 m³ ha⁻¹, 46 m³ ha⁻¹ and 56 m³ha⁻¹ are reported respectively).

Table 2. Error statistics of the random forest model predicting total volume and % hardwood

	RMSE Without BAWHT	RMSE With BAWHT	R ² Without BAWHT	R ² With BAWHT
Volume (m ³)	31.71	26.53	0.2444	0.4103
% Hardwood	33.32	30.16	0.4673	0.5470

Table 3. Error statistics of the random forest model predicting total volume, % hardwood and net growth of growing stock

	RMSE Without BAWHT	RMSE With BAWHT	R ² Without BAWHT	R ² With BAWHT
Volume (m ³)	32.36	27.38	0.2232	0.3855
% Hardwood	34.43	31.05	0.4394	0.5233
Growth (m ³ yr ⁻¹)	1.19	1.27	0.0573	0.0268

Table 4. Error statistics of the random forest model predicting total volume, % hardwood, net growth and mortality of growing stock

	RMSE Without BAWHT	RMSE With BAWHT	R ² Without BAWHT	R ² With BAWHT
Volume (m ³)	32.74	28.02	0.2091	0.3663
% Hardwood	34.77	31.51	0.4289	0.5116
Growth (m ³ yr ⁻¹)	1.17	1.26	0.0633	0.0279
Mortality (m ³ yr ⁻¹)	0.68	0.75	0.0512	0.0159

The four response variables (viz. volume, growth, mortality and removals) were imputed for each of the forty-seven counties selected in Michigan and were compared with the independent reference data obtained from FIA database using the EVALIDator tool. The validation statistics are given in the Table 5. The comparisons of imputation estimates of the parameter with the reference data set at the county level are presented separately in the scatter plots in Figures 6A-6D.

Table 5. Statistics of county level forest parameters comparison

Parameter	R ²	RMSE	Relative RMSE	Bias	Relative Bias
Total Growing Stock Volume (m ³)	0.8940	2686069.42	17.99%	-365700.67	-2.45%
Growth (m ³ yr ⁻¹)	0.7747	81248.23	30.40%	-49669.62	-18.59%
Mortality (m ³ yr ⁻¹)	0.7270	50834.26	42.70%	-12394.02	-10.41%
Removals (m ³ yr ⁻¹)	0.6843	1865.25	47.89%	-787.93	-20.23%

Figure 6A. Scatter plot of county level imputed volumes (m³) against the reference volumes obtained from FIA database.

Figure 6B. Scatter plot of county level imputed growths (m^3yr^{-1}) against the reference growths obtained from FIA database.

Figure 6C. Scatter plot of county level imputed mortalities (m^3yr^{-1}) against the reference mortalities obtained from FIA database.

Figure 6D. Scatter plot of county level imputed removals (m^3yr^{-1}) against the reference removals obtained from FIA database.

The validation of stand level volumes (m^3) against the reference volumes obtained from the Capstone project has also shown encouraging results (see Figure 7 A), though substantial negative bias is obvious in the prediction (bias: -1083.43 m^3 ; relative bias: -46.27%). However, we could not compare the imputed growth, mortality and removals at the stand level because of unavailability of such reference data (in the Capstone project). As expected, the plot level comparisons of imputed and measured forest parameters were worst (see Figures 7B) and the possible reasons are described in discussion section below.

Figure 7A. Scatter plot of stand level imputed volumes (m^3) against reference volumes from the Capstone project.

Figure 7 B. Comparison of plot level volumes (m³) estimated from the imputation technique and Capstone project inventory.

Discussion

The results observed in the study are consistent with previous studies. Although we selected $k=1$ to retain the variability of field attributes in the imputation mapping, the pixel-plot level accuracy of estimates was least and county level estimates were the best. Other studies have also found that pixel level accuracy of forest attribute estimations using kNN is low, but for larger areas more acceptable accuracy is reached (Holmstrom, 2003; McRoberts *et.al.*, 2007; Nilsson, 2002; Tomppo *et.al.*, 2002). For example, Reese *et.al.*, (2002) found that accuracy of the kNN estimates for all forest parameters was low at the pixel level (RMSE for total wood volume ranged from 58–80%), however, better accuracy was achieved over larger areas, with best results being 10% RMSE over a 100 ha aggregation.

The weak association between pixel level measured and imputed values can also be justified on the basis of error in spatial referencing of pixels, error in GPS coordinates of inventory plots and also the design of inventory plots. For example, the layout of the FIA plots is such that the four 24-foot-radius subplots are spread over a minimum of 4 pixels (see Figure 3). The plot level per acre values for the attributes supplied by FIA (used in this study) is based on averaging and up-scaling of the values from the four sub-plots. Therefore, there is not a clear one-to-one relationship between spectral values of Landsat pixel and corresponding FIA plot data. Additionally, the year of FIA plot measurements did not exactly match the year of Landsat image acquisition. In fact, the best available Landsat scenes (used for developing NDVI mosaic), over the years 2006-2010, from the peak of growing season (June to September) were considered to avoid the nuisance of cloud cover.

The county-level data for the four attributes (viz. volume, net growth, removal and mortality) retrieved (for validation purpose) directly from the FIA database using EVALIDator tool, were the estimates of growing-stock on forestland only that includes timberland, reserved forest land, and other forest land. The forestland according FIA definition is any land having at least 10 % crown cover. The FIA plots, according to current design, can also include areas having <10% crown cover (i.e. non-forest) and the imputation technique also considers such plots and gives prediction for both forested and non-forested pixels. However, in a surprising way our results show that the total of the imputed values for most of the counties are below the reference values (obtained from EVALIDator) as shown by the distribution of points below the 1:1 line in the Figures 6 and 7. This means that the imputation models are under predicting the forest parameters. This is something that we are still working on by excluding non-forest lands and including more predictor layers in the ongoing imputation process. Use of mask to exclude non-forest area and running imputation only for the forested region could possibly improve prediction and also reduce imputation time. This will be carried out in the upcoming version of Forest Biomass Information System (FBIS).

Since the study required grouping of NDVI and land-cover rasters in broader classes because of the security issues of FIA, the predictive power of the auxiliary layers was obviously less than it would have been without the grouping. The inclusion of BAWHT though improved the prediction accuracy significantly, our team decided not to use this variable while mapping the forest parameters because the height data was available for fewer numbers of plots in the study area. Further, the BAWHT and elevation values attached to the available plots in the reference data matrix were not extracted from the raster layers (we supplied to FAI), rather these values

were the results of field measurements made by FIA at the inventory plots. So there is likely inconsistency between the raster values and the plot-level values for these two variables and hence also bias in the estimation. Our team has further contemplated to include a disturbance element as an additional predictor to better estimate the forest attributes, particularly net growth, in the final version of imputation mapping. We are going to use time-series NDVI imageries from MODIS sensor to develop a raster layer as a predictor of disturbance in the upcoming edition of FBIS.

This research did not consider the differences in vegetation zones over the large study area. Operational application of the kNN method has also shown that the predictions may be biased if the area of interest is large and covers several vegetation zones with different tree species compositions (Tomppo, 2006). The biases can be reduced if the set of potential nearest neighbors can be restricted to strata by classifying the area into different vegetation zones. This is something to look at in future research.

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Sub-Task A2: Forest Biomass Information System for Michigan

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Executive Summary

Very high quality forest inventory data are available from the USDA Forest Service Forest Inventory and Analysis Program, for forests under all ownerships in the United States. These data span multiple owners in time and space and are known to be very accurate and of exceptionally high quality. Unfortunately, systems for non-technical users to access these data are not available, and furthermore, spatial analyses especially at small scales are difficult with extant public FIA database tools. In this project, a user-friendly, cross-platform interface to FIA data was developed, based on ESRI ArcGIS server software. Non-technical users, Mac, PC, Linux or other platform, can access the server system using a standard web browser. Both fixed-radius and irregular user-defined query areas are possible for users to define, and the web system presents both graphical and tabular summaries of forest inventory, growth, mortality, removals, net growth after removals, and potential logging residues associated with timber harvest. The new system is robust, stable, and effective at making dense and sparse inventory data available to non-technical users with continuous, 30 m resolution raster coverage for the entire state of Michigan. Analysis of accuracy of the underlying data is presented elsewhere. This report summarizes the functionality of the Forest Biomass Information System (FBIS), the WebGIS software environment and extensions that make the underlying data, developed recently and revised in the future, available to non-technical users.

Introduction

The best available forest inventory and growth data in Michigan are associated with the USDA Forest Inventory and Analysis (FIA) program (Bechtold and Patterson 2005). FIA is a national program with standardized inventory methods that rest on an extensive network of field samples that is the foundation of the FIA program. These samples are the product of cyclical visits to known forested locations and measurement of current tree inventory and attributes. Through successive visits, changes in inventory attributes, such as tree growth, mortality, and harvest removals can be calculated. Key strengths of FIA are that field plots are established on all forested lands, regardless of ownership. Furthermore, FIA data are of very high quality, and with one notable exception, are freely available to both public and private users and agencies for use in assessment and analysis of forest resources.

The notable exception regarding FIA data availability relates to a very strict policy of privacy regarding the actual geographic location of the field plots (McRoberts et al. 2005). An approximate location of an FIA plot is available, where the approximation is a product of two processes: fuzzing and swapping. Fuzzing means the addition of randomness to the actual coordinates, so that the released coordinate contains error. Swapping means that a proportion of FIA plots are paired with other FIA plots that are similar in forest composition and the fuzzed coordinates are exchanged within the pair. The policy makes precise geospatial analyses using FIA data impossible with public data. Alternatives include requesting custom spatial analyses performed by FIA staff or using public FIA interfaces. One example is the EVALIDator web system, where users can define spatial queries through a website, which are ultimately processed on FIA servers using actual coordinates.

Existing FIA data and systems, however, have constraints that need to be overcome to make data accessible to demands from an increasing array of often non-technical users. Key constraints are threefold. First, the FIA interface is currently a simple web-based and interactive form-driven query system, suited for occasional users who are familiar with the underlying FIA protocol, definitions, and limitations. Second, while the FIA inventory records the land ownership class at each field plot, no distinction is made between industrial and non-industrial private owners. This prohibits analyses that distinguish between these two very important owner types, who often have very diverse goals and practices.

A third constraint involves the size of spatial domain possible to analyze using FIA plot data. The FIA field plot network is a sample-based system, with a national standard intensity of about 1 plot per 6,000 acres, which was until 2005 intensified to 1 plot per 2,000 acres in the heavily forested parts of the State of Michigan. When used to generate averages for geographic areas of interest, the precision of those averages declines as the size of the area of interest declines. Ultimately, when areas of interest fall below 2,000 acres it is possible that they contain no FIA field plots, preventing any estimation of forest inventory whatsoever.

Increasing Non-Technical User Access to FIA Data

The Forest Biomass Information System for Michigan (FBIS) is an integration of several efforts to increase the access to FIA data for non-technical users, and to reduce the effect of existing constraints on the possibility for precise spatial analyses.

FBIS has three parts:

1. Geospatial (raster grid) forest inventory model
2. WebGIS server system interface to inventory and availability data
3. Availability module that defines the fraction of inventory that is available for harvest

The focus of this report is on the WebGIS server system, which is the public face to the FBIS for Michigan. Reports that summarize the other two components are available separately. Briefly, an overview of the other tasks is summarized here to provide context.

Geospatial Forest Inventory Model

The geospatial forest inventory is based upon FIA data and generates estimates of forest inventory attributes *in-between existing FIA plots*. The output is a continuous gridded, or “raster” based inventory data set, where the State of Michigan is divided into 30 m square grid pixels and inventory estimates are available for each pixel. This approach offers many advantages. In addition to providing an interpolation of inventory values between known points, the geospatial grid also transforms FIA data to a format and scale that permits seamless interface with other spatial data, such as road networks, soils and ownership. Benefits include facilitating value-added applications, such as spatial-based supply chain analysis and optimization. The geospatial inventory is the data foundation within FBIS, and was developed at Michigan Technological University.

Availability Module

Potential harvest is ultimately defined by forest inventory. However, landowners have many motivations for the harvest of forest products, or may be motivated to not harvest at all. Thus, the amount of forest inventory that is available for harvest may be viewed as a fraction of the

potential. If the harvest rate exceeds the growth rate, then forest inventories are depleted. If the harvest rate is less than the growth rate, then forest inventory is accumulating. Generally, sustainable utilization of forest resources generally implies a harvest rate that does not exceed growth rate; i.e., a “growth to removals” ratio of 1:1.

Michigan State University has assessed forest availability, which was intended to act as a set of “filters” in the WebGIS system. These filters act to reduce the harvest potentials that come from gross inventory and growth rate, to represent the practical portion of that potential that might actually be realizable, or available for utilization. A variety of scenarios were contemplated, including current restrictions and planned harvest levels that might deviate from past behavior. An objective in the development of the FBIS for Michigan was that these filters would be incorporated into the WebGIS system

Developing a Web-based Information System

Once gridded geospatial inventory and availability data are available a range of new possibilities for analysis are possible. For example, defined areas of interest may be overlain on the gridded inventory data set for some attribute of interest, and values for each grid cell summed to provide an area-based total. Filters can be applied to net down inventory, growth, etc., based on assumptions about constraints that limit the available portion of the standing inventory or to limit results to other subpopulations of interest (e.g., a specific forest cover type). All of these are enabled only within appropriate computing environments, such as in the ESRI ArcGIS workstation software, which are very powerful but rarely accessible to non-technical or users outside of institutions.

The approach in this project was to embed the geospatial library within an ArcGIS server system, and develop a custom web application that would deliver essential data management and query functionality through a conventional web browser (Figure 1). The system provides user-friendly WebGIS capabilities that enable customized spatial analyses in real time and in a platform independent way, with similar function regardless of the user’s computing environment (i.e., Windows, Mac, Linux or even tablet or smartphone browsers).

The WebGIS interface permits mapping and spatial analyses conceptually similar to the stand-alone GIS implementation entitled FIAMODEL (<http://forest.mtu.edu/data/fiamodel/>) but with a web browser interface, similar to the USDA Web Soil Survey (<http://websoilsurvey.nrcs.usda.gov>). Through this interface, users can interactively define areas of interest based on circles or irregular polygons that constrain reports or analytical operations, and display associated forestry data (e.g., inventory, removals). Outputs will include graphical displays and printable reports summarizing the available biomass under that scenario. Our original design imagined users having the option of specifying a set of availability filters that reflect differences in institutional constraints on availability, and gaming the nature of those constraints to reveal spatial utilization outcomes.

We call this system FBIS, and it is accessible at the URL <http://fbis.mtu.edu>.

Figure 1. Conceptual model of the FBIS.

Objectives

The overall goal of this project was to develop and integrated forest inventory and availability data warehousing and analysis system accessible to non-technical users. The system is accessible to users through standard web browser client software (e.g., Safari, Firefox, Internet Explorer) that is essentially operating system independent.

This goal was divided into several objectives:

1. Deployment of the basic software and hardware platform, including ArcGIS server, web server and necessary database back-end
2. A project website, hosted on the FBIS web server
3. Deployment of the WebGIS framework including base data, mapping functionality, availability model and query functionality
4. An embedded help system that acts as a user's guide to the data content and the WebGIS functionality

Methods

Geospatial Data

Forest Inventory

The data foundation for FBIS is a continuous, raster grid output from a geospatial model of the FIA inventory data set. The approach used was to construct a “mapping model”. The basic principle behind this approach is to model the relationship between the attributes of interest, which are measured on forest inventory plots (e.g., standing volume), and auxiliary information, such as remote sensing data from satellites (e.g., Landsat, MODIS), digital topographic maps and so forth. The FIA inventory plot data for Michigan was the reference data set used to train the mapping model.

Once the mapping model was developed it was used to predict, or impute, the attributes of interest at all of the points in-between the measured plots, using the auxiliary information, which was continuous. The result is a continuous gridded inventory data set. Technically, what is actually imputed to each pixel is the label of the FIA inventory plot that is most appropriate given the combination of auxiliary data for that pixel, as predicted by the mapping model. Then, forest attributes at the imputed pixel are automatically those associated with the reference plot. The development of inventory data was involved and only a brief summary is presented here. For more information on please refer to the project report for that task (Deo et al. 2011).

Forest Land Ownership

Unfortunately, there is no single and convenient source of geospatial land ownership data for the State of Michigan. Data for most public lands are available from those agencies. For state lands, ownership data were obtained from the Michigan Geographic Data Library (<http://www.mcgi.state.mi.us/mgdl/>). Similarly, data for Federal lands (National Forests) were obtained from the USDA Forest Service.

The remaining two categories of forest land ownership were industrial and non-industrial private owners. Unfortunately here is no public source of geospatial data on these ownerships. Data may be purchased from private companies (e.g., Rockford Map Publishers) who aggregate public records on ownership but these are only available at considerable cost. For this project, we relied upon a geospatial data set developed for research completed at Michigan Tech in 2007, the subject of which was corporate land ownership patterns in the Michigan UP (Froese et al. 2007). In this project a custom geospatial representation of corporate ownership, circa 2005, was developed. Since there are effectively no industrial forest land owners in the Michigan LP the data set was deemed sufficient for this project. Finally, lands that did not fall into the State, Federal or industrial classes is assumed to be in non-industrial private ownership.

Additional Spatial Data

Additional spatial data sets were included to provide contextual information that users might find valuable. Display of these sets is optional, on with only ownership included by default. Data were obtained from the Michigan Geographic Data Library and sets available in FBIS include cities, roads, rail, lakes, streams and county lines.

Server Hardware and Software Environment

The FBIS system resides on a dedicated server running Windows Server 2008 R2. Web services are provided by built-in Microsoft IIS software. The server is hosted at Michigan Technological University, and beyond the termination of the project will be maintained informally as long as time and resources allow.

The FBIS architecture was developed in two stages and released independently as two versions. Version one of FBIS utilized ArcGIS Server (.NET) and the WebADF framework to present a web browser based interface to the user, execute the geoprocessing models and pass the output back to the user. A sample map viewer application produced by ESRI was used as a starting point for development and all code was written in C#.

Version two of FBIS utilizes the ArcGIS Javascript API and REST (representational state transfer) service of ArcGIS Server to present a web browser based interface to the user, execute the geoprocessing models and pass the output back to the user. Sample code from the ESRI Javascript API sample library was utilized as a starting point for development and all code was written in Javascript.

Geoprocessing

ESRI's ArcMap software was utilized to develop two geoprocessing models to compute aboveground biomass based on a user-selected area. The first model utilizes a point/buffer specified by the user to determine the area of interest (AOI) to be used in the computation (Figure 2). The second model utilizes a user drawn polygon for the same purpose (Figure 3). The underlying data for both models is a raster of integers in which the pixel values represent a unique combination of ownership (corporate, state, federal or NIPF) and above ground biomass. The raster is clipped to the user specified area and joined to an attribute table (BiomassOwnerTable) that contains the above ground biomass values and ownership by pixel value. The biomass values for the selected area are then summarized by a custom software program, written in the Python programming language, and two sets of output are generated: (1) a comma delimited text file (.csv) and (2) a set of data values in JSON (Javascript Object Notation). The JSON output is passed back to the web browser where it is displayed as a chart or table. A link to the .csv file is also passed back to the web browser thus enabling the user to download the output and perform additional processing.

Figure 2. Geoprocessing model for an area of interest query defined by a point.

Figure 3. Geoprocessing model for an area of interest query defined by an irregular user-specified polygon.

Results

Root Website

The root of the FBIS web site is a set of seven web pages. The home page (<http://fbis.mtu.edu>) presents an attractive introduction to the FBIS collection from which a user may proceed directly to the mapping and query application, or learn more about the FBIS system. Featured prominently on the home page are links to sponsoring agencies (MTU, MEDC, DOE) and a link to the availability research completed by MSU.

Links are also provided to pages that meet specific navigation and information needs:

1. Home page – the “first page” that a user sees and links to other pages
2. What’s New – provides a summary of model releases and new features
3. Contact Us – links to email addresses for questions about the web application and underlying data
4. Browser Requirements – enumerates the web browser platforms that are known good
5. FBIS User Guide – a set of “help” or “manual” pages that describes the system
6. Sources of Funding – acknowledgements for MEDC and DOE as sources of funding
7. Disclaimer – text required by DOE

Each web page has a link back to the root page so that a user can return to the beginning at any time.

Figure 4. FBIS home page.

Figure 5. Web site "What's New" page.

Figure 6. Web site "Contact Us" page.

Figure 7. Web site "System Requirements" page.

Figure 8. Web site "Help" or "User Guide" page.

Figure 9. Web site "Sources of Funding" page.

Figure 10. Web site "Disclaimer" page.

FBIS Query Page

The FBIS query page presents a base image from the Microsoft “Bing” service (Figure 11). Zoom and pan can be controlled with a wheel mouse, or alternatively zoom can be controlled with a slide bar on the top left portion of the map. Controls and the map legend are presented as pull-down menus in the top right hand corner. This interface maximizes the available amount of screen space for map display.

Queries are initiated by selecting one of the biomass tools from the pull-down menus. Queries establish areas of interest for inventory summaries and may take one of two forms: circular or polygon. Circular queries (Figure 12) have a minimum radius of 5 miles and the user may select any location within the UP or northern LP as centroids. For polygon queries (Figure 13) the user draws polygon queries freehand, by clicking on the mouse to establish vertices for the polygon. A double-click on the final vertex completes the polygon. The system obligates a polygon to encapsulate an area of at least 6,000 acres.

Output from the geoprocessing models is rendered in the user’s web browser and consists of graphics representing the user selected area, a data table of above ground biomass in cubic feet, and a link to a downloadable .csv file.

Figure 11. FBIS query page as first presented to the user.

Figure 12. Example of a circular area query, defined by a point and buffer.

Figure 13. Example of a polygon based query, drawn by the user.

Discussion

The goals of this project were successfully met. The FBIS WebGIS system has proven to be a robust and stable software environment in testing, and meets the design goal of making inventory data available to non-technical users. The final version builds upon new Javascript tools and a linkage to public imagery to produce an application that maximizes user space for visualization. There are many opportunities to improve the user experience, information available, and capabilities of the entire FBIS system. Some depend on the development of rich base data, improving on the existing geospatial inventory model embedded in the WebGIS environment. The data set available here provides estimates of inventory, growth, mortality, removals and potential logging residues associated with removals, by major species group (hardwood and softwood). Future data products could include further detail, dividing for example major species groups into individual species, like maple, beech, ash, birch, etc. The programming effort to allow this function in the geoprocessing code would be relatively small. However, allowing for the reporting of a larger array of attributes would require modification to the user interface, because graphical or tabular outputs could become too large to display. Thus, more detailed query design would be needed.

The FBIS system presents an attribute called “net growth after removals”, which is the amount of annual growth accumulating as new inventory. Since landowner motivations vary, not all of this growth could be available for harvest; some landowners simply have no interest in cutting trees, though the growth of those trees is still accounted for in FBIS. So a plausible scenario for the actual fraction that might be available might be desired, and this is subject to assumptions. The original design for the WebGIS system included functionality where a user could select an availability scenario that reflected e.g., optimism or pessimism about availability assumptions. In a related task, MSU partners developed some information about availability, but it was decided that the decision about availability was best left to model users, and the functionality was not implemented in the WebGIS system. In the future, further information might be available that increases confidence about likely availability assumptions and these could be embedded in the software environment.

Factors other than landowner willingness to harvest ultimately limit the availability of timber and residue harvest. These could include topography, soils, access, wildlife habitat and other non-timber objectives, uncertainty about desired future stand conditions and silvicultural requirements, among many others. Analysis to support the determination of these factors has been completed for some lands in Michigan (e.g., Pederson 2005), and generalized approaches to estimating these for all stands in Michigan are possible. Adding such functionality to FBIS would allow for more realistic, and more certain, estimates of available roundwood and biomass harvests to be determined. This would further reduce uncertainty in the siting and management of new and existing wood products processing facilities, as well as provide the ability to use FBIS to “game” alternative scenarios to reveal possible futures.

As designed, FBIS presents interactive graphics and a downloadable table that includes all inventory attributes for the users’ query region. In the future, the user experience would be enhanced if the FBIS system could prepare a custom report, say in PDF format, that could be downloaded in addition to the inventory data. The report might include an attractive map that shows the query area and background map data, graphs and tables that illustrate the inventory

attributes, and some interpretive information that would aid especially novice users. These additions were beyond the scope of this project, but would be relatively straightforward to implement and should be considered in future revisions of the FBIS system.

Many other possible extensions of the FBIS environment are imaginable. The WebGIS environment is amenable to building spatial models of transportation networks and associated time, distance and cost metrics. These could be used to extend the spatial models of availability to spatial models of delivered wood cost, conditional on alternative facility siting options. Similarly, limiting factors to harvest often have a cost component themselves; i.e., steep slopes or wet terrain could mandate seasonal or equipment restrictions that have implicit effect on harvest cost. By combining the existing FBIS base data with new data on terrain, soils, and transportation, a very sophisticated model of roundwood and biomass inventory and availability would be possible.

The most exciting feature of the FBIS WebGIS system, however, is that it makes very extensive and very high-quality forest inventory data available to non-technical users, and in standard desktop computing environments. All of the sophisticated computer processing is off-loaded to the model developers and the web server system, which are external to the user. Whether this system has use for non-technical users remains to be seen, and collecting user-data would also be a valuable addition to the WebGIS system.

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Sub-Task A3: Assessment of Forest–Based Biomass Availability.

Reported by Karen Potter-Witter, Lee Mueller, Shivan GC, and Larry Leefers

Michigan State University

Final Report

(March 2009 through April 2011)

Task Summary

The purpose of this task was to model a set of conditions which would translate raw forest inventory data into volume available for harvest and to apply these to the entire State through the Forest Based Information System (FBIS) developed under Task A2. An assessment of forest based biomass availability provided key spatial based data layers for the FBIS. Current availability estimates began with annual growth less mortality on each forest type by sub-state region as input. Next, filters were applied by reducing this amount by past harvest trends and identified administrative, institutional or behavioral constraints particular to each ownership. Potential availability can be explored using the FBIS by choosing or relaxing specific constraints thus giving the user an idea of where investments may be made to improve availability.

Milestones in the project included construction of a database of forest biomass growth, removals, and harvest trends; completion of primary data analysis of a survey of the logging and mill sectors of Michigan's forest product industries; the gathering and analysis of public and institutional forest planned harvests; an in-depth analysis of an existing non-industrial private forest database (developed earlier at MSU); and the construction of production functions. This work was integrated with the FBIS and subsequently led to the analysis done under Task A4.

The MSU Subtask A3 team developed a forest inventory, growth, and removals database for Michigan (variable summaries are in Table A3.1). The data sources were the USDA Forest Service FIA online forest inventory and timber products output databases. Responses to the surveys of Michigan loggers and of Michigan primary forest products manufactures were entered into a database and summary analyses were prepared. Wood consumption information for each of Michigan's six commercial wood-burning power plants was obtained.

The MSU Subtask A3 team wrote a first draft of the statewide snapshot of biomass availability. This document included data compiled from USDA Forest Service FIA, Forest Service Plans, State Forest Plans, timber product output, and surveys conducted of mills, landowners, and loggers. The team also continued work with MTU Task A2 PI Robert Froese to structure these data for use in the FBIS model.

Potter-Witter and GC met with MTU PI Froese to review the beta version of FBIS and to develop a protocol to incorporate biomass availability information into the FBIS model. MSU drafted availability multipliers by region and ownership. A summary report of task A3 was posted to the Michigan Biofuels website.

Effort in the last quarter focused on integrating relationships determined from primary data collection into MTU FBIS model upon MTU completion of the model. MSU provided detailed

spreadsheets containing availability relationships by major ownership group and inventory region (Appendix A3(l)) to MTU PIs Robert Froese (Task A2) and Dana Johnson (Task B4) and graduate assistant Feng Li. These relationships were discussed at length via conference calls throughout the quarter.

Table A3.1. Timber harvest availability data and modeling scenarios for the Forest Based Inventory System.

For Each of Four Michigan Regions			
By the Following Ownerships			
Family Private Forest	Institutional Private Forest	National Forest	State Forest
net annual growth	net annual growth	net annual growth	net annual growth
historic harvest trends	historic harvest trends	historic harvest trends	historic harvest trends
proportion of owners who say they would be willing to harvest	estimated harvest levels	planned harvest levels	planned harvest levels
Modeling Results: Harvest Availability Estimates from FBIS Queries			
Example Scenarios:			
Status quo	Status quo	Status quo	Status quo
levels given increased harvests from landowner incentives	variations of estimated harvest levels	potential harvest with release of selected administrative constraints	potential harvest levels with key limiting factors removed

Potter-Witter (MSU), Froese (MTU), LaCourt (MEDC) and Abramson (Frontier) also met via conference call to discuss use of the biomass availability multipliers. One of the discussion points was the issue of potential public misuse of the multipliers if they were built into the GIS system. Another issue was the ability to program the multipliers into the FBIS system. The multipliers were provided to MTU in the form they requested.

Details of Task Accomplishments

Analyze logging and mill sector data from MSU survey (Milestones A3.1 & A3.2):

Forest inventory data containing net growth and removal information were compiled. These data were summarized by landownership, species group and region and formed a key section of the Statewide Biomass Availability Snapshot (Appendix A3(a)).

Analyze commercial energy sector data from MSU survey (A3.3):

The team obtained and catalogued timber harvest data from the U.S. Forest Service and the Michigan Department of Natural Resources (MDNR). These data were then compiled to illustrate harvest trends from public forests.

Build net growth database (A3.4):

The project team built a database of Michigan loggers which contains variables including location of headquarters, location of operations, number of employees, capacity, current production, prices paid for stumpage, sources of stumpage, and delivery distances to mill clients. The data were compiled from responses to our 2008 survey of Michigan loggers. A “Snapshot” of the logging sector was written to highlight the team’s findings (Appendix A3(c)).

Build removals database (A3.5):

The project team built a database of characteristics of Michigan primary forest products manufacturers containing variables including location of the primary plant., number of employees, capacity, current production, prices paid for delivered wood, distances from the mill for wood procurement, and use of wood residues produced by the plant. The data were compiled from responses to our 2008 survey of Michigan mills. A “Snapshot” of the primary forest products sector was written to highlight the team’s findings (Appendix A3(d)). A snapshot poster (Appendix A3(b)) and a peer reviewed article which discusses the attitudes of forest products manufacturers toward biomass fuel development in Michigan has been accepted for publication in the Forest Product Journal (GC and Potter-Witter in press Appendix A3(e)).

Build harvest trends database (A.3.6):

Wood consumption information for each of Michigan’s six commercial wood-burning power plants was obtained through face-to-face interviews of the plant managers. Leefers produced a snapshot of Michigan’s wood-using power plants (Appendix A3(f)).

Collect data on state and national forest harvest plans (A3.7 & A3.8):

Select harvest plans were obtained from the Michigan Department of Natural Resources for the State Forest system. Harvest Plans for each of Michigan’s National Forests were collected and the relevant data were compiled into a spreadsheet.

Collect data on REIT and TIMO harvest agreements (A3.9):

The timber sale conditions of the supply agreement between Plum Creek and NewPage and between the Forest Land Group and Verso Paper were obtained and built into the availability multipliers.

Format data on private forest harvesting behavior and trends (A3.10):

Surveys from 2003 were analyzed in an effort to model non-industrial private forest owner behavior. A report was written detailing private landowner beliefs and behaviors across the four Michigan regions: Western Upper Peninsula, Eastern Upper Peninsula, Northern Lower Peninsula, and Southern Lower Peninsula and a poster summary was presented at the 2010 Society of American Foresters Convention (Appendix A3(g)) Mueller completed his MS thesis analyzing the regional effects of NIPF landowner behavior and testing the feasibility and utility of grouping landowners according to their management objectives and values.

Compile report on Michigan’s biomass current inventory, availability, supply and potential from forests (A.3.11):

The Statewide Biomass Availability Snapshot (Appendix A3(j) and Appendix A3(m)) was published after a first draft was reviewed by peer reviewers Larry Leefers and Mike Vasievich. Revisions were made to include the most recent 2009 FIA data and the reviewers’ comments. It

was subsequently reviewed by the FBSCC Steering Committee, revised, and then published on the Michigan Biofuels website.

Integrate relationships determined from primary data collection into MTU FBIS model (A.3.12):

Task A3 team finished collecting and analyzing the availability data. The multipliers and documentation of their derivation are contained in the seven page spreadsheet “MI Timber Availability Factors and Multipliers” (Appendix A3(1)). PI Potter-Witter and team and MTU PI Robert Froese and team developed a protocol to integrate the availability data developed in this project into the FBIS model. The Steering Committee on 3/9/11 expressed concern regarding making the multipliers endogenous to the FBIS model. They are considering presenting the historical harvest data and possible scenarios which use the availability filters (multipliers). The MSU team is available to answer questions regarding the availability measures provided to MTU for use in the FBIS model and provide any additional information that we may have that would be useful to the FBIS model.

Supporting Documents:

- GC, S. and K. Potter-Witter. 2010. Michigan's forest products sector: are they ready for promoting bioenergy? Poster presented at the Society of American Foresters National convention held in Albuquerque, NM October 27-30, 2010. [Appendix A3(b)]
- GC, S. and K. Potter-Witter. 2011. Snapshot of Logging Firms in Michigan. Michigan Forest Biofuels Research, Forestry Biofuels Statewide Collaboration Center. Project-produced Factsheet. [Appendix A3(c)]
- GC, S. and K. Potter-Witter. 2011. Snapshot of Primary Forest Products Mills in Michigan. Michigan Forest Biofuels Research, Forestry Biofuels Statewide Collaboration Center. Project-produced Factsheet. [Appendix A3(d)]
- GC, S. and K. Potter-Witter. 2011. Status of Michigan's forest products industry in the changing market environment. *Forest Products Journal*. 61(1):77-82.
- Leefer, L. Snapshot of wood-using electric power plants in Michigan. Project-produced Factsheet. [Appendix A3(f)]
- Mueller, L. and K. Potter-Witter. 2010. Regional variation of non-industrial private forest owners in Michigan. Poster presented at the Society of American Foresters National convention held in Albuquerque, NM October 27-30, 2010. [Appendix A3(g)]
- Mueller, L. 2011. Nonindustrial private forest owners in Michigan: Examination at a finer scale. MS Thesis, Michigan State University, East Lansing, MI.
- Mueller L. and K. Potter-Witter. Regional variation among non-industrial private landowners in Michigan. Submitted to the *Northern Journal of Applied Forestry*. Manuscript attached. [Appendix A3(i)]
- Potter-Witter, K., L. Mueller and S. GC. 2010. Michigan woody biomass supply snapshot. Poster presented at the Society of American Foresters Michigan Chapter Meeting held in Grayling, MI (November 4-5, 2010). [Appendix A3(j)]
- Potter-Witter, K., S. GC, and B. Kuipers. 2011. Assessment of Michigan non-industrial private forest owners' willingness to supply biomass for bioenergy. Poster presented at Agricultural and Natural Resources Week, March 8, 2011. Kellogg Center, East Lansing, Michigan. [Appendix A3(k)]
- Mueller, L., S. GC and K. Potter-Witter. 2010. Michigan Woody Biomass Supply Snapshot. Michigan Forest Biofuels Research, Forestry Biofuels Statewide Collaboration Center. Project-produced Factsheet. www.michiganforestbiofuels.org/system/files/michigan-woody-biomass-supply-snapshot_0.pdf [Appendix A3(m)]

Appendicies

A3(a) – Table: Summary of Forest Inventory Data

Total forestland in acres	19,821,356	
Total timberland in acres	19,236,534 acres	Forest Service: 2,506,741
		Other Federal: 81,621
		State and Local Government: 4,437,035
		Private: 12,211,137
All live biomass on timberland	768,906,714.4 oven dry tons	
Volume of all live on timberland	29,250,069,725 ft ³	
All live merchantable biomass on timberland	509,710,818.3 oven dry tons	
Volume of growing stock on timberland	27,272,390,143 ft ³	
Volume of sawlog portion on timberland	12,793,031,186 ft ³	
Volume of pulpwood portion on timberland (i.e. growing stock volume on timberland –volume of saw log portion on timberland)	14,479,358,957 ft ³	
Volume of sawtimber on timberland	78,799,262,797 board feet	
Net annual growth of all live on timberland	863,978,132.9 ft ³ /year	
Net annual growth of growing stock on timberland	922,562,781.4 ft ³ /year	
Net annual growth of sawtimber on timberland	3,301,933,003 board feet/year	
Annual removal of all live on timberland	346,006,069.3 ft ³ /year	
Annual removal of growing stock on timberland	291,150,948.7 ft ³ /year	
Annual removal of sawtimber on timberland	890,078,778.6 board feet/year	
Average output of roundwood products in 1996, 2001 and 2006	384,540,000 ft ³	Softwood: 83,620,000 ft ³
		Hardwood: 300,919,000 ft ³
Average logging residue in 1996, 2001, and 2006	95,737,000 ft ³	Softwood: 24,652,000 ft ³
		Hardwood: 71,085,000 ft ³
Average mill residue (volume) in 1996, 2001, and 2006	115,144,000 ft ³	Softwood: 25,836,000 ft ³
		Hardwood: 89,308,000 ft ³
Average weight of mill residue in 1996, 2001, and 2006	1,633,000 dry tons	Softwood: 376,000 dry tons
		Hardwood: 1,256,000 dry tons
Average volume of not used by-product in 1996, 2001, and 2006	1,631,000 ft ³	Softwood: 174,000 ft ³
		Hardwood: 1,457,000 ft ³
Average weight of not used by product in 1996, 2001, and 2006	25,000 dry tons	Softwood: 3,000 dry tons
		Hardwood: 22,000 dry tons
Area of overstocked forestland in acres	1,280,213 acres	National forest: 221,217
		National park service: 18,923
		Fish and wildlife service: 1,652
		State: 371,239
		Local: 12,027
		Other non-federal lands: 1,547
		Undifferentiated private: 653,608

Data source: MSU Department of Forestry database developed from FIA field data, Forest Inventory and Analysis data available online, and Timber Products Output Report 1996, 2001, and 2006.

A3 (b) Abstract and Poster

GC, S. and K. Potter-Witter. 2010. Michigan's forest products sector: are they ready for promoting bioenergy? Poster presented at the Society of American Foresters National convention held in Albuquerque, NM October 27-30, 2010.

Abstract

Woody biomass has gained considerable attention in the US as a feedstock for producing renewable bioenergy. Nationwide, the pressure is mounting to meet increasing energy demands through renewable local resource mobilization rather than importing unsustainable fossil fuels. Michigan is no exception to this. The state is rich in forest resources that can be used for generating clean energy. However, the availability of woody biomass for bioenergy is determined, among other things, by the capacity of the logging sector and forest products industry within the state. Therefore, identifying the status of existing forest products sector, their strengths, limitations, and the challenges they face are critical for understanding both current and future role of these sectors in bioenergy supply chain. This study provides an insight into Michigan's forest products sector and their perception towards wood-based bioenergy. Though the results indicate positive response towards the introduction of wood-energy facilities in the State, other broader issues such as sustained wood availability, retention and strengthening of the existing operations, and improving their efficiency are identified as critical factors that need consideration for promoting bioenergy in the future.

Michigan's Forest Products Sector: Are They Ready for Promoting Bioenergy?

Shivan G.C¹, and Karen Potter-Witter²

¹Research Assistant and ²Professor, Department of Forestry, Michigan State University

Abstract

Woody biomass has gained considerable attention in the US as a feedstock for producing renewable bioenergy. Nationwide, the pressure is mounting to meet increasing energy demands through renewable local resource mobilization rather than importing unsustainable fossil fuels. Michigan is no exception to this. The state is rich in forest resources that can be used for generating clean energy. However, the availability of woody biomass for bioenergy is determined, among other things, by the capacity of the logging sector and forest products industry within the state. Therefore, identifying the status of existing forest products sector, their strengths, limitations, and the challenges they face are critical for understanding both current and future role of these sectors in bioenergy supply chain. This study provides an insight into Michigan's forest products sector and their perception towards wood-based bioenergy. Though the results indicate positive response towards the introduction of wood-energy facilities in the State, other broader issues such as sustained wood availability, retention and strengthening of the existing operations, and improving their efficiency are identified as critical factors that need consideration for promoting bioenergy in the future.

Introduction

A large forest resource base, good transportation system, and access to the Great Lakes makes Michigan ideal for promoting wood-based bioenergy. The total forest area in the state has increased by 1.4 million acres from 1980 to 2008 (fig 1) and the inventory data indicates greater wood accumulation than removal in recent years (fig 2). Despite these advantages, the availability of woody biomass for bioenergy is determined significantly by the capacity of the logging sector and forest products industry within the state.

Fig 1. Michigan's forest area by year and regions

Fig 2. Net growth and removals in MI timberlands

Logging firms are responsible for commercial harvest of timber and form a bridge between forest resources and wood based industries. They help meet society's demand for wood products and assist forest owners in realizing varied management objectives. Through these activities, loggers shape the structure and composition of forests determining both present and future productivity.

Fig 3. Wood as a source of energy

The forest products industry accounts for approximately 10% of the state's manufacturing sector jobs and generates \$12 billion in annual revenue. Hence, it is vital for Michigan's economy and wellbeing. However, it has been facing difficulties in recent years due to downturns in manufacturing business. Given this situation, an emerging bioenergy market could play an immense role in promoting this sector hard hit by recession. But this is possible only if sufficient resources are made available for different uses. This study thus attempts to explore the status of existing forest products sector and how they feel about wood-based bioenergy.

Methods

A mail survey of all MI logging firms and primary forest products mills was conducted in the fall of 2008, and spring of 2009 respectively using the Tailored Design Method. The overall response rates were 33% for mill survey and 12% for the loggers' survey.

Results

Status of MI logging firms

The average logging firm in MI has been in existence for approximately 29 years. More than half (60%) of them employed less than 5 individuals and were found to operate at 82% capacity in 2007. However, 75% are willing to expand the operation in future under favorable market conditions. Logging firms obtained 64% of their timber supply from nonindustrial private forest lands (NIPFs) and delivered the highest percentage (29%) of their output to pulp and paper mills and hardwood sawmills (29%). The majority of the sawlogs (90%) and pulpwood (72%) harvested were delivered within 90 miles of the logging site. Approximately 83% of the respondent logging firms left logging residues on site after harvesting.

Fig 5. Operating capacity of MI logging firms and primary forest products industry in 2007 and 2008.

Status of primary forest products industry in MI

Forty-six percent of the MI primary mills employed 5 or fewer individuals in 2007, whereas 10% employed more than 100 individuals. The average operating capacity of mills declined from 71% in 2007 to 63% in 2008. Approximately 40% of the wood used in 2007 came from NIPFs and 71% was delivered from within 90 miles distance of the mill site. The majority (97%) of the mill residue generated was utilized either by the mills themselves or sold to others for manufacturing purposes. Significantly higher number of respondent mills rated forest residues, mill residues, and non-merchantable timber as desirable wood use types for new facilities in their wood basket.

Perception towards the introduction of different wood using facilities

Fig 6. Most desirable wood-based manufacturing additions to the loggers and primary mills operating area in MI (1 = very desirable, 2 = desirable, 3 = neutral, 4 = undesirable, 5 = very undesirable)

Michigan's forest products sector is in favor of introducing wood-based bioenergy facilities within their wood basket.

Barriers to increased harvesting identified by the logging firms	Strategies adopted by the primary mills for promoting business
High stumpage and low mill price	Increasing mill efficiency
Shortage of capable labor force	Improving communication with loggers and landowners
Competition for stumpage	Purchasing wood at lower cost
Insufficient timber supply	Diversifying products
Insufficient sale from public forests	Cutting back production
High fuel prices	Lobbying for more timber harvest from public lands

Discussion and Conclusion

Recent mill closures in MI have imposed considerable negative impacts on the logging sector and forest products industry, threatening their retention in some cases. Given this scenario, the introduction of new bioenergy market could be a promising step for boosting forest products sector and forest based economies. The positive attitude among loggers and primary mill managers towards wood-to-energy facilities and willingness to expand operation in case of favorable market are encouraging observations. However, current harvesting equipment and technology may not be efficient for collecting feedstock for these new facilities. Thus, exploring the equipment configurations and investment market across the state seems necessary before proceeding any further. Also, as reduced timber supply from both private and public lands was identified as barrier to increased harvesting, strategies to promote harvesting may be through timber sale aggregation in private lands or through increased allowable harvest from public lands seem necessary.

Snapshot of Logging Firms in Michigan

Shivan G.C. and Karen Potter-Witter
Department of Forestry, Michigan State University

- The average logging firm has been in business for approximately 29 years and has 7 employees.
- In 2007, the average firm operated at 82% of its optimal capacity.
- Only 4% of the pulpwood volume harvested was chipped at the logging site.
- The logging firms left logging residues on site at 83% of their logging jobs.
- The average stumpage price of sawtimber ranged from \$63/MBF to \$204/MBF, boltwood ranged from \$22/cord to \$45/cord, and pulpwood ranged from \$19/cord to \$29/cord.
- Nonindustrial private forests are the major source of timber supply (64%) followed by State forests (16%), industrial forests (11%), and National forests (4%).
- Approximately 66% of the harvested sawlogs and 42% of pulpwood were delivered to facilities within 60 miles of the logging site.
- Approximately half of the logging firms (47%) used their own company trucks for transportation.
- The highest percent of output (29%) was delivered to pulp & a paper mills and hardwood sawmills (29%), followed by OSB mills (16%) and softwood sawmills (10%).
- Approximately 75% of the logging firms are willing to expand operations if markets improved.
- Limited wood availability, high stumpage prices and low delivered prices, fluctuating fuel prices, shortage of capable labor force, poor road conditions, and lack of financing were some of the barriers to increased harvesting identified by the respondent firms.
- Logging firms were supportive of introducing large facilities (pulp & paper mills, direct-fired wood power generation, wood-based biofuel plants, and wood pellet fuel mills) in their wood basket.

Snapshot of Primary Forest Products Mills in Michigan

Shivan G.C. and Karen Potter-Witter
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- Michigan's primary mills employed an average of 37 individuals per facility in 2007.
- The mills operated at 71% of full capacity in 2007 and 63% of full capacity in 2008.
- Hardwood and softwood production in 2007 averaged 2,450 MBF and 1,914 MBF respectively.
- Mills produced 27,298 tons of pulp chips and 57,000 tons of wood pulp on average in 2007.
- The average delivered price of sawtimber ranged from \$173/MBF to \$445/MBF, boltwood ranged from \$115/MBF to \$150/MBF, and pulpwood ranged from \$54/cord to \$74/cord.
- Nonindustrial Private Forests formed the major source of wood supply (40%), followed by industrial forests (9%), State forests (9%), and National forests (3%).
- Six percent of the delivered wood was imported from outside MI.
- Fifty-nine percent of the wood used was delivered from within 60 miles of the mill facility.
- For the survey respondents, 527,080 tons of wood residues were used as fuel for mill operations, 566,411 tons sold to others for manufacturing purposes and 344,650 tons were sold for industrial fuel.
- The majority of mills are supportive of introducing wood energy facilities in their wood basket.
- Primary mills preferred new wood using facilities to use non-merchantable timber, forest residue and mill residue rather than roundwood.

A3(e) – GC, S. and K. Potter-Witter. 2011. Status of Michigan's forest products industry in the changing market environment. Forest Products Journal. 61(1):77-82.

Snapshot of Wood-Using Electric Power Plants in Michigan

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Six wood-based electric generating facilities were surveyed in 2009 (Cadillac Renewable Energy, Genesee Power Station, Grayling Generating Station, Hillman Power Co., Viking Energy—Lincoln, and Viking Energy—McBain). On average, 191,300 megawatts-hours per plant was produced in 2008, a decline of 2 percent from 2007 (Leefers, unpublished data). The facilities had an average of 22 employees. Three of the plants were dispatchable (variable production depending on demand), and three were base load facilities. Dispatchable plants produced 50% more power than smaller base load plants. On average, the plants had 8,306 operating hours (~95% of potential operating time).

Fuel was mostly chips (2" minus) with moisture content ranging from 37-51%. On average, 265,000 green tons of wood was used per facility for a total of 1.6 million green tons per year. Only a small amount of the wood came from outside of Michigan. Logging residues were the primary source for wood in 2008 (Figure 1). A significant portion of fuel came from chips. This figure may have been higher than the norm and mill residues may have been lower due to poor market conditions for the wood-products industry. One respondent noted "Our wood supply is a byproduct of other industries. We need these industries to be healthy." The mean delivered price per green ton for chips was \$21.50; mill residue prices were somewhat lower, but logging residues prices were about the same chip prices. Over 90 percent of wood used in the six plants was transported less than 90 miles (Figure 2). Almost 80 percent was transported less than 60 miles.

Mueller, L. and K. Potter-Witter. 2010. Regional variation of non-industrial private forest owners in Michigan. Poster presented at the Society of American Foresters National convention held in Albuquerque, NM October 27-30, 2010.

Abstract

Recently increased pressure has been placed on Michigan private lands to produce wood fiber for both current and developing markets. Several programs have been specifically designed to encourage management on non-industrial private forest (NIPF) lands. Traditionally for policy, research, and discussion purposes NIPF owners have been combined into one homogeneous group across the State of Michigan. Considering that social, economic, and ecological factors vary across Michigan regions, it is unsurprising that NIPF lands are not as homogeneous as thought. To determine the scale and nature of regional differences in private land ownership we mailed a survey to 1600 NIPF landowners across the state. We asked landowners to provide information on their reasons for owning land, demographic variables and past management activities. Distinct regional differences were found in parcel size, reasons for owning forested land and management behavior. These results bring into question the practicality of combining landowners into a single group over large geographic areas. Policy makers may benefit from more carefully considering the implications of regional differences that could affect land ownership patterns.

Regional Variation of Non-Industrial Private Forest Owners in Michigan

Lee S. Mueller and Karen Potter-Witter
Department of Forestry, Michigan State University

Abstract

Recently increased pressure has been placed on Michigan private lands to produce wood fiber for both current and developing markets. Several programs have been specifically designed to encourage management on non-industrial private forest (NIPF) lands. Traditionally for policy, research, and discussion purposes NIPF owners have been combined into one homogeneous group across the State of Michigan. Considering that social, economic, and ecological factors vary across Michigan regions, it is unsurprising that NIPF lands are not as homogeneous as thought. To determine the scale and nature of regional differences in private land ownership we mailed a survey to 1600 NIPF landowners across the state. We asked landowners to provide information on their reasons for owning land, demographic variables and past management activities. Distinct regional differences were found in parcel size, reasons for owning forested land and management behavior. These results bring into question the practicality of combining landowners into a single group over large geographic areas. Policy makers may benefit from more carefully considering the implications of regional differences that could affect land ownership patterns.

Introduction

The State of Michigan has expressed interest in forests as a source of feedstock for alternative energy production. Considering the current utilization of forest products on public land, and the constraints on increasing public land timber harvests, some increase in woody biomass output will likely come from private forestland.

NIPF owners own 8.8 million acres of Michigan's 19.2 million acres of forest land¹. This forest land is controlled by an estimated 384,700 different landowners. With so many private forest owners it is unsurprising the NIPF category has been difficult to categorize or influence through the use of policy.

Programs are available at both the federal and state level to increase participation in responsible management. These programs target landowners across the entire state and require certain factors to be met for participation.

Owner's attitudes, beliefs and objectives for their properties have been shown to influence participation in a variety of management programs². Therefore, where private lands and landowners differ, participation in management and conservation programs can be expected to vary.

Considering the geographic diversity of Michigan it is expected that non-industrial private forest parcels and ownership characteristics vary by region. If this is the case, it could have implications for government programs which target forest owners. Our study sought to determine the extent of regional differences in owner demographics, parcel characteristics, reasons for owning forested land and management activities.

Figure 1. Michigan regions.

Methods

In 2003, a survey was mailed to 1600 regionally-stratified, randomly-selected private landowners. Respondents were asked to indicate basic demographic information, parcel characteristics, reasons for owning forested property and management activities. Responses were recorded by region (Figure 1) – Western Upper Peninsula (WUP), Eastern Upper Peninsula (EUP), Northern Lower Peninsula (NLP), Southern Lower Peninsula (SLP) – and examined for significant differences.

Results

With respect to demographic characteristics, WUP landowners tended to have a higher formal education than did those in the EUP and had higher incomes than did those in the SLP (Table 1). SLP respondents had held their property longer than had those in the EUP and more often were residing on their forested property. WUP respondents lived farther from their nearest forested parcel than did those in the SLP.

Table 1. Median responses to demographic questions.
(Like superscripts denote no significant difference, * mean, ** mode)

Variable	Region			
	SLP	NLP	EUP	WUP
Education	Some College ^{ab}	Some College ^a	Some College ^a	Bachelors degree or equivalent ^c
Income	\$40,000-59,999 ^a	\$40,000-59,999 ^{ab}	\$40,000-59,999 ^{ab}	\$60,000-74,999 ^b
Employment ^{**}	Employed Full Time ^a	Employed Full Time ^{ab}	Employed Full Time ^{ab}	Employed Full Time ^{ab}
Tenure [*]	30 years ^a	25 years ^a	28 years ^{ab}	26 years ^{ab}
Permanent Residence (Percentage)	67.90%	35.76 ^a	44.85 ^a	40% ^a
Distance	15 miles ^a	82.5 miles ^{ab}	25.5 miles ^{ab}	101.5 miles ^c

Mean parcel size differed significantly among all regions. The NLP contained the only instance of parcels larger than 999 acres, although the EUP contained the parcels with the largest average size (Figure 2). The SLP contained the greatest number of small parcels (0-40 acres).

Figure 2. Percentage of parcels in size category by region.

SLP respondents ranked "to protect nature and biologic diversity" as more important for owning forestland than did those in the EUP (Table 2). Additionally, more SLP respondents ranked the importance of their parcel as part of their home than did those in the NLP or WUP. Respondents in the NLP indicated "for cultivation/collection of non timber forest products" as more important than those in the SLP. EUP respondents reported "for production of sawlogs, pulpwood, or other timber products" as more important than did owners in other regions. Further, NLP respondents indicated "for hunting or fishing" as a more important reason for owning forested property than did those in the SLP or WUP. Likewise, EUP respondents considered the same reason as more important than did those in the WUP.

Table 2. Median rankings of importance of reasons for owning forested property by region. (Like superscripts denote no significant difference.)

Reason for owning forest property	SLP	NLP	EUP	WUP
To protect nature and biologic diversity	Very Important ^a	Very Important ^{ab}	Somewhat Important ^b	Very Important ^{ab}
As part of my home, vacation home, farm, or ranch	Very Important ^a	Very Important ^a	Very Important ^{ab}	Very Important ^b
For privacy	Very Important ^a	Very Important ^a	Very Important ^a	Very Important ^a
For cultivation/collection of non timber forest products	Neutral ^a	Somewhat Unimportant ^b	Neutral ^{ab}	Neutral ^{ab}
For production of sawlogs, pulpwood or other timber products	Somewhat Unimportant ^a	Somewhat Unimportant ^a	Neutral	Somewhat Unimportant ^a
For hunting or fishing	Somewhat Important ^{ab}	Very Important ^a	Very Important ^{ab}	Somewhat Important ^a

Table 3. Percentage of respondents having performed management activities by region. (Like superscripts denote no difference.)

Management Activity	SLP	NLP	EUP	WUP
Improved an existing stand for timber	37.9% ^a	48.9% ^{ab}	61.5% ^b	48.6% ^{ab}
Built or improved access road or trail	22.2% ^{ab}	16.5% ^a	37% ^a	23.7% ^{ab}
Harvested timber	37.7% ^a	49.6% ^{ab}	73.2% ^b	52.6% ^{ab}

A greater percentage of the EUP landowners had "improved an existing stand for timber" than had respondents in the SLP (Table 3). More EUP landowners had "built or improved access road or trail" than had those in the NLP. Moreover, a greater number of respondents in the EUP and WUP had harvested timber than had those in the SLP. In general, EUP landowners had performed more activities linked to timber production than had those in the other regions.

Discussion

Our analysis shows variation in several factors among Michigan's four regions. Where EUP respondents seemed to be more interested in utilitarian uses of their land, NLP and WUP landowners tended to value vacation uses of their forested parcels. In contrast, SLP landowners were focused on protection and non-consumptive uses of their forest property. Regardless of the factors driving these variation, our analysis does show that there is regional variability among values and behaviors of Michigan's private forest owners and among the characteristics of their parcels. These differences are likely to influence participation in forest conservation and management programs. Policy-makers should seek to understand these variations to effectively craft private forest management policies and programs.

As Michigan seeks to enter a new era of forest utilization, non-industrial private forest owners will become increasingly important as contributors to biomass output. Therefore, it has become even more important that we seek to understand private forest owners and their goals in order to balance societal and landowner objectives.

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Mueller, L. 2011. Nonindustrial private forest owners in Michigan: Examination at a finer scale. MS Thesis, Michigan State University, East Lansing, MI.

Abstract

Non-Industrial Private Forest owners are a diverse group of Michigan's landowners. This study seeks to manage NIPF variation through creation of groups which characterize landowner behavior and attitudes. The thesis is divided into two papers, each examining a different method of grouping Michigan's NIPF landowners. Both papers utilize information from a 2003 survey of 1600 Michigan NIPF landowners. The first paper utilizes Michigan's four regions, the Southern Lower Peninsula (SLP), Northern Lower Peninsula (NLP), Eastern Upper Peninsula (EUP), and the Western Upper Peninsula (WUP), to place landowners into sub-categories based on location. Distinct differences are found across regions in regards to landowner demographics, parcel characteristics, reasons for owning forestland, and management behavior. These differences suggest the need to take into account the effects of variation on policy success and informational outreach programs.

The second paper utilizes a market-segmentation approach to place landowners in segments based on their reasons for owning forestland. Three segments are developed: Game Wardens, Tenants, and Timber Barons. Each segment differs in relation to demographics, parcel characteristics, reasons for owning forestland, management activities, and preferences for policies or programs. These results suggest the ability to target specific landowner segments to achieve policy goals. Further, policy-makers and outreach extension specialists may wish to account for landowner differences when seeking to develop policies or programs with specific objectives or targets.

A3(i) – Mueller L. and K. Potter-Witter. Regional variation among non-industrial private landowners in Michigan. Submitted to the Northern Journal of Applied Forestry.

ABSTRACT

Nonindustrial Private Forest Owners have historically been characterized as a single group across the state of Michigan. We believe that such a large geographic category misses much of the distinct variation among private landowners. A survey mailed to 1600 landowners across four Michigan regions (Western Upper Peninsula, Eastern Upper Peninsula, Northern Lower Peninsula, and Southern Lower Peninsula) asked questions relating to landowner beliefs, attitudes, and management behavior. We found distinct differences between regions in categories such as parcel size, absentee residence, distance from nearest parcel, reasons for owning forest land, and past management behavior. Demographic differences were not significantly different. These results indicate the necessity to carefully consider the implications of combining private land ownership into large geographic categories.

A3(j) – Poster

Potter-Witter, K., L. Mueller and S. GC. 2010. Michigan woody biomass supply snapshot. Poster presented at the Society of American Foresters Michigan Chapter Meeting held in Grayling, MI (November 4-5, 2010).

**NO ABSTRACT
POSTER FOLLOWS ON NEXT PAGE**

MICHIGAN WOODY BIOMASS SUPPLY SNAPSHOT

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MICHIGAN STATE
UNIVERSITY

Michigan Timberlands

Forests cover more than half (54%) of Michigan's land area. Out of this, 19.2 million acres are capable of producing more than 20ft³ per acre of industrial wood per year and are known as timberlands. Private landowners form the major forest ownership group followed by the state and local government, and forest service respectively (fig 1).

Fig 1. Percentage of MI timberland by ownership

The state is divided into four geographical sub-regions; the eastern upper peninsula (EUP), the western upper peninsula (WUP), the northern lower peninsula (NLP), and the southern lower peninsula (SLP). Thirty eight percent of the total timberland is located in the NLP, 24% in the WUP, 21% in the EUP, and 17% in the SLP.

Fig 2. Map of Michigan by region and forested area

Current Growth and Removals

Fig 3. Average annual growth, removals, and mortality in MI timberlands by region

The annual growth of wood in MI is 766.6 million cubic feet of live trees. Out of this, 382.2 million cubic feet is removed each year, leaving an unutilized resource of approximately 384.4 million cubic feet per year. Among the regions, the NLP has the highest annual growth and removals. However, the WUP removes the largest percentage of growth (87%) followed by the EUP (67%), the NLP (42%) and the SLP (30%) respectively.

Fig 4. Percentage of the all live biomass removed annually from MI timberlands by ownership and region

Approximately 67% of the annual removals come from private forests, 19% from the forests owned by state and local government, and 5% from the national forests.

Future Potential

Wood removals are determined in part by the government agency planning and by state, regional and international timber markets. National and state forests utilize written management plans which specify removal targets as well as limits to removals. Private timberlands include the forests owned by timber management organizations (TIMOs) and non-industrial private forest owners (NIPF). While the management of TIMO owned forests are guided by the forest management plans, those under NIPF ownership usually lack such explicit plans and are determined more by owner preferences, beliefs, and attitudes.

Allowable annual harvests from the national forests exceed current harvest by 35.4 million cubic feet (fig 5), thus revealing the potential for increased harvesting in the future.

Fig 5. Current and allowable annual harvest from Michigan's national forests

In case of the state forests, the net annual growth of all live biomass exceeds the removals by 61.3 million cubic feet per year. According to the state forest management plan, approximately 53,000 acres of timberland are offered for sale annually and tentatively the same amount will be up for sale in the near future.

Fig 6. Net annual growth and removals of all live biomass from Michigan's private forests

Private lands remove 48% of the annual growth, thus retaining 280.3 million cubic feet of unused wood per year (fig 6). Majority of the NIPF owners cite non-economic factors as the most important reason for forest ownership.

However, 45.4% of them have harvested timber in the past. This trend can thus be assumed to remain in effect in the future as well.

Besides this, approximately 71.8 million cubic feet of harvest residue, and 1.6 million cubic feet of mill residue remain unused in the state at present. All this offer a promising future for wood availability in MI.

Challenges to increased harvesting

MI loggers indicate high stumpage and low mill price, shortage of capable labor force, competition for stumpage, insufficient timber supply from both public and private lands, and high fuel prices as some of the challenges for increased harvesting in the future. Nevertheless, majority of them (75%) are willing to expand the operation in future under favorable market conditions.

Potter-Witter, K., S. GC, and B. Kuipers. 2011. Assessment of Michigan non-industrial private forest owners' willingness to supply biomass for bioenergy. Poster presented at Agricultural and Natural Resources Week, March 8, 2011.

Abstract

Non-industrial private forest (NIPF) owners are the major forest ownership group in Michigan and own approximately 47% of the state's timberlands. Hence they play an indispensable role in the sustainability of the state's forests as well as in the continuing operation of the timber industry. Recently increased interest in bioenergy production has further emphasized the importance of this ownership group in the wood supply chain and a number of studies nationwide are being conducted to understand the harvesting behavior of NIPF owners. The objective of this Michigan study is to understand the perception of Michigan NIPF owners towards wood-based bioenergy and to identify the factors influencing their willingness or unwillingness to supply biomass for energy. The results indicate awareness of and positive attitudes towards woody biomass energy among a majority of the landowners. However, less than half (42%) of the landowners are currently willing to harvest timber from their forests for energy purposes. Lack of interest, concern about the ecological impact of harvesting timber and perceived low financial benefits are some of the main reasons landowners give for their reluctance to supply biomass.

Assessment of Michigan Non-industrial Private Forest Owners' Willingness to Supply Biomass for Bioenergy

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Abstract

Non-industrial private forest (NIPF) owners are the major forest ownership group in Michigan and own approximately 47% of the state's timberlands. Hence they play an indispensable role in the sustainability of the state's forests as well as in the continuing operation of the timber industry. Recently increased interest in bioenergy production has further emphasized the importance of this ownership group in the wood supply chain and a number of studies nationwide are being conducted to understand the harvesting behavior of NIPF owners. The objective of this Michigan study is to understand the perception of Michigan NIPF owners towards wood-based bioenergy and to identify the factors influencing their willingness or unwillingness to supply biomass for energy. The results indicate awareness of and positive attitudes towards woody biomass energy among a majority of the landowners. However, less than half (42%) of the landowners are currently willing to harvest timber from their forests for energy purposes. Lack of interest, concern about the ecological impact of harvesting timber and perceived low financial benefits are some of the main reasons landowners give for their reluctance to supply biomass.

Introduction

Increased interest in alternative energy production from woody biomass has recently been observed in Michigan due to concerns over energy security, environmental health, and economic growth. This has placed significant pressure on the state's timberlands, particularly private forests, for supplying wood fiber to meet the demands of both current forest products markets and emerging bioenergy markets. It is essential, therefore, to understand the fiber supply from the 8.8 million acres of non-industrial private timberland in the state. Predicting the harvesting behavior of NIPF owners is not simple as it includes a diverse and dynamic set of people with varying personal values, attitudes and management objectives. This study is an attempt to understand Michigan NIPF owners' opinions towards bioenergy and their willingness or unwillingness to supply biomass if markets existed for it in the future.

Fig 1. Wood as a source of energy

Study Area

The study area includes twenty nine counties located in the north-eastern region of Michigan. These counties lie within 150 miles radius of a proposed cellulosic ethanol facility in Kinross, Michigan.

Fig 2. Map of the study area showing counties used for the survey in red

Methods

A mail survey of 1,600 randomly selected landowners owning at least 20 acres of forest in the study area was conducted from November to December 2010 using the Tailored Design Method. The overall response rate after taking into account the undeliverable addresses was 39%.

Results

Demographic characteristics

- ❖ The majority of the respondents (85%) are male with an average age of 61 years and have at least some college education.
- ❖ Approximately half of them (49%) are retired with an annual income of more than \$60,000.
- ❖ Approximately 33% of the respondents reside on their woodlands, while others live on average 229 miles away from their nearest forested parcel.
- ❖ Privacy, to enjoy beauty or scenery, to protect nature and biological diversity, as part of residence, and hunting or fishing are all important reasons for owning the forest land.
- ❖ Approximately 83% of the landowners purchased their property while 17% inherited it.

Landowners' view towards bioenergy

Fig 3. Landowners' perception towards wood-based energy

Fig 4. Landowners willingness/unwillingness to supply biomass for bioenergy

- ❖ The majority of landowners (77%) are aware of alternative energy production from woody biomass and approximately 60% agreed that alternative fuel production from woody biomass can create economic opportunities for Michigan landowners.
- ❖ On average, 42% of the landowners are willing to produce and sell timber from their forests for bioenergy purposes.
- ❖ The price of timber and low investment costs are identified as the most important factors for producing and harvesting timber for conversion to alternative energy.
- ❖ Approximately 33% of the landowners are willing to establish energy plantations on their land and 8% are willing to lease their property for the same.

- ❖ Only 18% of the landowners are willing to harvest timber for biomass at the current market price of pulpwood (\$24/cord). However, this number increased to 52% when the price was doubled.
- ❖ A small percentage of the landowners (8%) showed a preference for harvesting timber for bioenergy over pulpwood. Likewise, 8% showed a preference for pulpwood over bioenergy.

Fig 5. Landowners' willingness to supply biomass at various price levels

Reasons for Landowners' unwillingness to supply biomass

Fig 6. Reasons for landowners' unwillingness to supply biomass for energy. (Median value 5 = high importance and 1 = low importance)

- ❖ Lack of interest in harvesting, the perception that income might not be worth the effort, and concern about ecological impact of producing and harvesting timber for energy are the major reasons for landowners' unwillingness to supply biomass.

Discussion and Conclusion

Our results indicate awareness and positive attitudes among Michigan landowners towards wood based bioenergy. While this is encouraging for the future of bioenergy sector within the state, many landowners seem to expect high prices for woody biomass compared to those for pulpwood. Knowledge about the types and quality of wood that can be used for bioenergy generation needs to be created. Since landowners are concerned about the ecological impacts of harvesting biomass, outreach efforts aimed at enhancing awareness regarding beneficial economic and ecological impacts of using woody biomass for bioenergy could also help promote woody biomass energy.

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Michigan timber available to harvest
Karen Potter-Witter, Professor
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Use of the tables

These tables have been developed to allow users to refer to information on previous harvest trends and planned timber removals from public forests, and for nonindustrial private forest the percentage of owners that have harvested in the past and are willing to do so in the future. This information may be used to adjust forest inventory, i.e. the amount of wood in standing trees, to the amount that might be available for harvest.

Users are cautioned that the planned or projected harvest, i.e. the volumes presented as those that timber owners may make available to the market are under the condition that state and federal policy will not change significantly and that timber market conditions will remain essentially the same as they have been over the analysis period.

Definitions of terms used in these tables are taken from the USDA Forest Service Forest Inventory and Analysis Unit and are available in Appendix A along with the timber volume conversion factors used in this report.

Statewide growth and removals

To provide background information, composite tables of average annual timber growth (Table 1) and average annual removals (Table 2) for the state by region and ownership class are summarized from USDA Forest Service inventory information (FIA 2010). The user can refer to these tables to develop a sense of what the growth and removal trends have been for each region and ownership. Next, similar information is presented in more detail for each ownership class, by region and species group (hardwoods or softwoods).

For **State Forest** timber harvests, the historical harvest level for the period 2000--2009 is displayed for each region by hardwood or softwoods (Table 3). This is an indication both of the current capacity in the State Forest System to make timber available for sale as well as the demand for state forest timber over the period. The Department of Natural Resources, Forest Management Division has a State Forest Management Plan which, among other things, sets a target for annual harvests from State Forest lands. This target level is not yet available by individual state forest or region. Lacking this forest level information, the planned harvest is allocated to each region and species group based upon historic harvest levels. This results in a case where the estimate of allocated harvest is greater than the average annual growth (Table 3, EUP hardwoods).

Users of course can use a greater amount, total state forest growth, for example, as the amount available for harvest if they would like to examine a scenario in which more of the state forest timber would be put up for sale.

For **National Forest** timber harvests, the historical harvest level for the period 2000 to 2009 is displayed for each region by hardwood or softwoods (Table 4). This is an indication of the recent levels of timber

volume made available for sale by each national forest as well as the volume of timber that has been purchased and harvested over the period. Information on the planned harvest levels for each of the four National Forests¹ in Michigan is also displayed. This is the level of harvest as planned from the respective National Forest Plan for each of the forests. Users of course can use a greater amount, total national forest growth, for example, as the amount available for harvest if they would like to examine a scenario in which more of the national forest timber would be put up for sale.

For **Non-industrial Private Forests** (NIPF) the historical harvest level for the period 2000 to 2009 is displayed for each region by hardwood or softwoods (Table 5). Since these forests are owned and managed by individuals, families or non-timber industry organizations, there is no centralized planning of timber harvest levels for the ownership class. The historic levels of timber harvests from NIPF lands are more a result of market demand and supply, i.e. at a given price how much owners are willing to sell and how much users are willing to buy. Next indications of what percentage of forestland owners have harvested timber or are willing to harvest timber is listed. These percentages were developed from 2003 and 2010 surveys of private non-industrial owners in Michigan (Mueller et al. 2010 and GC et al. 2010). Note that these figures are the percentage of landowners that say they have done or will do timber harvesting and that the respondents' answers are based upon many factors such as their experience and perceptions of current or future markets. Their actual behavior may be different than what they say they will do and their intentions and behavior may change if timber prices rise or fall appreciably.

Data on historical **timber investment organization** timber harvests are not available for Michigan. Forest Land Group, GMO and Plum Creek are the three investment forest owners with the greatest acreage in Michigan. Two of the ownerships currently have long-term contracts to specific wood-using mills in Michigan to supply raw material. These contracts will run out by 2015. One of the ownerships makes its timber sales available to the open market. Users are advised to determine how much of the timberland in their analysis is owned by these companies, if any, and adjust timber availability as they see fit.

¹ The Huron-Manistee National Forests are administered as one unit but are still two national forests

Table 1. Average annual net growth of live trees (thousand ft³/year) in MI timberlands by region, species group and owner class. (FIA 2000-2004 to 2005-2009).

Region	Species group	Ownership									
		Unknown	National Forest ²	Fish & Wildlife Service	Department of Defense or Energy	Other Federal	State ³	Local (county, municipal, etc.)	Other non federal lands	Undifferentiated private	Total
EUP	Softwood	122	17,740	288		35	16,014	-64		31,777	65,912
	Hardwood	64	8,701	176		925	5,780	-39		34,073	49,680
	Total	186	26,440	464		960	21,793	-103		65,851	115,591
WUP	Softwood	166	7,654		20	8	8,097	586	-31	30,398	46,898
	Hardwood	180	13,340		0	136	8,772	1,897	94	58,358	82,778
	Total	345	20,995		20	144	16,869	2,483	63	88,756	129,675
NLP	Softwood	240	17,435	-5	111	0	29,732	1,527	51	56,777	105,867
	Hardwood	-48	19,509	21	501	-8	37,590	3,373	150	153,569	214,656
	Total	191	36,943	16	612	-8	67,322	4,900	201	210,346	320,523
SLP	Softwood	92	135	0	0	0	719	776	0	10,831	12,553
	Hardwood	1,586	224	842	143	59	17,137	6,782	152	157,931	184,855
	Total	1,678	359	842	143	59	17,856	7,558	152	168,762	197,409
Statewide	Softwood	619	42,963	282	131	43	54,562	2,825	20	129,784	231,230
	Hardwood	1,781	41,774	1,039	644	1,111	69,279	12,014	396	403,931	531,969
	Total	2,400	84,737	1,321	775	1,154	123,841	14,839	417	533,714	763,198

National Park Service average annual growth = 0

² This column denotes average annual net growth of live trees in all timberlands on Michigan's national forests and not only those lands that are identified as suitable for timber management according to National forest plans.

³ This column denotes average annual net growth of live trees in all timberlands on Michigan's state owned forests.

Table 2. Average annual removals of live trees (in thousand ft³/year) in MI timberlands by region, species group and owner class. (FIA 2000-2004 to 2005-2009)

Region	Species group	Ownership					Total
		Unknown	National Forest	State	Local (county, municipal, etc.)	Undifferentiated private	
EUP	Softwood	1,480	6,484	5,636		14,154	27,754
	Hardwood	1,065	899	9,051		38,830	49,846
	Total	2,545	7,383	14,688		52,984	77,600
WUP	Softwood	1,815	5,090	1,669	1,963	14,735	25,273
	Hardwood	2,937	3,716	9,875	2,702	63,644	82,874
	Total	4,751	8,807	11,544	4,666	78,379	108,147
NLP	Softwood	2,921	1,170	13,614	411	17,859	35,976
	Hardwood	8,004	1,764	19,495	1,051	67,279	97,593
	Total	10,926	2,934	33,109	1,462	85,139	133,569
SLP	Softwood	1,448		76		511	2,036
	Hardwood	16,329		1,959		38,716	57,004
	Total	17,777		2,036		39,227	59,039
Statewide	Softwood	7,664	12,744	20,996	2,375	47,259	91,039
	Hardwood	28,334	6,379	40,380	3,753	208,470	287,317
	Total	35,999	19,124	61,377	6,128	255,729	378,356

National park service = 0, Fish and Wildlife Service = 0, Department of Defense or Energy = 0, Other Federal = 0, Other Non-federal = 0

Table 3. Growth and removals of live trees in MI state owned forests in the Upper Peninsula and Northern Lower Peninsula by region and species group (Source: FIA 2000-2004 to 2005-2009) ⁴

Region	Species Group	Average annual net growth of live trees in MI state owned forests (thousand ft ³ /yr)	Average annual removals of live trees in MI state owned forests (thousand ft ³ /yr)	Growth to removals ratio	Avg. annual removals to net growth ratio ⁵	Percent of harvests on state owned forest in northern 2/3 of MI	Example distribution of planned harvest level for State Forests in thousand ft ³ ⁶	Planned Harvest /Net Growth ³
EUP	Softwood	16,014	5,636	2.8	0.352	9.50%	5,252	0.33
	Hardwood	5,780	9,051	0.6	1.566	15.25%	8,435	1.46 ⁷
	Total	21,793	14,688	1.5	0.674	24.75%	13,688	0.63
WUP	Softwood	8,097	1,669	4.9	0.206	2.81%	1,555	0.19
	Hardwood	8,772	9,875	0.9	1.126	16.64%	9,203	1.05
	Total	16,869	11,544	1.5	0.684	19.45%	10,758	0.6
NLP	Softwood	29,732	13,614	2.2	0.458	22.94%	12,687	0.43
	Hardwood	37,590	19,495	1.9	0.519	32.85%	18,167	0.48
	Total	67,322	33,109	2.0	0.492	55.79%	30,854	0.46
N 2/3 MI	Total State Owned	105,985	59,341	1.8	0.560	100.00%	55,300 ⁸	0.52

⁴ The southern 1/3rd of Michigan is not included in this table since there are no State Forests in the region. The state land in the SLP is largely managed for recreation or wildlife habitat.

⁵ Average Annual Growth divided by net growth is the measure of historical performance.

⁶ Distribution is 55,300,000 cubic feet X percent of harvests on state owned forest for the region and species group.

⁷ Note that the state of Michigan DOES NOT plan a harvest level greater than growth. This number is a result of allocating the statewide harvest level to the regions. Additionally, this estimate does not take into account harvesting patterns due to stand type, species group or age class distribution which affects harvesting patterns.

⁸ Planned Harvest Level is based upon planned sales of 53,000 acres of timber with 13 cords per acre average. Additionally the 20 year average is 700,000 cords per year or 55.3 million cubic feet using 79 cubic feet per cord.

Table 4. Growth and removals of live trees on National Forests in the Upper Peninsula and Northern Lower Peninsula by region and species group (Source: FIA 2000-2004 to 2005-2009) ⁹

Region	Species group	Net volume of live trees on MI timberland (thousand ft ³)	Average annual net growth of live trees in national forests (thousand ft ³ /yr)	Growth to removals ratio	Removals to growth ratio	Species type percent of removals on each national forest	Planned allowable harvest		Allocated allowable harvest	Allocation of Planned Harvest/Net Growth
							MBF/year	thousand ft ³ /yr	thousand ft ³ /yr	
EUP = Hiawatha National Forest	Softwood	3,035,402	17,740	2.7	0.37	87.82%			15,057	0.85
	Hardwood	2,925,397	8701	9.7	0.10	12.18%			2,088	0.24
	Total	5,960,799	26,440	3.6	0.28	100.00%	108,516	17,146	17,146	0.65
WUP = Ottawa National Forest ¹⁰	Softwood	2,507,125	7,654	1.5	0.67	57.80%			8,228	1.07
	Hardwood	5,228,585	13,340	3.6	0.28	42.20%			6,008	0.45
	Total	7,735,710	20,995	2.4	0.42	100.00%	90,100	14,236	14,236	0.68
NLP = Huron-Manistee National Forests ¹¹	Softwood	3,521,995	17,435	14.9	0.07	39.89%			5,735	0.33
	Hardwood	7,790,898	19,509	11.1	0.09	60.11%			8,643	0.44
	Total	11,312,893	36,943	12.6	0.08	100.00%	91,000	14,378	14,378	0.39

⁹ The southern 1/3rd of Michigan is not included in this table since there are no State Forests in the region. The state land in the SLP is largely managed for recreation or wildlife habitat.

¹⁰ For the Ottawa National Forest, the planned allowable harvest is 90.1 million board feet/year for the first decade (2006-2015) of 2006 National Plan implementation and is 134.5 million board feet/year for the second decade.

¹¹ For the Huron-Manistee National Forests, the planned allowable harvest is 91 million board feet/year for the first decade (2006-2015) of 2006 National Plan implementation and is 100.2 million board feet/year for the second decade.

Table 5. Growth and removals of live trees in MI private forests by region and species group (Source: FIA 2000-2004 to 2005-2009)

Region	Species Group	Net volume of live trees in MI timberlands (thousand ft ³)	Average annual net growth of live trees in MI private forests (thousand ft ³ /yr)	Average annual removals of live trees in MI private forests (thousand ft ³ /yr)	Growth to removals ratio	Removals to growth to ratio	Percent of landowners willing to harvest based upon 2003 survey of MI NIPF owners ¹²
EUP	Softwood	3,035,402	31,777	14,154	2.2	0.5	
	Hardwood	2,925,397	34,073	38,830	0.9	1.1	
	Total	5,960,799	65,851	52,984	1.2	0.8	73.2 %
WUP	Softwood	2,507,125	30,398	14,735	2.1	0.5	
	Hardwood	5,228,585	58,358	63,644	0.9	1.1	
	Total	7,735,710	88,756	78,379	1.1	0.9	52.6%
NLP	Softwood	3,521,995	56,777	17,859	3.2	0.3	
	Hardwood	7,790,898	153,569	67,279	2.3	0.4	
	Total	11,312,893	210,346	85,139	2.5	0.4	49.6%
SLP	Softwood	432,113	10,831	511	21.2	0.0	
	Hardwood	5,545,791	157,931	38,716	4.1	0.2	
	Total	5,977,905	168,762	39,227	4.3	0.2	37.7%
Statewide	Softwood	9,496,635	129,784	47,259	2.7	0.4	
	Hardwood	21,490,671	403,931	208,470	1.9	0.5	
	Total	30,987,306	533,714	255,729	2.1	0.5	

¹² 46% in NE MI have harvested in the past 10 years and 36% plan to harvest in the next 10 years 35% are unsure about harvesting in the next 10 years (2010 survey). 41% in NE MI say they would be willing to produce and sell timber for converting it to alternative energy (2010 survey). In the short range these percentages could be influenced by changes in timber prices or procurement activity.

Table 6. Growth to removals ratio of all live trees in MI timberlands by region, species group and ownership (Source: FIA 2000-2004 to 2005-2009)

Region	Species group	Ownership							
		Unknown	National Forest	Other Federal	State	Local (county, municipal, etc.)	Undifferentiated private	Total	Current removals/ growth ratio
		Growth/Removals							
EUP	Softwood	0.1	2.7		2.8		2.2	2.4	0.42
	Hardwood	0.1	9.7		0.6		0.9	1	1.00
	Total	0.1	3.6		1.5		1.2	1.5	0.67
WUP	Softwood	0.1	1.5		4.9	0.3	2.1	1.9	0.53
	Hardwood	0.1	3.6		0.9	0.7	0.9	1	1.00
	Total	0.1	2.4		1.5	0.5	1.1	1.2	0.83
NLP	Softwood	0.1	14.9		2.2	3.7	3.2	2.9	0.34
	Hardwood	0	11.1		1.9	3.2	2.3	2.2	0.45
	Total	0	12.6		2	3.4	2.5	2.4	0.42
SLP	Softwood	0.1			9.4		21.2	6.2	0.16
	Hardwood	0.1			8.7		4.1	3.2	0.31
	Total	0.1			8.8		4.3	3.3	0.30
Statewide	Softwood	0.1	3.4		2.6	1.2	2.7	2.5	0.40
	Hardwood	0.1	6.5		1.7	3.2	1.9	1.9	0.53
	Total	0.1	4.4		2	2.4	2.1	2	0.50

Removals to growth ratio = average annual removals / average annual net growth

Appendix A. Definitions from USDA Forest Service Forest Inventory and Analysis

Average annual removals from growing stock.--

The average net growing-stock volume in growing-stock trees removed annually for roundwood forest products, in addition to the volume of logging residues, and the volume of other removals. Average annual removals of growing stock are the average for the years between inventories and are based on information obtained from remeasurement plots (see Survey Procedures in USDA Forest Service, Forest Inventory and Analysis User's Manual, 2010).

Average net annual growth of growing stock._

The annual change in cubic foot volume of sound wood in live sawtimber and poletimber trees, and the total volume of trees entering these classes through in- growth, less volume losses resulting from natural causes. Average net annual growing stock is the average of the years between inventories.

Growing-stock volume.-

Net volume in cubic feet of growing-stock trees 5.0 inches dbh. and over, from 1 foot above the ground to a minimum 4.0-inch top diameter outside bark of the central stem or to the point where the central stem breaks into limbs.

Net volume.-

Gross volume less deductions for rot, sweep, or other defect affecting use for timber products.

Live trees. -Growing-stock, rough, and rotten trees 1.0 inch dbh, and larger.

Volume Conversion Factors Used¹³:

1 Cord = 79 cubic feet

1 MBF = 158 cubic feet

¹³ Leatherberry, E.C. and J.S. Spencer. 1996. Michigan Forest Statistics, 1993. Resource Bulletin NC-170. St. Paul, MN: U.S. Dept. of Agriculture, Forest Service, North Central Forest Experiment Station.

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Executive Summary

In 2009, the Michigan Economic Development Corporation distributed \$1.4 million in funding from the U.S. Department of Energy to create the Forestry Biofuel Statewide Collaborative Center (FBSCC). The goal of the FBSCC is to “find solutions to the complex problem of supplying woody feedstocks to the bioenergy industry for the production of renewable energy, chemicals, and fuels, such as ethanol” (Forestry Biofuel Statewide Collaborative Center, 2009). Specifically, this report was commissioned to identify woody biomass supply and availability throughout the State of Michigan.

Michigan contains approximately 19.3 million acres of timber land which is capable of producing wood biomass for industrial purposes (Forest Inventory and Analysis, 2009). The majority (63.4%) of this land is owned by private individuals, followed by the state and local government (23.1%) and the remaining 13.4% is under the ownership of the federal government (Figure 1) (Forest Inventory and Analysis, 2005-2009). Michigan timberland grows 763 million cubic feet of live trees annually of which 378 million cubic feet is removed, leaving 385 million cubic feet of accumulated growth on timberland across the state (Table 1) (Forest Inventory and Analysis, 2000-2004 to 2005-2009).

Wood removals from Michigan timberlands are determined in part by government agency planning and by the state, regional and international timber markets. National and State forests utilize written management plans which specify removal targets as well as limits to removals on certain timberland or types of timberland. Private timberlands include corporate, tribal, Real-Estate Investment Trusts (REITs), timber management organizations (TIMOs) and non-industrial private forest ownership (NIPF). Timberland in TIMO ownership is guided by forest management plans in which timber markets are a large factor. Most NIPF lands are not managed according to an explicit management plan and harvest on these lands are determined by owner preferences, beliefs and attitudes much more than timber markets.

A 2008 survey of Michigan logging firms indicate that the logging firms were running at 82% capacity in 2007 (G.C. and Potter-Witter, 2011). Of these firms, 75% were willing to expand their operations. Logging firm owners said that they were generally supportive of new wood product industries with the exception of particleboard manufacturing (G.C. and Potter-Witter, 2011). In the same survey, 83% of the respondent loggers reported leaving harvest residue on site (G.C. and Potter-Witter, 2011).

As much as 95.7 million cubic feet of the logging residue is currently being removed from MI forests (Timber Product Output reports, 1996, 2001, 2006) and our assumption is that this amount may be available to those willing to collect and process it in the future as well, if not increase. Re-tooling or further capital development may be necessary in order to access this resource (Peterson, 2005). However, if Michigan woody-biomass retention guidelines are followed (Michigan Department of Natural Resources and Environment, 2010), which suggest an average retention of 25%, this number is reduced to 71.8 million cubic feet (Table 1).

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There are approximately 315 primary manufacturing facilities and 1294 secondary manufacturing

facilities in Michigan (Michigan DNR, 2010). A 2009 survey of the MI primary mills revealed that these facilities operated at an average of 71% capacity in 2007 (G.C. and Potter-Witter, 2011). This dropped to 63% in 2008 (G.C. and Potter-Witter, 2011). Michigan contains many small mill operations and a few key large ones (G.C. and Potter-Witter, 2011). If market conditions improve, current producers said that they are willing and able to increase the output.

An estimated 115.1 million cubic feet of mill residue (bark and wood) is produced annually within the state (Timber Product Output Reports 1996, 2001, 2006). The vast majority (99%) of this resource is currently utilized, however an estimated 1.6 million cubic feet of mill residue remains unused (Table 1) (Timber Product Output Reports 1996, 2001, 2006). Prices for these residues range from \$26-32 per green ton (Kuipers and Potter-Witter 2010, unpublished data).

Availability of wood fiber resources depend on many factors such as landowners' willingness or plans to harvest, accessibility of the resource, and market conditions. These challenges may be mitigated through targeted market facilitation and outreach programs. Regardless, current estimates indicate that Michigan has as much as 458.2 million cubic feet of unused annual growth and residues (Table 1).

This number represents a snapshot in time of Michigan's woody-biomass resource. As demand changes and Michigan's wood product industry develops new uses, this number is likely to change.

Sub-Task A4: Spatial Forest-Based Biomass Availability

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Executive Summary

Geospatial models were developed for the amount of growth in Michigan's forests that is net of both natural mortality and harvest removals. This metric, called *net growth after removals* (or NGAR) represents the relative accumulation or depletion of forest inventory at any given spatial location in Michigan. Where NGAR is positive there may be opportunities for additional biomass harvest, though ultimately many factors conspire to constrain the amount of NGAR that is actually available to a suitably motivated marketplace. Ultimately, if accurate data on availability and drain (current consumption) could be developed and combined with NGAR, an informative picture of opportunities for new industrial development, as well as areas where competition is already constraining current use would be possible.

Introduction

Ultimately, many factors interact to define the amount of biomass that may be harvested from Michigan's forests. Here, the term *biomass* is used to generalize the possible suite of fiber products that harvesting may be intended to supply. These include traditional roundwood harvest for veneer, sawn lumber, and pulp and paper manufacture, as well as intensified use of roundwood and logging residues for energy production.

An analysis of forest biomass availability begins with forest inventory, where inventory is defined as both the current amount and condition of forest resources, as well as how those resources are changing. Since forests are dynamic systems, so is forest inventory; each year trees grow larger, adding wood volume to the forest, and trees die or are harvested for consumption. If the rate of tree mortality and removals is approximately equal to the rate of tree growth, then the forest inventory remains relatively constant.

Growth, mortality and removals vary spatially across the State of Michigan because of a myriad of factors. These include biophysical factors, like differences in soils, climate, and natural disturbance, as well as anthropogenic factors, like differences in land ownership, institutional behavior and management objectives. When we combine these factors, we say we can define the *availability* of forest biomass, where availability is the amount of forest biomass is available for harvest each year.

This project is the fourth in a set of tasks conceived within the Forestry Biofuel Statewide Collaboration Center (FBSCC) to address the inventory and availability of forest based biomass in the state. The overall goal in this task was to construct geospatial data sets for biomass availability for Michigan. The ultimate application is an assessment of the capacity for Michigan's forests to meet renewable energy policy goals while supporting the existing forest-based products sector.

Methods

In the FBSCC Task A1 geospatial models of inventory were constructed for Michigan (Deo et al. 2011). These models were the foundation for the data sets developed in this project. Briefly, the approach in that task was to construct a spatial model, called a mapping model, of existing

ground-based inventory data collected by the USDA Forest Service, Forest Inventory and Analysis program. The mapping model relates known conditions from field samples to satellite based measurements at the same location. Then, since the satellite measurements are continuous, predictions can be made in-between the ground plots to *impute* the likely value of forest inventory attributes.

Differences were calculated between the imputed rate of forest growth and removals, in terms of merchantable cubic foot volume, in this project. This difference is termed *net growth after removals* or NGAR. The raw values of NGAR were added to the set of mapping model outputs and were embedded in a web-based information management system called the Forest Biomass Information System, or FBIS (see <http://fbis.mtu.edu>). This was the goal of the FBSCC Task A2 (Froese et al. 2011).

In the FBSCC Task A3, collaborators at Michigan State University analyzed past rates of timber harvest and management objectives for each of four major owner classes (GC and Potter-Witter 2011). These were: Federal, State, Industrial and Non-Industrial Private forest lands. Availability was defined as the fraction of growth that was planned for timber harvest.

The ultimate goal of this project, FBSCC Task A4, was an assessment of the capacity for Michigan's forests to meet renewable energy policy goals while supporting the existing forest-based products sector. To do this, data were required that represent forest biomass availability and demand, or drain, on the forest resource. These were the goals of the other three FBSCC Tasks A1, A2 and A3. Unfortunately, drain and availability data in a form and scale that would permit a spatial assessment were not developed in these tasks.

Spatial models of NGAR were derived by subtraction of removals from growth data at the pixel level. Because spatial error is high at the pixel scale (Deo et al. 2011), the NGAR data were generalized by smoothing using the focal statistics tool in ArcGIS 10, with a circular spatial average filter and a 2 km radius.

Results

The key product from this project is a set of spatial models of NGAR. These models are downloadable as raster (grid) data in an ESRI geodatabase format from the FBIS web site. Data are available for merchantable bolewood, in cubic feet, by major species group (softwood and hardwood). Illustrations of the two data sets are provided in Appendix 1 and Appendix 2.

Discussion

The accuracy of the NGAR data developed in this project is limited by the accuracy of the data from which they were derived, namely the imputed values of growth and removals for Michigan developed by Deo et al. (2011). Readers are encouraged to be familiar with the interpretation provided by those authors, and should review their report.

The concept of "NGAR" is intended to illustrate where, and to what degree, forest biomass is accumulating in Michigan's forests, because removals and natural mortality together are less than gross annual growth. In these areas, additional timber harvest may be possible without depleting

the standing inventory, or growing stock. Limiting removals such that NGAR is no less than zero over the long term is often viewed as the most rudimentary metric of sustainable management. Otherwise, if NGAR is negative for a protracted period of time, forests are essentially being depleted.

Ultimately it is essential that NGAR data be combined with realistic models of likely availability to estimate the true resource management potential. There are areas in Michigan where NGAR will be completely inaccessible to the wood or biomass products market, because landowners have no intention of ever permitting harvesting. Clear examples are parks and protected areas, but also National Forest lands, because there is now a long history of timber harvest on National Forests at far less than ASQ (Annual Sale Quantity) levels in approved forest management plans. Similarly, it is essential that NGAR be paired with a realistic model of drain, or current harvest consumption, by the wood products and energy sectors. Without this pairing it will be difficult to determine the locations within Michigan where supply and demand are such that new opportunity for forest utilization, and development of e.g. bioenergy facilities, exist. It will remain equally difficult to estimate where competition is already significant enough that current facilities are under pressure to obtain adequate raw material.

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Appendix 1 Net Growth After Removals for Hardwood Species

Appendix 2 Net Growth After Removals for Softwood Species

Sub-Task B1: Evaluation of Michigan Biomass Transportation Systems

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Executive Summary

Minimizing transportation costs is essential in the forest products industry, as the relatively low value and high weight of the products cause transportation to account for an exceptionally high portion of the overall cost. Forest products such as logs, chips, and residues (woody biomass) are one of the major business sources in Michigan, especially in the Upper Peninsula, and place different constraints on transportation and handling requirements.

This report details the transportation-related investigations conducted as part of the Forestry Biofuels Statewide Collaboration Center (FBSCC) project for the state of Michigan, supported by the U.S. Department of Energy (DOE) and the Michigan Economic Development Corporation (MEDC). The main objective of the transportation system evaluation under the FBSCC project framework was to identify and evaluate the capabilities of the Michigan transportation system to deliver woody biomass in general, and especially to nine biomass plants proposed through other parts of the study. The report concentrates on in-state movements only and uses either road (truck) transportation or combinations of either road with rail and/or marine transportation as the transportation chain alternatives.

The transportation analyses were divided to three main categories:

- **Infrastructure:** Inventory and assessment of current road, rail and marine transportation infrastructure in forest regions of Michigan with a main concentration on the northern part of Lower Peninsula.
- **Equipment:** Identification of the most suitable types of equipment for forest biomass transportation and evaluation of their availability in the State of Michigan.
- **Operations:** Operational and economic considerations and challenges for modal and multimodal transportation alternatives. This section also included developing general level estimates for delivery of woody biomass to the nine proposed facilities and review of the formation of transportation costs.

The research methods applied through this report included literature searches, interviews, database searches, field visits, surveys, and limited modeling of different transportation scenarios.

Literature Review

The first chapter provides a summary of conducted literature reviews, including specific reports reviewed as case studies for woody biomass transportation in the U.S. and Scandinavia. Biomass transportation has received little attention in literature and the majority of it has concentrated on truck transportation. Concentration on trucks is not a great surprise, as a majority of the trips are conducted by trucks. Multimodal freight transportation was largely absent in the literature reviews, with the exception of intermodal transportation of containers.

Based on literature reviews, a general comparison of perceived advantages and disadvantages of each transportation alternative was developed (Table 1). Although each situation must be evaluated individually, rail and marine transportation are typically considered cost-efficient for

large quantities and for longer distances. Based on research conducted by Searcy 2007, rail transport is often more economically viable than truck for biomass movements over 300 miles (500 km) and ship is more cost-efficient than rail transport after 900 miles (1500 km). However, type of biomass and availability of facilities can significantly affect the total cost of transport case by case (Searcy, et al, 2007). For example, in woody biomass transportation, rail is often considered competitive for movements over 100 miles.

Table 1-General comparison of transportation modes

Mode	Pros	Cons
Truck	<ul style="list-style-type: none"> -high flexibility and accessibility -suitable for short distances -combinable with other transport modes -low fixed rate - high reliability and fast service 	<ul style="list-style-type: none"> -costly for long distances -high variable rate -low capacity and volume per unit -higher risks of safety and security
Rail	<ul style="list-style-type: none"> -low variable rate -higher capacity in comparison to truck -suitable for mid and long distances 	<ul style="list-style-type: none"> -less accessible and flexible than truck -high fixed rates -low commercial speed -infeasible for short distances -often requires interchanging between companies - complex contractual agreements
Marine	<ul style="list-style-type: none"> -very low variable rate -reliability -highest capacity in comparison to truck and rail -suitable mainly for long distances 	<ul style="list-style-type: none"> -accessibility and flexibility -high fixed rates -very low commercial speed -infeasible for short and mid distances - limited equipment availability

The reports reviewed as case studies confirm the dominance of trucks as the preferred mode for biomass transportation. A study in New York recognized the potential for using rail in addition to trucks, but excluded it from the final recommendations due to unavailability of access points.

Transportation Infrastructure

The infrastructure analysis and respective maps of each transportation mode (road, rail, and marine) are presented in Chapter 2. Infrastructure is typically a fixed asset of transportation system and one of the most important and expensive components. Some examples of transportation infrastructure are highways and truck terminals, railroad tracks and yards, airports and marine ports. Figure 1 shows the main infrastructure available for biomass transportation in Michigan. It also represents the approximate locations of the biomass plants proposed in the study.

Figure 1- Snapshot of all potential transportation infrastructures that may be used for biomass transportation through the state of Michigan

The key **road infrastructure** for biomass transportation includes the all-season truck routes that are mainly part of state highway and interstate network. Truck axle loads and weight restrictions may affect the selected route and limit the truck movements, especially during the spring breakup season. Based on the analysis, bridge weight restrictions do not cause major limitations for truck movements, excluding the Mackinaw Bridge, which has a crossing toll and is limited to a maximum 72 ton (144,000 lbs.) Gross Vehicle Weight (GVW) limit.

The freight rail network in Michigan includes 4,412 miles of track which also supports three shared passenger rail corridors. The current network is owned and operated by 30 freight

railroads, mainly in the Lower Peninsula. Only CN, Lake Superior and Ishpeming (LSI) and Escanaba and Lake Superior (ELS) operate in the Upper Peninsula (UP). The key rail infrastructure components are main lines and rail sidings (stations) and yards. Rail access at points of origin and destination (facility or plant) and interchange locations are the most critical locations to determine the capability of rail for biomass transportation. As there is no rail connection between the UP and the LP, the only railroads capable of serving the proposed plants are the ones operating in the LP, especially in the northern LP. The greatest potential for biomass rail transportation in the LP is provided by Great Lakes Central and Lake State Railway, as all proposed biomass facilities are located in the vicinity of these two rail operators. Since most rail infrastructure in the northern LP is oriented in a north-south direction, it makes rail more usable for movements in these directions, and opportunities for cross-state movements would be limited. It also needs to be recognized that a rail network of any individual railroad is quite limited, so most movements typically require at least one interchange from one railroad to another, immediately reducing the applicability of rail transportation, especially if the maximum 100 mile radius harvesting criteria is maintained.

Marine infrastructure can be typically classified as port and dock facilities. Although there are several ports and docks located around the Great Lakes in the State of Michigan, not all of them are suitable and equipped for biomass transportation. The following attributes were used to refine the analysis for suitable ports and docks:

- Operational Characteristics: like dimensions of dock, depth of water, and conditions of dock
- Landside Connections: like access to the road and rail network, and adequate storage space
- Owner interest in using the dock for biomass transportation

After reviewing all existing ports and docks within the state of Michigan, three origin ports in the Upper Peninsula and five destination ports in the Lower Peninsula were identified to be potentially suitable for any further biomass transportation purposes in the state of Michigan. Since none of the proposed plant locations were on navigable waterways (with the possible exception of Traverse City), truck (or rail) drayage would have to be arranged from the port to the facility.

Transportation Equipment

Most suitable road, rail and marine equipment types for biomass transportation in Michigan were identified and reviewed in Chapter 3. **Trucking** is currently the main transportation mode and there are different types of trucks suitable for woody biomass transportation with various axle configurations. Chip truck trailer, chip truck, log truck and pup, and tractor-trailer are the main truck types with carrying capacity between 42,000 - 110,000 lbs. Increased demand for biomass transportation has also led to the development of new equipment types, such as the stump tuck developed in Scandinavia. In addition to the truck types, the loading and unloading facilities and technologies can also affect the overall productivity and speed of truck transportation. For instance, self-loading log trucks, tipping facilities in the mill or power plant to unload the chip trucks (Figure 2), and live floor technology in the chip trucks, are three examples that affect the overall productivity of truck transportation.

Figure 2- A type of chip truck tipper at woody biomass facility

According to the data received from Secretary of State (SOS) and previous studies, it has been estimated that over 1,000 log trucks are registered within the State of Michigan, with approximately a 2:1 split between the Upper Peninsula and Lower Peninsula. Outcomes of a survey that was conducted as part of the study suggested that most of the log trucks in the state of Michigan are equipped with self-loaders. It also revealed large variations between the average truck age, fuel consumption and annual mileage. Based on interviews with equipment manufacturers the capital costs for trucks and trailers vary significantly, from \$30,000 for a trailer to \$300,000 for log truck + pup trailer (Michigan specifications) and the demand for large biomass trucks has been weak, leading to limited inventory. However, smaller, more versatile trucks have been in higher demand and high powered “Michigan Special” tractors are also readily available.

Several different types of rail cars are capable of hauling woody biomass on railroads, but certain car types are preferred. Bulkhead flat cars and log cars are mainly used for logs and gondolas and hoppers for chips. The load capacity of each car varies between 75-110 tons and in some cases, volume limitations are reached before weight limits. Most rail cars require separate loading/unloading equipment and overall, logs are more widely transported by rail than chips, as unloading processes of chip cars tend to be either capital or labor intensive. Due to the interstate nature of rail assets, there are no dedicated rail cars that operate only in the State of Michigan, but rail service providers felt confident that in case of adequate demand, securing required equipment capacity would not be a problem. Currently, most rail cars for biomass transportation are owned by railroads, but the industry is shifting toward ownership by shippers, sometimes through pooling agreements, or leasing companies. The price of rail cars is not as diverse as trucks and it is placed between \$70,000 up to \$90,000 for new cars and \$15,000 up to \$50,000 for used cars. Vessels and barges are defined based on their physical specifications, operational limitations and legal requirements. A most likely vessel for biomass transportation would be a barge that is propelled by a tug. The barges have relatively low operating costs and capacity between 1,000 and 10,000 tons. In comparison, large vessels may have capacity for up to 60,000 tons. One of the

most significant legal requirements for marine transportation is the Jones Act that limits the pool of available vessels for transporting biomass between Michigan ports or with other states to U.S. flag vessels. More specifically, the Jones Act requires that any vessel transporting cargo for hire in the domestic trade should be:

- Registered in the U.S.
- Built in the U.S.
- Owned/managed by a U.S. company
- Crewed by U.S. citizens

The report provides current U.S. flag tug barges (as of October 2010) in the Great Lakes, with notations on size and suitability for the movement of biomass. Even though capacity for such movements exists, the barges may not be able to travel on all potential routes, as some of them may be engaged in long term contracts that render them effectively unavailable. In addition to current barges, a barge could be repositioned from an ocean coast or newly built, if a suitable market with an acceptable return on investment existed.

Modal and Multimodal Transportation Operations

Modal and multimodal transportation operations, including discussion on challenges and economics of transportation, are covered in Chapter 4. Operations refer to the combination of staff, information, tools, methodologies, techniques and finances needed to operate and maintain the overall transportation system in a safe and efficient manner. Figure 3 represents the alternative supply chains for biomass transportation. In most cases, biomass is transported from the forest landing to the final destination (mill or plant) by a truck in a single movement (Scenario 1), but the supply chain can also take advantage of multimodal transportation opportunities (Scenario 2), or utilize intermediate storage locations to break the transportation chain (Scenario 3).

Figure 3- Alternative supply chains for biomass transportation

There are numerous considerations that affect the selection between alternative supply chains and each situation needs to be reviewed separately. However, there are some common denominators that either support or limit the use of certain alternatives, such as:

- Location of harvesting area
- Location of final destination and availability, or adjacency to the railroad track/marine port facilities
- Total hauling distance and the volume of biomass material to be hauled. Longer distances and higher volumes increase the likelihood of multimodal scenarios. Lower volumes for short distances are more likely to be delivered by truck.
- Type of biomass material and required sorting, processing activities on the raw material
- Number of handling and switching's between truck to the other modes (rail and water) and number of switching or carrier interchanges during rail transportation.

In 2009, over 12 million tons of logs (more than 95% of the entire volume) were transported within Michigan by **trucks**, complimented by 3 million tons of other wood products. Operational characteristics of each truck for log and biomass transportation in Michigan can be typically summarized as:

- Eight to twelve hour operations per day and five days per week
- Two to three daily round trips between harvesting/log yard facilities and mills/power plants
- Trucks move with a payload for 25 percent of the daily operational time

The portion of transportation costs in the supply chain is highly dependent on the overall distance between origin (forest landing) and final destination (facility/plant). Several sources of data were used to define the average distance for current truck movements in Michigan which equaled 75-100 miles. This number correlated well with the 100 mile hauling radius used by the FBSCC modeling team and it suggested that most economical transportation method for biomass movements is by trucks, as such short distances are difficult to perform economically through multimodal alternatives.

Each transportation alternative faces operational challenges that must be considered in the decision-making process. Challenges related to truck transportation include:

- Un-optimized supply chain management
- Limited opportunities for backhaul movements
- Loading/unloading inefficiencies
- Mackinac Bridge, the vital link
- Spring weight restrictions

According to MDOT's analysis, Michigan's **railroads** carried over 110 million tons of freight in 2006, which is more than 25 percent of Michigan's total ground commodity movement. However, the portion of woody biomass, lumber and forest products were minor with only 3% of rail imports and 5% of exports. Almost all rail movements took place in the UP Even though Michigan has almost 30 operational railroads, few of them offer high potential for woody biomass

transportation services. The main opportunities for in-state movements exist in the northern part of LP and in the UP, which eliminates the majority of rail providers. Based on the logger survey, only 13% of shippers (28 out of 220) currently used rail to transport biomass. Even more significantly, all of these shippers were located in the UP and only 20% of their annual volume moved by rail. The major drawbacks to rail operations identified are reliability of rail service, limited rail access within main working areas, and low speed of delivery. Additional challenges for using rail transportation include:

- Short transportation distances, dispersed origins and numerous rail rates
- Rail car availability and transportation time / reliability
- Rail siding access to final destination
- Constructing new rail access to the facilities/plants
- Number of interchanges required en-route

Marine transportation benefits from economy of scale, but poses several operational requirements to be considered as a potential option for biomass transportation. In summary, marine transportation of biomass material is an option where the following key attributes are met in the design of the biomass supply chain:

- Navigable waterways connecting the supply to the demand locations with a depth of at least 15 feet for barge and tug operations.
- Port infrastructure that can support the volume of traffic
- Landside access from the ports to biomass supply and demand locations
- Suitable vessels to carry the biomass in the desired quantity
- The total landed cost of using marine transportation as part of the supply chain is competitive.

Similar to truck and rail operations, there are some challenges in front of marine transportation as:

- Infrastructure and vessel costs (very expensive)
- Vessel acquisition or new building equipment
- Marine haul business model challenges (risky business for operators)

Transportation Service Capacity for Proposed Biomass Plants

Nine potential biomass plant locations were identified as part of the FBSCC study. Since each plant was designed for specific annual feedstock demand (30, 40 or 50 million tons), the capacity and number of vehicles required to provide feedstock to each plant were estimated as part of the transportation analysis. Based on maximum demands for all biomass plants (50 million tons), the number of required loads by trucks, rail cars and barges was estimated (Figures 4 and 5) for each transportation alternative.

Figure 4 - Scenario 2: Number of trucks and rail cars needed to supply biomass for a 50 million gallon facility

Figure 5 - Scenario 3: Number of trucks, rail cars and barges needed to supply biomass for a 50 million gallon facility

Based on the current inventory, serving a single new biomass plant could be accommodated by the current truck fleet, but if all nine would be implemented, the majority of available trucks in the LP would have to be dedicated to the plants. Alternatively, new trucks would have to be added to the current fleet. Both rail and marine transportation service providers were interested, but only if sufficient and continuous volumes existed.

The lack of detailed plant analyses prohibited a detailed transportation cost analysis as part of the study. **Transportation costs** for truck transportation is typically provided as rate per ton-mile, but

rates for multimodal transportation like truck-rail combination have to be typically estimated case-by-case for each origin-destination pair. Instead of simply considering the transportation rates, evaluation should determine the total landed cost as presented in Chapter 4. An example of rate comparison between truck and truck-rail multimodal option within Upper Peninsula is provided in Figure 6.

Figure 6 - Comparison of rail rate versus Michigan log truck rate data (steep blue line)

According to the given rates of truck and rail operator policies and rates (CN) in the UP, the multimodal truck-rail option for biomass transportation can be more cost-efficient when the total transportation hauling length is over 120 miles. However, the break point between trucks and multimodal options fluctuates based on changing parameters, the most important of which is fuel price. Railroads enjoy comparative advantages in fuel economy when compared to trucks, so they tend to be less susceptible to increases in fuel prices. Shippers should be aware of this trend and adjust their supply chains based on fuel price changes.

Transportation Definitions and Terminology

This section summarizes some of the most common terminology used in the current report.

Road and General Transportation Terminology:

- **Bulk Transportation:** freight transportation in large quantities as in ships, railcars, tankers.
- **Cargo (Freight) Transportation:** goods or produce transported, generally for commercial gain, by ship, aircraft, train or truck.
- **Container:** A metal box used to unitize cargo for transportation. Provides easy transfer of complete container between different transportation modes, such as rail, ships and trucks.
- **GIS:** Geographic Information System (geospatial) designed to capture, store, manipulate, analyze, manage, and present various types of geographically referenced data.
- **GPS:** Global Positioning System used to track various kinds of transportation vehicles or assets.
- **L.P:** Lower Peninsula of Michigan
- **Leasing:** a legal agreement in transportation service which allows lessee to use a vehicle for a period of time, in return for a fee.
- **Lessee:** receiver of transportation asset in return for payment to owner.
- **Lessor:** the owner of transportation asset who let lessee to use the asset for a period of time.
- **Michigan Trunkline Highway:** all highways designated as Interstates, U.S. Highways and State Highways in the State of Michigan.
- **Multi-Modal (Intermodal) Transportation:** In multimodal transportation goods use more than one mode of transportation during its path from origin to destination. In intermodal transportation, the goods remain in the container from the origin to destination, even though container can be moved from ships to railroad cars and further to trucks.
- **Pup:** a short semitrailer used in combination with a dolly and another semitrailer to create a twin trailer.
- **State route:** A trunk line highway that is maintained and operated by respective State DOT authorities.
- **TEU:** Twenty-foot Equivalent Unit, a measure used for container capacity.
- **Tractor:** a truck having a cab and equipped with engine, used for pulling large vehicles such as vans or trailers.
- **Trailer:** a large unpowered transport vehicle designed to be hauled by a truck or tractor.
- **Truck tipper:** an inclining platform to raise the truck to a designated angle for unloading purposes.
- **U.P:** Upper Peninsula of Michigan
- **U.S. route:** an integrated system of numbered roads and highways in the United States within a nationwide grid.
- **Walking floor truck:** a type of truck with moving floor mechanism to assist in the unloading process.
- **Woody biomass:** woody biomass material, forest-based feedstock, woody chips and forestry biomass are used interchangeably in the report. May consist of logs, chips or residues.

Rail Transportation Terminology:

- **Demurrage:** is monetary charge for customers who keep rail car for loading purposes beyond allocated time.
- **Depot or Terminal:** one, or several stations, warehouses or yards where cars can be loaded, unloaded, maintained, inspected and interchanged. It may also refer to the Rail Terminal.
- **Interchange Points:** stations or yards where rail cars are transferred from one railroad company to another.
- **Main line:** a principle track, other than auxiliary track, utilized mainly for line haul rail transportation..
- **Rail Car:** any type of rail vehicle to carry freight or people, typically unpowered.
- **Rail siding:** an auxiliary track, usually used to allow train to pass each other on a single track or to load/unload rail cars in industrial lines.
- **RR:** Railroad.
- **Class I Railroad:** line haul freight railroads with 2010 operating revenue of \$398.7 million or more
- **Regional (Class II) Railroad:** railroads with annual carrier operating revenues of less than \$398.7 million* but in excess of \$31.9 million (2010 value).
- **Local or Shortline (Class III) Railroad:** railroads with annual carrier operating revenues of \$31.9 million or less (2010 value), and all switching and terminal companies regardless of operating revenues
- **Spur Track:** Any light duty track that branches off a main track, typically for industrial lines.
- **Switching (Terminal) Railroad:** a freight railroad company whose primary purpose is to perform local switching services or to own and operate a terminal facility within the limits of a yard. It generally consists of making up and breaking up trains, storing and classifying cars, serving industries within yard limits, and other related purposes.
- **Yard:** a system of tracks within defined limits for the purpose of storing and sorting cars.

Marine (or Water) Transportation Terminology:

- **Adrift:** A boat that is adrift is not fastened to anything or controlled by anyone.
- **Barge:** A long, large, usually flat bottom boat for transporting freight, (usually containers) that is generally unpowered and towed or pushed by other craft.
- **Basin:** An artificially enclosed area of a river or harbor designed so that the water level remains unaffected by tidal changes.
- **Breakwater:** A wall built out into the sea to protect the shore from the force of the waves.
- **Deadweight:** Total cargo capacity in short (net) tons of 2,000 pounds.
- **Dock:** A platform extending from a shore over water in port, supported by piles or pillars, used to secure, protect, and provide access to ships or boats for loading, unloading or repairs.
- **Draft:** The depth of water that a vessel requires to float freely; the depth of a vessel from the water line to the keel.

- **Drayage:** Is the transport of goods throughout a short distance, often as part of a longer overall move. It may also refer to the fee charged through handling and loading/unloading of such activity.
- **Dredge:** To remove mud or sand from the bottom of a river, harbor, etc.
- **Harbor:** An area of water next to the land where the water is calm and enough deep, so that ships are safe when they are inside it.
- **Pier:** A structure that is built over and into the water so that boats can stop next to it or people can walk along it.
- **Port:** Main marine infrastructure, a place where ships can be loaded and unloaded, including all of facilities and structures such as docks.
- **Shoaling:** A small hill of sand just below the surface of water that makes it dangerous for boats.
- **Tug:** A small strong boat used for pulling or guiding ships into a port, up a river, etc.
- **Vessel:** A large passenger or freight-carrying ship, boat, etc; typically equipped with powered engines.
- **Wharf:** A landing place or pier where ships may tie up and load or unload.

Introduction

This report details the transportation-related work conducted as part of the Forestry Biofuels Statewide Collaboration Center (FBSCC) project for the state of Michigan. The FBSCC project has been financially supported by the U.S. Department of Energy (DOE) and the Michigan Economic Development Corporation (MEDC). The overall goal of the FBSCC is to improve the long-term forest feedstock supply infrastructure to sustainably provide woody biomass for biofuel production in Michigan. Researchers sought to support the developing biofuel industry in identifying current operating procedures and opportunities to increase feedstock supply chain efficiencies, reducing costs, and assuring sustainability of the production, harvesting, processing, and transportation of woody biomass from Michigan's forests and energy plantations. An effective stakeholder collaboration structure is also being established to offer partners opportunities to participate in applied R&D projects designed to answer common challenges facing the biofuel industry.

The FBSCC project addressed several objectives and research milestones in areas of:

- Forest biomass assessment
- Improving harvesting, forwarding, and transportation systems
- Improving forest feedstock productivity and sustainability
- Engaging stakeholders across the value chain

1-1- Statewide Evaluation of Michigan Biomass Transportation Systems

Forest biomass can be procured in a variety of forms (chipped wood, harvesting residues, round wood logs), each with different constraints in terms of density and handling requirements. The main alternatives for transportation are trucks, rail and/or marine. Biomass is often procured in locations with limited access to major roads, rail sidings, or port facilities and each transportation mode requires a separate set of equipment, infrastructure and operational considerations.

The objective of the transportation systems evaluation under the FBSCC project framework was to identify and evaluate the capabilities of the transportation system to deliver feedstock to a factory gate in the State of Michigan. The specific tasks conducted under transportation analysis included:

- **Inventory and assessment of current road, rail and marine transportation infrastructure in forest regions of Michigan.** In addition to mapping the physical location of transportation infrastructure, researchers made efforts to incorporate other relevant information that affects the productivity of the system, such as highway and bridge weight restrictions, location of rail landings and yards and condition of docks and access roads.
- **Identification of most suitable types of equipment for forest biomass transportation.** In addition to identifying the best types of equipment, the team also investigated the

availability of appropriate road vehicles, rail cars and marine vessels in the State of Michigan. Factors potentially restricting efficient use of transportation modes, such as insufficient service levels, were documented and discussed with transportation industry representatives.

- **Operational and economic considerations.** The transportation team investigated operational and economic considerations when selecting between main transportation alternatives. Transportation mode selection depends on various factors, such as the overall volume of transportation, modal access, the availability of storage space and level of inventory needed.
- **Multimodal considerations.** Road, rail and marine (water) transportation are all potential transportation alternatives for forestry biomass. However, it is recognized that when rail or marine transportation is used, the overall transportation chain becomes multimodal by nature. The investigations identified potential synergies and challenges between modes that allow efficient use of a multi-modal transportation network.

In addition to a statewide evaluation, the team also provided supporting data and guidance to a modeling effort that identified nine potential locations for new biomass facilities. Locations were chosen based on perceived feedstock supply availability, proximity to major roads, railroads (<1 mile) or access to major waterways (< ¼ mile), location within population centers of a minimum size, and no existing or planned biomass facility located nearby. Figure 1-1 presents the nine biomass facility sites considered by the supply chain modeling team, all located in the northern part of Lower Peninsula (LP) of Michigan. Detailed transportation evaluations to deliver biomass to these facilities were out of scope for the project, but preliminary analysis and considerations for multimodal transportation supply chain were developed by the team.

Nine Potential Biorefinery Sites in L.P.

Figure 1-1- Proposed location for biomass facilities by FBSCC project

1-2- Limitations of the Study

Transportation analysis conducted during the project had the following limitations:

- The FBSCC supply chain model team determined that feedstock supply would be limited to a radius of 100 miles from each proposed facility. This reduced the opportunities for multimodal transportation which are typically more effective over longer trips, resulting in a greater focus placed on truck transportation.
- The forest-based feedstock considered included wood chips, round wood and forest residues with a primary focus on round wood and wood chip transportation.
- The transportation evaluation was limited to the movements within the State of Michigan. Rail and marine transportation often take place across state and even national borders, as higher fixed costs of these modes can often be overcome by their lower marginal costs for additional volume and distance. The “in-state” movement restriction increased the focus on truck transportation in this study.
- This report was not tasked with an examination of the cost of infrastructure damage or development such as highway damage from increased truck movements or the cost of dock development. Neither has this report assessed the impact of increased energy costs

on the supply chain, or assessing the external costs, such as air emissions, accident rates, water pollution or congestion impacts for marine, truck or rail supply chains. These factors may raise the costs for any of the modes and should be considered in the final supply chain analysis.

- Only transportation of woody biomass as feedstock to the facility was researched, not the transportation of the final product out of the facility. In reality rail, and in some cases, marine transportation, would gain significant benefits if both inbound and outbound movements were considered in the analysis.

1-3- Outline and Structure of Report

The specific tasks and the chapter where outcomes are discussed are presented in Table 1-1. The remainder of Chapter 1 provides a summary of literature review conducted as part of analysis, including specific case studies. Infrastructure and equipment analysis for each mode is presented in Chapters 2 and 3, respectively, followed by modal and multimodal operations and economics discussion in Chapter 4. More detailed information of various data collected during the study is included in the appendices.

Table 1-1- Project tasks and structure

Task #	Task	Chapter 1 Introduction	Chapter 2 Infrastructure	Chapter 3 Equipment	Chapter 4 Operations & Multimodal	Chapter 5 Conclusions	Attachment
B1.1	- Contact study area railroads, ports and road agencies to inquire infrastructure data						
B1.2	- Identify most suitable equipment for biomass transportation (based on tasks A1 and A3)						
B1.3	- Perform literature review on biomass transportation						
B1.4	- Identify data readily available on transportation infrastructure						
B1.5	- Collection of key infrastructure parameters (weight restrictions, rail/port facilities, capacities)						
B1.6	- Develop GIS layers of main transportation infrastructure						
B1.7	- Identify data sources for transportation equipment						

B1.8	- Interview selected transportation providers to define potential service capacity						
B1.9	- Identify key operational challenges for biomass transportation						
B1.10	- Inventory of the equipment available in the state of Michigan						
B1.11	- Industry inquiry to collect rate information for biomass transportation						
B1.12	- Synthesis on challenges and synergies between alternative modes						
B1.13	- Summary of transportation operations and available equipment						

1-4- Literature Review

The literature review consisted of more than 30 reviewed papers, articles, books and other references related to the biomass and forest product transportation. The review concentrated on North America and Scandinavia and included topics, such as forest product and biomass transportation, transportation methodologies and transportation cost. Case studies from Finland and New York were reviewed and are summarized in this section. A more detailed summary of each reviewed article is included in Appendix A.

1-4-1- Transportation

In general, transportation is "a system that provides for the movement of people (passenger), goods (freight), or both." (TRB, 2003) There are five major modes of transportation; road, rail, marine (or water), air and pipelines. All modes can provide both passenger and freight transportation, except pipelines, which are only for freight transportation. In some references, road and rail modes are also called "ground transportation". Since the current research concentrates on woody biomass material, there is no need to discuss passenger transportation systems or pipeline transportation. Freight air transportation is also omitted, as it is typically used for valuable freight material like express mails and parcels. Hence, the report focuses on road, rail and marine modes as likely options of forest biomass transportation.

Each mode of transportation can be divided to three main system components; infrastructure, equipment and operations. Infrastructure is typically a fixed asset and in many cases the most expensive component of system. Some examples of transportation infrastructure are highways and terminals, railroad tracks and yards, airports and marine ports. Equipment includes vehicles used for carrying people and goods, such as trucks, containers, trailers, rail cars, cargo planes, barges and vessels. Transportation operations refer to the combination of staff, information, tools, methodologies, techniques and finances needed to operate and maintain the overall transportation

system in a safe and efficient manner. More details about each transport system component, as they relate to biomass transportation are provided in following chapters.

1-4-2- Multimodal (Intermodal) Transportation

Freight can be transported from origin to destination via a single mode, or by multiple modes. Multimodal (or intermodal) transportation refers to operations that use more than one mode of transportation during the process. However, the whole shipment typically moves under a single freight bill and the chain is often managed by a single entity (The United Nations Trade Facilitation Network, 2011). Intermodal transportation refers to a specific type of multimodal freight transportation that utilizes containers and trailers either for domestic or international movements. In multimodal transportation, cargo gets transferred from one vessel to another; the goods in intermodal transportation remain inside the same transportation unit (container) that gets transferred between ships, railroad cars and trucks (Jones, et al, 2010).

Table 1-2 presents a general comparison of advantages and disadvantages of each main transportation alternative. Although each scenario must be reviewed individually, rail and marine transportation are typically economical and cost-efficient for large quantities and for longer distances. Based on a research conducted by Searcy 2007, rail transport is often more economic than truck for biomass movements over 300 miles (500 km) and ship is more cost-efficient than rail transport after 900 miles (1,500 km). However, type of biomass and availability of facilities can significantly affect the total cost of transport case by case (Searcy, et al, 2007). For example, in woody biomass transportation, rail is often considered competitive for movements over 100 miles.

Table 1-2- General specifications of biomass transportation modes

Mode	Pros	Cons
Truck	-high flexibility and accessibility, -suitable for short distances, -combinable with other transport modes, -low fixed rate - high reliability and fast service	-costly for long distances -high variable rate -low capacity and volume per unit -higher risks of safety and security
Rail	-low variable rate -higher capacity in comparison to truck -suitable for mid and long distances	-less accessible and flexible than truck -high fixed rates -low commercial speed -infeasible for short distances -often requires interchanging between companies - complex contractual rules
Marine	-very low variable rate -reliability -highest capacity in comparison to truck and rail -suitable mainly for long distances	-accessibility and flexibility -high fixed rates -very low commercial speed -infeasible for short and mid distances - limited equipment availability

1-4-3-Biomass Transportation

Biomass material is divided to three major categories:

- agricultural biomass (such as corn stover and switchgrass)
- woody biomass (such as forest products like wood chips, branches and residues)
- other material like urban wastes, rubber residues and tire-derived material

In different countries and based on the region, different types of biomass material are applied for varied purposes. For instance woody biomass has been used extensively in Scandinavian countries like Finland and Sweden, so a significant portion of transportation and logistics research and transportation equipment and systems development has taken place in these countries. In the U.S., different states and regions have varying interests in biomass transportation applications. In southern states, agricultural biomass is more important, while in northern areas such as Michigan, forest loose residues and woody biomass are in greater demand. This study focuses on woody biomass material and its respective transportation systems.

Although the truck, rail and marine transportation systems can all be used for moving biomass, trucking tends to be the main and most cost-efficient system for almost all types of biomass material. Historically, rail transportation played a larger role in delivering woody biomass materials due to its cost efficiency, especially for high volumes. For instance, the Biomass Transportation and Delivery Fact Sheets refer to a study in 1985 which showed that rail rates for fuel wood transport were about 35 percent lower than trucks for haul lengths averaging 80 miles (Stokes et al, 1993). In past years, the market share of trucking has been grown quickly and in 2005, approximately 90% of pulpwood was transported to U.S. mills by trucks (Schroeder, et al, 2007). Due to these trends, it is not surprising that a majority of biomass transportation literature discusses road transportation (truck), while rail, marine and multimodal transportation have received limited attention.

Transportation of biomass has typically two main challenges; providing suitable access to equipment to remove the material and making transportation economical, if the access roads are in poor condition (Wynsma, et al, 2007). Transportation of logs differs from the transportation of chips and loose residues. Typically, whole trees or cut-to-length sections are loaded for transportation by truck or in some cases, truck-rail or truck-barge systems for delivery to mills or manufacturers (Wynsma, et al, 2007). Residues, on the other hand, are currently a low value by-product of commercial timber harvesting operations and often left unharvested. If there is a high enough demand for chips/harvesting residue, loggers can add chippers/debarkers and get chip trailers or trucks to transport them, even though these operations increase operational and company costs (Jeuck, 2009).

Several methodologies for chip and loose residue transportation are currently applied in different regions and countries. Maertens points out that the Technical Research Center of Finland (VTT) issued a report explaining different methods of chip and loose residue supply chain and transportation. These are outlined in Figure 1-2 and the following paragraphs.

Figure 1-2- Woody biomass supply chains, by Alakangas, VTT-Finland (Cook, 2010)

Type of transportation for biomass depends heavily on the location, where it is converted to chipping. In general, chipping and related transportation can be divided into terrain, roadside, chipper-chip, terminal, loose residue and bundling methods.

Terrain Chipping: In this method, when the detachable chip containers of a terrain chipper are full, they are moved to the roadside by the terrain chipper to be loaded and transported to the heating and power plants by chip trucks (Parikka, 2006). Terrain chippers are relatively small (15-20 m³) and typically used at small harvesting sites with short forwarding distances. Generally, it is not a good idea to use terrain chippers during tough winter times because the quality management of residue chips is affected by snow and can cause quality problems (Maertens, 2009).

Roadside Chipping: In roadside chipping, chips are directly loaded into chip trucks and transported to their final destinations (Figure 1-3). This method is the most common delivery system in Finland and has several benefits, such as flexibility (used for all types of harvesting conditions) and availability of different types of machinery to perform roadside chipping. On the other hand, the large storage space required for logging residue is a disadvantage.

Figure 1-3- An example of harvesting-transportation cycle for chips material toward final destination (Parikka, 2003)

Chipper-chip truck: In this method, chipping and transportation equipment are combined together but the machine is heavy (37 tons), limiting the load capacity to 23 tons. The chipper-chip truck is more useful and efficient for transportation distances less than 30 km (Figure 1-4) (Maertens, 2009).

Figure 1-4- A chipper-chip truck during chipping and loading branches and residues¹⁴

Terminal chipping (loose residues): In this method, chips are comminuted in centralized terminals. Loose residue is transported as bulk material without any specific processing from roadside to the final destination. Since the density of loading in this method is low, it is not recommended for long distance transportation in comparison to the chips. New, large tandem trailers of 150-170 m³ (5300- 6000 ft³) can compress loose residue and provide more efficient use of cargo space.

¹⁴ : United Nations Development Program, Bioenergy, Republic of Belarus Government Project, accessed time: Aug. 2011
http://energoeffekt.gov.by/bioenergy/htdocs/en/trainings_finen.htm

Bundling: Bundled wood transportation is an economical transportation mode which is more common in Scandinavian countries, but the relatively high bundling cost has hindered its implementation (Figure 1-5). In the United States, only one commercial company was equipped with this method as of 2007 (Wynsma, et al, 2007). Some studies show that bundling method can provide the lowest total production cost for wood fuel, as it allows the same handling and administrative route as used for conventional round wood logging and transportation (Parikka, 2006). Since the density of bundling transportation with ordinary timber trucks is acceptable (between 60 to 65 bundles per truck), this method holds promise for long-distance hauling (Maertens, 2009).

Figure 1-5- Logging residue bundles stacked up and ready to be transported (Maertens, 2009)

1-4-4- Freight and Forest Product Transportation in State of Michigan

According to the U.S. Department of Transportation's, Research and Innovative Technology Administration, more than 282 million tons of freight commodities with values of \$409 billion were transported (transit, import, export or in-state movements) in 2007 in the State of Michigan, forming approximately 3.5% of total value (2.2% of total weight) of U.S. shipments in 2007. The majority of this volume (72%) was shipped by trucks (road). For in-state movements, this share was even higher, almost 85%. Almost 50% of domestic shipments originating in Michigan were

for less than 50 miles, 40% between 50 to 500 miles and less than 10% for more than 500 miles. Finally, less than two percent of in-state movements used multiple modes. The distribution of freight movements between modes for different categories is provided in Table 1-3.

Table 1-3- Shipments within, from, and to Michigan by mode in 2009 (FHWA, 2011)

State	Mode	Within State		From State		To State	
		Weight (Thous. ton)	Percent	Weight (Thous. ton)	Percent	Weight (Thous. ton)	Percent
MICHIGAN	Truck	195,257	84.46%	62,089	61.12%	78,424	49.07%
	Rail	15,033	6.50%	17,527	17.25%	52,696	32.97%
	Water	2,637	1.14%	5,584	5.50%	318	0.20%
	Air (include truck-air)	46	0.02%	12	0.01%	11	0.01%
	Multiple modes & mail	4,414	1.91%	7,923	7.80%	9,155	5.73%
	Pipeline	9,433	4.08%	7,462	7.35%	17,518	10.96%
	Other and unknown	4,375	1.89%	981	0.97%	1,693	1.06%
Total		231,195	100.00%	101,578	100.00%	159,815	100.00%

According to the FHWA, log transportation within Michigan equaled 12.3 million tons in 2009 and wood products added another 3.6 million tons. In total, these products accounted for approximately seven percent of overall in-state tonnage (Table 1-4). The volume of woody biomass transportation in Michigan is unclear as categories for such movements were not identified in the data.

Table 1-4- Commodity movements in Michigan (FHWA, 2011)

State	Mode	Within State		From State		To State	
		Weight (Thous. ton)	Percent	Weight (Thous. ton)	Percent	Weight (Thous. ton)	Percent
MICHIGAN	Cereal grains	22,617	9.78%	6,406	6.31%	3,080	1.93%
	Other ag prods.	6,950	3.01%	2,883	2.84%	2,427	1.52%
	Natural sands	7,594	3.28%	616	0.61%	572	0.36%
	Gravel	17,213	7.45%	9,488	9.34%	507	0.32%
	Metallic ores	13,485	5.83%	32	0.03%	6,566	4.11%
	Gasoline	14,612	6.32%	948	0.93%	495	0.31%
	Fuel oils	7,203	3.12%	899	0.89%	2,458	1.54%
	Coal-n.e.c.	12,477	5.40%	3,464	3.41%	30,838	19.30%
	Basic chemicals	7,673	3.32%	4,179	4.11%	7,642	4.78%
	Logs	12,356	5.34%	407	0.40%	26	0.02%
	Wood prods.	3,632	1.57%	2,342	2.31%	2,276	1.42%
	Nonmetal min. prods.	15,468	6.69%	6,661	6.56%	3,143	1.97%
	Base metals	10,219	4.42%	10,798	10.63%	10,183	6.37%
	Motorized vehicles	7,341	3.18%	7,586	7.47%	8,740	5.47%
	Waste/scrap	22,749	9.84%	2,319	2.28%	2,595	1.62%
Total		231,195	100.00%	101,578	100.00%	159,815	100.00%

1-5- Case Studies

Many countries in Europe as well as in North America have plans to improve biomass transportation for mills, power plants and other facilities. This section provides two biomass transportation related case studies conducted in Finland and in the U.S.

1-5-1- Finland

In Finland, wood is the second most important source of energy and several types of supply chains for woody biomass productions are used. A study was conducted to review the different alternatives for forest biomass production and transportation (Figure 1-6).

Figure 1-6- The proportion of supply methodologies of wood biomass material, 2004- Finland (Maertens, 2009)

Based on a research conducted by Ranta and Rinne in another study in Finland, transportation costs form approximately one-third of overall supply chain costs for forest chips and bundles, while for loose residues such as unprocessed chips, it may increase to almost half of the total cost. Figure 1-7 presents the most economic methods to transport woody biomass materials in Finland. Bundles provide the most economical transportation and loose residues the least economical transportation.

Figure 1-7- Transportation cost of alternative wood raw material options in Finland (Ranta, 2006)

The study also concluded that chipping in forest is more suitable for small scale operations. The best solution for transportation is to use large truck–trailer vehicles to transport different kinds of uncomminuted material to the plant, separately or mixed, instead of custom-built compressing equipment trailers. (Ranta, Rinne, 2006). Table 1-5 shows estimated trucks required for biomass transportation in Finland by 2010, based on actual demand of woody biomass transportation in 2003. Based on Ranta and Rinne, transportation of loose residue is expected to increase at the expense of transportation of chips made in woods, while the portion of bundled transportation is expected to remain stable. The overall transportation volume is expected to more than double over the period.

Table 1-5- Estimation of trucks needed for biomass transportation in Finland (Ranta, Rinne, 2006)

Raw material type	Current 2003			Estimate 2010		
	Amount (m ³)	Share (%)	Trucks no.	Amount (m ³)	Share (%)	Trucks no.
Residue bundles	360,000	18	25	700,000	14	40
Loose res. & stumps	200,000	10	15	2,000,000	40	110
Forest chips	1,440,000	72	80	2,300,000	46	110
Total	2,000,000	100	120	5,000,000	100	260

1-5-2- State of New York

Appendix F of the “Renewable Fuels Roadmap and Sustainable Biomass Feedstock Supply for New York” study discusses transportation and distribution (T&D) implications of increased biofuel feedstock and fuel production in the state of New York. It contains all biomass types including woody, agricultural and grass material. Based on three predefined scenarios for biofuel industry, the relevant transportation infrastructure requirements were evaluated in the report. The respective scenarios were: (Corbett, et al, 2010)

- **Scenario 1:** smaller scale feedstock production in comparison to the Scenarios 2 and 3 with four biorefinery locations in the state.

- **Scenario 2:** in this scenario feedstock availability for biofuels is greater than Scenario 1 and the biofuels industry is centralized, with few (but high capacity) biorefinery locations in the state.
- **Scenario 3:** “a distributed biofuels industry, with a greater number of lower capacity biorefinery locations in the State Feedstock.” In scenario 3 the average transportation distances are expected to be shorter than expected in centralized biofuels industry scenarios.

Transportation assumptions for all scenarios included:

- A full truckload carrying 22 tons of wet (moisture content at time of harvest) feedstock
- Feedstock is wet during the transport from origin county to destination county
- Alternative truck or feedstock weight configurations have not been examined.

Based on the above assumptions the average distance and ton-miles of transportation for each scenario and each selected mode is summarized in Table 1-6.

Table 1-6- Average distance and total ton-miles of transportation, based on feedstock type, scenario and mode (Corbett, et al, 2010)

Scenario	Mode	Average distance of transport (mile) to deliver feedstock material							Total ton-miles	Mode of Transport %
		Corn Stover	Grass	Willow	Softwood	Hardwood	Corn Grain	Soybeans		
Scenario 1a	Truck	24.3	n/a	46.5	38	37.2	122.7	227.4	312,686,129	100%
	Barge	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0	0%
Scenario 1b	Truck	79.4	59.6	59.4	57.4	57.7	122.7	227.4	904,526,088	100%
	Barge	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0	0%
Scenario 2a	Truck	79.3	69.7	60.9	57.5	61.4	122.7	227.4	1,453,422,236	98.80%
	Barge	179.2	179.2	179.2	178.7	176.1	n/a	n/a	16,987,955	1.20%
Scenario 2b	Truck	79.5	70.2	60.9	57.5	61.4	122.7	227.4	1,460,960,249	98.80%
	Barge	179.2	179.2	179.2	178.7	176.1	n/a	n/a	17,958,718	1.20%
Scenario 3a	Truck	24.4	26.3	22.7	39.3	30.1	122.7	227.4	658,127,426	98.80%
	Barge	146.9	158.1	179.2	179.2	179.2	n/a	n/a	5,358,149	1.20%
Scenario 3b	Truck	25.1	26.2	22.2	39	30.2	122.7	227.4	658,264,312	98.80%
	Barge	179.2	156.3	179.2	179.2	179.2	n/a	n/a	5,401,586	1.20%

The table reveals that trucks were used as the main transportation mode of feedstock delivery, based on a least cost production model. Although most feedstock production centers have access to the rail infrastructure, researchers questioned the true potential to use rail systems, as it depends on available rail transfer facilities and proximity of rail lines to feedstock collection points. Since all the current rail transfer facilities are mainly used for container transportation rather than bulk freight in New York, the rail system was not selected. If operation of at least two new bulk

transfer facilities between rail and other modes was established, the use of single mode or multimodal rail transportation could be eventually increased. (Corbett, et al, 2010)
 Table 1-7 presents a general comparison between average feedstock transportation rates for all three transportation modes considered in the study.

Table 1-7- Average freight rates for feedstock movement via truck, rail, and ship (Corbett, et al, 2010)

Mode	Truck	Rail	Ship
Cost per TEU-mile	\$0.87	\$0.55	\$0.50
Cost per Ton-mile, Feedstock Transport	\$0.11	\$0.07	\$0.06
Cost per Ton-mile, Fuel Transport	\$0.08	\$0.05	\$0.05

The study concluded that the number of trucks expected to enter the biorefinery is extensive for each scenario. For instance, refineries in Scenario 2 will receive 500 to over 850 trucks per day. This can increase the traffic congestion along the highways near biorefineries and aggravate risk of highway degradation and damages.

2.0 Transportation Infrastructure

Tasks covered in the chapter include:

Task	Description
B 1.1	Contact study area railroads, ports and road agencies to inquire infrastructure data
B 1.4	Identify data readily available on transportation infrastructure
B 1.5	Collection of key infrastructure parameters (weight restrictions, rail / port landings,
B 1.6	Develop GIS layers of main transportation infrastructure (road, rail and marine)

2-1- Introduction

Infrastructure is one of the most important and expensive components of transportation systems. In this chapter, the state of Michigan transportation infrastructure is reviewed for all three major transportation modes; road, rail and marine. Infrastructure data was collected from several sources, including databases (Roadsoft® software, Michigan Department of Transportation (MDOT), GIS Data Depot (<http://data.geocomm.com>), Oak Ridge National Laboratory Center for Transportation Analysis (CTA) (<http://cta.ornl.gov/cta/index.shtml>). In addition, transportation service providers and forest products companies were interviewed. All interviews and discussions conducted in this project are represented in Appendix B.

2-2- Road Infrastructure

As discussed in the previous chapter, roads are the most common transportation mode used for biomass materials. This section identifies road and highway infrastructure in the State of Michigan, concentrating on forest areas in the upper part of the Lower Peninsula and the Upper Peninsula (UP). All components of the transportation infrastructure were collected and organized in geospatial databases and provided for use by modeling team members. Road network data for the entire state of Michigan was obtained through RoadSoft asset management software. All publicly-owned roads in Michigan were included, along with a database of the legal description, functional classification, primary name, width, and ownership of each road segment. In addition, the seasonal and bridge weight restrictions were identified, including special considerations required by Mackinac Bridge.

The most important routes for biomass transportation include the all-season truck routes. Figure 2-1 presents the complete Michigan road network with all season truck routes and their relative location to proposed biomass facilities highlighted.

Figure 2-1- Michigan publicly-owned road network, all-season truck routes as designated by the MDOT

2-2-1- Road Classifications

There are two types of classification for all roads throughout the state, the National Functional Classification (NFC) and the National Classification. Road classifications are used to separate different types of public roads from each other, based on their intended function. The NFC is the most relevant classification, as its designation of a given road also determines whether the road is eligible for federal funds, either as part of the National Highway System (NHS -- usually limited to principal arterials) or through the Surface Transportation Program (STP). Most federal aid is limited to principal arterials, minor arterials, and urban collectors, but rural major collectors may also have some limited eligibility for federal funds. Classifications are important for biomass transportation considerations, as they often define the speed limits and allowed maximum axle loads. Specific attention should be paid to road networks that provide access to the facilities, as limitations may prevent full weight truck traffic from entering the facility.

The **National Functional Classification (NFC)** divides the road network to three categories, based on the mobility and land access. Different categories and some key parameters are presented in Figure 2-2 and Table 2-1.

Figure 0-1. Road classification (FHWA, 2011)

Table 0-1- NFC Road Classification (FHWA, 2011)

Classification	Function	Speed Limits	Examples
Local	Consists of all roads not defined as arterials or collectors; primarily provides access to land with little or no connectivity	20-45 mph	Residential streets
Collector	Provides a less highly developed level of service at a lower speed for shorter distances by collecting traffic from local roads and connecting them with arterials.	20-55 mph	County roads, connecting streets
Arterial	Provides the highest level of service at the greatest speed for the longest uninterrupted distance, with some degree of access control.	50-75 mph	State highways

2-2-2- Truck Axle Load and Seasonal Weight Restrictions

The main parameter used to protect the roads from extensive dynamic loads caused by trucks is limits on axle loads. MDOT provides clear instructions for axle load combinations and restrictions for all classes of trucks and places maximum allowable weight restrictions on selected state roads each spring to decrease damage from frost heaving. In addition to road classifications, these load restrictions should also be considered when selecting locations for biomass facilities. Figure 2-3 and Figure 2-4 present examples of maximum axle loads outside and during weight restrictions for two types of trucks.

Figure 2-3- Typical Michigan log truck combination (MDOT, 2010)

Figure 2-4- Typical Michigan tractor-trailer combination (MDOT, 2010)

The website of County Road Association of Michigan (CRAM) provides a list of roads with weight restrictions on a county by county basis. In addition, MDOT releases a truck operator map that highlights all truck routes and seasonal classification to help verify applied restrictions (Figure 2-5). The roads and restrictions are divided as follows:

- Routes designated as "All Season Routes" (green and gold on MDOT Truck Operator's Map), have no reduction in legal axle weight.
- Routes designated as "Seasonal" (solid or dashed red), have weight reduction of 25 percent for rigid pavements and 35 percent for flexible pavements.

Figure 2-5- Michigan truck operator's map for the northern part of the Lower Peninsula (MDOT, 2011)

2-2-3- Mackinac Bridge

The Mackinac Bridge is the only road link between the Upper and Lower Peninsula, creating a vital link for truck traffic. The team discussed bridge related restrictions with Mackinac Bridge Authority (Appendix C). The limiting factors caused by the bridge included:

- Maximum 72 ton (144,000 lbs.) Gross Vehicle Weight limit.
- All trucks have to pay \$4.50 per axle and there is no discount for trucks that pass over the bridge more frequently.
- Large commercial trucks require an escort over the bridge unless the trucker has a permit from the bridge authority to pass on their own.

Based on the data received from the authority, forest product trucks (both chip and log trucks) move over the bridge at a constant rate with an approximately 50-50% split between north and southbound movements. The team also reviewed the records of vehicle crossings by the number of axles and determined that there were no significant changes in truck volumes during the spring break.

2-2-4- Other Bridge Restrictions

Bridge weight restrictions can limit the movement of heavy 10 and 11-axle log trucks, commonly used for log and biomass transportation in the state of Michigan. The research team obtained information on bridge restrictions through data collected on Pontis software and stored in RoadSoft. Only 10 percent of the 2,803 bridges in the main study area (UP and northern part of LP) had no weight restrictions. The maximum weight for a fully-loaded 11 axle log truck is 82 tons (164,000 lbs.), so the team decided to identify bridges that had either 60 or 70 ton maximum limits. Table 2-2 presents the number of bridges with those weight restrictions. Based on more detailed investigation, none of these bridges were located on all-season truck routes, so excluding the Mackinac Bridge, weight restrictions pose a minor hindrance for biomass transportation by trucks. The approximate locations of bridges with critical weight restrictions are presented in Figure 2-6.

Table 2-2- Bridge Weight Restriction Data in UP and northern LP

Restriction Level	Bridges Flag / Total Bridges
Any potential weight restriction	281 / 2803
Max. 70 tons for 2-unit truck	242 / 2803
Max. 60 tons for 2-unit truck	209 /2803

Figure 2-6- Bridges with gross vehicle weight restrictions of 60 tons or less

2-3- Rail Infrastructure

This section summarizes current rail systems in the state of Michigan. The information includes location of track networks and identifies the operators and owners. It also provides a more detailed review of the rail sidings and terminals along the lines with potential to serve the nine proposed facilities.

2-3-1- Michigan Rail Lines (Current and Past)

Michigan has one of the most expansive rail systems in the U.S. in terms of track mileage, currently ranking 12th among the 50 states. The first rail operation in Michigan was started by Erie and Kalamazoo Railroad in 1837 and the rail network was at its largest in the early 20th century with over 9,000 miles of rail lines. According to the Michigan State Rail Plan (HNTB, 2011), over 50 percent of those miles have since been abandoned or removed. Michigan rail lines are almost exclusively used for freight transportation, similar to the rest of the U.S. rail network. There are only three intercity passenger corridors, all in the southern part of the state.

The current network is owned and operated by 30 private freight railroads. In addition, the state of Michigan owns about 530 miles of track which are currently leased for operators. Most of the

railroad companies operate in the Lower Peninsula. CN, Lake Superior and Ishpeming (LSI) and Escanaba and Lake Superior (ELS) are the only three rail companies with operations in the UP. The freight rail network in Michigan includes 4,412 miles of track which also supports three shared passenger rail corridors.

Table 2-3 provides the division of Michigan rail networks between different owners and operators. The majority of freight rail transportation is conducted by large Class I railroads, but for in-state biomass transportation, smaller Class II and Class III railroads hold most promise, as excluding CN in the UP, none of the other Class I railroads serve the forested areas in the Northern LP or UP.

Table 2-3- Total Freight Rail Mileage by Class in Michigan (HNTB, 2011)

Railroad	Class I- Freight	Class II- Regional	Class III- Shortline	Switching &Terminal	UP/LP
Adrian & Blissfield Railroad				30	LP
Ann Arbor Railroad Company			47		LP
Canadian National/Grand Trunk	1,017				LP/UP
Canadian Pacific Railway/Soo Line	1				LP
Charlotte Southern Railroad			4		LP
Conrail Shared Assets Operations				98	LP
Coopersville & Marne Railway Company			14		LP
CSX Transportation	569				LP
Delray Connecting Railroad				1	LP
Detroit Connecting Railroad			3		LP
Escanaba & Lake Superior Railroad			226		UP
Grand Elk Railroad			123		LP
Grand Rapids Eastern Railroad			65		LP
Great Lakes Central Railroad		396			LP
Huron & Eastern Railway			406		LP
Indiana & Ohio Railway		44			LP
Indiana Northeastern Railroad Company			70		LP
Jackson & Lansing Railroad Company			45		LP
Lake State Railway Company			231		LP
Lake Superior & Ishpeming			44		UP
Lapeer Industrial Railroad				2	LP
Marquette Rail, LLC			133		LP
Michigan Air-Line Railroad				8	LP
Michigan Shore Railroad				68	LP
Mid-Michigan Railroad, Inc.			56		LP
Michigan Southern Railroad Company				18	LP
Norfolk Southern Railway	642				LP
Saginaw Bay Southern Railway			67		LP
West Michigan Railroad Company				15	LP
Total by Class	2,229	440	1,511	240	LP/UP

2-3-2- Sidings and Terminals

Besides rail lines, sidings and terminals (or yards) are key facilities for freight loading, unloading and handling activities and for configuration of freight trains. The main differences between rail siding and terminal are defined in Table 2-4.

Table 2-4- Similarities and differences between rail siding, station and terminal definitions

Name	Main application	Size & # in network	Applications for Biomass
Rail siding	Short stretch of railroad track used for loading / unloading, to store rolling stock, or to enable trains on the same line to pass	<ul style="list-style-type: none"> - Different lengths and configurations (at least one track in addition to mainline) - Numerous sidings in the network 	Most logical location for biomass loading/unloading and in some cases for limited storage
Terminal (Yard)	Large rail facility for classifying, storing, interchanging and re-arranging trains. It may include facilities for maintaining and inspecting trains, tracks and other infrastructure.	<ul style="list-style-type: none"> - Numerous tracks and connections - Typically accessed by interchanging railroads 	Location for internal switching or for potential interchanges from one railroad to another

The key locations for biomass transportation are sidings and potential interchange locations between different railroads. Unfortunately, there is no complete list of operational sidings in the state of Michigan, but the research team used questionnaires and Google Earth maps to develop a partial list of more than 100 currently available sidings for biomass loading/unloading activities (Figure 2-7). Additional sidings exist in the southern parts of the state, but they are mainly outside forest regions, so they are of little usability for woody biomass transportation. Specific locations for interchange activities were not investigated, as the main concern for biomass shippers is whether interchange is required, not the specific location for the activity.

Figure 2-7- A GIS map of rail network and siding locations in the State of Michigan

2-3-3- Michigan Shortline Railroad Data

Since all proposed biomass plants are located in the northern LP, a more detailed investigation of rail lines in those areas was conducted. These areas are served by several shortline railroads listed in Table 2-5. To evaluate infrastructure and equipment capacity of these railroads, the

team developed a railroad questionnaire that was sent out to all operating Michigan shortline railroads (Appendix D). Class I railroads were excluded, as the current project concentrates on in-state moves and all proposed plants are located in the northern LP

Six out of the thirteen companies responded to the questionnaire. Relevant infrastructure data provided by each company is summarized in Table 2-5. Unfortunately, relevant information on several rail lines owned by Rail America Corporation was not made available to the research team.

Table 2-5- Summary of shortline railroad infrastructure data

Rail Operator	Infrastructure		
Railroad	Miles of Track	Public sidings capable for Biomass	Private Sidings capable for Biomass
Grand Elk Railroad	123	40	40
Great Lakes Central Railroad	396	Most GLC sidings	N/A
Lake State Railway (including Saginaw Bay Southern Railway)	300	24	A Lot
Michigan Southern Railroad	18	3	2
West Michigan Railroad	15	1	1
Marquette Railway	130	8-9	--

Figure 2-7 and Table 2-5 reveal that most rail infrastructure in the northern LP is oriented in north-south directions. This makes rail more usable for movements in these directions. The greatest potential for biomass rail transportation in the LP is provided by Great Lakes Central and Lake State Railway, as all proposed biomass facilities are located in the vicinity of these two rail operators. However, it needs to be recognized that the network of any individual railroad is quite limited, so most movements typically require at least one interchange from one railroad to another, immediately reducing the applicability of rail transportation, especially if the maximum 100 mile radius harvesting criteria is maintained. For a more detailed analysis of suitable rail infrastructure for biomass transportation, the following characteristics should be evaluated:

- Rail access at points of origin
 - Distance from harvesting sites to nearest rail sidings
 - Siding capacity (how many rail cars can be loaded and stored?)
 - Cargo handling equipment (most of the time self-loaders would have to be used at sidings)
 - Storage space available around siding
- Rail access at facility
 - Existence of railroad tracks in the facility (railroad facilities at plant locations are a “requirement” for economical rail transportation)
 - Track capacity at facility (how many cars can be stored at the facility at any given time?)
 - Maneuverability (can car switching be done within facility, or does it require entering main rail line?)
- Service along the line (discussed more as part of operational considerations)
 - How regularly is rail service provided by the railroad operator?
 - Does the route require interchange from one railroad to another?

2-4. Marine Infrastructure

This section reviews the marine infrastructure components and requirements. It focuses mostly on ports and docks in the state of Michigan and at potential origins and destinations around Lake Superior and Lake Michigan.

Greenwoods Guide to Great Lakes Shipping, 2010, Great Lakes Navigation System Five Year Development Plan Fact Sheets, US Army Corps of Engineers, 2008 and 2011, NOAA Coast Pilot #6, 2010 and Port Series #49 Lake Michigan Ports, US Army Corps of Engineers, 1995 were used as data sources for investigations, along with accessing port websites to explore existing dock facilities.

2-4-1- Potential Ports and Docks

Nine potential locations to construct and operate an ethanol facility were identified in the lower peninsula of Michigan, but none of the proposed locations are on navigable waterways with the possible exception of Traverse City. Table 2-6 lists the biorefinery locations and their distances from the nearest port. Most ports examined, if not all, had shipped logs at some point during their history, but most of the infrastructure has been abandoned or converted to other purposes after the 1960s. Two exceptions to the trend were log shipments that took place in the 1990s from ports of Frankfort and Menominee/Marinette.

Table 0-1- Nearest ports to proposed Biorefinery Sites

BioRefinery potential location	Nearest Port	Distance in miles to Nearest Port	Alternate Commercial Port	Distance to Alternate Port	Alternate Port	Distance to Alternate Port
Manton City	Traverse City	37	Frankfort	64	Manistee	64
Roscommon Village	Traverse City	66	Bay City	84	Charlevoix Harbor	85
Kingsley Village	Traverse City	17	Frankfort	38	Manistee	55
Kalkaska Village	Traverse City	25	Charlevoix Harbor	44	Frankfort	66
Mancelona Village	Charlevoix Harbor	31	Traverse City	37	Cheboygan	76
Gaylord City	Charlevoix Harbor	42	Cheboygan	62	Alpena	71
Clare City	Bay City	48	Traverse City	92	Manistee	93
West Branch City	Bay City	52	Traverse City	93	Alpena	95
Traverse City	Traverse City	0	Charlevoix Harbor	38	Frankfort	40
Boyne City	Charlevoix Harbor	32	Cheboygan	55	Traverse City	68

2-4-2- Preliminary Port and Dock Infrastructure Analysis

The parameters of the study limited ports to only those located in Michigan. A review of the port's attributes was undertaken including visits to all the potential locations and discussions with vessel operators. The first cut of origin ports was made by determining if the port was a Federal commercial or recreational port as defined by the U.S. Army Corps of Engineers (U.S. Army Corps of Engineers- Detroit District, 2011), as only commercial ports were evaluated. This eliminated recreational ports such as Petoskey Harbor. The selected commercial ports were then further evaluated to see if they had a maintained depth of at least 15 feet, had commercial dock space and landside infrastructure with a potential for woody biomass

operations. Some private harbors were also examined, but in each case they would have to be contacted in the next stage of the research to determine if the owners had an interest in having their harbors and docks used. The following attributes were used to refine the analysis for suitable docks:

- Operational Characteristics
 - Dimensions of dock: length, size of apron
 - Depth of water alongside dock
 - Cargo handling equipment
 - Condition of dock – ability to secure vessel (safe berth)
- Landside connections
 - Can trucks deliver and pick up logs?
 - Can rail cars deliver or pick up logs?
 - Is there adequate on-dock storage space for logs?
- Owner interest in using the dock for the proposed purpose
 - Current use and future plans
 - Properly zoned for log operations
 - Access areas zoned for log operations

Figure 2-8 represents all of origin and destination ports identified as suitable for biomass transportation.

Figure 2-8- Snapshot of all potential origin and destination ports for biomass multimodal transportation

The five identified ports and docks that are located in the LP can be considered as **destination ports** for the multimodal woody biomass transportation. Table 2-7 represents a summary of these ports. More details of each port are represented in Appendix E.

Table 2-7- List of potential Ports/Harbors considered as maritime destination for project

Port/ Harbor	Location	# of docks*	Advantages	Conditions/ Concerns	Water depth
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Charlevoix Harbor	East shore of Lake Michigan-MI	2	<ul style="list-style-type: none"> - commercial harbor with facilities in the town of Charlevoix - all docks have highway connections - ranked 31st among the Great Lakes Harbors with 1.5M tons of commerce in 2007 	lack of maintenance (dredging) may reduce the allowable draft	Over 100 feet
Frankfort Port	East shore of Lake Michigan, MI	2	<ul style="list-style-type: none"> - commercial port connected to Lake Michigan by an entrance channel - all docks have highway connections - It has shipping or receiving logs records in 1995 by US Army corps of Engineers. 	this area may be undeveloped	20 feet
Traverse City Harbor	Grand Traverse Bay, MI	1	<ul style="list-style-type: none"> -three active deep-draft facilities - owned and operated by Traverse City 	- current petroleum products handling in the harbor may complicate the biomass operations	18 feet
Manistee Harbor	east shore of Lake Michigan MI	4	<ul style="list-style-type: none"> -protected by breakwater - several deep-draft facilities -all docks have highway connections - some docks have rail connections but the condition of the rail service is unknown. 	principal cargo handled in the port is coal, with occasional shipments of salt, sand, limestone and machinery	25 feet
Cheboygan Harbor	western Lake Huron, MI	2	Two docks out of three may have the potential to handle biomass	<ul style="list-style-type: none"> -home port of the U.S. Coast Guard's - principal cargo handled in the port is coal, with occasional aggregates 	21 feet

*: number of docks suitable for biomass water loading/unloading activities

A suitable **origin port** will need to have the same attributes as the destination port and a sufficient capacity storage area for buffer stocks. In addition, a port must be far enough from the destination port to make the economies of marine transportation viable. A rail connection at the origin port is advantageous, as rail can provide access to more distant wood baskets in the UP A list of potential origin ports/harbors is summarized in Table 2-8 and more details on listed ports are provided in Appendix E.

Table 2-8-List of potential ports/harbors considered as maritime origin for project

Port/ Harbor	Location	# of docks*	Advantages	Conditions/ Concerns	Water depth
Menominee	17 miles NW of the Sturgeon Bay Ship Canal, MI	5	- three deep-draft facilities - All docks have highway connections and some have railway connections - in the early 1990s logs were shipped from one of the docks of this harbor	-Shoaling has been reported upriver - principal cargo: coal, with occasional shipments of pig iron, salt, limestone	19 feet
Escanaba	Escanaba, MI	2	- several deep-draft facilities - All docks have highway connections and some have railway connections	- principal cargo handled in the port is coal and limestone	28 to 40 feet
Gladstone	the west side of Little Bay de Noc, MI	2	- two deep-draft facilities - All docks have highway connections	- principal cargo of port: barrels, asphalt, coal, salt, limestone -One of the docks is tanker and unlikely to be ready for biomass movement	22 feet

*: number of docks suitable for biomass water loading/unloading activities

In addition to the larger ports identified above, several smaller ports with potential for biomass movements were identified by Mr. Dan Glawe during interviews with researchers from Michigan Technological University. These ports are highlighted in Table 2-9 with more detailed explanation in Appendix E.

Table 2-9- Suggested ports from Dan Glawe

Port Location	Notes From Dan
Detour	Good deep water port near Kinross (located in Upper Peninsula)
Cedarville	Good deep water port near Kinross (located in Upper Peninsula)
Frankfort	Shut down
Ludington	Only Deep water port on West side of Lower Peninsula
Manistique	Tough to get into due to having to go up river
Rogersville (Rogers City)	Would have potential for deep water port
Bay City	Is ok
Alpena	Not too good, The bay has a lime stone bottom

3.0 Transportation Equipment

Tasks covered in the chapter include:

Task	Description
B1.2	Identify most suitable equipment for biomass transportation
B1.7	Identify data sources for transportation equipment
B1.10	Inventory of the equipment available in the study area
B1.13	Summary of transportation operations and available equipment

Transportation equipment is often the second most expensive component of transportation systems. It typically refers to “vehicles”, such as tractors and trailers, rail cars or barges. This chapter reviews the main types of equipment suitable for biomass transportation by road, rail and marine.

The parameters discussed include:

- Technical and operational specifications
- Equipment cost
- Availability of different types of vehicles within the project area

Information presented in the chapter was collected from technical reports and documents issued by Midwest Departments of Transportation and from inquiries and interviews with forest product companies, equipment dealerships, transportation service providers and the Secretary of State (SOS).

3-1- Road Equipment for Woody Biomass Transportation

Trucking is the main transportation system for the delivery of logs and biomass. The weight/volume ratio of woody biomass varies significantly. Figure 3-1 shows the general size capacity of each type of woody biomass material with the same weight.

Figure 3-1- Different size capacity of materials with same weights (Schroeder et al, 2007)

Table 3-1 provides an overview of the most common types of equipment available for woody biomass transportation and respective load capacities.

Table 3-1- Road Transportation equipment suitable for biomass transportation

Type of Biomass	Equipment Type	Weight Limit (lbs.)	Typical Axle Combinations
Chips/Forest Residue	chip tractor and trailer	80,000 - 156,400	5 to 11
Chips/Forest Residue	chip truck	42,000 - 70,000	2 to 5
Pulp/Logs/Biomass Bundles	log truck and pup	80,000 - 164,000	11 (6 axle truck with 5 axle pup)
Pulp/Logs/Biomass Bundles	tractor trailer	80,000 - 164,000	Multiple axle configurations

3-1-1- Pulp/Logs/Biomass Bundles

In Michigan, pulp and saw logs are most commonly transported by an 11 axle log truck and pup configuration (6 to 7 axles on the truck with 4 to 5 axles on the pup trailer (Figure 3-2)). These vehicles have the maximum allowable loads with a gross vehicle weight of 164,000 lbs. Most of these trucks have the capacity to self-load or unload, increasing their versatility.

Figure 3-2- 11 axle log truck (6 axle truck + 5 axle pup) with selfer loader
(Photo by: H. Pouryousef - Feb. 2011)

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Tractor-trailer combinations are also used to transport round wood. Trailers come in a variety of configurations, including loader and crib style applications (Figure 3-3 and Figure 3-4). The crib style design is developed to improve the safety of log transportation. In crib trucks, logs are hauled lengthwise, the sides of the log-hauling truck are staked, and the truck is fitted with headboards and bulkheads at the front and back of the trailer (Michigan Association of Timbermen, 2011).

Trailer axle configurations vary from 2 to 8 axles with different spacing between axles to enable different gross vehicle weights. For complete listing of truck variations, see Biomass Transportation Equipment Tables in Appendix F.

Figure 3-3- Tractor-trailer combination with self-loader capability (Green et al. 2005)

Figure 3-4- Crib style trailer (Green et al. 2005)

3-1-2- Chips and Biomass Residue

Chips and loose forest residue are commonly hauled by tractor-trailers (Figure 3-5 and Figure 3-6) that consist of a tractor and large chip truck trailer (42 to 48 ft. in length) (Jeuck, 2009). For these types of biomass, it is common for trailers to reach their capacity before weight limits. Trailers come with different axle configurations and loading/unloading capabilities (Figure 3-5 and Figure 3-7). Chips can be either hauled in an open top or rear loading chip trailer while for residue, loading can only be done with open top trailers. Chip trucks without live floors are less versatile because they need a tipping platform and machinery to help them in unloading process (Figure 3-8) (Schroeder et al, 2007).

Figure 3-5- Truck with dual chip bin trailers loaded with chips ¹⁵

Figure 3-6- Tractor-trailer chip truck ¹⁶

Figure 3-7- Open top chip/biomass trailer ¹⁷

Besides the type of road vehicles and their technical specifications, the storage yard capability and current facilities typically determine what type of chip truck should be used. For instance, larger facilities usually use truck-tippers (Figure 3-8) to empty feedstock from almost any type of chip truck, while smaller facilities may not have such equipment, requiring use of trucks with self-unloading capabilities (Jeuck, 2009).

¹⁵ : Forestencyclopedia website, <http://www.forestencyclopedia.net/p/p2/p1136/p1296/p1313>

¹⁶ : Safe and Efficient Practices for Trucking Unmanufactured Forest- Virginia Tech., <http://pubs.ext.vt.edu/420/420-310/420-310.html>

¹⁷ : Pitts Trailers, http://pittstrailers.com/app/inventoryapp/logging_trailers/inventory_view/94-95-66-1.html

Figure 3-8- A type of chip truck tipper at a woody biomass facility (Jeuck, 2009)

An example of a truck with self-unloading capability for loose residue and chips is a live floor (walking floor) (Figure 3-9). Walking floor provides operational flexibility, but the high purchase cost and inefficient unloading process when compared to tipping can be considered disadvantages.

Figure 3-9- Left: walking floor truck during unloading; Right: inside of walking floor truck ¹⁸

3-1-3- New Technologies for Biomass Road Transportation

Due to an increased interest in biomass, especially in Scandinavian countries, new technologies and equipment have been developed and applied into service. Figure 3-10 shows a stump collection truck developed in Finland. These trucks are typically equipped with self-loaders and they have been designed to maximize the cargo space volume through high side walls. In addition, the trailer has a hydraulic system that can compress the load to increase its density and thus overall load capacity.

¹⁸ : <http://www.trucker.com/TrailerDetail.aspx?TrailerID=1006498&CompanyID=32292>

Figure 3-10- Truck-trailer for loose residue and chips transportation by UPM Kymmene Group-Finland (Maertens, 2009)

In the past few years, the use of roll-off pallet racks has been investigated as a way to find a cheaper woody biomass collection system. These systems can decrease transportation and handling costs under particular conditions, such as in small markets that require less than 50 green tons/day (Rummer, Klepac, 2004.) In this collection system, a forwarder is equipped with a roll-off or hook lift unit that can carry either residue bins or log rack into the woods. Once the forwarder has filled the bin, it returns to the landing and quickly transfers to a new bin. At the landing, can then pick up the bin or rack and haul it to the mill (Figure 3-11). The method allows for less down time and eliminates double handing of the material. It has been estimated that a roll on/off forwarder can eliminate one to two hours of total work from the conventional method of woods-to-roadside cycle. (Atkins, et al, 2007) However, in research done by Rawlings et al, it was concluded that a roll on/off container system is not competitive with a regular highway chip truck, unless loading site is inaccessible to the chip truck (Rawlings, et al, 2004).

Figure 3-11- Two types of Roll On/Off trucks (Wynsma, et al, 2007)

3-1-4- Road Transportation Equipment Available in the State of Michigan

The Secretary of State office is the prime source for inventory of available trucks within the state of Michigan. Even though detailed analyses of current truck inventory wasn't completed, as access to data required special arrangements, the research team was able to obtain total numbers for stake bed and tractor trailer trucks that are registered with log farm plates (codes L09 and L10) as of November, 2010. Vehicles registered with these log plates can only haul non-processed wood products (logs, chips and forestry residue). Processed wood products (wood pellets, lumber and strand board/plywood) should be hauled only by vehicles registered with commercial plates. On the other hand, trucks with commercial plates can also haul non-processed wood materials.

The SOS data revealed there were 1,190 log plate registered vehicles within Michigan. The number was compared to a Log Truck Study II report produced by Michigan Technological University in 2005 (*Green et al. 2005*) which used SOS and insurance company data along with field surveys to determine that there was an approximately 1,050 log trucks within the state. In 2005, the SOS registration data indicated that there was about a 2:1 split between the Upper Peninsula and Lower Peninsula respectively. Using the same ratio, the team determined that approximately 800 trucks reside within the Upper Peninsula region while 400 reside in the Lower Peninsula.

3-1-5-Equipment Manufacturer Interviews

The transportation team conducted interviews with equipment manufacturers and dealers to determine equipment specifications, trends and markets for biomass transportation equipment within the state of Michigan. The list of the companies contacted is provided in Appendix G. The companies ranged from manufactures to new and used equipment dealers and equipment refurbishing. It was decided to also collect data from Northern Wisconsin, as several equipment manufacturers and dealers located in Green bay, Appleton and Oshkosh area service the UP. The key findings of the interviews include:

- **Equipment and Cost**

- 75% of dealers cover both new and used equipment and the majority of the inventory includes trucks that are less than 10 years old. Approximately 25% of dealers have 164,000 lbs. Michigan log trucks in their inventory but almost all dealers carry “Michigan Special” tractors which are versatile and have high horsepower (550 to 600 hp).
- Most large biomass trucks are available based on demand. Dealers are facing limited interest for biomass trucks, but more inquiries for small, versatile trucks.
- Since 2009 the base price on a chassis has increased \$30,000 due to new government regulations on emissions and safety standards.
- Table 3-2 shows price ranges for each type of equipment surveyed.

Table 3-2- Road transportation equipment cost ranges

Equipment Type	Cost – (New)	Cost – (Used) (Typically 5 years or older)
6 to 7 Axle Log Truck (Just Truck)	\$130,000 to \$250,000	\$30,000 to \$80,000
6 to 7 Axle Log Truck (Truck and Pup Trailer)	\$240,000 to \$300,000	
Tractors (Tandem Axle)	\$110,000 to \$175,000	\$8,000 to \$70,000
Trailers (Log/ Pulp and Chip trailers)	\$30,000 to \$130,000	\$2,500 to \$30,000

- **Current market:**

- All dealers mentioned that sales for 2010 were down drastically (compared to 2004-2007) but higher than 2009 numbers. Many companies were upgrading and buying trucks before 2008 when the new emission regulation engines came into production.
- The inquiry for biomass equipment has declined due to the industry being unstable, rising transportation/maintenance costs and dwindling markets.
- Increased amount of refurbishing old trucks now being done

- **Services and Maintenance:**

- Approximately 90% of the dealers mentioned that they own a truck service shop, but only 60% use facilities for commercial maintenance and service centers.
- Truck serviceability depends on the region. Northern Wisconsin and the Southern Lower Peninsula locations offer very limited service. Upper Peninsula locations see several hundred biomass trucks a year where as the Lower Peninsula sees mainly smaller, Class 8 trucks.
- Since the 2008 emission regulations, there has been an increasing trend by operators to delay maintenance as a way to cut costs.

- Most companies didn't want to deal with the new engines (based on emission regulations) due to the fear of problems and added expense on both base prices and maintenance costs.

3-1-6-Logger Surveys

In addition to equipment manufacturers, forest product operators in the state of Michigan were surveyed about their use of truck and rail transportation. Two different survey campaigns conducted in 2009 and 2010 covered the trucking equipment and key operational features (Table 3-3 and Table 3-4 and Figure 3-12). Truck data was analyzed with all units aggregated together, but separate analyses for the larger 10-11 axle log trucks and chip vans were also conducted.

Table 3-3- State of MI trucking equipment summary

Truck Type	Responses	Year (avg / stdev ^b)	Fuel Use (avg / stdev)	Miles/year (avg / stdev)
All log trucks reported in surveys	146 – 168 ^a	2000 / 8	4.48 / 1.78	55,707 / 60,052
Large log trucks (10-11 axles)	66 – 78	2003 / 5	3.69 / 0.72	63,896 / 39,093
Smaller log trucks (2-9 axles)	74 – 84	1997 / 8	5.28 / 1.94	46,914 / 73,277
Chip vans	15 – 21	1998 / 7	4.19 / 0.99	42,800 / 28,357

a- numbers indicate number of survey responses. 'Large log trucks' and 'Smaller log trucks' are subsets of the category 'All log trucks'. In some cases, the sum of responses in the 'Large log truck' and 'Smaller log truck' categories do not equal the responses for 'All log trucks' due to additional entries where no axle number was recorded being omitted in the data breakdown by axle number.

b- numbers reported are the averages and standard deviations of survey responses

Table 3-4- Percentage of round wood transported by self-loading trucks

Responses	180
Average %	86.0
Standard deviation (%)	30.5
Responses that indicated 100%	128
Responses that indicated 0%	18

As expected, large log trucks had lower average fuel economy and higher annual mileage than other trucks represented in the survey. Overall, the distribution of annual mileage data for trucks varied considerably, as seen in Figure 3-12. The survey also revealed that most of the log trucks in the state of MI are equipped with self-loaders, as over 70% of respondents (128 / 180) had 100% of their round wood production transported with self-loading trucks.

Figure 3-12- Histogram of reported yearly mileage data for all log trucks

3-2. Railroad Equipment

Several different types of rail cars are capable for hauling woody biomass, but certain cars are typically preferred. Bulkhead flat cars and log cars are mainly used for logs and gondolas and in some cases hoppers are used for chips. All rail cars require separate loading/unloading equipment.

Due to the interstate nature of rail assets, there are no dedicated rail cars that operate in the state of Michigan. However, industry representatives felt that they are capable of securing necessary rolling stock assets if the demand for woody biomass transportation emerges. According to rail car manufacturers, the demand for biomass cars (mainly for chip transportation) has been quite low for extended period of time which has also led to an aging fleet.

Table 3-5- List of common railroad cars for forest and wood material transportation (CN, 2010)

Type of Biomass	Transportation Equipment Type	Load Capacity	Length	Material Used For and Notes
pulp/logs/biomass bundles	bulk head flat car	75-110 tons	50-66 ft.	used for metals and minerals/ aluminum and steel products
pulp/logs/biomass bundles	bulk head flat car	80-97 tons	52-66 ft.	forest products/lumber and panels
pulp/logs/biomass bundles	log car	75-85 tons	46-52 ft.	forest products/logs
chips/forest residue	wood chip hopper	75-83 tons	53-66 ft.	forest products/ wood chips, has bottom gates or no doors

3-2-1- Pulp, Log, and Biomass Bundles

The railroad designates two different types of cars to pulp/logs/biomass bundles. The first type of car is a simple bulkhead car (Figure 3-13). Table 3-5 contains two columns for these types of cars due to commodity usage and structural reinforcement/ durability between cars. These cars are designed with sturdy end-walls to prevent loads from shifting longitudinally and logs are typically loaded perpendicular to movement. Most railroads tend to shy away from using these cars due to the safety risk of the load shifting laterally, or logs sticking out from the side of the car into the railroad right-of-way.

Figure 3-13. Bulkhead car-Kansas City Southern Railway ¹⁹

The second, more commonly used rail car is a log car (Figure 3-14). In contrast to a bulkhead car, these cars have stakes on the sides and they carry the load longitudinally, like a crib style trailer. This secures the load and eliminates the concern for lateral shifting. Typically these cars can hold about 35 cords (~80 tons) of 8 foot cut-to-length logs.

¹⁹ : <http://www.answers.com/topic/flatcar>

Figure 3-14. Log car-BFPX²⁰

3-2-2- Chips and Forestry Residue Cars

For chips/forest residue or waste, a “wood chip gondola” is often used. They typically have interior space/area of approximately 9,200-10,000 cubic feet with higher than normal side walls (8-9 ft. in height) to increase the volume. In comparison, standard gondolas typically have interior space of about 2,000-2,500 cubic feet with side walls of about 4-5 feet in height. (Figure 3-15 and Figure 3-16). Typically, these cars have to be mechanically loaded and unloaded which places restrictions on efficiency. However, models with rotary dump capabilities or with tipping mechanisms have also been used.

Figure 3-15. Woodchip gondola with front and rear gates, Great Northern²¹

Figure 3-16 presents another type of car that can be used, an open top hopper. These cars are typically equipped with a bottom dump unloading system. To use this system, the mill would have to have appropriate facilities available for bottom dump.

²⁰ : <http://www.rpicturearchives.net/showPicture.aspx?id=467176>

²¹ : <http://www.rpicturearchives.net/showPicture.aspx?id=1423672>

Figure 3-16- Open top hopper with bottom discharge, GPSX ²²

3-2-3- Estimated Costs of Rail Cars

Similar to trucks, the rail car cost is very dependent on the type of the cars, features, manufacturer and age. Due to the longer life cycle of rail cars in comparison to the trucks (between 30 to 40 years), many industries prefer to buy second hand or used rail cars rather than purchasing new ones. The research team contacted twenty rail car manufacturers and dealers throughout North America to obtain more information on new and used rail car prices. Based on the information from four companies who responded to the inquiry (complete list is provided in Appendix H), the team summarized the prices of new and used rail cars commonly used for log/biomass transportation (Table 3-6). The cost of used cars varies broadly, since it is dependent on the condition of car, its accessories, age and capacity/size of the car.

Table 3-6- Price estimation for new and used car types used for biomass transportation

Biomass Type	Rail Type	Cost	
		New car	Used car
pulp/logs/biomass bundles	bulk head flat Car	\$80,000- \$90,000	\$15,000- \$50,000
pulp/logs/biomass bundles	log car	\$80,000- \$90,000	\$15,000 - \$50,000
chips/forest residue	wood chip hopper	\$80,000- \$90,000	\$15,000 - \$50,000
chips, waste wood products	standard gondola	\$70,000	\$15,000 - \$45,000

²² : <http://www.rrpicturearchives.net/showPicture.aspx?id=2119435>

Besides buying new and used cars, leasing or sharing (pooling) are two other procurement options for rail cars. Typically a rail car lease is in the range of \$450-\$650 per car per month. The benefits and drawbacks of these options are discussed in more detail in Chapter 4.

3-3. Marine Equipment

This section reviews major physical requirements and specifications for barges and vessels and presents an inventory of barges with their respective features. In addition, it reviews the legal requirements and operational limitations placed by the U.S. on marine transportation.

3-3-1-Legal requirements

Cargo that is transported between two U.S. ports without leaving country is governed by the Jones Act. The Jones act requires that any vessel transporting cargo for hire in the domestic trade be:

- Registered in the U.S.
- Built in the U.S.
- Owned/managed by a U.S. company
- Crewed by U.S. citizens

The legal requirements limit the pool of available vessels for transporting biomass between Michigan ports or with other states to U.S. flag vessels. This means that all Canadian flag or foreign flag vessels will not be able to engage in the movement of biomass that takes place within the state of Michigan. U.S. flag vessels may also be limited in their geographic range by the U.S. Coast Guard. The decision is based on the design of the vessel. A vessel designed for use on rivers or bays may not be safe to operate on the open waters of Lake Superior. Each vessel will have a Certificate of Documentation that defines the allowed area of operation. Vessels can be certified for additional bodies of water if the equipment meets the operational requirements for the new area of operation.

3-3-2- Physical requirements

In addition to being able to operate on the proposed route, the vessel needs to be capable of safely carrying the biomass cargo, including the loading and unloading operations. A large number of U.S. flag Great Lakes vessels are designed for specific trades such as aggregate, coal, taconite or liquids. The design of the vessel's holds or available cargo gear may make the vessels unsuitable for carrying logs. While a self-unloader may be capable of carrying wood chips, the vessels were designed for dense cargo rather than light bulky cargo. The capacity of the vessel is also an issue as the larger lake vessels with 20,000 ton and upward capacity would require a very large stockpile of wood chips before they could carry a full load. The self-unloaders are designed for quick loading and unloading and will not accept a long period in port. This would require a loading system in the port of origin for wood chips. While the use of a large size self-unloading vessel is not impossible, it is unrealistic.

A more likely vessel would be a barge that is propelled by a tug, (Figure 3-17). The barges have relatively low operating costs, have a smaller capacity (1,000-10,000 ton range), and costs are economical enough for a dedicated trade. With a suitable dock that allows the use of

a ramp between shore and barge, forklifts can be used to move the logs, reducing equipment costs. Wood chips may require specialized loading and unloading equipment for barges.

Figure 3-17- Tug W.N. Twolan and barge McAllister 132, in Duluth/Superior Harbor (Photo: Courtesy of Kenneth Newhams)

3-3-3- Barge Inventory

Only U.S. flag vessels could be used on the proposed routes. Table 3-7 presents current U.S. flag tug barges (as of October 2010) in the Great Lakes, with notations on size and suitability for the movement of biomass (Harbor House Publishing, 2009). This list does not include barges designed to handle liquid cargo. The deadweight tonnage of the barges ranges from 300 to 9,000 short tons. These barges may not be able to travel on all potential routes, as some of them may be engaged in long term contracts that render them effectively unavailable. In addition to current barges, a barge could be repositioned from an ocean coast or newly built, if a suitable market with an acceptable return on investment existed.

Table 3-7- U.S. Flag Great Lake Barges

Owner	Vessel/Barge	Type	LOA ¹	Beam ²	Comp. ³	Deadweight	Equipment
Basic Marine, Inc. Escanaba, MI	BMI-FDD-1		160'	65'	0	not listed	
	BMI-192		220'	55'	0	not listed	
	Greenstone		81'	24'	0	not listed	
Busch Marine, Inc. Carrolton, MI	STC 2004		250'	50'	flush deck	2,500	100 ton crane, clam, grapple, ro/ro, front end loader
Durocher Marine Cheboygan, MI	141		140'	9'	flush deck	800	75 ton excavator
	142		140'	9'	flush deck	800	150 ton crane
	D-2002		195'	12'	15	1,700	deck barge
	D-2003		195'	12'	15	1,700	deck barge
	D-2006		195'	12'	12	1,700	deck barge
	D-2007		195'	12'	12	1,700	deck barge
Geo. Gradel Co. Toledo, OH	Barge 717		128'	32'	flush deck	500	deck barge
	Clyde		134' 6"	41'	flush deck	800	deck barge
	Crow		110'	42'	flush deck	600	deck barge - 150 ton crane
	GL 170		120'	36'	flush deck	600	deck barge
	MCC 528		115'	27'	4	not listed	350 yard dump barge
	MCC 529		115'	27'	4	not listed	350 yard dump barge
	MOBRO 2000		180'	52'	flush deck	2,400	derrick barge
	MOBRO 2001		180'	52'	flush deck	2,400	derrick barge
	Moby Dick		121'	33' 2"	flush deck	835	deck barge
	Relief		160'	40'	flush deck	900	derrick barge
	Scow #32		128'	33'	4	not listed	550 yard dump barge
	Scow #33		128'	33'	4	not listed	550 yard dump barge
Great Lakes Towing Co. Cleveland, OH	Milwaukee		172'	40'	5	1,170	deck barge
Laken Shipping Cleveland, OH	Cleveland Rocks	dry cargo	390'	71'	18	9,000	boom
Malcolm Marine St. Clair, MI	504		120'	33'	0	not listed	50 ton crane
Marine Tech, LLC Duluth, MN	Dean R. Smith	crane	120'	48'	0	500	crane
	Alton Andrew	crane	70'	50'	0	300	crane
	MTI-H1	hopper	195'	35'	1	1,800	
	MTI-H2	hopper	195'	35'	1	1,800	
Pere Marquette Shipping Co. Ludington, MI	Pere Marquette 41	deck	403'	58'	flush deck	5,500	material handler, hooks, buckets, magnets
Ryba Marine Construction Co. Cheboygan, MI	CT150		150'	50'	12	1,600	crane barge
	CT251		197.9	43.1	7	not listed	dump scow
	CT252		197.9	43.1	7	not listed	dump scow
	Harbor Master		70'	27'	11	not listed	spud crane barge
	Jarco 1402		140' 1"	39' 1"	7	700	spud crane barge
	No. 4		120'	42'	8	not listed	spud derrick barge
	No. 18		140'	36' 7"	10	600	dump scow
	OB 185		180' 1"	54'	16	1,200	deck barge
	Tonawanda		120'	45'	6	600	spud crane barge
	Vulcan		100'	34'	2	not listed	deck barge

¹: Length overall,²: Width of ship,³: Compartments: Number of cargo compartments,

4.0 Modal and Multimodal Transportation Operations

Tasks covered in the chapter include:

Task	Description
B1.8	Interview selected transportation providers to define potential service capacity
B1.9	Identify key operational challenges for biomass transportation
B1.11	Industry inquiry to collect rate information for biomass transportation
B1.12	Synthesis on challenges and synergies between alternative modes
B1.13	Summary of transportation operations and available equipment

Transportation operations utilize the infrastructure and equipment to provide transportation services requested by the shipper community. The following sections review key operational features and considerations for biomass transportation, both from single and multimodal perspectives. The specific topics covered include:

- Biomass transportation supply chain alternatives
- Modal considerations and challenges (road, rail and marine mode)
- Biomass transportation capacity
- Transportation economic considerations
- Transportation outcomes of logger survey and biomass transportation case studies

4-1- Alternative Supply Chains for Biomass Transportation

Figure 4-1 represents the alternative supply chains for woody biomass transportation. In most cases, biomass is transported from the forest landing to the final destination (mill or plant) by a truck in a single movement (Scenario 1). However, supply chains can also take advantage of multimodal transportation opportunities (Scenario 2), or it can break the chain by using intermediate storage (Scenario 3). The common denominator for Scenarios 2 and 3 is that they tend to increase the overall time consumption and number of handlings required to deliver the biomass to the final destination. Each scenario is described in more detail below.

- **Scenario 1 - Truck Transportation:** Trucking is the most likely scenario for biomass transportation. In most cases, a single truck will haul the biomass from forest landing to final destination in one continuous move without intermediate stopping or handling requirements.
- **Scenario 2 - Multimodal Transportation:** The inclusion of rail or marine transportation typically means that the supply chain becomes multimodal. Biomass gets transported by trucks from the landing and transferred either to rail or marine transportation without storage in between. The loaded rail car or vessel may be delivered either directly to the final destination (mill, power plant) or it may have another handling between rail car (or marine vessel) and truck prior to final delivery. In either case, multimodal supply chains require at least one additional handling of the load, increasing the supply chain cost. On the other hand, these costs may be offset by lower transportation unit cost by rail or marine modes.
- **Scenario 3 - Intermediate Storage:** The third scenario adds an intermediate storage yard to the supply chain. There may be various reasons for using the

scenario, such as a lack of capacity at the final destination, or preparation for highway weight restrictions during the spring time. The scenario may utilize one or more modes of transportation, but will also increase the number of handlings required between origin and final destination.

Figure 4-1. Alternative supply chains for biomass transportation

There are numerous considerations that determine the selection between alternative supply chains and each situation needs to be reviewed separately. However, there are some common denominators that either support or limit the use of certain alternatives, such as:

- Location of harvesting area
- Location of final destination and availability, or adjacency to the railroad track/marine port facilities
- Total hauling distance and the volume of biomass material to be hauled. Longer distances and higher volumes increase the likelihood of multimodal scenarios. Lower volumes for short distances are more likely to be delivered by truck.
- Type of biomass material and required sorting, processing activities on the raw material.
- Number of handling and switching between truck to the other modes (rail and water) and number of switching or carrier interchanges during rail transportation.

4-2- Biomass Transportation Distances

The overall portion of transportation costs in the supply chain is highly dependent on the distance traveled from landing to the unloading location such as the mill/power plant. The transportation research team used three different sources of data to investigate the typical range biomass movements in Michigan. An on-going study by the University of Wisconsin-Superior and Michigan Technological University used Geographic Positions System (GPS) receivers in log trucks for two one month periods to research the movements of log and chip trucks in the Upper Peninsula. Based on the study, the average round trip distance between loading and unloading locations for each log/chip truck totaled approximately 150 miles (75 miles each way).

Another source for average transportation distances was the logger survey conducted as part of the project. The loggers were requested to provide information on typical trip distances in 30 mile intervals for chips, pulp logs and saw logs, respectively. The outcomes revealed that the majority of all three types of woody biomass are transported within a ninety mile radius from the landing with pulp logs traveling slightly longer distances than chips and saw logs (Figure 4-2).

Figure 4-2- Biomass transportation haul lengths based on loggers' survey

In 2009, Hicks analyzed more than 100,000 trip datasets of log trucks through the Michigan, Wisconsin and Minnesota regions. Based on the collected data, a histogram was constructed to show the relationship between tons of logs and transportation distances (Figure 4-3). The average distance of Hicks' sample was under 100 miles, but over 27% of production traveled more than 90 miles by truck. Hicks' study has the most comprehensive sample of log movements and its outcomes are comparable to the data from the other studies. However, it is notable that while the majority of trips were less than 100 miles, there were numerous trips between 100 and 200 miles and some even beyond 200 miles. (Hicks, 2009)

Figure 4-3- Log truck hauling distances in Michigan, Wisconsin and Minnesota (Hicks, 2009)

The data from all three references mentioned above suggests that the average hauling distance between 75 up to 100 miles is an accurate range for a typical biomass transportation movement. It also suggests that the 100 mile hauling radius used by the FBSCC modeling team seems justified. However, it must be remembered that above samples utilized only truck transportation data and did not include movements that took place with other modes, especially by rail.

4-3. Road (Highway) Transportation

With its extensive network covering the entire state, road offers the most flexible alternative for biomass transportation. Available road infrastructure and equipment form the backbone to the system, but there are also several operational aspects that should be considered.

4-3-1- Truck Transportation of Log/Wood Products in Michigan

Trucks play a significant role in Michigan transporting approximately 84% of total weight for in-state movements. Table 4-1 provides total volumes for log and wood products in Michigan in 2009. Over 12 million tons of logs were transported within Michigan, complimented by over three million tons of wood products. These volumes significantly outweighed the movements that crossed state borders. Unfortunately, it could not be defined whether chips were covered under log or wood product category.

Table 4-1- Log and wood product transportation by truck between Michigan and neighboring States in 2009 (FHWA, 2011)

ORIGIN	DESTINATION	Commodity	Total Tons (in thousands)	Total M\$
Michigan	Michigan	Logs	12323	450.82
Michigan	Michigan	Wood prods.	3065	1372.50
Michigan	Illinois	Logs	27	17.67
Michigan	Illinois	Wood prods.	142	91.78
Michigan	Indiana	Logs	143	23.92
Michigan	Indiana	Wood prods.	280	193.37
Michigan	Ohio	Logs	44	7.30
Michigan	Ohio	Wood prods.	147	96.05
Michigan	Wisconsin	Logs	88	50.87
Michigan	Wisconsin	Wood prods.	216	85.15
Illinois	Michigan	Logs	0.1	0.01
Illinois	Michigan	Wood prods.	123	81.57
Indiana	Michigan	Logs	3	4.96
Indiana	Michigan	Wood prods.	48	81.44
Ohio	Michigan	Logs	1	0.07
Ohio	Michigan	Wood prods.	78	90.31
Wisconsin	Michigan	Logs	3	1.01
Wisconsin	Michigan	Wood prods.	191	230.68

4-3-2- Truck Performance and its Operations Requirements

Operating trucks to transport log and biomass material is a low-profit business and the majority of truck transportation in Michigan is handled by independent owner-operators who often own only a single truck. The following section reviews operational aspects that should be considered when defining the capacity potential provided by the trucks.

According to movement data collected with GPS, log and chip trucks in the UP typically operate **8-12 hours per day and five days per week** (Figure 4-4). Saturday operations seem to depend on the season, as during the fall collection period, few trucks had any operations on Saturdays, while during the winter, Saturday operations were more common.

Figure 4-4- Average operating hours per day for three log and two chip trucks (derived from GPS study, 2011)

In the same study, the average daily distance traveled by log/chip trucks was approximately 270 miles and they conducted **two to three daily round trips** between harvesting/log yard facilities (origins) and destinations (paper mill or pulp mills, power plants, or private landings/yards). The trucks are typically equipped with radio and cell phone systems for logistics coordination, but GPS technology commonly used by on-road trucking is largely absent.

Trucks **move with a payload for only 30 percent of the operational time**, unless backhaul opportunities can be identified. Various types of stops can take almost 50 percent of the time, mainly due to loading and unloading activities (Figure 4-5). Unloading processes should be considered by a proposed biomass facility, as they have potential to speed up the overall supply chain. Even though unloading accounts for a smaller overall portion of stoppage time, it has larger variability, based on equipment available at the facility and the required waiting due to other unloading trucks.

Figure 4-5- Stop categories share for log/biomass trucks (derived from GPS-CFIRE project, 2011)

4-3-3- Operational Challenges for Truck Biomass Transportation

Even though truck transportation is the main alternative for biomass transportation in Michigan, there are some challenging aspects for the operations. Some of the specific challenges are provided below, followed by a short discussion of each challenge:

- Optimized supply chain management
- Limited opportunities for backhaul movements
- Loading/unloading inefficiencies
- Bridge tolls and restrictions (Mackinaw Bridge)
- Spring weight restrictions

4-3-3-1- Optimized Supply Chain Management

Chapter 1 provided an interesting case study from Finland, where central dispatching systems based on the mobile network and real time data communications between mills, loggers and truckers were used to optimize the log harvesting and transportation. Accurate GPS devices, together with continuous updates on the levels of inventory at harvesting sites and unmet demand at the mills could be used collaboratively by truckers to identify the most productive loading sites and routes. While the recent studies in Michigan suggest that loggers and truckers coordinate effectively in transportation planning, a more technology-based approach might offer potential to improve the larger scale coordination within the industry. The main challenge for implementing systems such as the one in Finland is the shortage of mobile

network coverage, the implementation cost and the potential anti-trust considerations, if a larger group was to collaborate.

4-3-3-2- Limited Opportunities for Backhaul Movements

One of the key priorities for optimizing the transportation chain is to minimize the empty miles and maximize percentage of movements with a payload. Backhauling is a common process in on-road trucking, but biomass transportation provides three challenges for such opportunities. First, the short overall trip lengths limit the potential origins for backhauls. Second, the equipment for woody biomass transportation is specialized and operates often under special registration, limiting its suitability to transport alternative materials. Finally, facility locations don't support backhaul opportunities, as harvesting areas tend to be in north and facilities in south. However, there are some success stories, such as the one mentioned by Dan Glawe on forest product movements over the Mackinac Bridge to the UP with backhaul to the LP. Overall, backhauling offers some of the most promising productivity improvements available and should always be maintained under consideration.

4-3-3-3- Loading/Unloading Inefficiencies

Since most of the trucks are equipped with self-loading systems on the truck or trailers, they can load or unload material in mills, landings, plants, rail sidings and refineries. In comparison to the fixed and mechanized loading and unloading systems in the mill or plants, the self-loading/unloading is more time consuming, sometimes up to three times. Providing mechanized and modern loading and unloading systems can help to save loading/unloading times which can increase the availability of trucks. However, a tradeoff exists in the capital and operations costs of such equipment. In addition, in some cases the waiting time by trucks at mills due to congestion may pose even bigger delay for truck movements than the actual unloading procedure.

4-3-3-4- Mackinac Bridge

The Mackinac Bridge is a major restrictor of movements between the UP and LP, mainly due to weight restrictions and crossing fees. Some of the main challenges of the Mackinac Bridge include:

- Proper axle configuration requirement for trucks and trailers
- Waiting time due to reconfiguration of the heavy truck and trailers
- The total cost of \$4.50 per axle (\$2-\$2.25/cord) to ship over the bridge (no volume or "frequent user" discounts available)
- Potential future requirement to split heavy trailers such as B-train trailers into two single trailers, if the total allowed weight is decreased from 144,000 lbs. to 100,000 lbs.

Based on the trucker interviews, woody biomass movements between the peninsulas are difficult to justify economically, unless a backhaul movement can be identified to reduce the empty miles traveled. Potential further reduction in allowable weights would make the situation even more difficult.

4-3-3-5- Spring Weight Restrictions

Temporary weight restrictions during spring break-up are a well-known challenge for any truck movement, as reduced loads decrease the productivity of the system. These restrictions form one justification for a development of a multimodal transportation system, as rail and marine transportation are not affected by the restrictions.

4-4. Railroad Operations

Railroads offer perhaps the most promising alternative for trucks in biomass transportation, even though the more limited reach of physical infrastructure, and in some cases equipment, pose challenges to its use. The following section discusses how railroads' operational features affect the overall usability of rail service to biomass transportation. A special focus is placed on shortline rail operators in the Lower Peninsula, as they are the only potential direct service providers to the nine plants proposed as part of the project.

4-4-1- Freight Rail Transportation in Michigan

According to MDOT's analysis, Michigan's railroads carried over 110 million tons of freight in 2006, which is more than 25 percent of Michigan's total ground commodity movements. However, the portion of woody biomass, lumber and forest products were minor with only 3% of rail imports and 5% of exports. Furthermore, the majority of exported lumber and wood products originated in the Upper Peninsula and was moved by E&LS and CN railroads to Wisconsin (HNTB, 2011)

More detailed information on the role of rail transportation in woody biomass movements was obtained as part of the Logger Survey. The survey inquired on the current use of rail, potential future willingness to increase the use of rail, and the main barriers to increase rail usage. The outcomes revealed that only 13% of shippers (28 out of 220) currently used rail to transport biomass. Even more significantly, all of these shippers were located in the UP and only 20% of their annual volume moved by rail. The survey outcomes confirm the limited role that rail transportation currently has for woody biomass movements, especially in the LP

4-4-2- Rail Performance and Operations Requirements

In railroads, freight moves in trains that consist of a locomotive or locomotives and typically several cars. The main train types are unit trains, intermodal trains and manifest trains (or carload trains). Since the origins for forest biomass are dispersed, they normally move in manifest trains that transport various types of freight. However, if sufficient volume was generated within a small area, a unit train carrying only forest biomass could be considered.

Even though Michigan has almost 30 operational railroads, few of them offer high potential for woody biomass transportation services. The main opportunities for in-state movements exist in the northern part of the LP and in the UP, which eliminates a majority of rail providers. If out-of-state movements were also considered, the number of potential rail service providers would be significantly higher.

4-4-2-1- Shortline Railroad Operations

Since most of the potential woody biomass harvesting locations and all nine proposed facilities are located in the Lower Peninsula, the shortline railroads operating in the vicinity

of selected locations were the main interest for rail transportation analysis. The infrastructure data obtained through a shortline questionnaire was discussed in Chapter 2 (Table 2-5) and the summary of the operational data collected in the same questionnaire is summarized in Table 4-2. The following discussion incorporates data from the questionnaire with data collected through interviews with two rail companies – Lake State Railway (LSR) and Great Lakes Central Railroad (GLC).

Table 4-2- Operational features of Michigan shortline rail operators

Rail Operator	Operation			
Railroad	Number of interchange points	Percent of moves interchanged	Average Delivery Time to interchange points (In Days)	Average Haul Length (Miles)
Grand Elk Railroad	4	99%	1	50
Great Lakes Central Railroad	4	98%	2	220
Lake State Railway (including Saginaw Bay Southern Rail Way)	4	Majority	1	25-90
Michigan Southern Railroad	2	100%	1.5	14
West Michigan Railroad	1	100%	1.5	2
Marquette Railway	2	100%	1-2	50-118

Some of the key findings include:

- Most public sidings available through rail providers are capable of loading/unloading biomass.
- There was a correlation with the size of the railroad and the number of interchange locations with other railroads (some interchange locations included switches with more than one railroad). It was also noticeable that almost 100% of the moves require at least one interchange from one railroad to another.
- Most railroads haul a wide variety of commodities including respondents interested in the opportunities for woody biomass hauling, but woody biomass movements seem to be non-existent.
- Railroads currently do not possess the equipment needed to move woody biomass, but they believe that equipment could be obtained, if sufficient demand existed to justify the business interaction. Railroads would be in a position to lease/purchase the cars, but they would also recommend shippers to consider obtaining their own cars.
- There is no simple or single formula for rail rates. Pricing mainly depends on quantity being shipped and distance traveled, but none of the railroads had specific rate tables for biomass moves. All interviewed companies would be interested in providing rate quotes on a case by case basis. In general, for year-round transportation, contract rates could be expected, unless the volume would

be really low (a few cars per month). Tariff rates, if available, would only be used for random moves.

- Railroads can typically move a carload within one to two days from loading. If shipment requires an interchange, cars can be moved to interchange locations within a day or two, but the overall transit time depends on the other carrier's interchange schedule.
- Most shortline railroads operate seven days a week, but some shut down for the weekends.

4-4-2-2- Rail Operations in the Upper Peninsula

In addition to the shortline rail companies, CN Railroad has a history in woody biomass transportation in the Upper Peninsula. CN is currently hauling logs within the Upper Peninsula and Northern Wisconsin for various paper mills, such as Verso in Quinnesec. The log volumes transported by rail used to be higher, which has led to closure of several sidings on the network. CN is interested in increasing the biomass transportation in the area and closed sidings could easily be brought back into operation if consistent demand existed. Escanaba and Lake Superior Railroad (E&LS) has also transported woody biomass, but interchange requirements with CN to access any of the main mills are a major hindrance for economic operations.

4-4-3- Key Operational Challenges for Rail Biomass Transportation

Roughly 33% of the loggers who responded to a question about their use of rail transport were interested in increasing the use of rail to transport forest biomass. However, there are factors that limit their enthusiasm to make the shift (Table 4-3). Overall, the most important factors identified by respondents to prevent an increased use of rail transportation were reliability (3.53), limited rail access (3.49) and speed of delivery (3.39).

Table 4-3- Limiting Factors for Increased Use of Rail Transportation for Forestry Biomass

Potential Limiting Factor For Increased use of Rail	Average score 1= Not Limiting, 5= Extremely Limiting
Lack of knowledge on rail contractual agreements	2.48
Reliability of service	3.53
Speed of delivery	3.39
Limited rail access within main working areas	3.49
Price is not competitive with other modes of transportation	3.03
Minimum shipment size is too large for operation	2.49
Existing contract with other providers	2.12

In addition to the factors identified by loggers, additional challenges to transporting woody biomass by rail include the following:

- Transportation distances, dispersed origins and numerous rail rates
- Rail car availability and transportation time/service reliability
- Providing rail access to final destination

4-4-3-1- Transportation distances, dispersed origins and numerous rail rates

As mentioned earlier, rail transportation tends to excel in longer distance, high volume movements. In addition, the optimized operations are most easily achieved on routes where trains move consistently between a limited number of defined origin(s) and destination(s), both equipped with proper facilities. As the average distance for in-state biomass movements used in the study is expected to be less than 100 miles, efficient rail transportation would be difficult to achieve. The fact that harvesting will take place in limited quantities at numerous geographically dispersed locations further complicates the situation. It is not practical and reasonable to have direct rail access to each individual harvesting site, so trucks are used to move wood material from harvesting to the rail siding. Typical distances for such truck movements from forest landings to rail sidings range between 20-30 miles (Hicks, 2009, Lahdevaara, 2010).

According to railroad interviews and questionnaires, the majority of public sidings are capable of handling woody biomass, but some rail operators like CN don't allow for log/biomass storage in their right-of-way for liability reasons. In such locations, shippers would either conduct all loading of rail cars directly from log/biomass trucks, or make inquiries to lease the specific siding for private use. As leases tend to be for multiple years and may include maintenance costs in addition to leasing costs, this approach would only be beneficial at locations with sustainable flows and storage needs.

Another source of complication is rail rates. Rail transportation rates are rarely readily available, as they don't typically follow simple tonnage/distance formulas. Instead, they tend to be determined for each case separately in a confidential contract agreement between shipper and rail provider, especially when larger quantities are considered. Rates are also tied to certain other requirements, such as the number of required interchanges between railroads. More detailed discussion on the importance of transportation distance and rail rates is provided as part of the transportation cost discussions.

4-4-3-2- Rail Car Availability and Transportation Time/Service Reliability

Rail car availability and interchange requirements are the two main parameters affecting the transportation time/reliability of shipments by rail. Rail car availability depends on multiple factors. Most rail cars are not dedicated to one specific rail operator or line segment, but rather operate across the whole U.S. rail system, based on demand. If shippers want to use cars that are in a general pool, the availability must be confirmed in advance by shipper and rail operator. As railroads have made a push for improved rail car utilization, they have reduced the size of these fleets by retiring old cars and tightened the rules for loading and unloading activities by customers. Today, a company is typically allowed 48 hours to load or unload a rail car, before railroads will start charging a fee (demurrage), to cover the cost of idling equipment (Cheaney, 2009).

If a shipper desires greater control of equipment to improve its availability, leasing, renting, and car-sharing are alternatives worth consideration. In addition to greater availability, there is also a smaller risk of contamination of the car, since it only carries the freight determined by the shipper. Car sharing is a suitable option for companies who have common sections of their desired route and whose shipments can share the same type of car. The actual lease

arrangements range between 1-10 years and the shippers involved often need to negotiate and make an alliance or agreement with each other, including particular conditions and specifications based on their own requirements. There are several alternative types of leases, such as net lease, full service lease, per diem lease, etc. Prior to making leasing decisions, shippers should educate themselves on the alternatives to identify the best one for their situation. “How to Ship by Rail”, a publication by Cheaney, can be a useful tool in this process. It is also in the interest of railroads to have their shippers select the best equipment alternatives, so their input is essential during the decision making process.

The main disadvantages of leased cars include the following:

- Leased cars are usually more expensive than railroad-owned pool cars due to leasing cost (monthly or semiannually) or mileage credits (loaded mileages during leasing). Lack of backhaul can also increase the “relative” rail rate since most of the log and biomass cars may come back empty to the origin, reducing the loaded car miles.
- Some types of leased cars (especially tank cars) should be taken out of service every year or two for tests and inspections mandated by federal law (the car may be unavailable 2-12 weeks, depending on the location of railcar's shop and the market zone).

Rail cars can be handled from origin to destination by a single railroad, or by two or more railroads. Transfer of rail cars between companies is called an interchange and they take place if rail service at the origin is provided by a different railroad than the final destination. Typical interchange locations are rail yards, where both companies have access. Interchanges tend to increase the travel time and transportation rate for the movement. There are numerous switching/interchange points between different Michigan railroads. The majority of them are located in the Lower Peninsula, especially in the southern part of the state, in the vicinity of Detroit and Lansing. There are limited opportunities for interchanges in the northern part of the Lower Peninsula where all nine proposed biomass facility sites are located, reducing the potential for cost effective rail service that requires interchange. Thus, the most cost efficient rail movements would be those that originate in the vicinity of landings provided by the two main railroads serving the region, Lake States Railway (LS) and Great Lake Central Railroad (GLC).

4-4-3-3- Providing rail access to final destination

Rail access to the final destination can be considered a requirement for efficient biomass movements, as additional handling from rail cars back to trucks at destination would negate any potential savings gained from rail movements. Typically, industry spur tracks provide such access, branching from the closest existing mainline track. If no current rail access exists, new construction must be considered. The construction cost of the new access freight track and relevant switches is dependent on the topographic conditions of the designated area, but typically ranges between 1-4 million dollars per mile. In addition, proper storage track arrangements and sufficient space for car maneuvering should be provided within the facility. Unless there are possibilities for extensive rail freight revenues, the capital and maintenance costs for track construction fall on the facility.

4-5. Marine Operations

This section reviews the main features and requirements of marine operations related to transportation of woody biomass. It represents the main attributes of marine biomass supply chain in addition to the operations characteristics of barging on the Great Lakes.

4-5-1- Marine Transportation Records and History in the Study Area

Marine transport has a long history of serving the wood products industry in the study region. In the past, logs were moved from forest to mill using log rafts (booms and headworks) pulled by tugs and timber schooners (hookers). The log booms were capable of economically moving significant quantities of logs (Figure 4-6). The last time a log boom was in used was in 1972 when boomed logs were moved across Lake Superior from Grand Marais, MN to Ashland, WI. The increased use of trucking, inexpensive energy, and the closure of many mills located on the Great Lakes shoreline eliminated this method of log transportation. Due to concerns about the environment and liability issues with logs going adrift, it is highly unlikely that log booms would ever be used again in the study region.

Figure 4-6- 4,000 Cord log boom on the Great Lake (Photo: Courtesy of the Lake Superior Marine Museum Association Maritime Archives at the University of Wisconsin-Superior)

Research indicated that logs were transported across Lake Michigan during the 1990s by tug and barge, but the operation failed due a combination of having only short term contracts and liability issues. There have been a few more trials over the past decade, as highlighted below:

- Summer 2005 – three trip trial with Buchanan Lumber (Thunder Bay) and Sappi (Cloquet), MN, started through an already established relationship between Buchanan and Sappi, and the movement of wood chips from Thunder Bay via truck. Sappi used hardwood and Buchanan used softwood so it was an “exchange” and the barge (handled by Hallet) was loaded in both directions. Birch logs were brought IN and pine, spruce, and balsam OUT. The operation had relatively simple requirements; approximately 300’ dock, unload/load equipment

- carried on the barge and forklifts as the shore side equipment. Trucks drayed product to and from the mill in Cloquet a distance of about 30 miles (Figure 4-7).
- Summer 2006 – Load to Elevator M in Superior with Buchanan and a local paper company, still with Hallett handling. Birch was brought IN and pine OUT. The last shipment Hallett handled was one to Elevator M in Superior, Wisconsin in 2006. The shipments stopped because materials were available closer, e.g. Sappi received wood from a WI mill that was shutting down. (Duluth Port Authority, 2010)

*Figure 4-7- Tug W.N. Twolan and barge McAllister 132, in Duluth/Superior Harbor
(Photo: Courtesy of Kenneth Newhams)*

4-5-2- Marine Operations Features and Requirements

Marine transportation is a capital intensive industry with financial and regulatory barriers to entry. A new U.S. built Great Lakes commercial vessel can cost from a few million to \$200 million depending on its size, (Singer, 2007). The Jones Act limits access to cargoes between U.S. ports to only U.S. built, U.S. flag, and U.S. owned vessels. Commercial traffic in the Great Lakes/St. Lawrence system is dominated by iron ore, coal, and stone with, roughly 81% of all tonnage generated by these three commodity groups, (USACE, 2010). U.S. Great Lakes marine transportation markets in break bulk cargoes, such as logs, have declined over the past decade due to low energy costs, government subsidies for road building, and the ability of railroads to operate year round.

While surplus vessels exist on the Great Lakes, they are usually designed for a specific trade. A self-propelled vessel built to haul ore, aggregate, or liquids would require extensive

rebuilding to be able to efficiently and economically transport biomass in the form of logs. Analyses indicated that barges with a tug providing propulsion is the most likely vessel combination that could be used to move log biomass. The tug and barges would need to be able to cross the open lake so they will need to be certified by the U.S. Coast Guard that they are capable of sailing on the intended routes. The number of U.S. flag barges that are capable of operating on cross lake trade is limited and the number of U.S. tugs that can engage in cross lake trade is also limited. The costs of acquisition and operations compel owners to seek long term contracts and this keeps the supply of cargo and demand for tugs and barges nearly at a balance. This means that existing vessels, if available, will take voyage charters only when it does not adversely impact service for their long term customers.

Marine transportation by vessel benefits from economy of scale. The capacity of vessels is measured in the thousands of tons, exceeding the capacity of unit trains. To justify marine transportation, there needs to be a large supply of wood within a reasonable distance of the port. Operators will want to have volume to justify their use of the high capital cost vessels. Most operators will make single voyage contracts but the best rates will be for long term contracts that ensure the best asset utilization for the operator. The high volume shipments require space to store the buffer stocks on either end of the supply chain. Navigation on the lakes, and certainly the locks, is closed due to ice in winter creating the need for buffer stocks to carry the mills through a 2-3 month period unless biomass is brought in by rail during the time period. The seasonal nature further increases inventory and storage costs unless addressed by wood brought in by other modes.

Frequently, shippers use marine transportation as leverage to prevent dominance by another mode. A wood products shipper that uses rail as their principal mode of transportation may move loads by water to ensure that the option is available and also to let the rail operator know that a viable alternative is available, thus putting pressure on pricing by the railroad. Like rail, use of the marine mode will increase the handling of the logs, leading to additional costs. As presented in Figure 4-1 earlier, handling could occur as often as five times compared to two times with a direct truck run or 3-4 four times with a rail service. If the trucks are loaded directly onto the vessel, then handling will be equal to rail service. Facilities that have docks adjacent to their operations will reduce their handling to two or three times depending on storage.

Two additional items will be impacted with the use of marine transportation. Unless there is a truck scale on the loading dock, the weights will have to be estimated at the port of origin. The other impact will be that, like all modes, marine costs are most easily lowered by a backhaul cargo. Opportunities for such market should be explored in another study. An ideal use of marine transportation would be to move large quantities of biomass on routes that provide a savings in distance, energy consumption and with a landed price less expensive than truck or rail.

In summary, marine transportation of biomass material is an option where the following key attributes are met in the design of the biomass supply chain:

- Navigable waterways connecting the supply to the demand locations with a depth of at least 15 feet for barge and tug operations.

- Port infrastructure that can support the volume of traffic
- Landside access from the ports to biomass supply and demand locations
- Suitable vessels to carry the biomass in the desired quantity
- The total landed cost of using marine transportation as part of the supply chain is competitive.

4-5-2-1- Options for Optimizing Marine Transportation

To maximize the potential for marine transportation of log biomass the following criteria would have to be met:

- The biomass plant would prepare a total cost supply chain study including financial and external cost. If the result of the study found that marine transportation was a viable option for part of the biomass, then the supply chain would be configured to take long term advantage of marine transportation.
- Multiple voyage contracts would be available for qualified carriers. The longer the term (1-5 year duration) the more likely that there will be a lower marine line haul rate. Long term contracts would also allow operators to purchase or build vessels for the trade.
- Ports would have safe berths, cargo handling equipment, the ability to fuel the vessel at one of the ports, and infrastructure to move the logs from the woods or to the biomass plant. Mobile cranes would likely be suitable cargo handling equipment unless the volume justified fixed assets.
- If there were sufficient volume the marine transportation company may elect to use three sets of barges and one tug. This type of operation puts a barge(s) in each port and one underway. When the tug and barge arrive in port, the barges are switched. With this system, the tug is always moving, which is its best asset utilization, and there is always a barge to be loaded or unloaded. This system requires a dock with sufficient length to put both barges alongside.
- A marine transportation option that may reduce cargo handling costs would be to use a roll-on-roll-off (RORO) barging system. This would allow loaded log truck trailers to be driven onto the barge then secured without the tractors. Upon arriving at the destination port a yard hauler removes the loaded trailers and put them in storage or they are coupled to a tractor to be drayed to the facility. The logs would only have to be loaded once in the woods thus reducing handling costs and the need for dockside equipment. These savings would have to be high enough to offset the costs of reduced total volume on the marine line haul, additional storage area for the same volume of wood and the costs of additional trailers. RORO systems are in successful use on a number of routes.
- Storage would exist at key points in the supply chain to minimize buffer stocks required due to the seasonal nature of Great Lakes marine transportation.
- Future biomass energy plants would be built at or near underutilized ports to reduce drayage costs and maximize the economies of scale inherent in marine transportation. In this case Traverse City seems to be a logical location in terms of marine transportation.
- This study is not tasked with examining the physical distribution of the final product from the facility. There may be a viable option in shipping the ethanol by marine

transportation from the tanker dock in Traverse Bay to destinations on the Great Lakes.

4-5-3 Barging Case Study on Lake Michigan

Mr. Dan Glawe from Northern Timberlands was interviewed as part of the investigations on biomass movements in the Great Lakes. The following is a synopsis of log transportation activity across Lake Michigan in the 1990's. Northern Timberlands had a three stage barge system where one barge would be loading while the second was being hauled across the lake and the third one unloading (each barge could carry about 1,200 tons of wood per load). All three duties were conducted simultaneously to minimize down time. Some wood was stock piled at the dock site to make sure there was enough wood to fill the barge at the time of loading. The company used a log loader with a 50 foot reach to load the barges and in some occasions, rocks were brought back as backhaul. When this was done, the barge would have to be cleaned in between to prevent contamination which would take about eight hours.

Northern Timberlands did find a tug and barges that they would have purchased, but the operation was halted when long term contracts could not be secured to justify the investment in the equipment. In addition, economy and market competition reduced the need for pulp wood and paper companies didn't feel comfortable committing to long term contracts. Today, similar operations would be difficult, as many of the capable harbors for these types of activities in the LP have been lost.

4-5-4- Key Operational Challenges for Marine Biomass Transportation

Since the origin and destinations of biomass transportation in the FBSCC project only moves within the state of Michigan, marine transportation is expected to play a minor role. Some of the main challenges of marine transportation include:

- Infrastructure capital costs
- Vessels: Capital and operational costs
- Marine haul business model challenges (risky business for operators)

4-5-4-1- Infrastructure Capital Costs

The decline in marine transportation has adversely impacted port infrastructure. Landside access to docks, loading equipment, water depth, and the docks themselves have not been maintained in operating condition. In some cases they have deteriorated to the point where extensive repairs or replacement would be necessary to operate at the location. Depending on which ports are used, the condition of the dock facilities may greatly increase the loading and unloading time and costs. If the proposed ports do not have shoreside loading equipment, the barge(s) will have to be fitted with cranes or front end loaders capable of loading and unloading the vessel. Barges can be fitted with this equipment but their placement increases cost, as the capacity of the barge is reduced, the equipment is subjected to the impact of spray and waves, vessel personnel need to be trained and certified in their operation, and if the barge is not in a dedicated biomass trade, the equipment will likely need to be removed and replaced for non-biomass voyages.

4-5-4-2- Vessels: Capital and operational costs

Additional vessels could be purchased or built for the biomass trade, but this will not be undertaken without a sound business plan that outlines markets, operational parameters, financials, and strategic planning. The acquisition of new or used vessels requires considerable capital that must be financed. Lending institutions are even more conservative than ship owners, especially when the overall market for marine transportation has been declining. This means that the financing providers will, in most cases, want the vessel owner to have a long term contract (charter) by a shipper before they will agree to the loan. The mortgager will also want experienced managers and preferably an existing marine transportation company with a proven track record.

The U.S. Maritime Administration (MARAD) is authorized to guarantee loans for shipbuilding thereby reducing rates and freeing up capital (MARAD, 2010). On January 16, 2009, the program made its first new commitment after almost four years of inactivity, and has approved a total of \$330 million in new commitments through September 2010 (MARAD, 2010). MARAD requires a sound business plan to apply for these loans. Defaults on Title XI loans have raised the expectation that future loans from this program will have more intensive evaluations during the application process and greater oversight during the loan's term.

In addition to the usual fixed and variable operational costs, new market single voyage charters may also incur cleaning fees, barge configuration costs, and repositioning expenses. A tug and barge that is operating on a fixed route between ports, and must divert from that route to a new port, may travel hundreds of miles to reach the new port without cargo aboard (deadheading). The expenses for the deadhead voyage will have to be captured in the freight rates, making the rates for a single voyage in the new market relatively expensive. Multiple voyages on the new route allows the new market expenses to be spread over time, reducing the per ton rate.

4-5-4-3- Marine Haul Business Model Challenges

The factors and challenges discussed in the last sections compel a vessel owner to have a fiscally conservative business operation that is risk averse. This business model has resulted in the reluctance by vessel operators to provide single voyage quotes for the movement of biomass. Vessel owners interviewed also believe that single voyage charters were often offered to vessels as an inducement for rail and/or truck freight rates to remain low. Rather than seeking marine transportation as a viable option, some shippers would use the potential for low cost marine transportation as a threat to other modes.

Without exception, the owners' first response was to ask the interviewer how many years the contract would cover and the annual volume of cargo being moved between origin and destination. The second question was if there was a backhaul cargo. Without a backhaul cargo, the carrier must capture both loaded and deadhead voyage costs from one shipper. Another challenge faced by the owner is that most of their costs are largely fixed. In order to break even, the set of equipment must be fully utilized. Most of the vessel owners we contacted would not provide a single voyage price estimate as they felt a single voyage was

an unrealistic proposal for a long term facility that will require millions of tons of biomass. The framework of this study did not provide volumes for O-D pairs.

The U.S. Army Corps of Engineers, in their Table 14 – Update of Fixed and Variable Vessel Costs from 2005 to 2008 Prices, provides daily cost estimates for bulk vessels operating on the Great Lakes. The smallest bulk vessel listed (class 2 Intra-Lake) had a daily operating cost in 2005 of \$26,915 or \$1,121 per hour, (USACE, 2010). These vessels typically carry 18,000 – 20,000 tons of cargo and travel at speeds of 15 miles per hour or 345 miles a day. The cost to deliver a cargo of 20,000 tons over a 250 mile voyage would be \$.93 per ton.

While instructive of the economies of scale provided by marine transportation, this class of vessel would not be used for biomass delivery. A tug – barge combination would be most suitable for the marine transportation of biomass. During the interview process, one vessel operator provided voyage cost estimates, but with several caveats. The quoted prices do not include loading and unloading costs or voyage time because the origin and destination ports could not be guaranteed. The vessel would only call at a “safe harbor and berth” and depending on the energy market; there may be a fuel surcharge. The operator is from the Lake Superior region and their vessel is capable of biomass movements.

4-6. Transportation Service Capacity for Proposed Biomass Plants

Nine potential locations for cellulosic ethanol facilities were identified within the Lower Peninsula of Michigan as part of the FBSCC project. The capacity of each facility was estimated to be between 30-50 million gallons. Even though detailed analyses of transportation requirements for each specific plant were beyond the project scope, the research team developed preliminary estimates to quantify the number of loads and equipment required to provide woody biomass to the facilities. The team used plant operational conditions provided by researchers in Task B4, together with equipment load capacity and performance data to quantify the equipment needed. Some of the key assumptions in the analysis included:

- Plant sizes: 30, 40 and 50 million gallons and green tonnage requirements of 750,000 tons, 1,000,000 tons and 1,250,000 tons, respectively.
- Based on previous studies, trucks typically operate five days per week. However, analyses were developed for five, six and seven day weekly operations.
- Annual facility operates 50 weeks per year (two weeks for maintenance).
- All trucks hauling into the plant would be 10 or 11 axle trucks with a gross vehicle weight of 164,000 lbs. (with an empty weight of 55,000 lbs.). The trucks would be eligible to carry a total weight of 105,000 lbs. (52.5 tons) of woody biomass per truck. As a safety factor for truckers to not reach the overweight mark, 50 ton /truck are used.
- All material would be provided in the Lower Peninsula, so there would be no need for movements over Mackinac Bridge.
- Standard rail car holds between 75 and 85 tons of material. The analyses used 80 tons per car. Estimated at 1 delivery trip per week.
- For marine transportation, barges were identified to hold between 1,000 to 3,000 tons of material on deck. The analyses used three 1,000 ton capacity barge that serves the mill per week.

- Cord of wood would weigh 2.35 tons/cord (local forestry industry accepted factor)(Hicks 2009).
- Trucks can deliver two loads per day to the plant and to/from barge dock facilities and three loads per day to rail sidings. All material from origin to barge dock facilities and docks to final destinations are handled by trucks.
- Transportation of final products was not considered, even though potential backhauls of final products might provide economic benefits for rail and marine transportation.

The analysis considered three different transportation scenarios for woody biomass:

- Scenario 1: 100% truck delivery
- Scenario 2: 80% by truck and 20% by rail
- Scenario 3: 60% by truck, 28% by rail and 12% by barge

Since rail cars and barges cannot pick loads up directly from the harvesting sites, trucks will have to deliver the biomass to the loading sites. The truck productivity for these deliveries is explained above and in Figure 4-8 and Figure 4-9. Additional requirements for these movements were included in the estimates.

Figure 4-8- Scenario 2: Number of trucks needed to fulfill supply chain for 50 million gallon facility

Figure 4-9- Scenario 3: Number of trucks needed to fulfill supply chain for 50 million gallon facility

Table 4-4 presents total volumes and load quantities for each alternative. 500 truck loads are necessary weekly to deliver needed material for 100% truck alternative. With 7 day service, the plant needs 36 trucks per day to support tonnage requirements, 42 trucks per day for 6 day service and 50 trucks per day for 5 day service (Table 4-5).

Transportation Mode	Percent of Tonnage Delivered by Mode					Tons/ Week Needed	Number of Truck Loads/ Week	Number of Rail Cars Loads/ Week	Number of Barge Loads/ Week	Delivery Mode from Marine shipment to Mill	
	Truck	Rail	Marine Transportation Delivery							# Trucks Loads to Mill (from barge delivery)	# Rail Cars to Loads mill (from barge delivery)
			Marine	Truck	Rail						
Truck	100	0	0	0	0	25,000	500	0	0	0	0
Truck and Rail	80	20	0	0	0	25,000	400	63	0	0	0
Truck, Rail and Marine	60	28	12	100	0	25,000	300	88	3	60	0

For 80% by truck and 20% by rail alternative, 400 truckloads and 63 rail cars are required to supply the necessary demand. Trucks needed to deliver material to rail sidings are 5, 6 and 7 (7, 6 and 5 day service); trucks needed to deliver to the mill are 29, 34 or 40 trucks to the plant (7, 6 and 5 day service). For 60% truck, 28% rail and 12% Marine alternative, there is a greater usage of multimodal transportation within the delivery process. Demands equal to 300 truckloads, 88 rail car loads and 3 barges (100% deliver by truck to plant location from barge). At 7 day service the plant needs 36 trucks per day to support tonnage requirements, 42 trucks per day for 6 day service and 50 trucks per day for 5 day service (seen in Table 4-5).

When truck and rail are used, there is a decline in the number of trucks needed due to shorter delivery distances (a single truck can make more trips, cutting down on the number of trucks needed). However, inclusion of marine transportation doesn't further decrease the number of trucks, as it was assumed that only two rounds trips can be made by truck to dock facilities. However, marine transportation would expand the radius of potential feedstock availability.

Table 4-4- Total Load Tonnages Needed by Mode

Transportation Mode	Percent of Tonnage Delivered by Mode					Tons/ Week Needed	Number of Truck Loads/ Week	Number of Rail Cars Loads/ Week	Number of Barge Loads/ Week	Delivery Mode from Marine shipment to Mill	
	Truck	Rail	Marine Transportation Delivery							# Trucks Loads to Mill (from barge delivery)	# Rail Cars to Loads mill (from barge delivery)
			Marine	Truck	Rail						
Truck	100	0	0	0	0	25,000	500	0	0	0	0
Truck and Rail	80	20	0	0	0	25,000	400	63	0	0	0
Truck, Rail and Marine	60	28	12	100	0	25,000	300	88	3	60	0

Table 4-5 - Truck Capacity Numbers Needed

Mode	Total Trucks to Deliver Multimodal Supply/ Days of Service			Total Trucks to Deliver to Mill/ Days of Service			Total Trucks Needed/ Days of Service		
	7	6	5	7	6	5	7	6	5
Truck	0.0	0.0	0.0	36.0	42.0	50.0	36.0	42.0	50.0
Truck, Rail	5.0	6.0	7.0	29.0	34.0	40.0	34.0	39.0	47.0
Truck, Rail & Marine	11.0	13.0	16.0	25.0	29.0	34.0	36.0	42.0	50.0

Based on the data collected on available trucks for biomass transportation in the Lower Peninsula, 50 trucks would account for more than 10% of the overall fleet, suggesting that necessary trucking capacity to support a single biomass plant exists in the Lower Peninsula.

During the interviews, industry experts suggested that equipment in the Lower Peninsula is currently underutilized due to closure of several plants. However, if all nine proposed plants were established, they would need the whole LP truck fleet, putting pressure on new investment on trucking equipment. Similar analysis for rail equipment was not conducted due to interstate nature of the equipment but securing 60-80 cars for continuous should be manageable.

An analysis of Table 4-6 indicates that from a highway distance perspective, the ports of Charlevoix and Traverse City offer the shortest highway routes for biomass delivered by vessels to final destinations. Marine transportation of biomass to the potential facilities has the greatest potential when moving biomass from Lake Michigan ports on the Upper Peninsula of Michigan to Michigan ports on the east coast of Lake Michigan. Total distances needed to transport the biomass are, in some examples, reduced by more than two thirds. The potential cost savings may provide an opportunity to make the UP wood basket a viable source of biomass for the Lower Peninsula of Michigan. While the port of Bay City would serve Clare and West Branch with the shortest drayage, the longer water route from origin ports negates any potential savings.

Table 4-6- Distance between Origin and Destination Michigan Ports Comparative Analysis ²³

Michigan Origin –Destination Pairs via ports	Miles Marine mode – statute miles	Drayage	Combined miles	Direct Highway miles
Escanaba to Manton via Traverse City	91	37	128	267
Escanaba to Manton via Frankfort	91	64	156	267
Escanaba to Kalkaska via Traverse City	120	25	145	241
Escanaba to Kalkaska via Frankfort	91	44	135	241
Escanaba to Mancelona Via Charlevoix	91	31	122	227
Escanaba to Kingsley via Traverse City	120	17	137	264
Escanaba to Kingsley via Frankfort	91	38	129	264
Menominee to Kingsley via Traverse City	138	17	97	317
Escanaba to Clare Via Bay City	129 + 210	48	387	291
Escanaba to West Branch Via Bay City	129 + 210	52	391	272
Ontonagon to Kingsley via Traverse City	274 + 90 +97	38	499	410
Ontonagon to Mancelona Via Charlevoix	274 + 90 + 56	31	451	360
Ontonagon to Boyne City Via Charlevoix	274 + 90 + 56	32	452	331
Ontonagon to Clare Via Bay City	274 + 246	48	568	423

4-7. Biomass Transportation Costs

Supply chain cost analysis is a complex process with potential to provide a competitive advantage to a firm when properly done. No mode should be selected without a supply chain cost analysis. This section provides a review of the cost estimation methods for biomass transportation, considering both single mode and multimodal options. It reviews standard formulas for cost estimation, followed by more detailed discussion and a case study on specific modal rates for biomass transportation in the state of Michigan. It should be noticed that the variables in these formula will need to be calibrated and computed to determine the lowest landed cost for any proposed biomass supply chain.

²³ : Distances Between US Ports, 10th Edition, National Oceanographic and Atmospheric Administration, Washington DC, 2009, Mapquest accessed 2011.

4-7-1- Lowest Landed Cost Estimation

In transportation, landed cost refers to the final price of a product delivered to the final destination. The total cost components include transportation, handling, storage, ordering, and inventory. Businesses spend considerable resources to calculate landed cost of a product and are acutely aware that this cost is not static. The total cost can be impacted by a large number of factors outside the control of the industry. Just-in-Time business models may work when transportation costs are low and the product value is high, but increases in transportation costs such as fuel may cause industry to rethink their supply chain model and carry more inventories to reduce the transportation cost side of the equation.

To minimize their landed cost, industries use several calculations. Buffer and safety stock costs are calculated using the formulas provided in Figure 4-10. Economic Order Quantity and inventory costs are calculated using the formulas in Figure 4-11 and finally, the total landed cost can be calculated using a formula presented in Figure 4-12 (Coyle, 1996).

Computing Safety Stocks

$$S_{Dt} = \sqrt{(t)(S_D)^2 + (D)^2 (S_t)^2}$$

Where:

- S_{Dt} = Units of Safety Stock required to satisfy 68 percent of sales levels during lead time
- t = Average delivery time
- S_t = Standard Deviation of delivery time
- D^2 = Average Demand
- S_D = Standard Deviation of Demand

Figure 4-10- An example of computing buffer and safety stocks

$$\text{Total Cost} = \text{OC} + \text{CC}$$

$$\text{OC} = \text{Order Placement Cost} = A(R/Q)$$

$$\text{CC} = \text{Inventory Carrying Cost} = 1/2(QVW)$$

Where:

Q = Optimal Order Quantity (EOQ)

A = Cost of placing an order

R = Annual Rate of use

V = Value per unit

W = Carrying cost as a percentage of average value of inventory

$$\text{EOQ} = Q^* = \sqrt{\frac{2AR}{VW}}$$

Figure 4-11- Economic Order Quantity and inventory costs

Total Cost Analysis

$$\text{Total Cost} = \text{OC} + \text{CC} + \text{Tr} + \text{PC} + \text{It} + \text{SS} + \text{Other}$$

$$\text{OC} = A(R/Q)$$

$$\text{CC} = 1/2(QVW)$$

$$\text{Tr} = rRwt/100$$

$$\text{PC} = VR$$

$$\text{It} = iVRt/365$$

$$\text{SS} = BVW$$

Where:

Q, R, A, V, W = As previously defined

r = Transportation rate per 100 pounds (CWT)

wt = Weight per unit

i = Interest rate or cost of capital

t = Lead time in days

B = Buffer of inventory to prevent stockouts

Figure 4-12- Landed (total) cost calculation

4-7-2- General Equation for Transportation Cost Estimation

Figure 4-13 presents a simplified formula for determining the charge (or price) per ton of biomass shipment by any transportation mode.

Transportation Charge Formulas:

$$1: \text{Rate per mile} = \frac{\text{Fixed costs} + \text{vehicle costs} + \text{profit margin}}{\text{Miles}}$$

$$2: \text{Haul cost} = (\text{rate per mile}) \times (\text{distance})$$

$$3: \text{Total Annual Haul cost} = (\text{Price per ton}) \times (\text{Total number of tons delivered})$$

Figure 4-13- Total cost formula for biomass transportation

It should be noted that additional “variable costs” may be added to the formula. Such costs may include interchange fees by railroads when shipments move from one carrier to another, clean up fees by barge operators and even increased mileage charge by truckers due to substandard access roads. There may also be surcharges, such as fuel surcharges, to protect carriers from fluctuations in operating expenses.

4-7-3- Cost Estimation for Truck Transportation

Truck transportation is a highly competitive area of business causing the rates between different service providers to be closely aligned. The charges are commonly based on the freight tonnage and length of haul making it easier to provide generalized rate estimations for various distances and tonnages in a single formula.

Round wood shipping rate data was obtained from a single operator in the Lower Peninsula to assess transportation costs in the LP. Several rates were obtained earlier for Upper Peninsula transportation. Movements that cross the Mackinac Bridge should receive \$4 per cord additional fee to cover the crossing fees. The rates provided are for single-directional movements. Potential backhauls or circuitry routes that increase loaded miles have potential to reduce the rates.

Figure 4-14- Lower Peninsula round wood transportation cost (red) as compared to aggregated costs for several Upper Peninsula trucking companies (blue).

4-7-4- Cost Estimation for Bimodal (Rail/Truck) Transportation

For rail transportation, rates are not as easy to determine as for trucks, since every rail service provider has a specific policy and rate to charge customers. In addition, rail service providers reward customers with consistent volumes with individually negotiated contract rates and some origin-destination pairs may require a transfer of load from one railroad to another (interchange), further increasing the cost. For these reasons, accurate transportation rates for multimodal truck-rail combination have to be typically estimated case-by-case for each origin-destination pair. Typically, the rail transportation rates are formed based on following criteria (Cheaney, 2009):

- **Freight volume:** To obtain a more economical contract rate, rail operators typically require minimum volume commitments.
- **Total mileage and amount of switching and interchanges** with other railroads required en route.
- **Equipment and fleet:** Types of the cars, loading and unloading facilities.

- **Availability of cars and trains:** number of cars and the period of the time which should be moved.
- **Car ownership:** rented, leased or owned by shipper versus railroad-owned pool.
- **Competition between rail operators** along those corridors with more than one rail service provider.
- **Customer bargaining power** based on reputation, long term shipping history, previous interactions.
- **Market attraction** based on the demand, growth rate, possible expansion.

No specific rate estimations for bimodal trips were developed for the study, as specific quantities and origin-destination pairs would have to be identified for the proposed facilities. However, as part of a recent study in the UP, a computer model was developed by a graduate student at Michigan Tech (Hicks, 2009) to combine knowledge of rail and truck rates with geographic information and further to attempt to optimize the transport of logs between a defined origin/destination pairs. The model was tested on 100,000 actual truck trips and has further been expanded to evaluate transportation cost to a specific destination in Kinross. The following section provides a short case study on the model and how it can be used for bimodal transportation rate estimations in Michigan.

As part of his study, Hicks was able to determine some of the tariff and contract rail rates offered by CN Railroad in the UP. These tariff rates were developed directly from the CN web site and contractual rates were derived from the Lake States Shippers Association (LSSA) data. Figure 4-15 presents the tariff rates and respective contract rates utilized in the analysis. The figure reveals a typical trend for rail rates, where cost per ton for initial 100 miles has a small variable cost, but after 100 miles this portion increases. This is due to the fact that for the first 100 miles, the majority of costs are caused by the handling and other operational costs, largely independent of the quantity being shipped. Figure 4-16 combines the rail and truck rates to form the bimodal rates. The analysis of truck data revealed that logs move on average 20 miles before they get loaded to the rail cars, so trucking charges for 20 miles is added to the rail rates to form the complete bimodal cost. Figure 4-16 reveals that truck transportation in the UP is more cost efficient than the bimodal alternative with trips under 130 miles of total (combined truck and rail) distance. The break point is slightly higher than in similar analyses conducted in Finland, which found it to be approximately 100 miles of total distance with 20 miles of truck transportation prior to rail loading (Lahdekorpi, 2010).

Figure 4-15- CN tariff and contract rail rates in the UP of Michigan

Figure 4-16- Comparison of trucking and bimodal transportation rates in the UP of Michigan

In addition to comparative rate calculations, “cost gradient maps”, such as the one presented in Figure 4-16 can be developed for larger scale planning analysis to evaluate the general costs of transportation for a specific destination. Figure 4-17 demonstrates one example of such comparisons by presenting expected transportation rates to Kinross, when bimodal transportation alternative is or is not available. The figure shows how available rail lines and sidings expand the lower cost area of transportation origins along the rail corridors. In the example case, the entire UP was divided into square miles and each of them was considered as a separate origin point for the trips. In addition to illustrating general rates, such maps can be used to investigate the sensitivity of rates to changes in diesel fuel price at times when surcharges are added to the rates.

Figure 4-17- Transportation cost gradient maps of log shipments from the Upper Peninsula of Michigan to proposed facility in Kinross.

Figure 4-18- Cost gradient map for the UP of Michigan. Fuel price = \$4.00.

A comparison of transportation costs per ton for single mode versus bimodal transportation is presented in Table 4-7 and Figure 4-19 in 30 miles increments and with different fuel price scenarios. The table reveals that increase in transportation distance causes a decrease in the percentage of trips that move by truck only. In order to demonstrate the cost savings from the price-optimized use of bimodal transportation options, the aggregated, optimized trip cost (using

bimodal trips when cost-effective) can be compared to the single-mode truck cost, which uses truck transportation for every trip (Column "Single mode" in Table 4-7). In longer trips, the two prices begin to deviate and a greater portion of traffic should be moved by bimodal trips. The aggregated bimodal average price appears to be lower for trips above 90 miles in this scenario.

Table 4-7– Transportation cost summary for different transport scenarios, UP case study

Transport Distance ^a (miles)	Cost of transport, \$ per ton					
	Fuel price = \$3/gal		Fuel price = \$4/gal		Fuel price = \$5/gal	
	Single Mode	Bi-modal (Optimized ^b)	Single Mode	Bi-modal (Optimized)	Single Mode	Bi-modal (Optimized)
0-30	5.26	5.26	5.48	5.48	5.71	5.71
30-60	7.17	7.17	7.67	7.67	8.17	8.17
60-90	9.69	9.69	10.55	10.55	11.42	11.40
90-120	11.95	11.69	13.14	12.46	14.34	13.01
120-150	14.25	12.36	15.77	12.82	17.30	13.28

a – mileage categories represent over-the-road trucking distances

b – optimized, using bi-modal (truck + rail) transport whenever the cost per ton of a bimodal trip was less expensive than the equivalent single-mode truck trip.

Figure 4-19- Summary of transportation costs for different fuel prices and transport scenarios for the Upper Peninsula case study.

All previous modeling efforts have included an assumption that all trucks are directly unloaded from a log truck to a waiting rail car during a bimodal trip (“hot-loading”). If rail cars are not present at the siding when log trucks arrive, logs will need to be unloaded to the ground and later loaded to the rail cars either by log trucks or designated loaders. This extra handling step represents an additional cost that will have to be considered in the bimodal transportation option (Figure 4-20). According to industry estimates, the estimated additional unloading/loading cost is \$4.00-\$6.00 per cord. To simulate the effect of a ‘ground storage’ in the bimodal transportation scenario, this extra handling cost was added to the fixed cost of a rail trip and applied to every scenario where rail was considered a transportation option. Outcomes suggest that while ground storage costs do increase the cost of bimodal transportation, there are still supply areas where rail use would offer a significant savings, especially for trips that require more than 120 miles of truck travel. In this 120-150 mile zone, only 12.5% of trips modeled were suggested to proceed with single-mode truck transport (data not shown).

Figure 4-20- Cost gradient map with additional handling, Fuel price = \$4.00.

Similar analysis was also conducted for material transported to Kinross from the Lower Peninsula. For these movements, the only transportation alternative is trucking, due to the requirement of crossing the Mackinac Bridge. Table 4-9 summarizes truck transportation costs from the Lower Peninsula, based on unit cost rates obtained from the LP, at a fuel price of \$4.00.

Table 4-9- Trucking Costs from the Lower Peninsula

Trucking distance (miles)	Single Mode Only \$ per ton (Fuel Price = \$4.00)
0-30	--
30-60	10.72
60-90	12.25
90-120	14.38
120-150	16.38

A transportation cost gradient map that demonstrates the sensitivity of shipping costs to fuel prices within almost the entire project supply area is included in Figure 4-21. The data represented in this figure considers fuel prices of \$3.00, \$4.00, and \$5.00 and assumes an efficient use of bimodal transport with contract rail rates and hot-loading for all potential Upper Peninsula bimodal trips. Transport costs do not appear to change as drastically in the Upper Peninsula when fuel prices increase from \$3 to \$5 as compared to the Lower Peninsula. This is due to the presence of rail as an alternative transport mode in the Upper Peninsula.

Figure 4-21- Transportation cost gradient maps with fuel prices of \$3.00, \$4.00, and \$5.00. Blue circle indicates 150-mile distance from Kinross facility.

4-7-5- Marine Transportation Cost Estimation

Marine rates follow the transportation cost formulas explained earlier in the section. For biomass movements, tug and barges can transport logs at a quoted price of \$120 per mile by a tug and barge with 1,000 tons load capacity. The following table (Table 4-8) provides a comparison between truck and marine on certain Lake Michigan ports and the potential facilities. The truck rates were calculated both using generic truck freight rates and specific rates provided by Michigan log truck service providers.

Table 4-8- Comparison between line haul truck and marine rates

Michigan Origin Destination Pairs	Marine distance in statute miles	Quoted rate per mile	Distance x per mile rate = line haul cost	Total tons transported each voyage	line haul cost/total tons = price per ton*
Escanaba to Manton via Traverse City	120	\$120.00 ¹	\$14,400	1000	\$14.40
<i>Truck - Escanaba to Manton (Generic freight rates)</i>	<i>267</i>	<i>\$2.27²</i>	<i>\$606.90</i>	<i>25³</i>	<i>\$24.25</i>
<i>Truck - Escanaba to Manton (Michigan Log truck rates)</i>	<i>267</i>	<i>Cost per ton = \$3.72 + \$0.074(mi) + \$1.70 toll</i>			<i>\$25.18</i>
Escanaba to Manton via Traverse City	120	\$120.00 ¹	\$14,400	2000 ⁴	\$7.20
Escanaba to Manton via Traverse City	120	\$120.00 ¹	\$14,400	3000	\$3.60
Escanaba to Kalkaska via Frankfort	91	\$120.00	\$16,200	1000	\$16.20
<i>Truck - Escanaba to Kalkaska (Generic freight rates)</i>	<i>231</i>	<i>\$2.27</i>	<i>\$524.37</i>	<i>25</i>	<i>\$20.97</i>
<i>Truck - Escanaba to Kalkaska (Michigan Log truck rates)</i>	<i>231</i>	<i>Cost per ton = \$3.72 + \$0.074(mi) + \$1.70 toll</i>			<i>\$22.51</i>
Escanaba to Kalkaska via Frankfort	91	\$120.00	\$16,200	2000	\$8.10
Escanaba to Kalkaska via Frankfort	91	\$120.00	\$16,200	3000	\$5.40

¹This price does not include storage, loading and unloading expenses.

²Freight rate index cost-per-mile increased to \$2.27 in December 2010, up from \$2.24 in November 2010. (*This Cost Per Mile (CPM) indicator is comprised of 8 main and 65 total cost and cost influencing components, it considers completely, every cost related to freight transport by land*) <http://www.sgrc.us/Transportation/documents/LogisticsMarketSnapshotDEC2010.pdf> However, This cost does not include bridge tolls crossing the Mackinaw Bridge.

³ The 25 ton payload assumes an 80,000 pound gross vehicle weight limit.

⁴The primary costs will be in the tug operation which will have some increases in variable costs. This assumes a single barge with at 1,000-3,000 ton capacity. The addition of more barges would likely raise this price.

The truck rates are calculated based on the obtained rates for Michigan log trucks, although it is questionable whether these rates would be valid for these longer trips, or if generic over the road trucking rates should be used instead of short haul log rates. Most log trucks stay within a 100 mile radius of a mill minimizing deadheading time. The marine line haul rate quoted does not include loading, unloading, drayage, and storage costs. Drayage will depend on the port and mill

locations. These factors may raise the cost of the marine operation substantially and should be considered in the final supply chain analysis. The drayage from Traverse City to Manton is approximately 37 miles and will require 40 truck movements for each 1,000 ton marine cargo unit delivered. A truck will be able to move about 4 loads in a day on that route with favorable weather and traffic conditions. This means that a single truck will require 10 days to dray the marine load to Manton or 5 trucks will move the load in 2 days or less. At a \$2.27 per loaded mile rate the extra cost of drayage would be:

$$40 \text{ truckloads} \times 37 \text{ miles} \times \$2.27 \text{ loaded per mile rate} = \$3,359.60$$

The drayage cost from the woods to the origin port docks cannot be computed without exact wood supply location data, but assuming a like distance, origin drayage costs for a 1,000 ton wood movement would be \$6,719.20. This would in effect increase the Escanaba-Traverse City-Manton marine per ton line haul rates for a 1,000 ton marine load to \$21.12 per ton. This is a rate still below the truck rate.

$$\$6,720 \text{ drayage} + \$14,400 \text{ line haul} = \$21,120 \text{ combined cost/1000 tons} = \$21.12 \text{ combined per ton rate}$$

Economics of scale by using larger barges would not impact the combined drayage costs but would have the ability to diffuse the drayage cost when computing the final landed cost. For instance, the drayage costs for a 3,000 ton marine load would be \$20,157. This would in effect increase the Escanaba-Manton marine per ton line haul rates for a 3,000 ton marine load to \$11.59 per ton. This is a rate significantly lower than all truck rates.

$$\$20,157 \text{ drayage} + \$14,400 \text{ line haul} = \$34,577 \text{ combined cost/3000 tons} = \$11.59 \text{ combined per ton rate}$$

At the quoted marine line haul rates coupled with drayage costs there appears to be some saving on the cited routes in using marine transportation for loads of 1000 tons. However, when the marine loads are increased to 2000 and 3000 tons, then marine transportation can provide a significant value added proposition for line haul rates. This assumes that the tug barge combination could move 2000 tons at, or near the quoted per mile rate. Frequently tugs that can haul a 1000 ton barge can haul barge(s) of up to 3000 tons with minimal increase in variable costs for fuel. This also assumes that the capacity of the barge can be from 1-3,000 tons. For the economies of scale to work, the supply chain would have to be able to cost effectively, and efficiently deal with single cargos of that volume moving in the system.

This financial analysis clearly indicated the financial benefits that can accrue from making use of the economies of scale and routes that marine transportation can provide for appropriate cargoes and supply chains. However, this would require movements from the UP to the LP or vice versa.

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Appendix

A- Literature Review

The following studies, papers, researches and reports on woody biomass transportation and the main technical and operational challenges regarding transportation were reviewed as part of the literature search (Table A-1). The review has concentrated in North America and Europe and only includes published references, excluding web pages or databases. The references in the table have been sorted based on their relevancy to woody biomass transportation. In “reference summary” column, the region or country of origin has been marked in the parentheses for each reference.

Table A-1- Summary of biomass transportation literature review

No.	Name	By	Type	Publisher	Year	Reference Summary
1	The profitability of transporting uncomminuted raw materials in Finland	T. Ranta, S. Rinne	Paper-PDF	Elsevier, Biomass and Bioenergy 30, pp 231–237	2006	(Finland) This paper concentrated on biomass transportation issue in Finland. In this paper, the consumed time and load size data have been gathered and evaluated based on a monitoring system combined with GPS installed in computers of trucks. The result shows that in the beginning of year 2004, the average total weight of loads for all types of uncomminuted raw material was less than maximum weight limit, 60 tons. There was around 10 tons of potential load capacity left. Recommendations for improvements include increasing the load size and decreasing the terminal waiting and processing times.
2	Michigan Log Truck Study II, Final Report	Christopher Green, et al	Report- PDF	Michigan Tech. University, Michigan Department of Transportation (MDOT)	2005	(USA) This study continues the Michigan Log Truck Study that was done in 2003. The primary focus areas of this study are: Update the Literature Review done in 2003, Inventory the Characteristics/Configurations of Log Trucks and Log Loads, Review Log Truck Crashes and Spills, and Recommend Practices and Innovations for Existing Documented Hazards. This study monitored sites in the Upper Peninsula and the northern half of the Lower Peninsula to determine the size and characteristics of trucks hauling logs in Michigan
3	The Relative Cost of Biomass Energy Transport	Erin Searcy, et al	Paper-PDF	Applied Biochemistry and Biotechnology; Vol. 136–140; pp 639-652	2007	(Canada) In this study, the relative cost of transportation by truck, rail, ship, and pipeline was estimated for some small- and large-project sizes. Study concluded that ship vs. rail transportation is not economic for distances under 800 km. Also transshipment from truck to rail is economical at 500 km for both if rail lines are available
4	Transportation logistics of Biomass for Industrial Fuel and Energy Enterprises	Klein Ileleji	Presentation- PDF	Purdue University-USA	2007	(USA) Complete presentation about biomass and the relevant definitions, including logistics and transportation procedure, operation and simulator tools (BmFLS) needed to deliver biomass productions specially corn stover to the destinations
5	Woody Biomass for Bioenergy and Biofuels in the United States—a Briefing Paper	Eric M. White	Report- PDF	Department of Forest Engineering, Resources and Management, Oregon State University	2009	(USA) This research focuses on potential biomass in US including different subjects such as woody biomass feedstock, and provides explanation of woody biomass from harvest residues, milling residues, municipal wastes and hazard fuel reduction. Through review of biomass from hazard fuel reduction, some information about treatment and transportation costs to remove and carry them to the roadside have been discussed. Supply curves of biomass feedstock and its relevant costs have been depicted and analyzed based on different types of biomass and different delivered prices.
6	Appendix F: Feedstock Transportation and Logistics,	James J. Corbett, et al	Paper-PDF	Renewable Fuels Roadmap and Sustainable Biomass Feedstock	2010	(USA) This appendix discusses transportation and distribution (T&D) implications of increased biofuel feedstock and fuel production in New York State based on “renewable fuels roadmap and sustainable biomass feedstock supply for New York” studies. For each scenario presented in the Roadmap, this analysis evaluates capacity, energy,

No.	Name	By	Type	Publisher	Year	Reference Summary
				Supply for New York ;the NY State Energy Research and Development Authority		and environmental impacts associated with moving feedstock and fuel throughout the State. The analysis reveals potential capacity constraints and economic issues regarding infrastructure needs and opportunities to support a sustainable biofuels industry.
7	Bioenergy out of byproducts from forestry in Finland	Dimitri Maertens	Thesis-PDF	KH Kempen University, Finland	2009	(Finland) Through this thesis, the main issues of woody biomass productions have been described in Finland. Supply chains of logging residue chips has been reviewed based on discussion about terrain chipping, roadside chipping, chipper-chip truck, terminal chipping, loose residue and bundling. In addition, the role of UPM Forest Company in forestry and bioenergy in Finland and all over the world has been reviewed through this thesis.
8	Modeling the Multi-Modal Transport of Logs and the Effects of Changing Fuel Prices	JUSTIN W HICKS	Thesis-PDF	Civil and Environmental Engineering Department, Michigan Tech. University	2009	(USA) In this M.S. thesis, log transportation by either truck or bi-modally by truck/rail has been compared in Upper Michigan to evaluate the price-optimal use of each mode. The study found that with current fuel cost, 22% of the logs moving by trucks should have moved bi-modally with truck and rail. In addition, the study suggested that 7% of the total ton-miles should shift from truck to rail for every one dollar increase in fuel prices.
9	Woody Biomass Supply Chain, Guidelines, Costs and Logistics, the Minnesota Experience	Dalia Abbas	Presentation- PDF	International Conference on Woody Biomass Utilization- Mississippi	2009	(USA) In this paper, main features of woody biomass supply chain including harvesting guidelines, supply chain costs and logistics have been reviewed. As case study a harvesting area in Minnesota has been selected and supply chain facilities and requirements have been analyzed, in addition to the sensitivity analysis of supply chain costs based on six hypothetical distance scenarios.
10	A Study of How to Decrease the Costs of Collecting, Processing and Transporting Slash	Craig Rawlings, et al	Report- PDF	Montana Community Development Corporation	2004	(USA) The state of the art for transporting forest residues in Montana has been reviewed. The study concluded that roll on/off container transport system was the most appropriate mean for wood products and this system has this capability to yield 9 to 10 chip van loads per day, as opposed to the current system's 3 to 4 loads
11	Forest Biomass Removal on National Forest Lands – first progress report	Placer County Chief Executive Office, TSS Consultations	Report- PDF	Sierra Nevada Conservancy, Placer County, and the Placer County Air Pollution Control District	2008	(USA) The primary objective of this project is the removal of woody biomass waste material from national forests located within the service area. In addition to review of some specifications of transport and collection machineries, study emphasized that the total costs to collect, process and transport are higher than current market value of biomass feedstock.
12	A Report on Conceptual Advances in Roll On/Off Technology in Forestry	Dave Atkins, et al	Report- PDF	Smallwood Utilization Network; the Montana Community Development Corporation	2007	(USA) This study focused on different approaches and advantages of using different types of roll on/off containers such as Hooklift-enabled truck, Hooklift-enabled forwarder and harvester, Roll on/off container for slash and Roll on/off bunk for logs and biomass transportation; because these trucks can reach slash piles that are too remote for large chip vans.

No.	Name	By	Type	Publisher	Year	Reference Summary
13	The Economics of Biomass Collection, Transportation, and Supply to Indiana Cellulosic and Electricity Facilities	Sarah C. Brechbill and Wallace E. Tyner	Report- PDF	Purdue University-USA	2008	(USA) A complete research about corn stover and switchgrass biomass products through IN, including transportation analysis and rates based on varied acres and distances. Study doesn't have any specific data on woody biomass.
14	Wood to Energy	Martha C. Monroe, et al	Report- PDF	Interface South Program (BY University of Florida) USA	2007	(USA) A Complete research of wood biomass program in Florida including a list of bibliography and some limited description of transportation and logistics requisites, such as assessing transportation cost based on haul time rather than distance. Accounts for road infrastructure in a woodshed by using GIS to account for speed limits assigned to U.S. TIGER roads layers.
15	GIS for Sustainable Development	GIS Best Practices	Report- PDF	ESRI (ArcGIS software producer)-USA	2007	(USA) It contains summary of 5 different case studies developed in ArcGIS software regarding sustainable development, including summary of a project on "Measuring the Economics of Biofuel Availability" with some guidance and information about using ArcGIS on Biomass transportation.
16	Information Needs for Increasing Log Transport Efficiency	T. McDonald, et al	Paper-PDF	Forest Products Journal 47(9)- USA	1997	(USA) Through this paper, production aspects of utilizing used pallets to produce wood pellets and current markets for wood pellets and wood pellet stoves has been discussed and analyzed. It reviews three methods of dispatching trucks to loggers were tested using a log transport simulation model: random allocation, fixed assignment of trucks to loggers, and dispatch based on knowledge of the current status of trucks and loggers within the system.
17	Harvesting and Transportation of Forest Biomass	Bob Rummer	Paper-PDF	US Forest Service, Auburn-AL	2008	(USA) This paper addresses the usual methods of woody biomass harvesting applications as well as transportation models from harvesting site to the roadside. Also it has pointed out that primary transportation of small woody biomass can be performed by manual skidding or forwarding methods. A generic biomass removal model based on defining common parameters for the basic functions has been explained through this paper to compare alternative harvesting and removal approaches of woody biomass productions.
18	Economics of Harvesting Woody Biomass in North Carolina	James Jeuck	Report- PDF	NC Woody Biomass, NC State University	2009	(USA) In this research the basics of cost factors on biomass harvesting, processing and transportation process in North Carolina have been reviewed, since the cost of biomass harvesting and transportation reduces its value for market. Economical aspects of harvesting and transportation issues, such as average harvesting and transportation costs, cost analysis between biomass, pulpwood and saw-timber and review of biomass trucking methods are explained.
19	Woody Biomass Feedstock Yard Business Development Guide	The Federal Woody Biomass Utilization Working Group	Report- PDF	Biomass Research and Development Board, Forests and Rangelands.gov- USA	2010	(USA) This Guide provides an overview of the challenges and opportunities to establish a woody biomass feedstock yard in the United States. It includes information on biomass sourcing; facility site selection and equipment; biomass sort yards; biomass collection, concentration, and distribution; biomass handling, sorting, and economic considerations; etc. Information about transportation interaction with feedstock yard allocation has also been reviewed briefly.

No.	Name	By	Type	Publisher	Year	Reference Summary
20	Wood Fuel Production Chains in Europe	Matti Parikka	Paper-PDF	Swedish University of Agricultural Sciences, Department of Bioenergy	2006	(EU) The aim of this work is to assess sustainable production chains of wood fuel. Technical systems for the production of wood fuel are analyzed and the most suitable technologies are identified. Studying and comparing the most promising ECHAINEs in European countries has indicated two factors: a) Different methodologies prevail to characterize the chains; no common terminology exists, b) There are large differences in geographical regions and accessibility (including seasonal accessibility).
21	Energy Wood Production Chains in Europe	Matti Parikka	Paper-PDF	Bio-Energy Enlarged Perspectives Conference; Budapest	2003	(EU) The idea of this paper is explaining the supply chains of wood productions in Europe as ECHAIN program which consists of several EU countries. Through this paper the framework and expectations of this program have been discussed and reviewed.
22	Woody Biomass Utilization Desk Guide	Barry Wynsma, et al	Report- PDF	Forest Management, Department of Agriculture; Washington D.C.	2007	(USA) This guide addresses definitions and the process of all woody biomass application stages in US. Information about woody biomass transportation technologies is discussed based on whole-tree and log-length transport, chip and loose material transport, and finally bundle transport. The harvesting and yarding tools and technologies are addressed including whole-tree and log-length, chipping and bundling and loose material handling equipments. Also some information about different types of wood harvesting and utilization contracts in the US are described through this guide.
23	Conventional Wisdoms of Woody Biomass Utilization	Dennis R. Becker et al	Report- PDF	USDA Forest Service Northern Research Station, University of Oregon, Michigan Tech, University of Minnesota	2009	(USA) Several subjects on technical and operational issues of woody biomass utilizations have been discussed and surveyed through ten different case studies and numerous interviews with biomass contractors in US territory. Also transportation cost concerns are emphasized and criteria that influences transportation price have been reviewed, such as distance, accessibility to the harvesting site, fuel cost, infrastructure conditions, legislation and policy, and appropriate scale of processing.
24	Evaluation of Roll-Off Trailers in Small-Diameter Applications	Bob Rummer, John Klepac	Paper-PDF	USDA Forest Service	2004	(USA) In this paper, using roll-off trailers through woody material transportation and collection has been evaluated based on time assessment of loading and un-loading actions, in addition to the cycle time evaluation of wood removal by roll-off trailers along different types of roads and highways.
25	Analyzing and Estimating Delays in Wood Chipping Operations	Raffaele Spinellia, Rien J.M. Visserb	Paper-PDF	Elsevier, Biomass and Bioenergy 33, pp 429–433	2009	(USA) This paper analyzes the delay component of sixty-three chipper time-study data sets from thirty-six different chipping machines. Regardless of operation type, two thirds of the total delay time is caused by organizational delays and remainder by either mechanical or operator delays.
26	Biomass Transportation and Delivery, Fact Sheets 4.5; Sustainable Forestry for Bioenergy and Bio-based Products	Schroeder, R; et al	Paper-PDF	Southern Forest Research Partnership, Inc., GA-USA	2007	(USA) In this Fact Sheet, two major delivery and transport systems for woody biomass material (trucks and trailers) were reviewed. It pointed that 90 percent of the pulpwood delivered to U.S. mills in 2005 arrived by trucks. It concluded that tractor-trailer/bulk van combination is the most economical mode of woody biomass transportation in the South region.

No.	Name	By	Type	Publisher	Year	Reference Summary
27	The harvest of forest residues in Europe	Leen Kuiper en Jan Oldenburger	Report- PDF	Report on bus ticket no. D15a, Netherlands	2006	(EU) This research has been performed to investigate whether Dutch forest owners would be willing to harvest forest residues (tops and branches) from their forests. It concluded that in Netherlands, the removal of forest residues after regular thinning is too expensive.
28	Increasing Security and Reducing Carbon Emissions of the U.S. Transportation Sector: A Transformational Role for Coal with Biomass	David Gray, et al	Report- PDF	National Energy Technology Laboratory- USA	2007	(USA) Good reference on Emission impacts of transportation when comparing with Biomass productions. Includes some information on biomass transportation topics.
29	Roadmap for Agricultural Biomass Feedstock Supply in the United States	Office of Energy Efficiency and Renewable Energy, Biomass Program	Report- PDF	U.S. Department of Energy	2003	(USA) A research on agricultural biomass in US includes varied subjects, such as Production, Harvesting and Collection, Storage, Preprocessing, System Integration and their corresponding technical barriers. The transportation section is the smallest section and without specific data.
30	Michigan's Wood Biomass Inventory	Anthony Weatherspoon	Presentation- PDF	Michigan Department of Natural Resources-USA	2007	(USA) This presentation file discusses briefly woody biomass definitions and sources, current uses and markets for woody biomass in Michigan. It does not include any specific information about biomass transportation in MI.
31	Wood Staging Area Concept Design Project for Biofuel Production Facility at Michigan State University	Michael Sonko, et al	Report- PDF	School of Planning, Design and Construction, Michigan State University	2009	(USA) This preliminary report is prepared to size a staging area for urban wood waste processing, used as a bio-fuel at the T. B Simon Power Plant at Michigan State University (MSU). Includes different activities such as receiving, sorting, grinding, chipping, loading, and transportation operations.
32	Woody Biomass for Energy in Michigan	Bill Cook	Abstract-PDF	Michigan State University Extension Forester	2010	(USA) In this short paper, a summary of movement and supply chains of woody biomass productions from the forest to the mills and plants have been depicted based on a research done at Technical Research Center of Finland (VTT).
33	The Biomass Assessment Handbook	Rossilo-Calle, et al	Book	Earthscan -UK	2007	Good reference for Biomass definitions and technical subjects but irrelevant to Transportation issues
34	Liquid Transportation Fuels from Coal and Biomass	National Academy of Sciences	Book	The National Academies Press- USA	2009	Technical issues about Biomass but irrelevant to Transportation problems

B- Meetings, Interviews and Discussions

B.1. Meetings and Discussions in Scandinavia

Since Finland is one of the leading countries in the use and transportation of biomass, the team looked at getting more familiar with the operational and technical research and activities of transportation and supply chain issues. Several meetings, site visits and discussions were arranged between Dr. Pasi Lautala and representatives of companies and academic institutions in October, 2010. The main discussions are summarized in following sections.

B.1.1 Meetings with Proxion Train Corporation

First meeting was conducted on October 12, 2010, with Kimmo Rahkamo from Proxion Train Corporation which is a new freight rail service provider established in April 2009, planning to start operations in 2012. The establishment of private rail services in Finland is interesting, as it shifts the freight rail system a step closer to the US system. Proxion sees energy biomass transportation to be significant area of business in future, but it's only getting started. Potential large volumes and their regularity are interesting for Proxion, but biomass industry hasn't really developed its strategy yet. Key points of other discussions include:

- Freight rail opened to competition in Finland in 2007, but so far no new operators have emerged, as the initial step and investments are high.
- The lack of alternative providers for rail traffic is considered a big problem in Finland by major customers. It's difficult to evaluate cost / benefits without competition.
 - o The new company thrives to have a high usage capacity of equipment (a typical freight car of the current national operator (VR) only makes 50 trips per year, with average distance of 270 km).
- Proxion's main customers are expected to be heavy industries (high and regular need for heavy transportation).
 - o Trains would be mainly shuttle trains and intermodal trains and would mainly use containers.
 - o Necessary volumes and consistency of demand are main challenges.
 - o Some of the transportation volume expected to come from trucks, some from VR.
 - o Two tentative customers would transport goods for approximately 300 km.

B.1.2 Meetings with VTT (National Research Center of Finland)

The second meeting was arranged with Arto Nokelainen from VTT (National Research Center of Finland) on October 12, 2010, about transportation and woody biomass researches conducted by VTT. The discussions evolved mainly around development of biomass industry, water transportation and transportation related emissions. Key points are highlighted below:

- Forest products industry is shifting toward biomass energy applications. A new power plant is being planned either to Porvoo or Imatra by StoraEnso and Fortum.
- VTT has done a lot of research on water transportation potential
 - o Floating of logs has been started again in Lake Saimaa and with some import of wood from Russia
 - o A new ship concept "barge-mother-ship" has been researched to transport paper directly from mills to the Central European customers. Four barges can be floated to the mother ship and then transported as one ship the rest of the way. Paper rolls would be in containers, containers in the barges. VTT is investigating, if this

approach could be used for biomass and planning to simulate the “barge-mother-ship” concept with Aker Arctic Technology.

- VTT has developed an open-access database for emission data of all transportation modes, called www.Lipasto.vtt.fi. They also use a life cycle model that uses the formulas and values from Lipasto (KCL-Eco). VTT is currently working on a proposal to EU to establish “the Transport Chain Carbon Footprint” calculation model for the whole Europe which 14 institutions involved in the proposal.
- VTT is also working on a project to investigate the service level of ice-breakers.
 - o Current capacity is not enough even during regular winters.
 - o In winter 2010, some commercial ships waited 12 days in the ice (recommendation is 4 hours)
 - o Simulation model used one year production of Stora Enso as a starting point to define how many barges and tugboats would be needed.

B.1.3 Meetings with Jyväskylä University Researchers

On October 18, 2010, representatives from Jyväskylä University and Technical College were met for biomass discussion. Central Finland has been one of the most active clusters of biomass development in Finland. Discussion topics varied from general biomass discussions to transportation optimization and intermodal transportation. A newly developed system to ship biomass in bundles was also introduced.

B.1.3.1 General biomass discussions, Markku Paananen:

The forest resources in Finland have been increased for long time and about 70% of annual wood growth is currently used for production. By the end of 2010, there will be nine combined heat and power production facilities (10-500 MWh) using forest biomass and Finland is starting to see market forces to shape the business.

- Most counties in central Finland obtain their heating from district heating facilities that use biomass. In 2006, 50% of all energy in Jyväskylä area was produced locally with biomass. The participants of the cluster have developed vision together for future objectives and are investing together to move toward common goal (and common projects and clients).
- 800 000 m³ of chips are used annually (close to 1 million)
- Finland is one of the leaders in bio-energy use and research, but profitability of supply chains is not very good at the moment. Transportation and harvesting tasks are the least profitable segments of supply chain.

B.1.3.2 Intermodal transportation opportunities, Antti Laakso, JYKES (Jyväskylä Development Agency)

Latest priority of transportation planning is harmonization of bioenergy transportation within Scandinavia (through intermodal transportation). For rail transportation, the min. distance is 120-150 km, or in some cases closer to 180-200 km.

- Scandria is a project to establish “green corridor” through Europe. Sweden is way ahead of Finland in green transportation and some green corridors already exist in Sweden.
- Majority of biomass will move directly from forest to plants. Yards will be only for spring breakups. There is some interest to develop terminals into commodity marketplaces. It has been estimated that 8,000 containers are required to have competitive intermodal terminal in Jyväskylä.

B.1.3.3 Biomass transportation optimization, Hannu Lahdevaara, JAMK

There is an optimization model used for biomass transportation in the whole country.

Optimization model revealed that biomass could be transported from 150-180 km distance to Keljonlahti plant in the Jyväskylä area (from North). Model used VR log transportation rail rates which are expected to be slightly too low, as biomass transportation can't take advantage of whole capacity of the car.

- Current transportation distance of biomass to Keljonlahti plant is 100 km on average, for railway the distance is about 200-250 km.
- Producers purchase biomass to their terminals, sell it and handle logistics. Sometimes subcontractor handles chipping and transportation (producer only purchases the right to harvesting from the owners.)
- Only 3 percent of biomass transportation moves by rail. In log transportation, percentage is closer to 30.
- Water transportation is not used much in Finland for biomass. New ship was developed (so-called "bioship"), but it was too expensive, so unit cost was too high. Objective was to fit approximately 5,000 m³ of loose chips to the ship. Ship was developed by Lafkomp and its price was about 2 million Euros, but distances are not long enough for economic water transportation, unless a lake needs to be crossed.
- Speeds of rail transportation are being increased, so transportation effectiveness could be improved.
 - o Rauhalahti power plant in Jyväskylä gets a weekend train that keeps the crusher busy (truckers don't want to drive on weekends)
 - o Train size defined based on the facility.
 - o Moss and other types of biomass transportation have also been tested. Old chip cars are used for moss (old-fashioned unloading).
- Storage costs haven't been investigated yet. The rule of thumb for energy plant is to have 1.5 years' worth of wood in storage.
- The optimal location for chipping activities is still under debate. Chipping at mill could improve the quality and expedite the supply chain.

B.1.3.4 Bundling harvesting system (Fixteri), Markku Hakkinen, Fixteri

Fixteri is a new bundling system for energy wood harvesting. It is used mainly for smaller trees with 4-15 cm diameter, but it can be also used for biomass, or for paper mill feedstock. Current technology can also separate cellulosic fibers from needles and leaves, etc. Fixteri has currently two machines in-use by clients and two own prototypes have been used for over 10,000 hours, since 2003. The company is currently concentrating in Finland, but they are interested in trying the machine abroad through research collaboration.

- Bundler by John Deere uses only residues, so it doesn't work for same purpose as Fixteri.
- Logman provides currently the base for the machine (Ponsse won't fit, as its cabin doesn't spin). Some John Deere machines would already work.
- Each bundle weighs about 500-600 kg.
- Bundles are clean, as trees are cut while standing and inserted directly to bundling machine, so they won't touch the ground, except during storage. This saves in equipment maintenance frequency and costs. In Finland the bundle length is 2.6 m, based on the size of trucks and rail cars.

- Wood dries faster, as the bundler breaks the surface fiber. The second advantage is the dryness and cleanness of the trees, which are both better in bundling method.
- Greatest challenge is currently the cost of bundling. The longer the distance, the more competitive the system is, as the unit cost for log truck transportation is much lower than for chip transportation.
- Finland and UPM want to double or triple forest energy usage by 2030. Distances will get longer and especially with train transportation, bundling may become the only sensible alternative.
- The volume and speed of transportation in the forest is several times faster than with typical harvesting and chipping methods and the bundling method removes the need for chipping at roadside. Bundles should never be chipped at roadside.
- When bundling is not used, roadside chipping is the only way to get enough weight to trucks. Currently over 60% of chips are done at roadside. However, chip transportation is complicated, as in winter, they freeze and in summer they start “rottening”. Stumps are always crushed at final destination.
- Saimatec is developing chip-dryer, but the energy source for using the dryer hasn’t been determined.

B.1.3.5 Meetings with Tamminen Co.

On October 11, 2010, Dr. Lautala met with representatives from a Finnish log and biomass transportation company to learn about various aspects of movements of woody biomass by truck or multi-modal transport. Main points of interest are summarized below.

- A typical Finnish rail log truck is equipped with a self-loader. Chip cars are also available for biomass residues. Typical fuel consumption for Finnish log trucks are 4.0 – 4.4 miles/gallon and loading times for a log truck vary from 30-45 min (logs, including securement) to 1 hour (biomass residues). Unloading typically takes 1 hr, including cleanup. Factory unloading machines can do it much more quickly (10 min), but longer wait times (up to an hour) are common.
- On-site chipping has been preferred for residues because it is inefficient to transport intact branches, tree tops, etc.
- Average truck transport distance from harvest landing to an intermediate storage yard is 80 km, but it is growing as rail costs increase.
- Contracts between loggers and forest products companies are normally 3-5 years, but the durations or procurement levels are not always honored by forest products companies.
- Log transportation information systems – vary for each major company, typically run through laptop or notebook over mobile phone network. Storage locations, mill orders all displayed in real-time. Drivers can make independent decisions or can be directed where to move (central dispatching)
- www.EHM.fi has more technical information on the trucks used in Finland.
- Some information about log/biomass transportation capacity in Finland:
- Branches and stumps:
 - o Volume about 130-150 m3 (restrictive dimension for branches and stumps)
 - o Weight about 20-25 tons (metric) for stumps and branches
 - o Truck weight about 27-32 tons (leaves 10 tons extra)
- Logs:
 - o Trucks about 18-19 tons, self-loader about 3 tons

- 60 tons total max.

B.2 Discussion with Log and Wood Biomass Companies

On August 1-3, the MTU transportation team visited with several individuals involved in log and wood biomass business in Michigan to gain industry input on the topic (Table B-1. Some of the topics discussed were issues and opportunities for wood biomass and biofuel transportation in Michigan as well as challenges. The discussions revealed that both Northern Lower Peninsula and Upper Peninsula have potential to increase the volume of woody biomass use and transportation although there are some operational and technical requirements that should be considered through development and planning.

Table B-1- Companies/individuals visited in UP and Lower Peninsula in August 2010

Date	Company name	Representative	Title
8/1	Carey Logging and Excavating	Jim Carey	CEO and Owner of Company
8/1	Verso Paper, Quinnesec Mill	Sid Dye	Procurement Coordinator
8/3	Northern Timberlands	Dan Glawe	NA

B.2.1 Discussions with Representative of Carey Logging and Excavating

On August 1st, the research team met with Jim Carey (owner of Carey Logging and Excavating). Jim was able to give insight into the shipping and chipping of biomass material. One of the topics was the factor that all log trucks have a log truck plate which restricts their use to hauling raw logs or chips. Hauling processed material (like processed lumber or other processed materials) is not allowed.

Jim runs a fleet of 1 log truck and 6 chip vans. He also has several independent contractors that haul for him (both logs and chips). Most of the equipment is 2002 and newer. His Forestry crews are made up of a harvester and forwarder for one crew and a feller buncher, skidder and delimber for the second. His chipping crew consists of a whole tree chipper, two forwarders, horizontal grinder and chip van fleet.

Jims tries to work within about a 100 mile radius from the delivery point for his chipping operation. He supplies chips to a new plant at Gwinn that makes wood briquettes to power plants from chips. A different truck has to be used to ship the briquettes. Since the briquettes are a final product, a truck with commercial plates would have to be used. With current equipment, he has the capacity to produce 2,200 tons of chips per week.

B.2.2 Discussions with Representative of Verso Paper

The team met with Sid Dye (Quinnesec Procurement Coordinator) of Verso Paper at Quinnesec Mill to discuss how an industrial size mill operates and handles several different types of modal transportation shipments.

Verso paper is one of the main paper mills within the Upper Peninsula. Verso consumes about 1.65 million tons of hardwood per year. From the pulp that is made, 60% is sold to open markets with the other 40% being used for their own paper production. In November 2011, their

new steam turbine generator will go online. It will use about an additional 250,000 tons of biomass a year. Electricity generated will be sent to the grid and a portion will be bought back (only way to get green credits) to power the plant. All deliveries of chips/biomass material will remain by trucks, no rail equipment or unloading facility will be needed. The steam turbine will also generate steam for paper production, making the plant over 30% self-sufficient.

Verso receives approximately 17% of their raw forestry material by rail (25% in 2008). Currently, Verso is receiving between 350 and 400 cars of logs a month (between 12,000 to 14,000 cords a month). Sid stated that for rail to be profitable, the wood would have to come from sources outside of 120 miles radius from the mill. Sid also mentioned that if logs have to be trucked over 30 miles to a siding site, that it is more economical for them to be trucked the rest of the way to the mill. Verso is currently leasing 40 to 44 log cars, but the \$2 dollar per cord reduction in cost does not cover the lease and maintenance fees.

Verso owns/leases several rail yards around the Upper Peninsula. Each of these yards is operated by an independent contractor that has the equipment necessary to load the cars. These yards allow a structured flow of wood into the mill, but it costs \$3 per cord extra to cover contractor expenses.

Verso contracts out all trucking with owner-operators which is recognized as the only economical way to do it. Verso pays these loggers by a shipping zone rate structure. There are 4 zones that are 50 miles apart, up to 200 miles. Anything over 200 miles out from the mill has a general rate assigned. Truck drivers that haul into the mill, need an authorization card to be able to enter the facility (Authorization cards also identifies truck and person/company to receive payment). The truck enters on a scale where he or she weighs their load and opens a transaction. After weighing, the truck proceeds to the unloading platform. Once unloaded, the trucker then proceeds to a different scale where they weigh up empty. This is where the trucker also closes out the transaction before he leaves.

B.2.3 Discussions with Representative of Northern Timberlands

On Wednesday (August 3rd) research team met with Dan Glawe from Northern Timberlands. Northern Timberlands opened the Caffey log yard about 30 years ago, which is currently being ran by them for Verso Paper. The Caffey yard has considerable amount of wood flow from the east end of the Lower Peninsula, but such movements are very difficult to justify without a back haul. Timberland sends logs to Pot Latch and bring back lumber to the Lower Peninsula (from LP plant at Sagola). They do this with b-train trailers to maximize payload for both directions. On rail side, Dan Said, "For their yards, the time to load a rail car if the pile is next to the car, takes about 35 to 45 minutes to load 35 cords of wood. If it has to be loaded to a trailer and hauled to the car, the time is about double".

The bridge is a major obstacle for hauling wood in any direction, at the moment trucks have to pay \$4.50 per axle to cross the bridge. Loggers need to increase the number of axles on their trucks to maximize payload potential. By doing this, they are also increasing the cost to cross the bridge. There is talk at the Bridge Authority about raising toll cost for commercial trucks and there are no discount rates for trucks that frequently cross the bridge. Most of the companies that have to cross the bridge regularly are trying to get the Bridge Authority to set up a sliding price scale for frequent users, but the Bridge Authority stated that it does not want to do this because most of the damage/wear and tear on the bridge are from commercial trucks. The Bridge Authority also mentioned about bringing the bridge weight from 144,000 lbs to 100,000 lbs. For Dan, this means that the B-train trailers that are getting shipped to the Upper Peninsula would have to be split into two single trailers and ran across the bridge, raising the cost in which it

would take to get across. Dan also mentioned that with the current rate structure, it costs about \$2 -2.25 a cord to ship over the bridge.

During the visit, research team had to cross the bridge several times, at each crossing, we saw several chip trucks either entering or exiting the Upper Peninsula. Dan mentioned most of the chip vans coming over the bridge that we have been seeing are coming from Beaver and Pine Tech (mills in the Cadillac area) and are hauling clean chips. Most of these trucks are going to New Page in Escanaba, but some go to a particle board plant in Sue St. Marie.

The logging infrastructure in Northern Lower Peninsula is almost absent, due to three major mills closing within the last six years. The industry lost a demand for 1.2 million tons of wood due to the closures. In the Lower Peninsula, there is hardly any pulp wood market which makes it hard to even get high value saw timber (as both are logged simultaneously). Northern Timberlands has a mechanical sorter in Vanderbilt that sorts between pulp and saw logs (learned from Finland) but it is sitting most of the time because there is no market for the pulp logs that come out of it.

Northern Timberlands has 14-15 wood product trucks, out of which 7-8 trucks run 24 hours a day. They only have two self loaders, and they own 36 b-train trailers. B-train trailers allow them to maximize the weight going over the bridge and allow them to bring lumber back down to the Lower Peninsula. The use of the trailers allows for back haul potential. All trucking operations for Northern Timberlands are controlled by one central dispatch in Vanderbilt.

Dan said, “Any trucks that strictly carry logs or chips are registered under a Log license plate”. These plates are a lot cheaper than commercial plates. Any vehicle that would carry processed material, like pellets or lumber needs to have a commercial license plate. The team didn’t receive actual rates, but Dan said the cost comparison between plates would be like paying \$200 for a log plate a year compared to \$2,000-3,000 thousand for a commercial plate. Trailers have a onetime registration fee.

Northern Timber used to ship logs by rail from the Lower Peninsula through Chicago and to a mill in Pennsylvania, but had some problems with shipments. They also barged wood from the Lower Peninsula across Lake Michigan for three years in the mid 90’s. They shipped from Frankfort, MI to Manitowoc, WI for Thilmany Paper. The mill had a need for pulp wood and the Lower Peninsula had the quantities needed to fulfill it. Northern Timberlands had a three stage barge system going. One barge would be loading while one was being hauled across the lake and the final one would be unloading (each barge could carry about 1,200 tons of wood per load). All three duties would be going on simultaneously to minimize down time between zones. They had a deal with a towing company out of WI to tow the barges across the Lake Michigan.

Some wood was stock piled at the dock site to make sure there was enough wood to fill the barge when the time came to load it. Dan said that they used a log loader with a 50 ft reach to load the barges. Sometimes, they would bring rocks back to MI as backhaul. When this was done, they would have to clean the barge to prevent contamination which would take about 8 hrs. What killed the whole operation was there were no long term contracts to justify in investing in the equipment needed. Northern Timberlands did find a tug and barges that they would have purchased if operations had continued. Also, economy and paper completion brought down the need for pulp and helped contribute to its loss.

At the end of our discussion, Dan mentioned that there several of the capable harbors (Table B-2) for this type of activities in the LP, but many have been lost due to development and lack of maintenance of shipping channels. Ports with potential to be used as a port or harbor for loading logs would need 20 ft of draft.

Table B-2 Review of Port and maritime facilities in MI

Port Location	Notes From Dan
Detour	Good deep water port near Kinross (located in Upper Peninsula)
Cedarville	Good deep water port near Kinross (located in Upper Peninsula)
Frankfort	Shut down
Ludington	Only Deep water port on West side of Lower Peninsula
Manistique	Tough to get into due to having to go up river
Rogersville	Would have potential for deep water port
Bay City	Is ok,
Alpena	Not to good, The bay has a lime stone bottom

The meeting with Mr. Glawe was very insightful and allowed us to see several shipping aspects that were tried within one company.

B.3 L'Anse Powerplant Site Visit

In August 5th, 2011 research team visited L'Anse Warden powerplant located in L'Anse-MI to obtain more practical information on biomass transportation and its processing issues within an existing powerplant. The L'Anse powerplant receives different types of fuel including Tire-derived Fuel, woody biomass and disposal wood ties of railroads. The key operational notes of biomass multimodal transportation of this site are summarized below.

Tire-derived Fuel (TDF):

- The consumption of TDF is about 40 tons / day, which is about 8% of daily fuel input (500 ton/s day total)
- TDF comes from a large tire shredding operation in Savage, MN (southern suburb of Twin Cities, 350 miles away). Trucks haul about 25 tons on average; need 11-12 trucks per week of TDF. Usually about 2 trucks / day arrive.

Railroad Ties:

- MA Energy Resources (a 3rd party) is responsible for aggregating and delivering railroad ties to the site, so MA Energy is the main point of contact with CN Railroad.
- Shipments are highly variable, but the powerplant get deliveries usually 3-4 times per week.
- Rail cars are unloaded at the fuel aggregation facility (FAF) within 24hrs and are often picked up by CN after just one day.
- After chipping railroad ties by grinder, they are hauled from FAF to main plant via an access road.
- The procedure and different steps of RR tie shipment includes ordering empty railcar(s), securing track space/siding for car placement, moving loading equipment, loading cars, creating a waybill/release form
- M.A. supply zone for L'Anse Powerplant crossties is appx 600 miles to the West, appx 400 miles to the East, and appx 1,100 miles to the south

Woody Biomass:

- Another 3rd party (Norman Pestka-Ontonagon) is responsible for aggregating and delivering wood chips for the L'Anse Warden plant.
- Wood chip trucks typically haul between 35 and 38 tons of wood chips.
- The FAF is equipped with tippers for fast unloading of chip trucks. (Figure B-1)

- The chipped woody biomass is stored at the FAF along with the RR Ties, but they are kept separate throughout the handling and processing steps in the facility.
- When chipped biomass is delivered to the main facility, either from the FAF or from elsewhere, the total process of weighing in, filling out paperwork, backing up and unloading the fuel into a hopper, weighing out and filling out paperwork takes about 25-30 minutes. Actually unloading the fuel into the main facility hopper takes about half of this required time, which is restricted by the ability of the conveyor belts to move fuel into the main facility.
- Chip trailers unloading at the main facility must be equipped with a walking floor or a revolving belt to unload chips.

Figure B-1- Chip truck is tipped and unloaded at the facility close to the rail spur and piles of disposal ties-about half mile far from power plant (Photo by H. Pouryousef, Aug. 2011)

In addition to the site visit of L'Anse powerplant, the research team interviewed with MA Energy Resource representative, Scott Waring, about biomass transportation requisites and key challenges for L'Anse powerplant and other biomass facilities served by MA Energy Resource company. The main discussions with Scott are summarized below:

Multimodal Transportation Operations:

- M.A. utilizes the Inland Waterway System, Great Lakes, Rail, and Truck transportation to move their fuel products.
- M.A. woody biomass programs are very specific and limited in scope - mainly focused on export for international customers.
- M.A. Energy Resources supplies over 30 facilities in the Eastern half of the US (Rocky Mountains East). Customers include pulp/paper mills, power and combined heat/power utilities, and cement kilns. Their fuel programs consist of TDF (tire derived fuel), CDF (crosstie derived fuel), and woody biomass.
- The biomass demand does not have any particular monthly or seasonal peak, although the demand for TDF sometimes goes up in colder months because it has a higher BTU value.

- The most common types of trucks are either walking, rolling, or moving floor trailer, or end dump capability for processed materials.
- The common vessel used by MA is open hopper barges with 11 – 14 foot high sidewalls.
- The barge size used for biomass transportation by MA is: Rake (1400 tons), Box (1600 tons), Lake box barge (2500 tons for their materials, normally 5000 tons), there are 6-32 barges at a time on inland river system.
- There are no marine/rail movements though, except for some large energy utilities.
- The choice of end user and their ability to receive different shipments is the most important criteria to select the transport mode (truck only vs. truck/rail, or truck/barge, etc.)
- In reliability, the order of transport modes is: 1st-Trucks, 2nd-barges, and 3rd-Railroad. Rail services are the least reliable mode, especially with 2+ companies involved.

Railroad Operations:

- Railroads usually dictate the route taken for a given O-D pair. Main RR can coordinate the interchange, but then they own the shipment (more control for them), or client can try to coordinate interchange points. M.A. tries to determine the rail routes together with railroad representative. If an interchange is required (to second railroad track ownership), routing and rates must be established prior to car order. Downside is increased cost and transit time.
- Car freight, demurrage at both origin and destination, switch/interchange fee (if applicable), and car damage are other additional fees related to rail transportation.
- Securing an empty rail car takes 5-8 days depending on time of year, demand, weather conditions, origin location. Car loading origin and final destination drives time line. Example of a Chicago to L'Anse rail move would have 2- 2.5 car turns per month. MA tracks all car moves and monitor car turns (car velocity). They do the same for all barge movements. (days on marine/transit time)
- The most common types of rail cars are Standard or Wood chip gondolas (12 ft sides vs. 4 ft regular).
- 1, 3, 5 year commitments are typical long term contracts with rail companies.
- The rail car availability can be classified as:
 - Pool cars: 3rd party or RR owned, but these cars travel a user-defined route over and over, consistency!
 - Leased: you can send them anywhere, but no control over route, etc.
 - Own: do whatever you want with them

Railroad Tie Transportation:

- The burning of crossties for energy is very common. The buyers for RR ties have long-term procurement contracts with MA Energy, to deliver a certain quantity of material consistently, although there are some cases with short-term contract.
- MA Energy is the agent for one of the Class I railroads and has both spot and multi-year contracts with others, including some short line railroads.
- MA Energy handles from “cradle to grave” deliveries in some cases (client may expect MA to provide equipment and operators in field) and in other situations they accept crossties on a delivered basis.

- MA has fairly consistent flow of ties moving by rail through spring to fall. Winter months slow up due to several factors, but car loadings/unloading occur every week of the year. Due to the possibility of unexpected delays, including Force Majeure, the best way to control fluctuation is by holding inventory at end users location.
- The majority of cost for using rail ties mostly comes from A. Operations, B. Transportation, and C. Purchase. (sometimes B and C are inverted)
- The minimum quantity of ties per shipment when rail is used is: 1-40 cars at a time.

C- Mackinac Bridge Questionnaire

Table C-1 Information from Kim Nowack, Chief Engineer, Mackinac bridge authority

Question	Answer
Do you keep track of traffic that crosses the bridge? If so, what sort of characteristics do you monitor and how do you monitor them?	We record how many axles each truck has when they cross. They are charged per axle. The axles are counted visually by the collector and mechanically as they cross the treadle in the pavement at the toll booths. We can only differentiate the trucks by axle counts. Most log/chip haulers are 11 axle vehicles, but not all 11 axle vehicles are log/chip haulers.
For traffic, about how much truck traffic goes into the UP? How much goes to the Lower Peninsula? What is the % into/out of the UP?	We have log trucks, bark/chip haulers etc. moving both northbound and southbound across the bridge at a regular frequency. It is about 50-50 % north vs south bound. See attached traffic counts.
How many Tractor trailer trucks pass over the bridge per day (roughly)?	See attached traffic counts. 11 axle trucks are class "21" vehicles. Trucks in general are class 5 through 21.
How many log trucks pass over the bridge per day (roughly)?	Undefined (see above)
How many chip trucks pass over the bridge per day (roughly)?	Undefined (see above)
What the general procedure is for a large truck to cross the bridge: Do any of these vehicles have to be escorted across the bridge?	They require an escort since they are so heavy. This doesn't cost anything and if they are frequent crossers they can sign up for our trucker permit program. This requires that they get training in our rules for crossing and then eventually they receive a permit card and can cross without an escort
Are there any other restrictions or requirements placed for trucks crossing the bridge?	Regulations for crossing the bridge found on bridge website.
What are the maximum weights for trucks crossing the bridge?	72 tons gross plus Michigan axle weight regulations apply.
What are fare rates for tractor trailer trucks (log trucks / chip trucks)?	They pay \$4.50 per axle. Frequent commercial users can also sign up for the MBA debit account program and then they don't have to pay with cash.
Are there discounts on fare rates for trucks that cross the bridge frequently?	We have had representatives from the forest products industry approach the Mackinac Bridge Authority board to ask for a reduced frequent user rate for these wood hauling trucks, but this will probably not happen due to the weights of the trucks in question and the fact that these vehicles cause the vast majority of wear and tear on the bridge and result in our need for maintenance.
What is "regular frequency" for crossing?	See attached traffic counts.
What are typical axle configurations seen for forestry product vehicles crossing the bridge?	Most log/chip haulers are 11 axle vehicles, but not all 11 axle vehicles are log/chip haulers.
Are there truck inspections before trucks pass over the bridge?	There are no routine inspections before crossing. The MSP has a presence at the bridge they will inspect vehicles at their discretion. The Dept of Agriculture has inspection check points for emerald ash borers in the welcome centers at Mackinaw City and St. Ignace. We believe that frequent wood haulers are allowed to declare ahead of time what they

	are hauling and bypass the check points.
Do you see a larger amount of forestry product trucks crossing the bridge during spring break up?	See attached traffic counts.
At what wind speeds in the straits do you shut down truck crossings? How often does this happen?	We begin escorting high profile vehicles at an average wind speed of 35 mph. We do not allow high profile vehicles at an average wind speed of 50 mph (called "partial closure") Loaded log trucks are considered high profile and would be escorted in winds between 35 and 50 mph. Unloaded log trucks would not be high profile and could cross without escort with winds between 35-50. No trucks of any kind can cross with winds above 50 mph. See attached summary of closures for more info. Most closures are short (1-3 hours), but closures over 10 hours have occurred 5 times in the last 15 years.
What is average wait time (for log trucks) to cross the bridge? And how long does it take to cross the full span of the bridge?	Trucks with a permit can cross immediately without waiting. Those requiring an escort may have to wait up to 20 minutes depending on what the MBA staff is working on at the time. Crossing takes about 15 minutes. Escort service is available 24-7.
How are truck weights monitored at the bridge?	MBA has weigh in motion (WIM) scales northbound and southbound. MBA also has a static scale for MSP motor carrier use. When an overweight truck alarms the WIM, a motor carrier is called to investigate and issue a ticket or impound the vehicle.

D- Shortline Railroad Questionnaire

Several shortline railroads from Lower Peninsula of Michigan were contacted to inquiry on rail transportation services. Outcomes, as received, are presented in Table D-1.

Table D-1- Railroad questionnaire data

Railroad	Infrastructure			Operation						
	Miles of Track	Public sidings capable for Biomass	Private Sidings capable for Biomass	Number of interchange points	Percent of moves interchanged	Average Delivery Time (In Days)	Average Haul Length (Miles)	Availability of Cars for Biomass	Main Commodities	Approx price (\$/ton mile)
1	123	40	40	4	99%	1	50	Can be Obtained, if necessary	Auto parts, plastics, metals, forest products, agricultural and aggregates	Depends on Quantity
2	400	Everything	N/A	4	98%	1	220	Can be Obtained, if necessary	Just about Everything	\$110-\$130 Mostly based on contract rates
3	300	24	A Lot	4	Majority	1	25-90	Can be Obtained, if necessary	Everything except Auto's	Depends on Length and number of cars
4	18	3	2	2	100%	1.5	14	Can be Obtained, if necessary	Pulp board, plastics, fertilizers, soybean oil	\$25
5	15	1	1	1	100%	1.5	2	None	Food Products	\$150
6	130	8-9	--	2	100%	1-2	50-118	None (owner lease cars)	Bulk board, chemicals, agricultural, lumber, boards, fertilizers	Tariff rate (discount on car loads over 25 per year)

E- Port Infrastructures, Origins and Destinations

E.1 Biomass Destination Ports and Docks

E.1.1 Charlevoix Harbor, MI

Located on the east shore of Lake Michigan, 276 miles northeast of Chicago, IL and 75 miles northeast of Frankfort, MI, Charlevoix is a commercial harbor with facilities in the town of Charlevoix and on Lake Charlevoix. (Figure E-1) The port was ranked 31st among the Great Lakes Harbors with 1.5M tons of commerce in 2007.

The U.S. Army Corps of Engineers has project depths of 18 feet in Lake Michigan and; 17 feet in inner channels to Lake Charlevoix. However, recent shoaling and a lack of maintenance dredging may have reduced the allowable draft in portions of the channel. Lake Charlevoix extends about 14 miles SE from the head of Pine River and is from 1 to 2 miles wide, with depths to over 100 feet and deep water generally close to shore. Boyne City, MI, is at the SE end of the lake.

Figure E-1- Charlevoix, MI Harbor, Google Earth

Potential Biomass Docks in Charlevoix Harbor:

All the docks in this harbor have highway connections. Depths alongside are reported depths and not verified. The availability of the docks for biomass use has not been confirmed. At Advance, MI, about 2.5 miles west of Boyne City on Lake Charlevoix the Wolverine Power Supply Cooperative has a coal dock providing 630 feet of berthing space with dolphins, a deck height of 11 feet, and a depth of 25 to 30 feet alongside. This site may provide an option for the unloading of biomass if there is sufficient space and the owners were interested.

Approximately 1.5 miles west of the port of Charlevoix along the Lake Michigan shoreline there is located a facility for shipping cement and receiving coal. This is a privately owned and maintained facility by Medusa Cement Company. According to the Coast Pilot the entrance channel and slip are reported to be dredged to 24 feet annually. The slip is about 100 feet wide. The N side, 645 feet long, is used to ship cement. The south side dock is 556 feet long and is used to receive coal for plant consumption. The docks have a deck height of 10 feet. This site may provide an option for the unloading of biomass if there is sufficient space and the owners were interested.

E.1.2 Frankfort

Frankfort is a commercial port located on the east shore of Lake Michigan, 204 miles northeast of Chicago, IL and 28 miles north of Manistee, MI. Frankfort Harbor, 4.3 miles south of Point Betsie, is in Betsie Lake, which is connected to Lake Michigan by an entrance channel. (Figure E-2) In October 2005, the controlling depth of the channel was 22 feet in the entrance, through the outer basin and between the piers to the inner basin.

Figure E-2- Frankfort Harbor, Google Earth

Potential Biomass Docks in Frankfort:

All the docks in this port have highway connections. Depths alongside are reported depths and not verified. The availability of the docks for biomass use has not been confirmed. Koch Fuels, Inc. receives petroleum products at a 425-foot wharf on the S side of the inner basin. The wharf has a deck height of 8 feet with reported depths of 18 to 20 feet alongside. There is tank storage for 310,000 barrels of petroleum.

Luedtke Engineering has a dock facility at the north end of the inner basin with (according to chart 14907) a depth of 7 feet. Of note is the fact that in the U.S. Army Corps of Engineers Port Series 48 published in 1995 the following dock in Frankfort is listed as shipping or receiving logs at that time. The dock at the time of the survey was owned by the state of Michigan and the facility operated by Woodland Harvesting Inc.

“Woodland Harvesting Dock. Elberta, south side, Lake Betsie, approximately 2,300 feet east of entrance from Lake Michigan. 1213 Furnace Avenue Elberta County: Benzie Purpose: Shipment of pulpwood. Owner: State of Michigan Operator: Woodland Harvesting Inc. Latitude N 44.628611 Longitude W 86.23889 Depth Alongside (feet): 30 Total Berthing Space (feet): 400 Remarks: Open storage area at rear has capacity for approximately 30,000 cords (3,840,000 cubic feet) of pulpwood”. A Google earth image observed in 2011 indicated that this area may be undeveloped and have potential.

E.1.3 Traverse City, MI

Traverse City, MI, at the head of West Arm of Grand Traverse Bay, is the principal harbor on Grand Traverse Bay. (Figure E-3) The cargoes handled in the port are petroleum products and coal. The commercial docks are located north of the village of Greilickville and Traverse City.

Figure E-3- Coal Dock north of Traverse City, MI, Google Earth

Potential Biomass Docks in Traverse City:

Traverse City has three active deep-draft facilities. However two of them handle petroleum products and biomass operations may be difficult if not impossible at petroleum docks. All the docks described have highway connections. Depths alongside are reported depths and not verified. This is not listed as a federal dredging project. The availability of the docks for biomass use has not been confirmed.

One dock that may have potential is the Traverse City Coal Dock: (44°47'11"N., 85°38'08"W.); 210-foot face; 18 feet alongside the north end with a deck height of 6 feet; vessels dock port side to; open storage for 16,000 tons of coal; receipt of coal and slag. The facility is owned and operated by Traverse City.

E.1.4 Manistee Harbor, MI

The port of Manistee is located on the east shore of Lake Michigan, 179 miles northeast of Chicago, IL and 26 miles north of Ludington, MI. Manistee Harbor is on the Manistee River,

which flows from the N end of Manistee Lake for 1.5 miles to Lake Michigan. (Figure E-4) There are extensive facilities along both sides of the river and on the W side of Manistee Lake. The principal cargo handled in the port is coal, with occasional shipments of salt and machinery.

The entrance to Manistee River is protected on the SW by a breakwater. A dredged entrance channel leads from deep water in Lake Michigan through the north part of the outer harbor basin to the river entrance between two piers and through the river channel to Manistee Lake. In February 2011, the controlling depths were 25 feet in the entrance and 23 feet in the river channel to Manistee Lake.

Figure E-4- Manistee, MI, Google Earth

Potential Biomass Docks in Manistee Harbor:

Manistee has several deep-draft facilities that are all privately owned and maintained. All the docks have highway connections; some were reported to have rail connections but the condition of the rail service is unknown. Depths alongside are reported depths and not verified. The availability of the docks for biomass use has not been confirmed.

Seng Crane and Excavating Dock No. 1 on the south side of the head of Manistee River has a 900-foot face with 20 to 25 feet depth alongside. There is a deck height of 5 feet with open storage for 300,000 tons of material; receipt of sand, salt, and coal; owned and operated by Seng Crane and Excavating, Inc.

Morton Salt Co. Coal Dock: (44°14'36"N., 86°18'29"W.); 400-foot face; deck height, 4 feet; open storage for 45,000 tons of coal; receipt of coal; owned and operated by Morton Salt Division of Morton International, Inc.

The Packaging Corp. of America Dock is located on the south side of the head of the Manistee River (44°13'10"N., 86°17'22"W.). The dock has a 767-foot face with 24 feet alongside. Coal is the principal product received and it is reported to be owned by Packaging Corp. of America and operated by TES Filer City Station Ltd.

Morton Specialty Chemical Products, Manistee Stone Dock: across slip S of Coal Dock; 600-foot face; covered storage for 10,000 tons of limestone; receipt of limestone; owned and operated by Morton Specialty Chemical Products, Division Morton International Inc.

Akzo Nobel Salt, Manistee Plant Dock: (44°13'51"N., 86°18'06"W.); about 400 feet of berthing space; 19 to 21 feet alongside; deck height, 6 feet; open storage for 200,000 tons of coal; receipt of coal; owned and operated by Akzo Nobel Salt, Inc.

E.1.5 Cheboygan

Cheboygan harbor is located at the mouth of the Cheboygan River, emptying into western Lake Huron approximately 16 miles southeast of the Straits of Mackinac. (Figure E-5) According to the USACE the channel has a project depth of 21 feet to the turning basin and 18.5 feet above the basin. Durocher Marine, a tug barge operator, is located in Cheboygan. This is the home port of the U.S. Coast Guard's only U.S. heavy ice breaking resource, the cutter Mackinaw.

Potential Biomass Docks in Cheboygan:

There may be docking space and log storage space on the west side of the channel across from the turning basin. The US Coast Pilot lists three docks. One dock is a tanker berth and the other two may have the potential to handle biomass.

G.E.F.S. Marine Terminal: W side of the river immediately above Northwood Oil Co. Dock; two 300-foot sections; 21 feet alongside; deck height, 3 feet; open storage for 40,000 tons of coal; receipt of coal; owned and operated by G.E.F.S. Marine Terminal.

Aggregates Dock: E side of the river above Amoco Oil Co. Wharf; deep-draft vessels lay in dredged channel and discharge by boom; 160,000 square feet open storage; receipt of aggregates; operated by various concerns.

Figure E-5- Cheboygan, MI, Google Earth

E.2 Biomass Origin Ports

E.2.1 Menominee, MI

The twin ports of Marinette, WI, on the S side, and Menominee, MI, on the N side, form a deep-draft harbor at the mouth of Menominee River. The harbor is on the west side of Green Bay, about 33 miles SW of Porte des Morts Passage and 17 miles NW of the Sturgeon Bay Ship Canal. (Figure E-6) A dredged entrance channel leads SW from deep water in Green Bay between parallel piers at the mouth of Menominee River and thence upstream for about 1.7 miles to about 600 feet below the Dunlap Avenue Bridge. In July 2009, the controlling depths were 19 feet in the entrance, between the piers, and in the river channel to just above the turning basin. Shoaling has been reported upriver from the turning basin.

Figure E-6- Menominee, MI Google Earth

Potential Biomass Docks in Menominee:

There are three deep-draft facilities at Menominee and Marinette that are privately owned and maintained. All the docks described have highway connections and some have railway connections. Depths alongside are reported depths and not verified. The availability of the docks for biomass use has not been confirmed.

Menominee Paper Co. Dock is located on the north side of the river mouth. It has 550 feet of berthing space with a depth of 18 feet alongside. The dock has a deck height of 6 feet with open storage for 60,000 tons of coal; receipt of coal for plant consumption; owned and operated by Menominee Paper Co.

Marinette Fuel and Dock Co. Dock: (45°05'42"N., 87°35'42"W.), located on the south side of river mouth; 1,400-foot face, N side, and 700-foot face, S side; 22 feet and 16 feet depth alongside, respectively; deck height, 2 feet; two 50-ton crawler cranes; open storage for 150,000

tons of coal; receipt of dry bulkhead commodities, including coal, pig iron, salt, limestone and lime; owned and operated by Marinette Fuel & Dock Co. No rail connection

Ansul Fire Protection, Coal Dock: (45°05'42"N. 87°36'42"W.), S side of the river 1.5 miles above the pierheads; 600-foot face; 19 feet alongside; deck height, 8 feet; open storage for 8,000 tons of coal; receipt of coal by self unloading vessel; owned and operated by Ansul Fire Protection.

K&K Warehousing Menominee Wharf is located in Menominee on the left bank of the Menominee River approximately 0.5 mile above Ogden Street Bridge. Latitude (decimal): 45.096389 Longitude (decimal): -87.60917. The facility has a railway connection of one platform level track inside the warehouse. The depth alongside the 600 foot wharf was 25 feet. This facility has a steel frame metal-covered warehouse at rear with 300,000 square feet of storage area for wood pulp and other commodities.

Specification Stone Products, Inc., Manitowoc Dock Manitowoc, left bank, Manitowoc River, above 10th Street Bridge is used for the shipment of stone and rip rap, and logs. There is a railway connection where the tracks in the rear of the dock connect with CN railroad. The reported depth alongside is 20 feet with 300 feet of berthing space. Note: in the early 1990s logs were shipped from this dock which at the time had approximately 2 acres of open storage area is located at rear.

E.2.2 Escanaba, MI

Little Bay de Noc is the west arm of the north end of Green Bay and forms the entrance waters to the ports of Escanaba and Gladstone Michigan. Escanaba, MI, is on the West side of Little Bay de Noc, 6 miles NE of Ford River and 7 miles NW of Peninsula Point. (Figure E-7) The harbor has depths of 28 to 40 feet within 0.4 mile of shore. Escanaba has several deep-draft facilities on the W side of the harbor N of Sand Point.

Figure E-7- Escanaba, MI, Google Earth

Potential Biomass Docks in Escanaba:

All the docks described have highway connections and some have railway connections. Depths alongside are reported depths and not verified. The availability of the docks for biomass use has not been confirmed.

The C. Reiss Coal Co., Dock No. 2: 1 mile WNW of Escanaba Light; 1,900-foot face; 21 to 24 feet alongside; deck height, 7 feet; open storage for 120,000 tons of coal and 360,000 tons of limestone; receipt of coal and limestone; owned and operated by The C. Reiss Coal Co.

The C. Reiss Coal Co., Escanaba Dock No.1: 2.1 miles NW of Escanaba Light, 1,050-foot face; 21 to 27 feet alongside; deck height, 5 feet; open storage for 125,000 tons of coal; receipt of coal; owned by The C. Reiss Coal Co. and operated Upper Peninsula Power Co.

E.2.3 Gladstone, MI

The port of Gladstone is on the west side of Little Bay de Noc, 7 miles N of Escanaba. A dredged channel leads from the deep water in Little Bay de Noc to a basin off the waterfront at Kipling, 1.5 miles N of Saunders Point. (Figure E-8) In 1990, the controlling depth was 22 feet in the channel and basin except for 20 feet along the E edge of the basin.

Figure E-8- Gladstone MI, Google Earth March 2011

Potential Biomass Docks in Gladstone:

Gladstone has two deep-draft facilities on the N side of Saunders Point. All the docks described have highway connections. Depths alongside are reported depths and not verified. The availability of the docks for biomass use has not been confirmed.

Payne and Dolan, Inc., Escanaba Dock: 0.3 mile NW of Saunders Point Light; 250 feet of berthing space with dolphins; 23 feet alongside; deck height, 5 feet; tank storage for 161,000

barrels; receipt of asphalt; owned and operated by Payne and Dolan, Inc. This is tanker dock and unlikely to be available for biomass movement.

Upper Lakes Coal Co., Dock: immediately W of Payne and Dolan, Inc. Dock; 910-foot face; 21 feet alongside; deck height, 10 feet; open storage for 328,000 tons of bulk material; receipt of limestone, coal, salt, and miscellaneous bulk materials; owned and operated by Upper Lakes Coal Co., Inc. This facility has no rail connection.

E.3 Discussion with Mr. Dan Glawe:

Cedarville, MI, is on the Upper Peninsula of Michigan on the Lake Huron shoreline in the Les Cheneaux Islands Channels, MI. According to the US Coast Pilot the approach to the harbor is through shallow, privately maintained channels. The port of Cedarville has a marina with a 50-ton lift that can handle 60-foot boats for hull and engine repairs. There are no commercial docks listed in the Coast Pilot or in the USACE port listing. The USACE lists this port as a shallow draft recreational harbor with over 7.5 miles of maintained federal channel at project depth of 7 feet. With no commercial dock facilities and a shallow harbor Cedarville is unsuitable for an origin port.

Port Dolomite, MI, is on the Upper Peninsula of Michigan on the NE side of the entrance to McKay Bay about 4 miles E of Cedarville. This is a private dock owned by the Michigan Limestone Operation's Cedarville Plant. There is a privately dredged approach channel, marked by a private 309° lighted range, leading to the SW side of the dock where vessels berth. In July 2004, the controlling depth alongside the main dock was 23 feet. This dock has a loading system that moves up and down the dock and is connected to a conveyor system. This dock is unsuitable for the stowage of logs. Northwest of the main dock there is a smaller dock that has no facilities, but does have storage space and road access. This second dock may have potential to support the marine transportation of biomass if: there is sufficient draft alongside, the dock is in good repair, it is long enough for a barge to secure alongside and most important a business deal could be worked out with the owners. This dock area is too close to the destinations for the FBBSC study region to be cost effective even if it could be used. However if biomass were being shipped in from ports at the south end of the lower peninsula of Michigan it could have potential to feed Kinross.

Detour, MI is located on west side of the Upper Peninsula of Michigan in the approaches to St. Mary's River. The USACE lists it as a shallow draft recreational harbor with project depth ranges between 8 and 10 feet. With no commercial dock facilities and a shallow harbor Detour is unsuitable for an origin port.

Manistique Harbor, MI at the mouth of Manistique River is located on the north shore of Lake Michigan 73 miles west of the Straits of Mackinac. According to the USACE the harbor has a channel with a maintained depth of 12.5 feet. The harbor is used by a tug-barge operator serving Beaver Island. Based on examinations of satellite photos there appears to be no storage space at the dock used by the tug barge for Beaver Island.

Port Inland, MI is a private harbor of the Inland Lime & Stone Co., built on the lake in front of the company's plant about 10 miles NE of Manistique. According to the US Coast Pilot, the privately dredged entrance channel has a depth of 25 feet up to and alongside the 900 foot dock. On that dock a shiploader that moves up and down the dock would make the storage of logs difficult if not impossible. There is a smaller dock area at the north end of the harbor. This second dock on the north end may have potential to support the marine transportation of biomass if: there is sufficient draft alongside, the dock is in good repair, it is long enough for a barge to secure alongside and most important a business deal could be worked out with the owners.

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F- List of Truck Variations

Table F-1-Complete list of truck variations

Type of biomass	Transportation equipment type	Number of axle configuration (truck + trailer)	Weight (lbs)	Self loading	Self unloading	Notes
chips	Walking Floor Chip van	3+8	164,000	no	yes	example
chips	chip van	3+2	80,000	no	no	tandem axle grouping
chips	Walking Floor Chip van	3+2	80,000	no	yes	tandem axle grouping
chips	chip van	3+3	86,400	no	no	(3 axle grouping)
chips	Walking Floor Chip van	3+3	86,400	no	yes	(3 axle grouping)
chips	chip van	3+4	104,400	no	no	triaxle grouping with a 9ft spread axle set forward
chips	Walking Floor Chip van	3+4	104,400	no	yes	triaxle grouping with a 9ft spread axle set forward
chips	chip van	3+5	117,400	no	no	four axle grouping with 9ft spread set ahead
chips	Walking Floor Chip van	3+5	117,400	no	yes	four axle grouping with 9ft spread set ahead
chips	chip van	3+6	130,400	no	no	five axles grouping with a 9ft spread set ahead
chips	Walking Floor Chip van	3+6	130,400	no	yes	five axles grouping with a 9ft spread set ahead
chips	chip van	3+7	148,400	no	no	five axles grouping with two 9ft spread axles set ahead
chips	Walking Floor Chip van	3+7	148,400	no	yes	five axles grouping with two 9ft spread axles set ahead
chips	chip van	3+8	156,400	no	no	seven axle grouping with a 9ft spread axle set ahead
chips	Walking Floor Chip van	3+8	156,400	no	yes	seven axle grouping with a 9ft spread axle set ahead
chips	Chip Truck	2	42,000	no	yes	single rear axle
chips	Chip Truck	3	50,000	no	yes	tandem axle grouping
chips	Chip Truck	4	68,000	no	yes	three axle grouping
chips	Chip Truck	5	70,000	no	yes	four axle grouping
pulp/logs/biomass bundles	log truck	3+2	86,000	yes	yes	tandem axle
pulp/logs/biomass bundles	log truck	4+2	104,000	yes	yes	tandem axle with spread on truck
pulp/logs/biomass bundles	log truck	4+3	122,000	yes	yes	tandem with spread on truck, three spread axle on pup
pulp/logs/biomass bundles	log truck	5+3	106,000	yes	yes	four axle grouping
pulp/logs/biomass bundles	log truck	5+3	129,000	yes	yes	three axle grouping with spread axle on truck, three spread axle pup
pulp/logs/biomass bundles	log truck	5+4	143,000	yes	yes	three axle grouping with spread axle on truck, tandem dolly with two spread axle on pup
pulp/logs/biomass	log truck	5+5	146,000	yes	yes	three axle grouping with spread axle on truck, tandem dolly with

Type of biomass	Transportation equipment type	Number of axle configuration (truck + trailer)	Weight (lbs)	Self loading	Self unloading	Notes
bundles						two spread axles on pup
pulp/logs/biomass bundles	log truck	6+3	137,000	yes	yes	five axle grouping on truck and three spread axle on pup
pulp/logs/biomass bundles	log truck	6+4	151,000	yes	yes	five axle grouping on truck and tandem axle dolly with two spread axles
pulp/logs/biomass bundles	log truck	6+4	156,000	yes	yes	four axle grouping with spread axle on truck and tandem axle dolly with two spread axles
pulp/logs/biomass bundles	log truck	6+5	154,000	yes	yes	four axle grouping with spread axle on truck and tandem axle dolly with triaxle grouping on pup
pulp/logs/biomass bundles	log truck	6+5	159,000	yes	yes	four axle grouping with spread axle on truck and tandem axle dolly and triaxle grouping on pup
pulp/logs/biomass bundles	log truck	7+4	164,000	yes	yes	six axle grouping on truck with tandem axle dolly with two spread axles on pup
pulp/logs/biomass bundles	tractor trailer (log hauler)	3+2	80,000	All trailers can have the possibility of having a loader		tandem axle grouping
pulp/logs/biomass bundles	tractor trailer (log hauler)	3+2	83,400			9ft spread axle
pulp/logs/biomass bundles	tractor trailer (log hauler)	3+2	83,400			crib trailer, spread axle
pulp/logs/biomass bundles	tractor trailer (log hauler)	3+3	86,400			(3 axle grouping)
pulp/logs/biomass bundles	tractor trailer (log hauler)	3+3	91,400			tandem axle with 9ft spread axle
pulp/logs/biomass bundles	tractor trailer (log hauler)	3+3	101,400			three axles, 9ft spread between each
pulp/logs/biomass bundles	tractor trailer (log hauler)	3+4	104,400			triaxle grouping with a 9ft spread axle set forward
pulp/logs/biomass bundles	tractor trailer (log hauler)	3+4	119,400			four axles, 9ft spread between each
pulp/logs/biomass bundles	tractor trailer (log hauler)	3+5	117,400			four axle grouping with 9ft spread set ahead
pulp/logs/biomass bundles	tractor trailer (log hauler)	3+6	130,400			five axles grouping with a 9ft spread set ahead
pulp/logs/biomass bundles	tractor trailer (log hauler)	3+7	143,400			6 axle grouping with 9ft spread axle set ahead

Type of biomass	Transportation equipment type	Number of axle configuration (truck + trailer)	Weight (lbs)	Self loading	Self unloading	Notes
pulp/logs/biomass bundles	tractor trailer (log hauler)	3+7	148,400			five axles grouping with two 9ft spread axles set ahead
pulp/logs/biomass bundles	tractor trailer (log hauler)	3+8	151,400			eight axles grouping
pulp/logs/biomass bundles	tractor trailer (log hauler)	3+8	156,400			seven axle grouping with a 9ft spread axle set ahead
pulp/logs/biomass bundles	B-Train Log hauler	3+3+2		no	no	three axle grouping on first trailer and two axle grouping on second
pulp/logs/biomass bundles	B-Train Log hauler	3+3+3	145,400	no	no	four axle grouping with a 9ft spread axle on first trailer and two axle grouping on second trailer
pulp/logs/biomass bundles	B-Train Log hauler	3+5+2	143,400	no	no	four axle grouping with 9ft spread axle on first and two axle grouping with a 9ft spread axle
pulp/logs/biomass bundles	B-Train Log hauler	3+5+3	161,400	no	no	three 9ft spread axles on first trailer with a tandem axle grouping and 9ft spread axle on second

G- List of Truck Dealers

G.1. Truck Dealers Contact in Michigan and Northern Wisconsin

Table G-1- List of equipment dealers and manufacture to contact

Company	Interviewed
Central Wisconsin Body and Hoist Inc.	No
Great Lakes Trailers	Yes
Lakeshore Equipment Sales	No
Peterbilt Wisconsin	Yes
Prairie Trailer	No
Scaffidi Truck Center	No
Schultz Equipment and Parts Co	Yes
Three Lakes Truck and Equipment	Yes
U.P. Truck Center Inc.	No
V&H	No
Wisconsin Kenworth	Yes
Reefer Peterbilt	Yes
Brecheisen Diesel Service	Yes
Dearborn Kenworth	Yes
Grand Rapids Kenworth	Yes
Wolverine Freightliner	Yes
Great Lakes Western Star	Yes
JX Peterbilt	Yes

G.2- Interview with truck dealers and manufacturers:

G.2.1- Equipment Interview Summary

Through an analysis of the collected data, the team was able to determine equipment types, years and trends within the study area. It was determined that 75% of dealers deal in both new and used equipment sales. Most dealers tried to keep inventory stock of equipment from early 2000's to new. Older trucks that are traded in are either sold to smaller used equipment dealers (which commonly deal in older equipment) or parted out. Most dealers try to keep their stock within 10 years of age. Only about 25% of dealers within Michigan and Northern Wisconsin deal large 10 to 11 axle Michigan log trucks, but almost all dealers carried Michigan Special Tractors (tractors with high horsepower – 550 to 600 hp) with 18 speed transmissions, 20,000 lb front axles and either 46 to 52 thousand lb rear axles. These trucks are very versatile and are used mainly for the forestry and construction industries. Less than half of the dealers interviewed deal with or sell forestry equipped trailers.

G.2.2- Equipment Service

As equipment prices on new models increase, more owners are choosing to refurbish older trucks lengthening their life spans. About 90% of the dealers interviewed mentioned that they own a truck service shop but only 60% use facilities for commercial maintenance and service centers. Truck serviceability depends on the region of the state they are located in. Northern Wisconsin and Southern Lower Peninsula locations only service very few if any. Upper Peninsula locations

see several hundred biomass trucks a year where as the Lower Peninsula sees mainly Class 8 (80,000 GVW) over the road commercial trucks.

G.2.3- Sales and Inquires

As a tool to predict the future expansion of the industry if needed, dealers were surveyed on equipment sales (past, present and future), biomass inquires and changes that they have seen within the industry and what they see to come. All dealers mentioned that sales for 2010 were down drastically (compared to 2004-2007 years) but rose from 2009 numbers. For most dealers, 2004-2007 were great years for them. A lot of companies were upgrading and buying trucks before 2008 when the new emission regulation engines came into production. For dealers, 2011 is looking to be a better year (but not to the standards of pre 2008 sales) but many are remaining optimistic.

When talking to dealers on biomass equipment inquires, most said that they receive very few to none. They mentioned that a large reason for this is due to the industry being unstable, rising transportation/maintenance costs and dwindling markets make it hard for transportation companies, manufactures and dealers to invest the time and money needed to develop products. A few dealers are getting more inquires for smaller versatile trucks and trailers allowing them to be open to more markets.

One of the major changes that dealers mentioned was the emission regulations and new engine requirements. Dealers said there 2007 year was so good for truck sales, was due to owners and companies wanting to upgrade their fleet before the new regulations went into effect. Most companies didn't want to deal with the new engines due to the fear of problems and added expense on both base prices and maintenance costs. For them, emissions are playing a major role in how people are buying and refurbishing equipment.

G.2.4- Cost

Since the 2008 emission regulations, rise in equipment costs are causing owner operators to skip maintenance as a way to cut costs. Since 2009 the base price on a chassis has raised \$30,000 due to new government regulations on emissions and safety standards. One dealer mentioned that he priced a truck for a municipality last year for \$146,000 and he just priced the same truck at \$177,501. The prices of trucks are going up drastically due to new standards and regulations coming out and product prices are dropping at mills. This makes it very hard for owners to not only justify a huge investment but also to get financing and to keep up with additional system and maintenance costs.

H- List of Rail Car Dealers and Equipment Manufacturers

Table H-1- List of contacted rail car dealers and manufacturers

Company Name	Website	Contact	email
ACF Industries	http://www.acfindustries.com	Dennis Nibert	Dnibert@ACFindustries.com
American Railcar Industries, Inc.	http://www.americanrailcar.com	Al Lullman	alullman@americanrailcar.com
A-Z Railcar	http://www.azrailcar.com	NA	info@azrailcar.com
C.K. Industries, Inc.	http://www.ckindustries.net	Richard E. Meyers	rmeyers@ckrail.net
Chicago Freight Car Leasing Co.	http://www.crdx.com	Bill Elwess	Bill.Elwess@crdx.com
David J. Joseph Company	http://www.djj.com/VideoDefault.asp	NA	info@djj.com
Everest Railcar Services	http://www.everestrailcar.com	NA	admin@everestrailcar.com
GATX	http://www.gatx.com/wps/wcm/connect/gatx/gatx_site/home	Thomas Clark	thomas.clark@gatx.com
GLNX	http://www.glnx.com	Cyndy Rabbitt	cyndyr@glnx.com
JFS Railcar, Inc.	http://www.jfsrailcar.com	NA	sales@JFSRailcar.com
Kasgro Rail	http://www.kasgro.com	Jeff Kettermann	jeff.kasgro@wildblue.net
Pioneer Railcorp	http://www.pioneer-railcorp.com	Joseph Evans	evans@pioneer-railcorp.com
Procor	http://www.procor.com	NA	enquiry@procor.com
Railcar Deals	http://railcardeals.com	NA	information@railcardeals.com
RGCX	http://www.rgcx.com/index2.htm	Robert Hebbeler	robert.hebbeler@rgcx.com
Rocky Mountain Transportation Services, Inc.	http://www.railcar.com/RMTS/Index.html	NA	tc@railcar.com
SEA-Inc	http://www.slvx.com	NA	SEA-Inc@slvx.com
Southern Illinois Railcar Company	http://sircrail.com	Jon Sparks	jsparks@sircrail.com
Southern Rail Leasing	http://www.srlx.com	John Chambers	chambers@srlx.com
Southwest Rail Industries	http://www.southwestrail.com	Jason Huette	jhuette@southwestrail.com
Texas Railcar Leasing	http://www.trlx.net	NA	sales@TRLX.net

**Sub-Task B2: Analyze the Economic and Logistics Performances of
Woody Biomass Harvesting, Forwarding, and Processing Systems
from Natural Forest Stands and Energy Plantations in Michigan**

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EXECUTIVE SUMMARY

This report pertains to Sub-task B.2, “Analyze the Economic and Logistics Performances of Woody Biomass Harvesting, Forwarding, and Processing Systems from Natural Forest Stands and Energy Plantations in Michigan,” and is a section of the overall project entitled “Forestry Biofuels Statewide Collaboration Center.”

The goal of the sub-task was to address the question: How can we efficiently harvest, move and produce biofuel in Michigan? To attempt to answer this question, two more questions needed to be addressed:

- Is there enough workforce and equipment capacity in Michigan to supply biomass from natural forestlands and plantations?
- What is the optimal biofuel potential from different biomass supply systems including natural forests and plantations?

This sub-task examines the harvesting, forwarding, and processing (HFP) systems in Michigan. The first step was to complete an inventory of HFP equipment and methods used statewide in Michigan. This required contacting logging companies, extension educators, and equipment manufacturers. Data collected includes equipment capital cost, operating cost, field capacity and efficiency. Second, an assessment of these HFP systems commonly used in Michigan was made. Systems most commonly used in Michigan are whole tree harvesting followed by skidding to landing site and cut to length followed by forwarding. Several models to compute system cost were considered that would be suitable for Michigan conditions. Some available models required knowing all machine and stand data needed to calculate cost such as machine prices, fuel consumption, productivity and forest stand data. FRCS model, developed for western United States had some desirable features such as it had built in regression equations to compute the necessary attributes needed to calculate production cost for a HFP system. However, these regression models did not adequately represent Michigan conditions. Thus the model was adapted to Michigan conditions using results of the logger’s survey for comparison. A sensitivity analysis was conducted to determine the impact of the various management parameters on production cost.

This study analyzed the supply chain and logistics linked to harvesting natural forestlands and plantations in Michigan and their optimal conversion potentials for different bioenergy scenarios. To understand the extent of the operating capacity and the state of the technology of harvesting operations, it was necessary to assess existing logging capacity to harvest and supply biomass from natural forests and plantations-based woody biomass. Subtask B.2 was divided into three sections that are reported herein: 1) a comprehensive survey of the logging community within Michigan; 2) modeling of supply chain scenarios for the supply of wood from natural stands using different harvesting operations in Michigan; 3) analyzing the conversion of natural stand or plantation material to woodchips, wood pellets and torrefied wood pellets at Regional Biomass Processing Depots (RBPDs) in Michigan. The bioenergy systems examined in Subtask B.2 were compared to develop recommendations for future analyses.

Surveying Michigan loggers resulted in a snapshot of the harvesting, forwarding and processing equipment available in 2009 and 2010. Several observations can be made after reflecting upon the survey results. First, as most harvesting operations were from partial cut treatments, it would not be prudent to assume that an entire area would be clear cut to supply biomass to new facility. Second, most products were extracted from lands defined as “private non-industrial” and then delivered to pulp and paper industries. Third, saw logs and pulpwood were the most common types of product removed from the forest while woodchips were the least. Fourth, a variety of logging equipment was used; including mechanical whole tree harvesting, cut-to-length harvesting and manual whole tree harvesting. Fifth, skidding distance was reported and show the significance of biomass skidding costs. A sixth observation is that most biomass procurement operations do not involve equipment for residue removal or chipping. These observations and others were borne of the loggers’ survey and are discussed more thoroughly in Section I of this report. Overall, the survey was successful in receiving responses from over 200 logging firms statewide.

Modeling of biomass supply from natural stands provided estimates of biomass costs for the various supply chains relevant in Michigan as determined by the survey. Table B2.1 contains the cost of producing wood chips from natural stands under different treatment scenarios for a variety of stand conditions. Values in this table range from \$13.28 to \$23.14. Increasing the amount of removal significantly reduces these costs. Overall, harvesting costs are highly variable and dependent upon the type of equipment, level of harvesting (clear-cut vs. selective cut), type of forest, and the tree stand density. Generally, the FRCS predicted costs were higher than those provided by the loggers’ survey, which suggests increased productivity by Michigan loggers. Pulpwood harvesting costs ranged from as low as \$8.91/GT for clear-cutting natural hardwoods by WT system to as high as \$27.11/GT for 30% natural hardwoods by CTL system.

Table B2.1 Production cost (\$/ton) for biomass products using a WT harvesting system (whole-tree chipping)

	Forest type	Felling	Skidding	Chipping	Total
30% Cut	Natural Hardwoods	8.72	8.27	4.37	21.36
	Mixed Hardwood / Softwood	8.86	8.41	4.37	21.65
	Natural Softwoods	9.63	9.14	4.37	23.14
	Softwood Plantations	8.09	7.68	4.37	20.15
70% Cut	Natural Hardwoods	6.85	6.50	4.37	17.71
	Mixed Hardwood / Softwood	7.01	6.65	4.37	18.03
	Natural Softwoods	6.46	6.13	4.37	16.96
	Softwood Plantations	6.02	5.71	4.37	16.10
Clear cut	Natural Hardwoods	4.76	4.51	4.37	13.64
	Mixed Hardwood / Softwood	4.92	4.67	4.37	13.96
	Natural Softwoods	5.05	4.80	4.37	14.22
	Softwood Plantations	4.57	4.34	4.37	13.28

In addition to comparing harvesting and handling systems for delivering woody biomass, alternative preprocessing technologies were compared to identify potential bioenergy supply chains for electrical power generation. Comparisons were made by determining the cost of electricity generation at a 100 MWe power plant in which wood chips, wood pellets, or torrefied wood pellets were co-fired with coal. In accordance with Michigan Public Act 295, ten percent of the electrical power produced in our model scenarios was assumed to be provided by renewable energy. The specific preprocessing technologies considered for bioenergy production included chipping, pelletization and torrefaction with pelletization. Chipping and pelletization create a material that is more easily transportable than forest slash and small diameter plantation trees, while torrefaction produces a mildly carbonized wood product with several desirable characteristics. In the systems analyzed, preprocessing was assumed to occur at either the roadside or in Regional Biomass Preprocessing Depots (RBPDs) that are located near to harvest regions because densification is central to reducing transportation cost. Finally, these technologies were compared to determine the bioenergy systems that are most appropriate for the range of site conditions within the State of Michigan.

Torrefaction is a preprocessing technology that upgrades woody biomass to a form with desirable physical and chemical properties. In torrefaction, heat is added in the absence of oxygen to perform a mild pyrolysis of the structural components of biomass. Torrefaction has been previously investigated by the Energy Center for the Netherlands (Bergman, P.C.A. 2005a) and Agri-Tech Producers LLC (2011) for the purpose of determining technical and economic feasibility. The advantages of torrefied wood pellets versus wood chips include: 1) reduced transportation costs due to densification, 2) improved storage stability due to increased hydrophobicity, and 3) reduced grinding costs due to increased friability. Scenarios that involve long distance transportation are especially benefitted by torrefaction and pelletization. Overland truck transport costs reflect this conclusion for the three products investigated by our analysis as shown in Table B2.2. We conclude that for bioenergy systems that involve long transportation distances, torrefaction and pelletization are justified. It is important to note, the cost contribution to electrical power generation portrayed in the figure and tables of this report does not include the cost of coal. As only 10% of the total electricity is produced by these bioenergy systems, the actual cost contribution to power generation is one tenth of that reported when coal is assumed to produce the remaining 90%.

Table B2.2. Costs of wood chips, wood pellets and torrefied wood pellets using poplar (grown in a six year rotation) as feedstock when delivered to the power plant assuming a 300 mile transport distance. Costs are portrayed as \$ per ton (as received); \$ per GJ (as received; lower heating value); and cents per kWh of electricity produced (cost contribution of feedstock to the cost of electrical power; not including coal).

	Wood chips	Wood Pellets	Torrefied Wood Pellets
Moisture wt. %	20%	8%	3%
\$/t	71.01	97.71	117.59

\$/GJ	5.917	5.851	5.600
\$/Kwh	0.059	0.059	0.056

Figure B2.1. Cost contribution to electrical power generation from wood chips, wood pellets and torrefied wood pellets when a distance of 300 miles from the RBPD to the power plant is applied. Poplar was used as the feedstock at a biomass cost of \$41.33/dt.

As seen in Figure B2.1, the cost of poplar wood chips is the largest contributor to overall cost for each of the three scenarios. Torrefaction costs are also a large cost component when torrefied wood pellets are produced, but the equipment costs required at the power plant to store, handle and grind wood chips and wood pellets are not included in this study. As such, we recommend that further analysis be performed to examine the costs of generating wood chips, wood pellets and torrefied wood pellets. Though energy plantations of this sort currently do not exist, the Billion-ton StudyUpdate (Perlack, R.D. and Stokes, B.J. 2011) clearly states the importance of such energy crops. For long distance transportation (250 miles by truck in this study), the costs of torrefied wood pellets are lower than those for wood pellets and wood chips. Shorter transportation distances may also be justifiable when the additional processing costs at power plants are included for wood chips and when accurate torrefaction investment costs are made available. Multiple modes of transportation (truck/rail/ship) offer reduced cost for some scenarios and could be considered in further studies. Optimization of torrefaction will provide a clear opportunity for further reducing the costs of this bioenergy scenario, and new torrefaction technologies should be considered to improve the outlook for this alternative energy technology.

A SNAPSHOT OF THE EXISTING LOGGING INDUSTRY IN MICHIGAN

Introduction

The availability of a steady source of woody biomass at a cost effective price is critical to developing a biofuels industry. This depends upon the logging capacity as determined by the number and type of logging equipment available for harvesting woody biomass. In order to determine the current logging capacity and related operational characteristics in the State of Michigan, a comprehensive survey was completed in 2011. The survey was conducted over two stages that started in 2009-2010 that covered the Upper and Northern Lower Peninsula of Michigan and another in 2010-2011 with similar questions that covered the remaining parts of the state. Results were collected, aggregated and analyzed to provide an overall statewide snapshot of the state of the logging industry. Results of both surveys are presented here to summarize the status of the logging industry in Michigan.

Methodology

In 2009 at the onset of the project, the project team contacted local experts and reviewed the literature about existing information. No comprehensive study of the existing harvesting and transportation technology in the state existed. As a result it very difficult to undertake a study that explains harvesting and supply logistics technology for the entire state of Michigan without knowing the information presented in this section of the report. As a result, a comprehensive analysis of needed questions was developed to explain the business sectors, equipment use and productivity, and operational capacities. The survey development process took around 6 months of consultations and edits. When a draft was prepared it was piloted with local logging firms. The result was a 14-page survey that was mailed out to an entire group of logging firms from an existing MSU-database. Full survey and notices using the Dillman method were sent out to logging firms, but there were several incorrect mailing addresses and firms that were no longer in business. Finally, the survey was successful in receiving responses from over 200 logging firms statewide. The data collected offers a unique opportunity to understand the state of the harvesting technology in the State of Michigan. Based on survey response a large database was developed that spanned over 500 records of responses.

Developing Survey Instrument

ID CODE # _____

Logging Equipment and Transportation Survey

The purpose of this study is to identify the logging capacity in the State of Michigan. This survey serves as a key component of the larger research project that Michigan State University and Michigan Technological University are carrying out to assess existing logging capacity to identify optimum harvesting, forwarding and processing equipment and systems for timber and biomass harvested from natural forest stands as well as plantations. Your responses to the survey questions will help describe the current state of the harvesting and transportation equipment, the current production, the potential production and what is needed to reach this potential production for the start-up of potential new facilities. Your participation in this survey is voluntary and the information provided is confidential and will be used only for study purposes.

You can complete an online version of the questionnaire instead at: <http://www.loggingMI.ippsr.msu.edu/>

You indicate your voluntary consent to participate in the study by completing and returning the questionnaire by mail or fax to:

Office for Survey Research - IPPSR
321 Berkey Hall
Michigan State University
East Lansing, MI 48821-1111 Fax (517) 432-1544

If you have questions or comments about the research, please contact:

Dr. Dalia Abbas, Department of Biosystems and Agricultural Engineering
Michigan State University
Tel. (517) 355-7493 Fax (517) 432-2892
Email: abbasd@msu.edu

Please return your completed questionnaire in the envelope provided. Thank you very much for your help and for taking the time to complete this survey.

Questionnaire designed by the Office for Survey Research

Survey instrument development involved identifying, developing and piloting questions based on project objectives outlined in the proposal. Request for information and survey criteria were developed with relevance to the program objectives for a snapshot of existing harvesting technology in Michigan. A larger survey was first developed to accommodate every thought possible in the process. The survey was approved by MSU Institutional Review Board to comply with human subjects' protection. The steps in developing the survey involved consultation with loggers regularly both in the State of Michigan and out of state. Several survey drafts were developed and passed on to expert loggers and forest engineering experts nationwide for their critique.

Survey Method and Stages

The survey was based on Dillman's (2000) mail and internet survey tailored design methods and approach to mail in surveys. Each respondent had a unique web and survey ID that was entered when respondents chose the online option using the website <http://www.loggingMI.ippsr.msu.edu/>. Below are the stages of the survey method, in consultation with Prof. Hembroff in the Office of Survey Research of Michigan State University:

- Mailing #1: Pre-notice by mail to notify about the survey.
- Mailing #2: Mail contains the survey, a cover letter, and a business postage-paid return envelope
- Mailing #3: Postcard reminder/thank you, containing the URL to the survey site; sent to everyone about two weeks after mailing #1
- Mailing #4: Mail sent to non-respondents only about two weeks after the postcard mailing; contains a replacement questionnaire, with cover letter that includes the URL to the survey site, and a postage-paid return envelope

Results

Geospatial Distribution of Logging Firms

Out of the total 83 counties surveyed, responses were received from 44 counties (three of which are Wisconsin counties). A larger number of logging firms were located in the Upper Peninsula of Michigan. This is not surprising since this is the location of the highest concentration of timber resources in the state. Furthermore, four counties out of Wisconsin bordering Michigan responded to the survey. Those were the counties of Marinette, Florence, Vilas and Wexford. Figure B2.3 shows responses from the various counties in Michigan.

Figure B2.2. Survey introductory page

Figure B2.3. Map of Logging Firms in Michigan based on Survey Responses Employment Analysis

The state of employment in the logging industry nationwide has been impacted by several sectors of economy. A few of these sectors are the housing, and pulp and paper industries that have witnessed a decline. In an attempt to capture the data without bias to a particular year, the survey inquired about the number of employees per firm in the particular year of the survey as well as under normal conditions. Based on survey results, on an average firms employed 6.5 employees per year.

Table B2.3. *Number of Employees in MI Logging Firms under Normal Conditions*

Mean	6.46
Number of respondents	195

Logging Firms Ownership Trends

As a part of the survey questions, we sought to better understand the age of the logging industry Michigan. On an average firms have been in business for 28 years. The question was not targeted to the individual respondent, rather, the logging firm's age.

Table B2.4. *Years Firms in Business in MI*

	<i>Years Firms in Business</i>
Mean	28
Number of respondents	216

Trends in logging firm ownership indicate that most equipment operators own their equipment. This is followed by an 8% of operators who do not own equipment and 5% of owners who do not operate the equipment they own. This is also shown in Figure B2.4.

Figure B2.4. Logging Firms Ownership

Operational Capacity

Below in Table B2.5 is a summary of harvesting equipment owned by survey respondents. Respondents were asked about the number of equipment type they owned, along with basic descriptive information on the equipment. Cut-to-length processors were the predominant type of harvesting equipment seen throughout the state, and forwarders were the most common type of skidding equipment. As might be expected, there was a large variety in machine usage and fuel use among the different respondents, but the averages between surveys that were collected over 2009 and 2010 were very similar.

Table B2.5. Combined state of MI logging equipment summary

Equipment type	Model year (responses)	Total machine hours (responses)	Fuel use gallons/hr (responses)
Cut-to-length processor	2003 $\pm$ 4.1 ^a (132)	9,286 $\pm$ 6,543 (151)	4.9 $\pm$ 2.3 (142)
Feller-buncher	1996 $\pm$ 8.3 (35)	9,384 $\pm$ 6,696 (38)	6.3 $\pm$ 2.6 (37)
Feller-delimber	1988 (1)	12,467 $\pm$ 6,788 (3)	2.7 $\pm$ 0.6 (3)
Forwarder	1997 $\pm$ 9.5 (153)	10,666 $\pm$ 6,138 (165)	3.2 $\pm$ 1.9 (159)
Harwarder	2001 $\pm$ 5 (5)	9,053 $\pm$ 7,586 (6)	2.2 $\pm$ 0.5 (5)

Chainsaws	2006 ± 4.9 (113)	668 ± 990 (36)	1.1 ± 0.6 (35)
Grapple skidder	1995 ± 8.1 (47)	11,583 ± 6,116 (31)	5.1 ± 2.3 (33)
Cable skidder	1976 ± 8.8 (17)	8,889 ± 3,772 (9)	2.4 ± 1.0 (11)
Loaders	1996 ± 6.7 (30)	7,525 ± 7,429 (24)	3.8 ± 1.9 (26)
Grinders	2003 ± 1.0 (5)	2,459 ± 772 (6)	8.0 ± 0.9 (4)
Slashers	1995 ± 7.6 (14)	9,607 ± 7,140 (15)	3.9 ± 1.8 (18)
Delimber	1996 ± 8 (3)	6,220 ± 3,561 (5)	3.0 ± 0 (3)
Debarker	1997 ± 2 (2)	7,333 ± 1,155 (3)	13.3 ± 2.9 (3)
Chippers	1997 ± 9.1 (18)	8,798 ± 8,584 (17)	14.5 ± 8.9 (18)
Bulldozers	1992 ± 14.0 (72)	4,866 ± 3,226 (87)	3.8 ± 2.1 (79)

^a - Numbers following ± represent standard deviations, based on number of responses in parentheses. Below in Tables B2.6 is the reported roundwood harvesting productivity of different machine configurations, in cords of green timber per hour. Respondents were asked which harvesting equipment configuration they utilized for different harvesting scenarios, and in different forest types. Equipment configurations were grouped into three main categories to simplify the analysis, based on the type of equipment that would be cutting down the trees.

A – full processor/forwarder

B – feller buncher/skidder/slasher

C – chainsaws/skidder

Respondents also indicated their reported productivity in cords or tons of wood per hour. To simplify the analysis and reduce error from including respondents that own many pieces of equipment but do not use them equally or at all times, we focused on respondents which owned only 1 or two pieces of cutting equipment (full processors, feller-bunchers), but any respondents that indicated chainsaw use were included. Productivity was normalized to a single cutting equipment unit (i.e., productivity for 2-unit respondents was divided by 2), and the number of cutting equipment units included in the analysis is listed as N in the table. This procedure was not followed for chainsaw-based harvesting, as it is commonly assumed that multiple chainsaws are used by logging crews relying on this equipment configuration. This procedure is explained in greater detail in the COEE Q5 report. For full processors and forwarders the average reported productivity increased as the harvesting scenario increased in intensity from 30% selective cut up to clear-cutting, as would be expected. In almost every case, productivity in each harvesting scenario was highest in softwood plantations, which are typically on even terrain and stocked

with optimal timber for harvesting. Tables B2.6 and B2.7 explain productivity estimates for different logging equipment configurations.

Table B2.6. Full Processor / Forwarder

Treatment	Forest Type	Productivity per harvester (cords/hr-machine)		
		N	Average	Std. Dev
30% Cut (Selective)	Natural Hardwoods	54	3.34	1.38
	Mixed Hardwood / Softwood	48	3.83	1.48
	Natural Softwoods	47	3.95	2.16
	Softwood Plantations	37	4.57	2.11
70% Cut (Selective)	Natural Hardwoods	43	4.09	1.80
	Mixed Hardwood / Softwood	41	4.51	1.81
	Natural Softwoods	38	4.66	2.15
	Softwood Plantations	29	4.97	2.13
Clear-cutting	Natural Hardwoods	43	5.51	2.74
	Mixed Hardwood / Softwood	47	5.67	2.50
	Natural Softwoods	40	6.07	2.79
	Softwood Plantations	35	6.97	4.02

Table B2.7. Feller-buncher / Grapple Skidder/ Slasher

1 Harvester - Productivity (cords/hr)				
Treatment	Forest Type	N	Average	Std. Dev
30% Cut (Selective)	Natural Hardwoods	15	3.72	1.52
	Mixed Hardwood / Softwood	15	3.66	1.31
	Natural Softwoods	13	3.37	1.32
	Softwood Plantations	8	4.01	0.93
70% Cut (Selective)	Natural Hardwoods	14	4.74	1.43
	Mixed Hardwood / Softwood	15	4.63	1.42
	Natural Softwoods	16	5.02	1.60

Clear-cutting	Softwood Plantations	9	5.39	1.73
	Natural Hardwoods	13	6.82	2.68
	Mixed Hardwood / Softwood	13	6.59	2.98
	Natural Softwoods	11	6.42	2.83
	Softwood Plantations	9	7.10	4.19

Average production per cut types

Most operators cut 30% treatments [45%] followed by 70% removals [29%] followed by clear-cuts [26%]. This means that the supply of biomass from clear-cuts would not be expected to exceed 25% of the supplied feedstock. This is particularly important when accounting for the location of a facility or its radius of feedstock supply.

Figure B2.5. Percentage of Cut Type of Treatments in Harvesting

Table B2.8. *Normalized Values of different Percentages of Removal Operations from Forest Stands*

	<i>Percent of operations 30% removal</i>	<i>Percent of operations 70% removal</i>	<i>Percent of operations clear cut</i>
Mean	45.69	27.39	26.92
Number of respondents	194	194	194

Skidding and forwarding distances

Skidding material on site is a significant cost of harvesting operations. The study attempted to inquire about average and maximum skidding and forwarding of material distances. Responses were in line with data collected both years from the northern and southern regions, for verification. The skidding and forwarding distances calculated were a key factor to assess the harvesting economics using the FRCS model and employing data collected from the study.

Table B2.9. *Average and Maximum Skidding Distances*

	<i>Number of respondents</i>	<i>Average (miles)</i>
Average Distance	172	0.26
Maximum Distance	165	0.78

Average Shift Hours during Summer and Winter Months

Average shift hours were collected to explain the expected number of hours operators work in summer and winter conditions. Results were overall not significantly different; however, winter hours were slightly lower. This finding is expected since winter days are shorter. The data, however, has shown that respondents were not double shifting. On average, summer weekly shift hours were 37.6 hr/week, and winter hours were 37.4 hr/week. The survey attempted to capture the number of hours spent to repair and maintain equipment. The average reported repairs hours per day were 1.3 hours, with the equipment requiring the most repairs was the cut-to-length processor. The time spent repairing and maintaining equipment results in time taken out of production thereby increasing the cost.

Equipment Ownership

Configurations with Cut-to-Length operations were almost 3 times those of feller-bunchers. On the other hand, chainsaws were the largest in number of equipment used. However, chainsaws are also used to remove vegetation and unneeded brush obstructing heavy machinery. There are twice as many forwarders as there are skidders which is a good reflection of the higher number full processor-forwarder configuration used by the logging industry. Forwarders in number are followed by skidders that yard material for both the feller-buncher and the chainsaw equipment.

However, a few chainsaw operators reported yarding material using a skidder. The table below is a representation of the type of equipment used in Michigan to enter a stand and harvest sawlogs, pulpwood and chip material.

Table B2.10. Equipment Ownership

Equipment type	No. of reported equipment
Whole Tree Buncher	57
Whole Tree Feller	4
Delimber	
Whole Cut Processor	191
Chainsaws	569
Harwarder	18
Forwarder	247
Grapple Skidder	86
Cable Skidder	26
Loader	54
Slasher	24
Delimber	8
Debarker	4
Grinder	9
Chipper	31
Bulldozer	132
Other equipment	40

Type of Products Removed from Harvest Operations

Survey results attempted to collect information about the type of products loggers were involved with. Results were structured into the percentage of their operations that involved sawlogs, pulpwood and woodchips products. Summary of results is presented below.

Table B2.11. Type of Products Removed from Harvest Operations

	Response Rate	Total number of respondents
Sawlogs	97%	206
Pulpwood	95%	206
Woodchips	15%	132

Production Capacity

Individual responses included MBF (thousand board feet), cords and tons values. The general rules of 2.3 tons/cord and 2 cords/MBF were used. Analysis for this section involved converting all MBF values to international 1/4 log rules. All Scribner log rule values were multiplied by a factor of 0.83 and all Doyle log rule values were multiplied by a factor of 0.62. Final statistical analysis was developed on converted values as shown below:

Table B2.12. Production Capacity

Mean	3,438	4,328	3,228	15,668	13,889
Number of respondents	112	142	132	23	18

Harvested Stands Size Data

Survey results collected data to identify the maximum, minimum and average size of harvested stands as well as the volume of products removed. Stand size is important to help explain the cost of overall harvesting operations, since the trucking of equipment to site is a significant cost factor. When the area harvested or the volume removed is small, the entire cost of the harvest operations increase.

Table B2.13. Harvested Stands Size (acres)

<i>Statistical Analysis</i>	<i>maximum stand size harvested</i>	<i>minimum stand size harvested</i>	<i>average stand size harvested</i>
Mean	159.97	17.12	47.54
Number of respondents	174	177	184

Table B2.14. Volume of Smallest Operation (cords)

<i>Volume of Smallest Operation (cords)</i>	
Mean	665.64
Number of respondents	173

Percentage of Operating Capacities among Survey Participants

The forest-based industries were heavily impacted by the decline of several industries such as the housing and pulp and paper industries. To that end the emergence of biofuels industries would help ameliorate the decline. As a result, the survey aimed to capture potential decline in operating capacity.

Operations per Terrain Types

Operating on different terrain types has a significant cost increase in overall harvesting operations. As a result it was critical to understand the percentage of operations on different terrain types. Based on survey results most operations fall within the flat grounds, followed by rolling grounds, then low grounds followed by steep hills. The question required an overall 100% sum of responses to those percentages of operations per terrain types. However, this was not always the case when responses were summed up. To present valuable responses, data below shows all forms of responses. The first set describes the actual responses. The second set removed all responses that did not add up to 100% and a 0 value was inserted in empty cell responses, from those responses that added up to 100%. Trends between both normalized and real data were similar.

Table B2.15. *Actual Representation of Terrain Type Data without Normalization*

	<i>low ground operations</i>	<i>flat operations</i>	<i>rolling operations</i>	<i>steep hilly operations</i>
Mean	28.71	37.57	35.64	16.22
Number of Respondents	164	173	172	125

Figure B2.6. Percent of Operations on different Terrain Types

Percentages of operations that involve residue removals

To better understand the extent to which operations involved residue removal, survey questions inquired about percentages of clear-cut and partial removal operations that involved dealing with residue. Most operations do not involve residue removal. Percentage of residue removal is highest in partial cut harvesting.

Figure B2.7. Residue Management Options

Percentages of Operations from different property types

Since land ownership to a large degree determines the amount of available resources to removal, the survey inquired about the landownership that operators worked with. Almost 60% of landownership came from private non-industrial lands.

Figure B2.8. Percent of Land Ownership

Percentage of Operations with Purchased Stumpage

After a few face-to-face interviews with Michigan based logging firms, the issue of stumpage purchase was listed as a reason that stumpage purchase ought to be further considered when compensating loggers. Stumpage purchase is a very significant part of the total harvesting and supply cost incurred. As indicated by survey results the average percentage of operations that involve stumpage purchase are 70%. Whereas most of the respondents reported that in 100% of their operations they would purchase stumpage.

Percentage Delivery of Products to End Users

In order to understand the market requirements per different products removed during harvesting operations, the survey inquired about the end users that receive those products. The question required an overall 100% response to those percentages of delivery to end users. However, this was not always the case when the responses were summed up. To present valuable responses, data below shows all forms of responses. The first set describes the actual responses. And the second set removed all responses that did not add up to 100% and a 0 value was inserted in empty cell responses, from those responses that added up to 100%. Data trends between both normalized and real data were similar.

Table B2.16. Actual Representation of Values of Percent Deliveries of Products to End Users

Percentage of wood products supplied to	Mean	Number of respondents
Hardwood sawmill	26.76	173
Softwood sawmill	19.09	128
Veneer mill	8.91	111
Pulp mill	47.58	146
Other panel mill	13.59	54
Oriented strand board mill	23.11	66
Wood pellet fuel mill	5.51	35
Wood power generator	7.97	38
Truck/rail landing	15	50
Other location	33.78	40

The graph below presents percentages of products that were delivered to different facilities. Pulpwood and hardwood sawmills received the largest percentage of products totaling both almost 59% of the products generated from logging firms.

Figure B2.9. Percent of Deliveries to End Users

Truck Transportation Distances of Main Forest Products

Similar to the summary of harvesting equipment, the logging survey also asked for information about trucks used by respondents to transport biomass. Below in Table B2.17 and B2.18 we summarize some of the main characteristics of trucks owned by survey respondents. Truck data were analyzed with all reporting units. A separate analysis was conducted for the larger 10-11 axle log trucks and chip vans. Large log trucks had lower average fuel economy and larger annual usage than other trucks in the survey, but the distribution of annual mileage data for trucks varied considerably. Based on a question in the survey asking how much of the roundwood produced by each respondent was hauled by self-loading trucks (Table B2.18), we can infer that most log trucks in the state of MI are equipped with self-loaders. Over 70% of respondents (128 / 180) indicated that 100% of their roundwood production was transported with self-loading trucks.

Table B2.17. State of MI Trucking Equipment Summary

Year	Fuel Use (gallons/hour)	Miles/year
<u>All trucks reported in FBSCC logger survey</u>		
2000 ± 7 (156)	4.47 ± 1.79 (148)	54,940 ± 59,868 (150)
<u>Large Log trucks (10-11 axles)</u>		
2003 ± 6 (76)	3.66 ± 0.87 (71)	65,326 ± 39,276 (66)
<u>Chip Vans</u>		
1998 ± 7 (15)	4.19 ± 0.99 (21)	42,800 ± 28,357 (20)

Table B2.18. Percentage of Roundwood Transported by Self-loading Trucks

Responses	180
Average %	86.0
Standard deviation (%)	30.5
Responses that indicated 100%	128
Responses that indicated 0%	18

Forest products are delivered to a variety of end-users and intermediate supply chain points. Survey respondents were asked what percentage of their annual production was delivered to the different destinations listed in Table B2.19. Because not everyone responded to each destination, the average percentages in Table B2.19 do not sum to 100%, and represent the average percentage of those respondents who indicated that they delivered to the destination in question (respondents to each destination are indicated in the table as well). Pulp mills were the most popular destination for forest products in the state of Michigan. Hardwood sawmills were the most common destination, but only 27.7% of production volume went to these facilities.

Table B2.19. Deliveries summary table

Different destination	Responses	Percentage of production
Hardwood sawmill	148	27.7 ± 25.5
Softwood sawmill	110	19.8 ± 20.0
Veneer mill	88	8.1 ± 9.4
Pulp mill	124	49.6 ± 26.5
Particle board, med. density fiberboard	40	16.7 ± 17.9
Oriented strand board mill	44	25.8 ± 23.5
Wood pellet fuel mill	16	11.6 ± 22.2
Direct-fired wood power generator	22	12.4 ± 13.2
Truck or rail landing	36	16.9 ± 20.7
Other – mostly firewood	28	45.9 ± 40.6

^a Numbers following ± represent standard deviations based on indicated number of responses

Transport distances for each of the three main forest products (sawlogs, pulpwood, chips) followed a similar pattern (Table B2.19, Figure B2.10). Respondents were asked to list what percentage of their annual production of sawlogs, pulpwood, and chips was transported by truck for several mileage categories. Sawlogs were the product transported the smallest distance, as the average amount of sawlogs transported under 60 miles was over 55% as opposed to ~ 45% for

the other two forest products. Wood chips were the product transported the longest distance, with over 27% of production traveling more than 90 miles by truck.

Figure B2.10. Reported Truck Transport Distances for Main Forest Products

Rail transportation

Rail transport is utilized unevenly throughout the state of MI for the transportation of forest products. In the 2010 survey respondents were asked about their most recent use of rail transportation, and over 60% of the respondents that answered the question indicated that they had never used rail transport (Table B2.20). We can also reasonably assume that a majority of the respondents who did not answer the question also did not regularly utilize rail transport. In a different survey question, respondents were asked what percentage of their annual production was moved using rail transport. The 28 respondents that indicated some portion of their production had been moved by rail (roughly 12.7% of responses) moved roughly $22.1\% \pm 19.2\%$ of their annual production by rail, a significant amount. It should be noted that all of the respondents indicating a use of rail transport were based in the Upper Peninsula.

Table B2.20. Most recent use of Rail Transportation

Time Frame	Responses	% of respondents
(1) In past 6 months	9	14.1
(2) In past year	2	3.1
(3) In past 3 years	3	4.7
(4) In past 5 years	4	6.3
(5) In past 10 years	5	7.8
(6) In past 15 years	2	3.1
(7) Not at all	39	60.9
() No response	46	--

a – data originated from 2010 respondents to FBSCC survey

When asked about the factors that limited their use of rail transport for moving forest products, survey respondents indicated that reliability of service and limited access in main work areas were the primary reasons that rail transport was not used more extensively (Table B2.21). Existing transport contracts and lack of knowledge about rail were the factors that limited use of rail transport the least among survey respondents.

Table B2.21. Reasons that rail use for forest products is limited in state of MI
1= not limiting, 5 = extremely limiting

Lack of Knowledge Rail Contractual Arrangements	2.48
Reliability of Service	3.53
Speed of Delivery	3.39
Limited Rail Access in Main Work Areas	3.49
Prices Not Competitive With Other Modes	3.03
Minimum Shipment Too Large	2.49
Existing Contract with Other Provider	2.12

Significant Observations

Key observations from the study included

- Most logging firms in the state fall within the northern Upper Peninsula of Michigan and most firms are run by owner and operators of logging firms.
- Production capacities collected in this survey offered a unique level of analysis that would help make estimates of the productivity of harvesting operations.
- It was determined from the survey results that most operations were from partial cut treatments, especially within 30% selected cut types. This would need to be factored in decisions made to start industries based upon existing geographical locations within the state. In other words, it would not be prudent to assume that an entire area would be clear cut for the supply of an existing or new facility.
- Skidding distances reported have shown to what extent skidding is a significant cost factor in the delivery of biomass. Survey generated results helped in reaching calculations for harvesting supply logistics cost assessment in the next section.
- At the start of the project there was an overall understanding that industries were not working at full capacity. It turned out that a large number of respondents were operating

at 100% capacity, but on average logging firms reported working over 70% of their operational capacity.

- The survey inquired about the terrain types. Most operations are within flat and rolling grounds, which is an important factor when determining where to deploy operations when identifying a location for a forest products facility.
- A significant finding in the study was that most operations do not involve residue removal or chipping of material.
- Another significant finding was that most products were extracted from other public lands whereas most products were delivered to pulp and paper industries. The age of harvesting and transportation equipment has helped describe the state of the harvesting technology in Michigan.
- Michigan loggers use a variety of logging equipment. Most commonly used systems were mechanical whole tree harvesting, cut-to-length harvesting, manual whole tree harvesting. Among the equipment owned, cut-to-length processors were the newest (average model year = 2003) with feller bunches being the oldest.
- Saw logs and pulpwood were the most common types of product removed from the forest while woodchips were the least. Consequently, pulp mills were the most common destination followed by hardwood sawmills, OSB mills, and softwood saw mills. Only a small number of loggers reported supplying woody material to pellet mills and wood power generators.
- Equipment data such as age, productivity, and fuel use were useful in completing the life cycle assessment for the forest biomass supply chain in Michigan.

ECONOMIC ANALYSIS OF HARVESTING LOGISTICS

Introduction

The primary goal of the project was to calculate cost of harvesting, extracting, and processing woody biomass for both natural forest and plantations using different harvesting systems that were commonly used in Michigan under conditions most prevalent within the State. To provide a frame of reference we assumed that the biomass would be used as feedstock to generate electrical power. It was also the objective of the study to evaluate which form of biomass upgrading would be most cost effective as biofuel feedstock. For example, round wood, woodchips, wood pellets, torrefied wood chips, or torrefied wood pellets from both natural forests as well energy plantations. This section covers the cost analysis of harvesting woody biomass from natural forests.

Methodology

There are two elements to calculating logging cost: 1) hourly operating cost of logging equipment; and 2) harvesting system cost.

Hourly rate of logging equipment: Machine hourly rate is expressed in \$/SMH, whereas SMH = scheduled machine hours. Machine hourly rate in \$/SMH can be converted to \$/PMH (PMH = productive machine hours) by multiplying machine utilization rate (PMH/SMH). Once cost in \$/PMH is determined, cost in \$/GT (GT=green ton) is determined by dividing this number by machine productivity (GT/hour). Machine productivity can either be determined by conducting time-and-motion studies or estimated using published data. Machine productivity is highly dependent of stock and stand tables for a given tract or plot and the type of harvesting operation i.e. partial cutting or clear cutting. In this report we used the available Forest Inventory Data (FIA) to estimate stock and stand data.

Machine hourly cost has three primary components:

1. Fixed (Owning) cost. This is the cost of owning the machine and includes depreciation, interest on investment and cost of taxes, insurance and housing of the machine. These costs are calculated as follows:
 - a. $D = (P - S) / (N \cdot SMH)$, where
D is Depreciation in \$/SMH
P is Purchase price in \$
S is Salvage value in \$
N is Machine economic life in years
 - b. $AAI = (P - S) \cdot (N + 1) / (2 N) + S$, where
AAI is Average Annual Investment in \$
 - c. $(Int + Ins + T) = \% \text{ rate} \cdot AAI / SMH$, where
Int + Ins + T is the total cost for interest, insurance, and tax in \$/SMH
2. Variable (Operating) cost. This cost is incurred when machine is operated and includes fuel and lube, tires and tracks, and repairs and maintenance. Fuel and lube cost depends on the rated fuel consumption of the machine and fuel and lube costs. Repair and maintenance cost can be estimated based on records if available or obtained from literature.

- a. Repairs and Maintenance (\$/PMH) = Depreciation x Repair and maintenance factor (%/Depreciation)
3. Labor. This cost includes hourly labor rate and labor fringe benefits (%) expressed in terms of \$/SMH.

Harvesting system cost: Once costs of each machine used in logging operation is determined in terms of \$/SMH it is possible to compute harvesting system cost expressed in terms of \$/GT. Harvesting system cost depends upon the logging system used such as cut to length (CTL) or whole tree (WT) harvesting. The following are harvesting system cost components:

1. Felling. Cost of felling depends, in addition to the type of machine used to perform felling operation, upon the type of harvesting operation such as partial cutting (thinning) or clear cutting. It also depends on the type of forest i.e. hardwood, softwood or mixed and on tree size and stand density.
2. Skidding. This operation is necessary to bring cut trees to the landing site for loading onto trucks for hauling or for further processing such as chipping. The cost of skidding depends upon primarily skidding distance, terrain conditions, skid trail layout, and average turn volume.
3. Loading. This operation represents loading logs onto truck for hauling to their final destination. Please note that in this portion of the study hauling cost is computed elsewhere in the report under a separate section.
4. Move-in costs. This cost represents deployment of harvesting, forwarding, and processing equipment to the tract and depends upon tract size, moving time, and distance from home. It also depends on site preparation including roads to be built and to establish entrances. In this study we did not include any site preparation cost and assumed that all tracts were already prepared.
5. Support cost. This cost includes pickups, chain saws, foreman, and overhead. This cost is generally expressed as \$/cord and then converted to \$/GT.

Therefore, total harvesting cost is computed by adding all above costs in terms of \$/GT.

To compute harvesting system costs we were interested in identifying a model that could be adapted to Michigan conditions and would allow cost calculations for the various equipment systems commonly used by Michigan loggers. A literature review was carried out to identify the best available model that would determine the cost of harvesting biomass from natural forests and plantations. The review was structured into two phases; the first offered a literature summary of abstracts that was organized into three categories: Modeling Fuel Reduction/Forest Harvesting, Timber Harvest Outputs/Supply Chain, and Economics/Market Impacts. The second phase was based on extensive discussions with national forest harvesting experts. The models that were of particular interest to the project were those that required customized inputs based on Michigan particular conditions. Three models were found. These are a Virginia Tech model (<http://cnre.vt.edu/harvestingsystems/logcost9.html>), a Auburn Harvesting Analyzer developed at Auburn University and modified by R. Visser (<http://cnre.vt.edu/harvestingsystems/costing.htm#auburnharvester>) and a Fuel Reduction Cost Simulator (FRCS) model developed by Bruce Hartsough and Dennis Dykstra. The VT and Auburn models require user to input all values whereas the FRCS model has many built-in default features. To use this model successfully it is critical that built-in features as well as input

data flexibility allowed be clearly understood and input parameters for Michigan conditions be clearly determined. The logger's survey played an important role in our developing an understanding of the Michigan logging industry and in determining input parameters for cost calculations.

Based on the Logger's survey the most common systems used in Michigan are:

1. Whole tree system (WT) - Felling and skidding with and without chipping at landing
2. Cut to length (CTL) system - harvesting and forwarding with and without chipping at landing

The following tables list the assumptions made to compute machine costs (Table B2.22), machine hourly rate calculation intermediates (Table B2.23), and machine hourly rate calculation results (Table B2.24).

Table B2.22: Machine cost assumptions and survey-based variables

	Small F-Buncher	Small Harvester	Small Skidder	Small Forwarder	Small Slasher
Purchase price as of Dec 02, P (\$)	150,000	350,000	140,000	240,000	350,000
Machine power rating (hp)	150	120	120	110	120
Machine life (n, years)	5	5	5	5	5
Salvage value, S (% of P)	20	20	20	25	25
Utilization rate (%)	75 ^a	75 ^a	75 ^a	75 ^a	75 ^a
Repair and maintenance (% Depr)	100	100	100	100	100
Interest rate (%)	8	8	8	8	8
Insurance and taxes (%)	7	7	7	7	7
Fuel consumption rate (gal/hp-h)	0.026	0.029	0.028	0.025	0.022
Fuel cost per gallon (\$/gal)	3.228	3.228	3.228	3.228	3.228
Lube and oil (% of fuel cost)	37%	37%	37%	37%	37%
Crew size (persons)	1	1	1	1	1
Crew wage (\$/SMH)	19.43	19.43	19.43	19.43	19.43
Crew fringe rate (%)	40%	40%	40%	40%	40%
Scheduled machine hours (SMH/year)	1800 ^a	1800 ^a	1800 ^a	1800 ^a	1800 ^a

^a: Survey-based variables.

Table B2.23: Machine hourly rate intermediate calculations

	Small F.-	Small	Small	Small	Small
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	Buncher	Harvester	Skidder	Fowarder	Slasher
Salvage value (\$, \$)	30,000	70,000	28,000	60,000	70,000
Annual depreciation (\$)	0 ^a	0 ^a	0 ^a	0 ^a	0 ^a
Average yearly investment	30,000	70,000	28,000	60,000	70,000
PMH	1350 ^b	1350 ^b	1350 ^b	1350 ^b	1350 ^b

^a:When a piece of equipment is completely depreciated, the annual depreciation is 0.

^b:Survey-based productive machine hours.

Table B2.24: Machine hourly rate calculation results

	Small F.- Buncher	Small Harvester	Small Skidder	Small Fowarder	Small Slasher
Owning costs:					
Interest cost (\$/year)	2,400	5,600	2,240	3,840	5,600
Insurance and taxes(\$/year)	2,100	4,900	1,960	3,360	4,900
Yearly owning cost (\$/year)	4,500	10,500	4,200	7,200	10,500
Owning cost per SMH (\$/SMH)	2.50	5.83	2.33	4.00	5.83
Owning cost per PMH (\$/PMH)	3.33	7.78	3.11	5.33	7.78
Operating costs:					
Fuel cost (\$/PMH)	12.59	11.23	10.85	8.88	8.52
Lube cost (\$/PMH)	4.66	4.16	4.01	3.28	3.15
Repair & maintenance cost (\$/PMH)	17.78	41.48	16.59	28.44	41.48
Operating cost per PMH (\$/PMH)	35.03	56.87	31.45	40.61	53.16
Labor costs:					
Labor (\$/SMH)	19.43	19.43	19.43	19.43	19.43
Benefits (\$/SMH)	7.77	7.77	7.77	7.77	7.77
Labor cost per SMH (\$/SMH)	27.2	27.2	27.2	27.2	27.2
Machine hourly rate:					
Machine hourly rate in SMH (\$/SMH)	55.97	75.69	53.12	61.66	72.90
Machine hourly rate in PMH (\$/PMH)	74.63	100.92	70.83	82.21	97.20

Description of Michigan-based Plots used in the Analysis

FIA data were analyzed to establish plot conditions. Real Forest Inventory Analysis (FIA) database were integrated into regional forest plot values by Dr. Mike Vasievich to compute plot input data.

Total stands analyzed exceeded 10,000 plots from natural stands with soft and hardwood species. After removing data errors or plot data that could not be used due to missing information such as the size of trees, for example, about 2000 were over- and fully- stocked FIA plots. Aspen

feedstock was differentiated from other species since it was assumed that aspen forest types would undergo clearcut treatments and all other forest types would undergo partial cut treatments. Tables below show plot data for non-Aspen data for clear cut harvesting treatment and for Aspen clear-cut treatment.

Table B2.25: Non Aspen Stand Characteristics Using Partial Cut Treatments

	Slope	Treatment area (ac)	Trees / ac	ST residue fraction	ft ³ / tree	lb/ft ³	ST hardwood fraction
Mean	4.54	2002	238	0.20	9.74	58	0.56
Minimum	0.00	28.19	6.02	0.13	1.22	41.2	0.00
Maximum	40.00	6437	1062	0.35	77	84.3	1.82
No. of plots analyzed	1600	1600	1600	1600	1600	1600	1600

Table B2.26. Aspen Stand Characteristics Using Clear Cut Treatments

	Slope	Treatment area (ac)	Trees /ac	ST residue fraction	ft ³ /tree	lb/ft ³	Hardwood fraction
Mean	4.66	1910.12	158.8	0.25	6.39	57.9	0.89
Minimum	0.00	17.21	6.02	0.14	1.32	41.2	0.00
Maximum	37.00	4057.25	691.7	0.35	33.08	84.3	1.75
No. of plots analyzed	359	359	359	359	359	359	359

Average Statistical Analysis between stands to determine how stand characteristics inputs result in different harvesting costs between non-aspen and aspen plots. Non-aspen plots had larger trees on average. Aspen stands had lower number of trees per acre. The hardwood fraction contributes to a larger harvesting cost, and aspen stands have a higher portion of hardwoods.

Table B2.27. Comparison between Non Aspen and Aspen Stand Characteristics

	Trees/ac	Residue Fraction	ft ³ /Tree	lb/ft ³	Hardwood Fraction	Slope
Non Aspen	238.67	0.20	9.74	57.63	0.56	4.54
Aspen	158.87	0.25	6.39	57.97	0.89	4.66

Harvesting System Productivity based on Logger's Survey. The following table includes harvesting system productivity data as determined from logger's survey.

Table B2.28. Survey-based equipment configuration productivity (tons/hr. – based on the conversion of 1 cord/hr = 2.3tons/hr.)

Treatment	Forest Type	Feller-Buncher – Skidder-Slasher	Harvester - Forwarder
30% Cut (Selective)	Natural Hardwoods	8.56	7.68
	Mixed Hardwood / Softwood	8.42	8.81
	Natural Softwoods	7.75	9.09
	Softwood Plantations	9.22	10.51
70% Cut (Selective)	Natural Hardwoods	10.90	9.41
	Mixed Hardwood / Softwood	10.65	10.37
	Natural Softwoods	11.55	10.72
	Softwood Plantations	12.40	11.43
Clear-cut	Natural Hardwoods	15.69	12.67
	Mixed Hardwood / Softwood	15.16	13.04
	Natural Softwoods	14.77	13.96
	Softwood Plantations	16.33	16.03

Results and Discussion

Survey-based production cost (\$/ton)

Production cost for log products

Table B2.29 shows the production cost of log products in terms of \$/ton as they are delivered to the landing in a WT harvesting system. Whole trees can be processed into log products with limbs and tops as by-products. Usually, limbs and tops will be either piled and burned or further ground or chipped up by a grinder or a chipper for biomass energy purpose.

Table B2.29: Production cost (\$/ton) for whole trees delivered at the landing using a WT harvesting system

	Forest type	Felling	Skidding	Slashing	WT total
30%					
Cut	Natural Hardwoods	8.72	8.27	11.36	28.35
	Mixed Hardwood / Softwood	8.86	8.41	11.54	28.32
	Natural Softwoods	9.63	9.14	12.54	31.31
	Softwood Plantations	8.09	7.68	10.54	26.32
70%					
Cut	Natural Hardwoods	6.85	6.50	8.92	22.26
	Mixed Hardwood / Softwood	7.01	6.65	9.13	22.78

	Natural Softwoods	6.46	6.13	8.42	21.01
	Softwood Plantations	6.02	5.71	7.84	19.57
Clear-cut	Natural Hardwoods	4.76	4.51	6.20	15.47
	Mixed Hardwood / Softwood	4.92	4.67	6.41	16.01
	Natural Softwoods	5.05	4.80	6.58	16.43
	Softwood Plantations	4.57	4.34	5.95	14.86

In a CTL harvesting system, materials shuttled to the landing will be in the form of log length. When biomass is recovered in a CTL system, a separated forwarder trip would be required to transport limbs and tops from stump area to the landing. Table B2.30 shows the production cost of log products in \$/ton as they are delivered to the landing in a CTL harvesting system.

Table B2.30: Production cost (\$/ton) for log products using a CTL harvesting system

	Forest type	Harvesting	Forwarding	CTL total
30%				
Cut	Natural Hardwoods	13.14	9.60	22.74
	Mixed Hardwood / Softwood	11.46	9.76	21.22
	Natural Softwoods	11.10	10.61	21.71
	Softwood Plantations	9.60	8.92	18.52
70%				
Cut	Natural Hardwoods	10.72	7.54	18.27
	Mixed Hardwood / Softwood	9.73	7.72	17.45
	Natural Softwoods	9.41	7.12	16.53
	Softwood Plantations	8.83	6.63	15.46
Clear-cut				
	Natural Hardwoods	7.97	5.24	13.20
	Mixed Hardwood / Softwood	7.74	5.42	13.16
	Natural Softwoods	7.23	5.57	12.80
	Softwood Plantations	6.30	5.03	11.33

Production cost for biomass products

In a whole tree harvesting system, if only limbs and tops of harvested trees are chipped or ground up to biomass product, limbs and tops are the by-products of felling and skidding for merchantable part (log products), the only cost that should be assigned to biomass products is the chipping or grinding cost.

The FRCS model uses 1600 SMH/year for a small chipper, we will adjust that to 1800 SMH / year to match the SMH for other machines. Therefore, the machine hourly rate was adjusted to 104.24 \$/PMH. With this adjustment, the FRCS model predicted chipping cost is 4.37 \$/ GT.

As a variety of a whole tree harvesting system, if a fraction of harvested whole trees (e.g. typically small-diameter trees) goes to a chipper or a grinder directly, or all harvested trees are chipped or ground up to biomass products, felling and skidding cost should be assigned to biomass products. At this time, felling and skidding costs of log products (if any) are equal to the felling and skidding cost of biomass products. Table B2.31 shows the production cost for biomass products in this harvesting system variety based on the existing felling, skidding and chipping calculations:

Table B2.31: Production cost (\$/ton) for biomass products using a WT harvesting system (whole-tree chipping)

	Forest type	Felling	Skidding	Chipping	Total
30% Cut	Natural Hardwoods	8.72	8.27	4.37	21.36
	Mixed Hardwood / Softwood	8.86	8.41	4.37	21.65
	Natural Softwoods	9.63	9.14	4.37	23.14
	Softwood Plantations	8.09	7.68	4.37	20.15
70% Cut	Natural Hardwoods	6.85	6.50	4.37	17.71
	Mixed Hardwood / Softwood	7.01	6.65	4.37	18.03
	Natural Softwoods	6.46	6.13	4.37	16.96
	Softwood Plantations	6.02	5.71	4.37	16.10
Clear cut	Natural Hardwoods	4.76	4.51	4.37	13.64
	Mixed Hardwood / Softwood	4.92	4.67	4.37	13.96
	Natural Softwoods	5.05	4.80	4.37	14.22
	Softwood Plantations	4.57	4.34	4.37	13.28

In a CTL harvesting system, trees will be cut and processed in the stump area. In the circumstance when biomass is recovered, only forwarding cost and grinding/chipping cost should be assigned to the biomass products.

Our survey-based results included productivity for forwarding log products. This productivity cannot be used to estimate the cost of forwarding biomass products. A Michigan-based field study, conducted by Dr. Fei Pan in 2011, of forwarding biomass indicated that when using a medium-sized (14-ton loading capacity) forwarder to shuttle stump area biomass to landing with an average forwarding distance of 225 feet, the production rate was 34.56 GT/PMH. With a machine hourly rate of 82.21 \$/PMH for forwarder (Table B2.24), the Michigan-based biomass forwarding cost will be 2.38\$/GT. This is a low forwarding cost due to the fact that the machine has been completely depreciated, which results in a low machine hourly rate. In addition, the forwarding distance in this Michigan-based case is short compared with our survey-based average forwarding distance. This significantly shorten the operation cycle time and increase the productivity. With a FRCS model project chipping cost of 4.37 \$/GT, the total cost for biomass products in a CTL harvesting will be 6.75\$/GT.

FRCS Model simulation

Four scenarios were simulated in the FRCS model for harvesting cost projection. These scenarios include using a WT harvesting system and a CTL harvesting system to harvest non-Aspen and Aspen trees, respectively. Simulation results are summarized in Table B2.32. A comparison between survey-based production cost and FRCS model projected production cost (Table B2.33) showed that the FRCS model predicted values were significantly higher than survey-based results.

Table B2.32: FRCS model predicted production cost (\$/ton) for various scenarios

	Non-Aspen trees, partial cut (\$/GT)	Aspen trees, clear cut (\$/GT)
Whole-tree harvesting system	29	32
Cut-to-length harvesting system	26	33

Table B2.33: Production cost (\$/GT) comparison between survey-based results and FRCS model predicted results.

	Non – Aspen trees, partial cut		Aspen trees, clear cut	
	Survey-based cost (\$/GT)	FRCS predicted cost (\$/GT)	Survey-based cost (\$/GT)	FRCS predicted cost (\$/GT)
Whole-tree harvesting system	19.57 – 31.31	29	15.47	32
Cut-to-length harvesting system	15.46 - 22.74	26	13.20	33

Sensitivity analysis

Sensitivity analysis was performed to determine the effects of different variables on the production cost, while keeping all the other variables constant. Results comparisons and scatter plots showed how the production cost changed with the corresponding value changes in the tested variables, which included buying new machines, machine economic life, and diesel price.

Effect of purchasing new equipment on production cost**Table B2.34:** Machine hourly rate calculations when purchasing **new** equipment (Assumptions in Table B2.22 applied)

	Small F.- Buncher	Small Harvester	Small Skidder	Small Forwarder	Small Slasher
Salvage value (\$, \$)	30,000	70,000	28,000	60,000	70,000
Annual depreciation (\$)	24,000	56,000	22,400	38,400	56,000
Average yearly investment	102,000	238,000	95,200	163,200	238,000
PMH	1350	1350	1350	1350	1350
Owning costs:					
Interest cost (\$/year)	8,160	19,040	7,616	13,056	19,040
Insurance and taxes(\$/year)	7,140	16,660	6,664	11,424	16,660
Yearly owning cost (\$/year)	39,300	91,700	36,680	62,880	91,700
Owning cost per SMH (\$/SMH)	21.83	50.94	20.38	34.93	50.94
Owning cost per PMH (\$/PMH)	29.11	67.93	27.17	46.58	67.93
Operating costs:					
Fuel cost (\$/PMH)	12.59	11.23	10.85	8.88	8.52
Lube cost (\$/PMH)	4.66	4.16	4.01	3.28	3.15
Repair & maintenance cost	17.78	41.48	16.59	28.44	41.48

(\$/PMH)					
Operating cost per PMH (\$/PMH)	35.03	56.87	31.45	40.61	53.16
Labor costs:					
Labor (\$/SMH)	19.43	19.43	19.43	19.43	19.43
Benefit (\$/SMH)	7.77	7.77	7.77	7.77	7.77
Labor cost per SMH (\$/SMH)	27.2	27.2	27.2	27.2	27.2
Machine hourly rate:					
Machine hourly rate in SMH (\$/SMH)	75.30	120.80	71.17	92.59	118.01
Machine hourly rate in PMH (\$/PMH)	100.41	161.07	94.89	123.45	157.35

Using the existing survey-based equipment productivity, the harvesting production costs were summarized in the following Tables B2.35 and B2.36 for WT and CTL systems, respectively. Production cost comparison in Table B2.37 shows that with the use of completely depreciated equipment the production cost can be reduced significantly. Results in Table B2.37 also indicated that when performing a 30% partial cut, the use of depreciated machine has the strongest effect on production cost reduction, because the production rate in the prescription of 30% partial cut is the lowest, which amplify the effect of using depreciated machine on production cost.

Table B2.35: Production cost (\$/GT) of a WT system when purchasing *new* equipment

Forest type		Felling	Skidding	Slashing	WT total
30%					
Cut	Natural Hardwoods	11.73	11.09	18.38	41.20
	Mixed Hardwood / Softwood	11.93	11.27	18.69	41.88
	Natural Softwoods	12.96	12.24	20.30	45.50
	Softwood Plantations	10.89	10.29	17.07	38.25
70%					
Cut	Natural Hardwoods	9.21	8.71	14.44	32.35
	Mixed Hardwood / Softwood	9.43	8.91	14.77	33.11
	Natural Softwoods	8.69	8.22	13.62	30.53
	Softwood Plantations	8.10	7.65	12.69	28.44
Clear-cut					
Cut	Natural Hardwoods	6.40	6.05	10.03	22.48
	Mixed Hardwood / Softwood	6.62	6.26	10.38	23.26
	Natural Softwoods	6.80	6.42	10.65	23.88
	Softwood Plantations	6.15	5.80	9.64	21.60

Table B2.36: Production cost (\$/GT) of a CTL system when purchasing *new* equipment

Forest type		Harvesting	Forwarding	CTL total
30%	Natural Hardwoods	20.97	14.42	35.39

Cut				
	Mixed Hardwood / Softwood	18.28	14.66	32.94
	Natural Softwoods	17.72	15.93	33.65
	Softwood Plantations	15.33	13.39	28.71
70% Cut				
	Natural Hardwoods	17.12	11.33	28.44
	Mixed Hardwood / Softwood	15.53	11.59	27.12
	Natural Softwoods	15.03	10.69	25.71
	Softwood Plantations	14.09	9.96	24.05
Clear cut				
	Natural Hardwoods	12.71	7.87	20.58
	Mixed Hardwood / Softwood	12.35	8.14	20.50
	Natural Softwoods	11.54	8.36	19.90
	Softwood Plantations	10.05	7.56	17.61

Table B2.37: Production cost (\$/GT) comparison between using new and depreciated equipment

Forest type		WT total		CTL total	
		New machine	Depreciated machine	New machine	Depreciated machine
30% Cut					
	Natural Hardwoods	41.20	28.35	35.39	22.74
	Mixed Hardwood / Softwood	41.88	28.32	32.94	21.22
	Natural Softwoods	45.50	31.31	33.65	21.71
	Softwood Plantations	38.25	26.32	28.71	18.52
70% Cut					
	Natural Hardwoods	32.35	22.26	28.44	18.27
	Mixed Hardwood / Softwood	33.11	22.78	27.12	17.45
	Natural Softwoods	30.53	21.01	25.71	16.53
	Softwood Plantations	28.44	19.57	24.05	15.46
Clear cut					
	Natural Hardwoods	22.48	15.47	20.58	13.20
	Mixed Hardwood / Softwood	23.26	16.01	20.50	13.16
	Natural Softwoods	23.88	16.43	19.90	12.80
	Softwood Plantations	21.60	14.86	17.61	11.33

Effect of machine economic life on production cost

To test the effect of machine economic life on production cost, the scenario of 70% partial cut of mixed hardwood/softwood using a CTL harvesting system was used, as this is determined to be the most representative forest type and harvesting system used currently in the State of Michigan. The production cost change by adjusting machine economic life in the other scenarios has been tested to follow the similar pattern shown in Table B2.38.

Sensitivity analysis showed that with an increase of machine economic life, machine hourly rate will decrease, resulting in a final production cost reduction. Results in Figure B2.11 also shows that the change of production cost has an exponential trend, indicating that with the increase of machine economic life, the production cost will be less sensitive to the machine economic life. This strengthens the importance of machine maintenance work at the beginning stage of its life when machine life has a stronger effect on production cost.

Table B2.38: *Production cost (\$/GT) and machine hourly rate (\$/PMH) change of a CTL harvesting system when applying different machine economic life (Years)*

Machine economic life (Years)	Harvester hourly rate (\$/PMH)	Forwarder hourly rate (\$/PMH)	Total production cost (\$/GT)
4	111.29	89.32	19.12
5	100.92	82.21	17.45
6	94.00	77.47	16.34
7	89.07	74.08	15.55
8	85.36	71.54	14.95

Figure B2.11: Effect of machine economic life (years) on total production cost (\$/GT)

Effect of diesel price on production cost

Diesel price is the most concerned factor during harvesting operations, as once the harvesting equipment is purchased and harvesting site is laid out, the daily fluctuated diesel price becomes the most variable part for the harvesting cost control. Diesel price will affect machine operating cost, which will be reflected in the production cost. To test the effect of diesel price on production cost, the scenario of 70% partial cut of mixed hardwood/softwood using a CTL harvesting system was used again. Results in Table B2.39 shows that with an 1\$/gal diesel price increase, the production cost will increase by 0.81 \$/GT. Figure B2.12 shows a straight line in production cost change, indicating the effect of diesel price on production cost is constant, at some point when diesel price is high enough, the total production cost will be inflated to a level that would make the entire operation cost prohibitive.

Table B2.39: Production cost (\$/GT) and machine hourly rate (\$/PMH) change of a CTL harvesting system when applying different diesel price (\$/Gal)

Diesel price (\$/Gal)	Harvester hourly rate (\$/PMH)	Forwarder hourly rate (\$/PMH)	Total production cost (\$/GT)
2.00	95.06	77.58	16.45
3.00	99.83	81.35	17.27
4.00	104.60	85.12	18.08
5.00	109.37	88.89	18.89

Figure B2.12: Effect of diesel price (\$/Gal) on total production cost (\$/GT)

Assumptions used in cost calculation

Most machine hourly cost calculation assumptions used in this report are obtained from literature (Miyata, 1980) and has been used in the FRCS model as defaults. In realistic production cost calculation, however, all the assumptions need to be verified to be reasonable. For example, the repair and maintenance cost used in the machine hourly cost calculation was assumed at 100% of yearly depreciation. When a piece of equipment is completely depreciated, it is heavily biased by the assumption that the yearly repair and maintenance cost is still 100% of yearly depreciation when this particular machine was new. Personal contact with logging contractors indicate that even when machines are completely depreciated, the repair and maintenance costs are far less than 100% of yearly depreciation. For example, the yearly repair and maintenance cost for a completely depreciated, 6 year old forwarder is around 7,000 \$/year, which is less than 20% of its yearly depreciation. The decrease in repair and maintenance cost will finally lead to a reduction in production cost. Since our survey did not request this information from loggers, we kept the repair and maintenance cost at the standard level.

FRCS model predictions

Harvesting production cost comparison between our survey-based results and FRCS model predicted values showed that FRCS model always has a higher production cost. FRCS model is a

forest harvesting and processing cost projection model originally developed in western United States. It has been recently updated by adding location variants to make it work for the northern states, including Michigan. However, FRCS model still has limitations. For example, when simulating a WT harvesting system in Michigan, the FRCS model relevance weights information indicated that the model used nine past studies in California hardwood plantations and southern pine plantations for production cost prediction, partially because harvesting production cost information was not well documented for Michigan although the state has a long history of logging activities. The significant difference in site and terrain conditions between Michigan and other regions suggests high risks in such model predictions, especially when western mountainous areas are usually associated with higher harvesting costs.

The task of analyzing the cost of large-scale forest harvesting operations is not straightforward and is not quite involved. The nature of forest stands in terms of stand conditions and different operating technologies and logistics results in a diverse set of cost values when compared to harvesting plantation. To attempt to address this issue, the project utilized the existing Fuel Reduction Cost Simulator (FRCS) model developed by the USDA Forest Service. Model-run results employed overstocked and fully stocked stands that were harvested using partial cut for all non-aspen stands, and clearcut for all aspen stands. The results understandably were spread out. The survey results were used in an attempt to make comparisons with the FRCS results. Productivity per configuration reported in the survey was converted to units of tons per hour. Using the costing method of the FRCS model for whole tree harvesting, cut to length harvesting and manual harvesting, 43 unique values for the cost of a harvested green ton of biomass were calculated. This is an indication of the non-fixed nature of harvesting under natural stand conditions—no one size fits all. This issue was less of a concern with harvesting plantations. Plantations offer a fixed yield/year/acre that is calculated to reach harvesting cost. Variables in models are less complicated than natural stands variables. Plantation-based models use fixed input values of the number of trees per acre, spacing between stems, rotation age and production per year. Under site-specific conditions in plantations and natural forest stands there is no cheaper or more expensive option, however, plantations do offer a more steady cost analysis option. Natural stands need to be analyzed on a site-specific basis to compare with a plantation productivity cost assessment.

BIOMASS PROCESSING TECHNOLOGIES FOR BIOFUELS/BIOENERGY PRODUCTION

Introduction

In addition to comparing harvesting and handling systems for delivering woody biomass, alternative preprocessing technologies were compared to identify potential bioenergy supply chains for electrical power generation. Comparisons were made by determining the cost of electricity generation at a 100 MWe power plant in which wood chips, wood pellets, or torrefied wood pellets were co-fired with coal. In accordance with Michigan Public Act 295, ten percent of the electrical power produced in our model scenarios was assumed to be provided by renewable energy. The specific preprocessing technologies considered for bioenergy production included chipping, pelletization and torrefaction with pelletization. Chipping and pelletization create a material that is more easily transportable than forest slash and small diameter plantation

trees, while torrefaction produces a mildly carbonized wood product with several desirable characteristics. In the systems analyzed, preprocessing was assumed to occur at either the roadside or in Regional Biomass Preprocessing Depots (RBPDs) that are located near to harvest regions because densification is central to reducing transportation costs. Finally, combinations of these technologies were compared to determine the bioenergy systems that are most appropriate for the range of site conditions within the State of Michigan.

Torrefaction is a preprocessing technology that upgrades woody biomass to a form with desirable physical and chemical properties. In torrefaction, heat is added in the absence of oxygen to perform a mild pyrolysis of the structural components of biomass. Operating conditions include temperatures ranging from 200°C to 400°C and residence times from 5 to 60 minutes, depending upon feedstock quality and the product mix required. Typical values for many applications are expected to be 250-280°C for 8-10 minutes. Generally, 70% of the starting mass is retained in the torrefied wood and this product contains 90% of the energy because a large amount of oxygen is liberated as water and carbon oxides in the product gas.⁴ Heat required by the torrefaction reactor can be supplied by combusting this gas in air with the addition of small amounts of natural gas, though autothermal operation can be achieved if sufficient gas is produced during torrefaction. Torrefaction has been investigated by the Energy Center for the Netherlands (Bergman 2005a) and Agri-tech Producers, LLC (2011) for the purpose of determining technical and economic feasibility. The analysis contained herein serves to provide guidance for the deployment of the selected technologies under Michigan-specific site conditions.

Three bioenergy systems are compared in this analysis. Different preprocessing technologies are used by each system to upgrade woody biomass; the scenarios include: 1) “Wood Chips” for direct co-firing at the power plant, 2) “Wood Pellets” with pelletization at RBPDs, and 3) “Torrefied Wood Pellets” with torrefaction and pelletization occurring at RBPDs. The bioenergy systems for creating electricity from each scenario are depicted in Table B2.41.

The bulk properties of wood chips, torrefied wood chips, wood pellets, and torrefied pellets are included in Table B2.40. The heating value per weight of torrefied materials is greater than wood chips because of the carbonization that has occurred during torrefaction. Wood pellets have a larger lower heating value (LHV) because much of the water has been removed by drying before pelletization. Moisture contents are lower for torrefied and pelletized products as is expected for these processes due to conventional drying operations and heat addition during torrefaction. Finally, the density of the pelletized materials, torrefied and otherwise, was provided by information available in the literature (Bergman 2005b; Suurs, R. 2002; Wu, M.R. et al. 2011; Prins, M.J. et al. 2006).

Table B2.40. **Properties of “wood chips,” “torrefied wood chips,” “wood pellets” and “torrefied pellets”.** Torrefied wood chips have low bulk density and are not analyzed as a separate scenario.

		Chips (dried on-site)	Torrefied Chips	Pellets	Torrefied Pellets
LHV (as received)	GJ/t	12	21	16.7	21
Moisture	%	20%	3%	8%	3%
Density	tonne/m ³	0.2-0.5	0.23	0.60	0.80

The aim of this analysis is to identify the optimum system for electricity production from woody biomass grown in Michigan. Several densification systems are compared using feedstocks from poplar plantations, willow plantations, and natural stands. Chipping is an existing technology and its deployment is well understood. Though wood chips can be co-fired with coal, the costs of transporting wood chips, additional grinding, and costs associated with storage instability pose barriers to coal displacement. To reduce the cost of delivering biomass, densification by pelletization is deployed at RBDs situated near to biomass harvesting areas. Increasing the bulk density of the feedstock reduces the number of trucks needed for hauling biomass to the power plant, and hence the total transportation cost. Though the bulk and energy density are increased by pelletization, the reduced transportation cost must offset the cost of capital to justify this approach. Furthermore, pelletization neither addresses the storage instability due to on-site wood decomposition nor the friability standards desired at co-fired power plants. These limitations can be overcome by RBDs that include torrefaction followed by pelletization. Torrefaction creates a friable, hydrophobic solid with a larger heating value than wood chips or wood pellets. As such, torrefied wood pellets are considered drop-in fuels because they have physical and chemical properties that are similar to coal. Specifically, we aim to determine the circumstances that justify the expenditure of capital to purchase equipment for torrefying and pelletizing woody biomass as well as establish the parameters that encompass optimal deployment of capital equipment at RBDs compared with investment at power plants.

RBD Process Description

Drying

Fresh wood chips can have a moisture content exceeding 50% by weight. In order to reduce the costs of transportation and drying, harvested trees were dried on-site before chipping. It was assumed in this analysis that on-site drying for a period of eight months lowered the moisture content of biomass from 50% to 20%. As 20% moisture is still too wet for the RBD to convert the wood chips to solid fuel, the wood chips were dried using a tube bundle dryer. For the torrefied wood pellets, the drying cost can be reduced due to the replacement of natural gas using torrefaction gases. These off-gases from biomass during torrefaction consist of a wide variety of combustible organic components¹ which can provide the heat needed for drying. As a result of drying, the cost of subsequent transportation is reduced as undesired moisture is no longer carried to the power plant.

Pelletization

Biomass pelletization is a process for reducing the bulk volume of the material by mechanical means to produce cylindrical pellets of compressed biomass. Due to smaller volume and higher volumetric energy density, wood pellets are easier to handle, transport and store compared to wood chips. The production of pellets requires small feedstock particles with a maximum characteristic length of 3–20mm and a moisture content below 10%-15% (Repellin, V. et al., 2010). A ring die pelletizer is used in this analysis as discussed by Thek et al. (2004). For this type of pelletizer, die replacement is a significant cost because of abrasion of metal surfaces.

Grinding

Hammer mills were selected to grind biomass prior to pelletization. Because torrefaction increases the friability of woody biomass, the scenario 3 (torrefied wood pellets) grinding cost was reduced greatly. Increased friability as a result of torrefaction has been documented to save up to 90% of the energy used for grinding (Repellin, V. et al., 2010).

Torrefaction

Torrefaction is a pretreatment technology that involves heating biomass to temperatures between 200°C and 400°C in the absence of oxygen to improve its heating value and storage stability. Transportation costs are reduced for torrefied wood pellets as the heating values approaches 21 MJ/kg which is greater than wood chips or wood pellets. Torrefaction and pelletization are typically performed in sequence to produce a densified, torrefied product (Bergman, 2005a) that can be transported large distances by rail, ship or truck. Storage losses are also minimized by torrefaction as torrefied wood resists the microbial decomposition that effects wood chips and wood pellets. The application of torrefaction at power plants to improve friability prior to size reduction was not considered by this analysis, but may also merit examination in future assessments.

Storage

In order to maintain continuous operation at RBPDs, the on-site storage capacity was assumed to be 8% of the annual production rate (Thek et al., 2004). As wood chips are more susceptible to microbial degradation during open storage, enclosed storage units are required. Silos are the most widely used storage units for the wood chips, and investment costs typically range from \$500,000 to \$900,000. According to Surrs et al., 2002, the storage cost of silos is equal to \$13.5/m³.

Storage units are also needed at the power plant and will differ according to the various products. While wood chips and wood pellets require an enclosed system, torrefied wood pellets can be stored outdoors. Furthermore, because of the low energy density of wood chips, more wood chips have to be stored at the power plant in order to provide enough feedstock to continuously operate the boiler.

Figure B2.13. A depiction of the three systems being compared. 1) “Wood Chips” for direct co-firing at the power plant, 2) “Wood Pellets” with pelletization at RBPDs, and 3) “Torrefied Wood Pellets” with torrefaction and pelletization occurring at RBPDs.

Methodology

Select most Appropriate HFP Models for Michigan

Michigan provides suitable growing conditions for cultivating poplar and willow in energy plantations. After surveying the existing plantation models for estimating the “farm-gate” costs of harvested biomass, the EcoWillow model (v. 1.0) developed at the State University of New York (SUNY) (Tharakan, P.J. et al., 2005) and a model for poplar plantations developed at Oak Ridge National Laboratory (ORNL) were adopted and adapted for our analyses.

The SUNY model was first released in April 2008 for describing willow plantations. It is based on over 20 years of research on shrub willow as a dedicated energy crop in upstate New York. This model was used to estimate the costs of site preparation, cultivation, harvesting, and chipping. Though capable of estimating transportation, this component of the SUNY model was removed so that the costs of willow can be directly compared to the costs of biomass predicted by the ORNL and FRCS models, which do not include transportation. The model inputs to the SUNY model reflect those that can be expected of Michigan site conditions. Examples of model inputs are shown in Table B2.41. These inputs are subjected to either three or four year rotations (an option of the SUNY model) to estimate the farm-gate costs for a specified investment time frame

Table B2.41. SUNY model inputs for cultivating shrub willow under Michigan-specific site conditions.

Model Inputs	Units	Value
Project life	yrs	22
Land costs (tax, lease and insurance)	\$/acre/yr	32
Headlands	% of acreage	8%
Annual harvest yield	dry ton/acre/yr	5
Planting density	cuttings/acre	5,800
Planting stock	\$/cutting	0.12
Harvester speed	mi/hr	4

The ORNL model estimates the cost of harvesting poplar grown in plantations. Rotation timeframes of six and twelve years can be temporally modeled and tree spacing of 6 ft x 6 ft and 10 ft x 10 ft can be spatially modeled. The model was modified to reflect Michigan site conditions which dictate an 8 ft x 8 ft spacing (681 trees per acre) and a six year rotation (MSU Extension, 2011). Examples of model inputs are shown in Table B2.42.

Table B2.42. ORNL model inputs for growing poplar under Michigan-specific site conditions.

Model Inputs	Units	Value
Land costs (tax, lease and insurance)	\$/acre/yr	32
Annual harvest yield	dry ton/ac/yr	6
Price/cutting	\$/tree	0.10
Planting price/cutting	\$/tree	0.05
Spacing (6 yrs rotation)	ft ²	64
Planting density (6 yrs rotation)	trees/acre	681
Spacing (12 yrs rotation)	ft ²	100
Planting density (12 yrs rotation)	trees/acre	436

Specific manufacturers of harvesting equipment were not specified in the SUNY model. Harvesting parameters that served as SUNY model inputs are displayed in Table B2.43. Conventional harvesting systems are employed by the ORNL model and the input parameters are included in Table B2.44. After drying, chipping was performed on-site prior to hauling 20 miles to the RBPB or in the case of wood chips, 20 miles plus the specified transportation distance to the power station. The cost of chipping for all scenarios is included in Table B2.44. Again, all inputs are based on Michigan site conditions.

Table B2.43. Harvesting inputs for the SUNY model.

Parameters	Units	Value
Number of harvesters		1
Transport harvester	\$/mile	11
Distance	mile	50
Harvester rental	\$/hr/unit	180
Harvester fuel consumption	gal/hr	16
Trailer-tractor rental	\$/hr/unit	60
Trailer-tractor fuel consumption	gal/hr	2.6
Blower-tractor unit rental	\$/hr/unit	50
Blower-tractor fuel consumption	l/hr	5
Maintenance	\$/acre	5

Table B2.44. Harvesting inputs for the ORNL model including chipping parameters.

Equipment	Purchase Price (\$)	Salvage Value (\$)	Service Life (yr)	Annual Use (hrs)	Fuel use (gal/hr)
Feller-buncher head	35,000	4,353	4	1,000	0.00
100 HP tractor	40,100	6,262	12	833	4.94
Skidder-120 HP	130,000	26,713	5	2,000	3.50
Chipper-400 HP	175,000	20,437	5	2,000	9.17
Pickup truck	18,400	3,312	10	2,000	2.25

Select Feasible Processing Technologies

Biomass processing includes such unit operations as size reduction by chipping or grinding, densification by pelletization or briquetting, and feedstock upgrading by torrefaction. Alone or in combination, these processing steps are used to produce a feedstock for blending with coal at power plants. Three scenarios were considered in this study: 1) chipping in the field and direct transport to the power plant (denoted as the “wood chips” scenario), 2) chipping in the field followed by pelletization at a RBPD and transport to a power plant (“wood pellets”), and 3) chipping in the field, followed by torrefaction, milling, and pelletization at a RBPD and then transport to a power plant (“torrefied wood pellets”). As each power plant feedstock has a different heating value (as received) when combusted, comparisons are made by computing the cost contribution of each scenario to the electrical power cost, expressed in units of dollars per kilowatt-hour (\$/kWh). All three scenarios are scaled to provide sufficient raw material to provide 10% renewable electricity at a 100 MWe power plant. Therefore, each scenario was solved in reverse, starting with the amount of electrical power produced in one year, followed by determining the required mass flow rate of power plant feedstock, the mass flow rate to the RBPD, and finally the amount of biomass harvested. Once the amount of harvested biomass was determined, the area of harvest was calculated assuming that only 20% of the surrounding area was available for harvest.

The costs for each scenario were determined by constructing cost models using standard engineering practice. Costs of capital and operation for each unit operation were included in the model. Feedstock costs, the largest single cost at the RBPDs, were estimated using the FRCS model for natural stands, the SUNY model for willow plantations, and the ORNL model for poplar plantations. Chipping cost information was provided by Surrs, R. (2002) while the cost of pelletization was determined by Thek et al. (2004). Torrefaction costs were estimated using the reports provided on-line by Agri-tech Producers, LLC. Models were constructed in Microsoft Excel such that key process parameters, feedstock properties and product properties can be varied to examine the sensitivity of cost to varying inputs.

Analyze Economies of Scale for Regional Processing Technologies

The effect of processing capacity on the scale of capital investment was included in this analysis using the sixth tenths rule. The sixth-tenths rule is widely accepted as appropriate for scaling

capital investment and involves the use of a power law model to relate the ratio of capital investment costs (large divided by small) to the ratio of processing capacities (large divided by small) to the six-tenths power. Capital equipment costs obtained from academic literature, on-line sources, reference libraries, and vendors were scaled in this fashion to accurately compute the capital investment at the scale needed to deliver sufficient power plant feedstock to produce 10 MWe (10% of 100 MWe).

Conduct Sensitivity Analyses for HFP Systems under Consideration

A sensitivity analysis of willow plantations was performed using the SUNY model. A base case scenario using a four year rotation cycle was selected because of favorable cost. This base case scenario was simulated for a plantation area of 20 acres, a biomass yield equal to 5 dt/acre/yr, and a land cost of \$32/acre. As land costs range from \$14/acre to \$50/acre in Michigan according to Dr. Ray Miller (2011) (Director of the Forest Biomass Innovation Center), land cost in the SUNY model was varied within this range to predict costs. Yield was also selected due to its anticipated effect on biomass cost. Willow yields in Michigan's Upper Peninsula range from 3 dt/acre/yr to 5 dt/acre/yr, while yields in the Lower Peninsula can approach 7 dt/acre/yr. Harvest yields were varied within the range of 3 to 7 dt/acre/yr to determine the impact on cost. In addition to varying land cost, diesel price and harvest yield, the cost of labor was varied. The costs of four laborers and one foreman were projected to determine total costs of willow at the farm gate.

A similar sensitivity analysis was performed on poplar plantations using the ORNL model. A six year rotation cycle was selected because of favorable economics versus twelve year rotations. The base case scenario included a tree spacing of 8 ft × 8 ft, a biomass yield 6 dt/acre/yr, and the land cost of \$32/ acre. Land cost, harvest yield, diesel price and labor rate were varied in the same manner as for willow to reflect the variability to be expected in Michigan.

A sensitivity analysis was also performed for the third bioenergy scenario involving torrefaction and pelletization at RBPDs. A plot of torrefied pellet cost per gigajoule (\$/GJ) versus the change in each selected variable in an amount relative to the base case (in %) was constructed to identify the variables most affecting the cost of power plant feedstock. Biomass price at the gate of the RBPD was included because of its anticipated impact on torrefied pellet cost. Electricity usage at the RBPD is a major cost when grinding and pelletization equipment are included at the RBPDs, so electricity consumption is varied accordingly. Service life was examined because the torrefaction reactor, grinding mills, and pelletizers involve moving metal parts that are subject to abrasion and corrosion. Transport distance to the power plant is included as a variable as transportation by truck impacts biomass cost. Finally, the cost of labor was varied to determine whether a refinement of the labor analysis is justified to improve the model's accuracy. The results of the sensitivity analysis for the RBPD producing torrefied pellets are applicable to the wood chips and wood pellets scenarios as these scenarios comprise a subset of the torrefied pellet scenario.

Compare Alternative Scenarios

Power generation from wood chips, wood pellets and torrefied wood pellets were compared to determine the best application of each technology sequence in the State of Michigan. The aim of this comparison is to determine the conditions for which each scenario is favored. This comparison anticipates that long-distance trucking will favor scenarios two and three which involve pelletization and the magnitude of this distance is to be determined through analysis. The cost of each scenario is computed per kWh of electricity produced from biomass alone, not including the costs inside the power plant. The cost contribution towards electrical power was then compared amongst the bioenergy systems.

Results and Discussion

Three different bioenergy scenarios were selected for producing a feedstock for electrical power generation; these scenarios are depicted in Figure B2.11 and include: 1) chipping in the field and direct transport to the power plant (denoted as the “wood chips” scenario), 2) chipping in the field followed by pelletization at a RBPDP and transport to a power plant (“wood pellets”), and 3) chipping in the field, followed by torrefaction, milling, and pelletization at a RBPDP and then transport to a power plant (“torrefied wood pellets”). The cost contribution to electric power was determined by estimating the costs of each component and unit operation in the system. Poplar and willow costs were estimated from previously developed plantation models by ORNL and SUNY, respectively. Capital investment was estimated using equipment costs provided in the literature and scaling with capacity using the six-tenths rule. Comparisons amongst the bioenergy scenarios are made upon determining the cost per kWh of electricity produced.

Plantation models

The SUNY model (EcoWillow v.1.0 beta) was used to estimate the costs of site preparation, cultivation, harvesting, and chipping. As mentioned in the methodology, the transportation component of this model was removed to compare the cost of biomass with the ORNL and FRCS model outcomes. The results of the SUNY model are displayed in Table B2.48 for rotation cycles of three and four years, which is an option provided by the SUNY model. As portrayed in Table B2.45, willow chips can be produced at a farm-gate cost of \$55.92 per dry ton when using a four year rotation cycle under Michigan site conditions. Biomass at this cost should be available for bioenergy production as per the Billion-ton Study Update (Perlack, R.D. and Stokes, B.J. 2011).

Table B2.45. Results computed for willow by the SUNY model for three and four year rotation cycles.

SUNY Results for Willow	Rotation Cycle	
	3 years	4 years
Cultivation (\$/dt)	36.20	35.50
Harvesting (\$/dt)	21.30	16.00
Chipping (\$/dt)	4.42	4.42
Total (farm gate chips \$/dt)	61.92	55.92

The ORNL model was used to calculate the cost of wood chips from poplar plantations on six and twelve year rotations using a plant spacing of 6 ft x 6 ft and 10 ft x 10 ft. Michigan site conditions better support an 8 ft x 8 ft spacing for a six year rotation cycle as indicated by MSU Extension in Escanaba, Michigan (2011). Table B2.46 contains the results computed by the

ORNL model for poplar plantations using six and twelve year rotation cycles. Under the six year rotation cycle, poplar chips can be made available at \$41.30 per dry ton under Michigan site conditions. The cost of poplar is less than willow because fewer cuttings per acre are required due to a relatively long rotation cycle, i.e. six or twelve years vs. three or four years for willow. The cutting cost for poplar is \$68/acre, which compares favorably to willow which can be as high as \$580/acre. In addition, poplar has a higher annual yield at 6 dt/acre-yr compared with willow at 5 dt/acre-yr. A larger biomass stock when harvesting poplar, due to a higher yield and a longer rotation cycle, results in more efficient harvesting. Biomass at this cost should be available for bioenergy production as per the Billion-ton Study Update (Perlack, R.D. and Stokes, B.J. 2011).

Table B2.46. Results computed by the ORNL model for 6 and 12 year rotation cycles.

ORNL Results for Poplar	Rotation Cycle	
	6 years	12 years
Cultivation (\$/dt)	20.65	25.81
Harvesting (\$/dt)	16.23	10.39
Chipping (\$/dt)	4.42	4.42
Total (farm gate chips \$/dt)	41.30	41.23

Both plantation models were subjected to a sensitivity analysis to show the effects of variable inputs, parameters or properties on the output cost. Each variable was changed independently of the other variables, therefore while variation in output cost was assessed for one variable, the others were held constant. By plotting the output cost versus the percent change for each variable examined, the variable with the largest effect on output cost can be clearly identified. Figure B2.14 is a sensitivity plot of harvest yield, land cost, labor rate, and diesel fuel price versus the output cost of willow chips for a four year rotation and a 13 year investment timeframe. The base case cost of \$55.92 per dry ton is presented in Table B2.46 at a change rate (abscissa) of 0%. Clearly, the harvest yield has the greatest effect on output cost, as only a slight increase in yield of 10% will decrease the output cost to approximately \$50 per dry ton. Land cost, labor rate, and diesel fuel price have a lesser effect on the cost of willow chips. Figure B2.15 shows a similar analysis for poplar chips using the ORNL model for the six year rotation cycle. Again, a 10% increase in yield reduces the cost of poplar chips from \$41.30 to approximately \$39 per dry ton. Also consistent with willow chips, the cost of poplar chips is less sensitive to fluctuations in land cost, labor rate and the price of diesel fuel.

Figure B2.14. Sensitivity analysis for willow chips using a four year rotation and a 13 year investment period. A change rate of 0% corresponds to the base case specified in Table B2.45.

Figure B2.15. Sensitivity analysis for poplar chips using a six year rotation. A change rate of 0% corresponds to the base case specified in Table B2.49.

Preprocessing model scenarios

Three models were constructed to determine the costs and to identify the barriers to implementation associated with each scenario. All three scenarios were scaled to provide sufficient feedstock to displace 10% of the fossil energy required to operate a 100 MWe power plant for a time period of one year. The input cost to each preprocessing model was computed using the appropriate feedstock model, i.e. the SUNY model for willow plantations, the ORNL model for poplar plantations, or the FRCS model for natural stands. Scenario 1, which consists of cultivation, harvesting, on-site drying, chipping, transportation, on-site storage, and conversion to electrical power was developed by formulating mass and energy balances for each

component in the system. The amount of energy required for chipping, and hence the cost, was computed by ORNL model. Transportation costs were determined upon estimation of distance-fixed and distance variables costs, \$3.72 per ton and \$0.074 per ton-mile respectively. Scenarios 2 and 3 also include cultivation, harvesting, on-site drying, chipping, transportation and storage costs (though storage losses at the power plant by scenario 3 are negligible). Transportation costs decrease when hauling densified material because of increased load size per truck. Scenario 2 includes the electrical costs associated with operating a pelletizer as reported by Thek et al. (2004). Scenario 3 includes pelletization costs similarly, though pelletization occurs after torrefaction and grinding. Torrefaction costs, both capital and operating, were modeled in accordance with the different reactors developed by Agri-tech Producers, LLC, and the Energy Center of the Netherlands (ECN). Grinding costs after torrefaction were modeled to reflect the increased friability observed by Repellin, V., et al. (2010). Capital and operating costs estimates are to be regarded as preliminary in nature, and may be portrayed as accurate to within plus and minus 50%. Further analytical, laboratory and pilot-scale efforts are needed to narrow the expected estimation error and further de-risk these bioenergy production systems.

Capital costs

Equipment costs were determined using previously reported costs by the academic literature and institutional reports as well as company information from brochures, websites and personal communications. All equipment costs were determined in the year 2004 or later, and these costs were not adjusted for inflation. Table B2.47 contains costs for the major equipment items in the three scenarios for the production capacities that are specified. The equipment costs displayed in Table 8 were calculated using the base equipment cost and capacity provided by the referenced source to the desired capacity using the six-tenths power-law model for scaling capital investment. Installed costs for equipment were determined using a Lang factor of 3.1, which is consistent with mature industries. A capacity of 10 MWe, which is capable of displacing 10% of the fossil electrical power produced at a 100 MWe power plant, was selected as the output for each scenario.

Operating costs

Preliminary operating costs were determined for the three scenarios. Feedstock costs were determined by the ORNL model for poplar plantations, by the SUNY model for willow plantations, and by the FRCS for natural stands. Table B2.48 contains the cost of torrefied wood pellets from each feedstock source. Natural stand feedstocks were found to be the most costly when either the FRCS was applied or when using the results of our logger survey. Poplar was found to be the least costly, because of the significantly lower cultivation and harvesting costs, therefore poplar is chosen as the feedstock for assessing the three bioenergy scenarios under consideration. Natural gas and electricity are the two primary utilities used by the three scenarios. Electricity was assumed to be available at 7.2 cents/kWh, which is in accordance with the industrial retail price in Michigan in 2010 (U.S. EIA). Natural gas was assumed to be \$9.3 per standard thousand cubic feet, a value based on the average industrial retail price in 2010 in Michigan (U.S. EIA). Costs of the three products, i.e. “wood chips,” “wood pellets,” and “torrefied wood pellets,” were determined using poplar in six year plantations and are shown in Table B2.49. Wood pellets and torrefied wood pellets have higher operating costs than wood chips because of greater capital investment and higher maintenance costs. However, wood chips require further processing at the power station because of high moisture content and reduced

friability when compared with coal. Therefore, when the cost of drying, constructing storage facilities, and additional grinding equipment are included in the analysis at the power facility, the cost of wood chips will increase.

Table B2.47. Capital costs and important operating information for the major equipment items considered in the three scenarios. Base equipment costs were obtained from the references provided. The equipment costs portrayed were computed by scaling the base equipment cost with capacity using the six-tenths power law model. Equipment capacity is sufficient to displace 10% of the fossil energy required to operate a 100 MWe power plant.

Parameter	Units	Value
<i>Drying (Suurs, 2002; Thek et al., 2004)</i>		
Unit type		Tube bundle dryer
Investment	\$	983,890
Water evaporation rate	t/hr	6.7
Utilization period	yr	15
Required electrical power	kW	77.5
<i>Torrefaction (Bergman, 2005a,c; Agri-tech, 2011)</i>		
Unit type		Torre-tech 5.0
Investment	\$	6,436,000
Capacity	t/hr	5.4
Utilization period	yr	15
Required electrical power	kW	225
required heat energy	Btu/hr	200,000
<i>Grinding (Suurs, 2002; Repellin, 2010; Thek et al. 2004)</i>		
Unit type		Hammer mill
Investment	\$	193,622
Capacity	t/hr	5.4
Utilization period	yr	10
Required electrical power	kW	110
<i>Pelletization (Suurs, 2002; Thek et al. , 2004)</i>		
Unit type		Ring die
Investment	\$	438,000
Capacity	t/hr	3
Utilization period	yr	10
Required electrical power	kW	233
<i>Cooling (Thek et al. , 2004)</i>		
Unit type		Counter flow
Investment	\$	29,970
Capacity	t/hr	5
Utilization period	yr	10
Required electrical power	kW	12
<i>Peripheral Equipment (Thek et al. , 2004)</i>		
Unit type		
Investment	\$	1,152,000
Utilization period	yr	10
Required electrical power	kW	90

Table B2.48. Comparison of torrefied wood costs using feedstock from poplar plantations, willow plantations, or natural stands. A stumpage cost of \$12/green ton has been included in the cost of natural stands. Green wood was assumed to contain 50% moisture by mass.

		Biomass Cost	Torrefied Wood Pellet Cost
Natural stands		\$/dry ton	(\$/GJ)
Partial Cut	Survey based results	89.48	8.18
	FRCS based results	95.38	8.52
Clear cut	Survey based results	71.66	7.15
	FRCS based results	111.02	9.43
Plantations		\$/ dry ton	\$/GJ
Willow	3 yrs rotation	61.92	6.59
	4 yrs rotation	55.92	6.25
Poplar	6 years rotation	41.33	5.40
	12 years rotation	41.23	5.40

Table B2.49. Costs of wood chips, pellets and torrefied pellets using poplar (grown in a six year rotation) as feedstock when delivered to the power plant assuming a 100 mile transport distance. Costs are portrayed as \$ per ton (as received); \$ per GJ (as received; LHV); and cents per kWh of electricity produced (cost contribution of feedstock to the cost of electrical power).

	Wood Chips	Wood Pellets	Torrefied Wood Pellets
\$/t	54.80	90.67	111.39
\$/GJ	4.567	5.429	5.304
Cents/kWh	4.75	5.58	5.46

Costs for the three scenarios are also compared in Figure B2.14, which displays the relative costs of each component when feedstock is transported 100 miles. The costs are determined on a kWh of electricity basis so that the three scenarios can be equivalently compared. From Figure B2.14, the cost of wood chips is greatest for the “wood chips” scenario because the higher moisture content of wood chips causes lower thermal efficiency. Storage costs are the greatest for the “wood chips” scenario as wood chips are subject to microbial degradation. Further, because the energy density of wood chips is the lowest, the largest land area is needed for on-site storage. Transportation costs for “wood chips” are also greater than for “wood pellets” or “torrefied wood pellets,” a result of the increased energy density of biomass that has been pelletized. It is important to note that the lower overall costs of the “wood chip” scenario do not reflect additional equipment at the power plant that may be needed for further grinding or moisture removal. Upon including these additional equipment items, the difference between scenario costs is expected to narrow significantly when feedstock is transported 100 miles to the a centralized power plant. Comparisons of scenarios two and three reveal several differences even though the overall cost contributions to electrical power generation are approximately the same. Wood chip cost is greater for torrefaction because of the mass loss that accompanies mild heat treatment. The cost of peripheral equipment and labor is lower for torrefaction because a higher energy value per products ton leads to more efficient operation of equipment and increased worker efficiency. Drying costs are significantly lower for torrefaction, as the co-product gas provides the needed

heat, while for pelletization the purchase of natural gas is required. Though the expense of torrefaction is significant, as seen in Figure B2.16, the subsequent costs of grinding and pelletization (after torrefaction) are reduced because of increased friability and the increased specific energy of torrefied wood. Storage costs are lower for torrefied wood as unlike wood pellets, torrefied wood is not subject to microbial degradation. Decreased transportation costs are a result of the increased energy density of the torrefied wood pellets versus wood pellets. If the costs associated with biomass torrefaction can be reduced, the torrefaction scenario will offer significant advantages versus the combustion of wood chips and wood pellets even when the transportation distance is only 100 miles.

Figure B2.16. Cost contribution to electrical power generation from wood chips, wood pellets and torrefied wood pellets when a distance of 100 miles from the RBPD to the power plant is applied. Poplar was used as the feedstock at a biomass cost of \$41.33/dt.

The choice of scenario clearly changes upon increasing the transportation distance from 100 miles to 300 miles as shown in Figure B2.17. Even when the purchase of grinding and drying equipment at the power plant is not considered, the cost of wood chips exceeds the cost of wood pellets and torrefied wood chips, as a result of low energy density. Torrefied wood pellet costs are lower than wood pellet costs at this transport distance, as the increased energy density of torrefaction becomes more significant. Figure B2.18 contains a plot of transport distance versus the cost contribution to electrical power generation for the three scenarios under consideration. At distances that exceed 250 miles, the cost of torrefaction is lower than the cost of chipping and direct co-firing. Also from Figure B2.18, torrefaction is always less costly than pelletization alone, due to the increased energy density and improved properties of the torrefied wood pellets. As torrefaction appears to offer considerable benefits, further analysis is needed to verify the findings of this study. As can be clearly concluded from Figures B2.16 and B2.17, technologies that reduce the associated torrefaction cost should be actively researched and pursued to lower this component of the overall cost.

Figure B2.17. Cost contribution to electrical power generation from wood chips, wood pellets and torrefied wood pellets when a distance of 300 miles from the RBPD to the power plant is applied. Poplar was used as the feedstock at a biomass cost of \$41.33/dt.

Figure B2.18. Cost comparison of the three scenarios at the power plant gate at varying transportation distance. Transport cost was calculated using a fixed cost of \$3.72/ton and a variable cost of \$0.074/ton-mile. An individual truck capacity of 40 tons was used for this analysis.

Figure B2.19 presents the costs of power plant feedstock for each scenario on a dry ton basis. Comparisons between the scenarios should not be made from this figure, as the energy content of each feedstock is significantly different. The relative costs of each supply chain component can be compared within each scenario using this diagram. For wood chips, cultivation, harvesting

and chipping are the dominant costs, though storage and transportation are also significant. Peripheral equipment and labor, drying and transportation are also important costs for the wood pellet scenario. The cost of torrefaction contributes significant cost to the overall cost of torrefied wood pellets, and again, the design of low cost torrefaction technologies should be pursued. Overall, the cost of wood chips at least comprises the plurality of cost for all components considered.

Figure B2.19. Costs of power plant feedstock of each scenario on a dry basis. Transportation cost is included as a distance of 100 miles is assumed. Poplar at a cost of \$41.33/dt was used as feedstock.

Sensitivity Analysis of Scenario 3 (Torrefied wood pellets)

A sensitivity analysis of scenario 3 was performed to determine the input variables that most affect the output cost. From this analysis, graphically portrayed in Figure B2.20, the most significant variable is the biomass cost at the farm gate. Increasing biomass cost from \$27/dry ton to \$62/ dry ton increases the torrefied wood pellets cost from \$4/GJ to \$7/GJ. Service life of the equipment is the second most sensitive input, as the longer period for capital depreciation lowers the overall cost. As was previously concluded, the capital investment of the torrefaction reactor is especially important when devising a plan to reduce the costs for this scenario.

Figure B2.20. Sensitivity analysis for scenario 3: “Torrefied wood pellets.” Costs are in U.S. dollars per GJ of torrefied wood pellets.

Summary

Torrefied wood pellets are hydrophobic and friable and are not likely to require significant modifications in the storage, handling and size reduction areas of the power plant. Conversely, wood chips contain significant water and will either require drying or will result in reduced combustion energy in the power plant’s furnace. Furthermore, outdoor storage subjects both wood chips and wood pellets to infiltration by rainwater which will further reduce the energy quality during combustion. Wood chips and pellets will begin to decompose at moisture contents above 20% as microbial contamination converts biomass into gaseous products. Covered storage options can be explored, but will require further investment. Additionally, the cost of size reduction is greater for wood chips and pellets versus torrefied pellets because of the fibrous nature of woody biomass. Upon pulverization, particles of woody biomass tend to remain interconnected, which reduces the efficiency of combustion in the power plant’s furnace. Torrefaction increases the friability of woody biomass which reduces the pulverization costs in conventional ball mills. Because of improved storage stability and increased friability, torrefied wood pellets can potentially serve as “drop-in” fuels for renewable electric power production.

Torrefied wood pellets offer significant advantages versus traditional wood pellets and wood chips. However, the cost contribution of torrefied wood pellets to electrical power generation remains greater than coal. For scenarios 2 and 3, the biomass cost contribution to electrical power generation at the entry gate of the RBPD exceeds \$0.02 per kWh. Processing costs within the RBPD and subsequent transportation of 300 miles adds another \$0.03 per kWh, for a total power plant feedstock cost of around \$0.056 per kWh. Torrefied wood pellets and wood pellets offer another approach to meeting the 10% renewable electricity mandate set forth in MI Public Act 295 for the year 2015.

The advantages of torrefied wood pellets versus wood chips include: 1) reduced transportation costs due to densification, 2) improved storage stability due to increased hydrophobicity, and 3) reduced grinding costs due to increased friability. Scenarios that involve long distance

transportation are especially benefited by torrefaction and pelletization. Preliminary analysis suggests that significant cost savings can be found when employing transoceanic transport of torrefied wood pellets versus non-densified biomass. Overland truck transport costs reflect this conclusion for the three products investigated by our analysis. We conclude that for bioenergy systems that involve long transportation distances, torrefaction and pelletization are justified.

We recommend that further consideration and analysis be given investigating the torrefaction of both poplar and willow plantation materials. Though energy plantations of this sort currently do not exist, the Billion-ton Study Update (Perlack, R.D. and Stokes, B.J. 2011) clearly states the importance of such energy crops. For long distance transportation, the costs of torrefied wood pellets are lower than those for wood pellets and wood chips. Shorter transportation distances may also be justifiable when the additional processing costs at power plants are included for wood chips and when accurate torrefaction investment costs are made available. Optimization of torrefaction will provide a clear opportunity for further reducing the costs of this bioenergy scenario, and new torrefaction technologies should be considered to improve the outlook for this alternative energy technology.

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

Surveying Michigan loggers resulted in a snapshot of the harvesting, extracting and processing equipment available in 2009 and 2010. Based on the observations made after reflecting upon the survey results, several conclusions and recommendations can be made for future work. First, as most harvesting operations were from partial cut treatments, it would not be prudent to assume that an entire area would be clear cut to supply biomass to a new facility. Second, from the survey, most products were extracted from lands defined as “other public lands” and then delivered to pulp and paper industries. It is recommended that the amount and types of material on “other public lands” be accurately assessed. Third, saw logs and pulpwood were the most common types of product removed from the forest while woodchips were the least. The cost of chippers and the breadth of experience that loggers have using chippers will require further assessment. Fourth, a variety of logging equipment was used; including mechanical whole tree harvesting, cut-to-length harvesting and manual whole tree harvesting. Both mechanical whole tree and cut-to-length systems were capable of delivering biomass at lower costs than the manual systems, as such loggers should consider mechanical harvesting at the large volumes required by bioenergy systems to displace fossil energy sources.

The costs of chipped wood ranged from \$13.28 to \$27.11 per green ton as calculated based on survey based data for a clear cut in softwood plantations and for 30% cut in natural hardwoods, respectively, and by adding \$4.37 for chipping cost.. Increasing the amount of removal significantly reduces cost, which are further reduced when clear cutting. Overall, harvesting costs are highly variable and dependent upon the type of equipment, level of harvesting (clear-cut vs. selective cut), type of forest, and the tree stand density. Generally, the FRCS model predicted costs were higher than those provided by the loggers’ survey. Management factors affecting cost were found to be machine economic life and price of diesel fuel.

Torrefied wood pellets are hydrophobic and friable and are not likely to require significant modifications in the storage, handling and size reduction areas of the power plant. Conversely, wood chips contain significant water and will either require drying or will result in reduced combustion energy in the power plant's furnace. Furthermore, outdoor storage subjects both wood chips and wood pellets to infiltration by rainwater which will further reduce the energy quality during combustion. Wood chips and pellets will begin to decompose at moisture contents above 20% as microbial contamination converts biomass into gaseous products. Covered storage options can be explored, but will require further investment. Additionally, the cost of size reduction is greater for wood chips and pellets versus torrefied pellets because of the fibrous nature of woody biomass. Upon pulverization, particles of woody biomass tend to remain interconnected, which reduces the efficiency of combustion in the power plant's furnace. Torrefaction increases the friability of woody biomass which reduces the pulverization costs in conventional ball mills. Because of improved storage stability and increased friability, torrefied wood pellets can potentially serve as "drop-in" fuels for renewable electric power production.

Torrefied wood pellets offer significant advantages versus traditional wood pellets and wood chips. However, the cost contribution of torrefied wood pellets to electrical power generation remains greater than coal. For scenarios 2 and 3, the biomass cost contribution to electrical power generation at the entry gate of the RBPD exceeds \$0.02 per kWh. Processing costs within the RBPD and subsequent transportation of 300 miles adds another \$0.03 per kWh, for a total power plant feedstock cost of around \$0.056 per kWh. Torrefied wood pellets and wood pellets offer another approach to meeting the 10% renewable electricity mandate set forth in MI Public Act 295 for the year 2015.

The advantages of torrefied wood pellets versus wood chips include: 1) reduced transportation costs due to densification, 2) improved storage stability due to increased hydrophobicity, and 3) reduced grinding costs due to increased friability. Scenarios that involve long distance transportation are especially benefited by torrefaction and pelletization. Bergman et al ¹ determined that significant cost savings can be found when employing transoceanic transport of torrefied wood pellets versus non-densified biomass. Overland truck transport costs reflect this conclusion for the three products investigated by our analysis. We conclude that for bioenergy systems that involve long transportation distances, torrefaction and pelletization are justified.

We recommend that further consideration and analysis be given investigating the torrefaction of both poplar and willow plantation materials. Though energy plantations of this sort currently do not exist, the Billion-ton Study Update (Perlack, R.D. and Stokes, B.J. 2011) clearly states the importance of such energy crops. For long distance transportation, the costs of torrefied wood pellets are lower than those for wood pellets and wood chips. Shorter transportation distances may also be justifiable when the additional processing costs at power plants are included for wood chips and when accurate torrefaction investment costs are made available. Optimization of torrefaction will provide a clear opportunity for further reducing the costs of this bioenergy scenario, and new torrefaction technologies should be considered to improve the outlook for this alternative energy technology.

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B2(a): Comprehensive Literature Review of Available HFP Models

INTRODUCTION

Current research on the harvest system cost and modeling was examined in the literature review. This review was organized into three categories where the fundamentals of each article were summarized together into key attributes. The Three categories included the modeling and research associated with “*Modeling Fuel Reduction/Forest Harvesting*”, “*Timber Harvest Outputs/ Supply Chain*” and “*Economics/ Market Impacts*”. The review that follows includes these category titles followed by a summary of the literature within that category.

MODELING FUEL REDUCTION/FOREST HARVESTING

TITLE: Assessing the cost of fuel reduction treatments: A critical review

Author(s): Rummer B

Source: FOREST POLICY AND ECONOMICS Volume: 10 Issue: 6 Pages: 355-362

Published: AUG 2008

Abstract: The basic costs of the operations for implementing fuel reduction treatments are used to evaluate treatment effectiveness, select among alternatives, estimate total project costs, and build national program strategies. However, a review of the literature indicates that there is questionable basis for many of the general estimates used to date. Different approaches to estimating cost have been used. Four methods are reviewed with discussion of the appropriate applications to fuel reduction cost analysis. Critical gaps identified in the understanding of operations costs include business overhead, repair and maintenance reserves, and estimates of the cost of risk. Future analyses of fuel treatments should be cautious in extrapolating cost numbers from the existing literature. Published by Elsevier B.V.

TITLE: Objectives and considerations for wildland fuel treatment in forested ecosystems of the interior western United States

Author(s): Reinhardt ED, Keane RE, Calkin DE, et al.

Source: FOREST ECOLOGY AND MANAGEMENT Volume: 256 Issue: 12 Pages: 1997-2006

Published: DEC 10 2008

Abstract: Many natural resource agencies and organizations recognize the importance of fuel treatments as tools for reducing fire hazards and restoring ecosystems. However, there continues to be confusion and misconception about fuel treatments and their implementation and effects in fire-prone landscapes across the United States. This paper (1) summarizes objectives, methods, and expected outcomes of fuel treatments in forests of the Interior West, (2) highlights common misunderstandings and areas of disagreement, and (3) synthesizes relevant literature to establish a common ground for future discussion and planning. It is important to understand the strengths and limitations of fuel treatments to evaluate their potential to achieve an objective, develop sensible fire management policies, and plan for their effective use. We suggest that, while the potential of fuel treatment to reduce wildfire occurrence or enhance suppression capability is uncertain, it has an important role in mitigating negative wildfire effects, increasing ecosystem resilience and making wildfire more acceptable.

TITLE: Analyzing the effectiveness of alternative fuel reductions of a forested landscape in Northeastern China

Author(s): Liu ZH, He HS, Chang Y, et al.

Source: FOREST ECOLOGY AND MANAGEMENT Volume: 259 Issue: 7 Special Issue: Sp. Iss. SI
Pages: 1255-1261

Published: MAR 20 2010

Abstract: Successful management of forest fire risk in the Northeastern China boreal forest ecosystem often involves trade-offs between fire dynamics, fire hazard reduction, and fiscal input. We used the LANDIS model to study the effects of alternative fuel reduction strategies on fire dynamics and analyzed cost effectiveness for each fuel reduction strategy based on cost-benefit theory. Five levels of fuel treatment area (2, 4, 6, 8, and 10% for each decade) and two fuel treatment types (prescribed burning [PB] and mechanical treatments in combination with prescribed fire [PR]) under current fire suppression simulated by LANDIS were compared in a 5 x 2 factorial design over a 300-year period. The results showed that PR scenarios are more effective at reducing the occurrence and burn area of catastrophic fires than PB scenarios. In addition, area burned by high intensity fire can be tremendously reduced by increasing low intensity fires with a higher level of treatment area under the various PR scenarios. The cost effectiveness of alternative fuel reduction strategies is strongly dependent on treatment area. In general, PB scenarios will be more cost effective in larger treatment areas and PR scenarios in smaller. We recommend mechanical treatments in combination with prescribed fire, with 4% of landscape treated in each decade (PR04) to be the optimal fuel reduction strategy in the study area based on risk control and cost efficiency analysis. However, the most challenging work in China is to make local forest policy makers and land managers accept the ecological function of fire on forest ecosystems. (C) 2009 Elsevier B.V. All rights reserved.

TITLE: Determinants of National Fire Plan Fuels Treatment Expenditures: A Revealed Preference Analysis for Northern New Mexico

Author(s): Shepherd C, Grimsrud K, Berrens RP

Source: ENVIRONMENTAL MANAGEMENT Volume: 44 Issue: 4 Pages: 776-788

Published: OCT 2009

Abstract: The accumulation of fire fuels in forests throughout the world contributes significantly to the severity of wildfires. To combat the threat of wildfire, especially in the wildland-urban interface (WUI), US federal land management agencies have implemented a number of forest restoration and wildfire risk reduction programs. In the spirit of revealed preference analyses, the objective of this study is to investigate the pattern and determinants of National Fire Plan (NFP) expenditures for fuel reduction treatments in northern New Mexico (USA). Estimation results from a set of Generalized Estimating Equations models are mixed with respect to risk reduction hypotheses, and also raise issues regarding how risk reduction should be defined for a region characterized by both pockets of urban sprawl into the WUI and large areas of chronic rural poverty. Program preferences for project funding under the federal Collaborative Forest Restoration Program in New Mexico are shown to be distinctly different (e.g., exhibiting greater concern for social equity) than for other NFP-funded projects.

TITLE: Modeling and validating spatial patterns of a 3D stand generator for central Appalachian hardwood forests

Author(s): Wang JX, Sharma BD, Li YX, et al.

Source: COMPUTERS AND ELECTRONICS IN AGRICULTURE Volume: 68 Issue: 2 Pages: 141-149

Published: OCT 2009

Abstract: A 3D stand generator and visualization system was developed for generating a spatially explicit forest for central Appalachian hardwood forests. Spatial pattern of the stand generator was modeled and validated by characterizing a 75-year old central Appalachian mixed hardwood forest dominated by red oak, chestnut oak, red maple, and yellow poplar. All the trees larger than 12.7 cm diameter at breast height (DBH) were measured for DBH, total height, crown height and crown width along with their locations in thirty 0.162 ha plots. Stand attributes, i.e. species compositions, mean DBH, total height, basal area and volume in the generated stand never exceeded a difference of 10% from the actual stand attributes. The generated stand can thus be used as an alternate to time consuming manual measurement of spatial location of trees for related ecological studies and training purposes and to visualize the same in 3D perspectives. The results also indicated the potential of using this stand generator in simulating stand spatial patterns and generating stands in other regions with some modification in growth functions.

TITLE: Spatial fuel data products of the LANDFIRE Project

Author(s): Reeves MC, Ryan KC, Rollins MG, et al.

Source: INTERNATIONAL JOURNAL OF WILDLAND FIRE Volume: 18 Issue: 3

Pages: 250-267 **Published:** 2009

Abstract: The Landscape Fire and Resource Management Planning Tools (LANDFIRE) Project is mapping wildland fuels, vegetation, and fire regime characteristics across the United States. The LANDFIRE project is unique because of its national scope, creating an integrated product suite at 30-m spatial resolution and complete spatial coverage of all lands within the 50 states. Here we describe development of the LANDFIRE wildland fuels data layers for the conterminous 48 states: surface fire behavior fuel models, canopy bulk density, canopy base height, canopy cover, and canopy height. Surface fire behavior fuel models are mapped by developing crosswalks to vegetation structure and composition created by LANDFIRE. Canopy fuels are mapped using regression trees relating field-referenced estimates of canopy base height and canopy bulk density to satellite imagery, biophysical gradients and vegetation structure and composition data. Here we focus on the methods and data used to create the fuel data products, discuss problems encountered with the data, provide an accuracy assessment, demonstrate recent use of the data during the 2007 fire season, and discuss ideas for updating, maintaining and improving LANDFIRE fuel data products.

TITLE: Potential biomass and logs from fire-hazard-reduction treatments in southwest Oregon and northern California

Author(s): Barbour RJ, Fried JS, Daugherty PJ, et al.

Source: FOREST POLICY AND ECONOMICS Volume: 10 Issue: 6 Pages: 400-407

Published: AUG 2008

Abstract: The FIA BioSum model was used to simulate three fire-hazard-reduction policies in an area comprising northern California, southwestern Oregon, and the east slopes of the Cascade Mountains in Oregon. The policy scenarios, all subject to a stand-scale fire-hazard-reduction effectiveness constraint, included maximize torching index improvement (Max TI), maximize net revenue recovery (Max NR), and minimize merchantable timber removal (Min Merch). Differences in the area treated under each scenario were considerable, ranging from 15 to 96% of the area for which effective treatments are technically feasible. For each scenario, weight, species, and source tree size of both dirty chips (hogfuel

or biomass) and saw logs were estimated. The mix of species and sizes removed under each scenario was surprisingly similar, although the Min Merch scenario did remove more noncommercial species such as hardwoods and more saw logs in the midsize classes (10 to 16in. diameter at breast height (dbh); 25.4 to 40.6cm) than the other two scenarios. Saw logs accounted for 67 to 79% of the weight removed. Under all scenarios, the Douglas-fir (*Pseudotsuga menziesii*)/larch (*Larix*) and white woods (*Picea* spp., *Tsuga* spp., and *Abies* spp.) species groups accounted for nearly all of the saw logs removed. Tops and limbs of commercial species and noncommercial species accounted for most of the dirty chips. Stems of low value commercial conifers (7 to 16in; 17.8 to 40.6cm) were also an important source of dirty chips. Trees smaller than 7in. (17.8cm) dbh were a relatively minor component of the dirty chip mix.

TITLE: Efficacy of mechanical fuel treatments for reducing wildfire hazard

Author(s): Huggett RJ, Abt KL, Shepperd W

Source: FOREST POLICY AND ECONOMICS Volume: 10 Issue: 6 Pages: 408-414

Published: AUG 2008

Abstract: Mechanical fuel treatments are increasingly being used for wildfire hazard reduction in the western U.S. However, the efficacy of these treatments for reducing wildfire hazard at a landscape scale is difficult to quantify, especially when including growth following treatment. A set of uneven- and even-aged treatments designed to reduce fire hazard were simulated on 0.8 million hectares of timberland in Colorado. Wildfire hazard ratings using torching and crowning indices were developed; stands were selected for treatment; treatment was simulated and hazard ratings were reassessed. The results show that the even-aged treatments initially place more area within our hazard thresholds than do the uneven-aged treatments and that the uneven-aged treatment that removes more small stems reduces risk more than the treatment removing more large stems. The treatment costs follow the same pattern, with the even-aged treatments costing least. However, potential revenues are, as expected, higher for the uneven-aged large treatment. The results also show that both higher costs and higher revenues accrue to the treatments applied to the higher risk stands. Treatments also have differing risk reductions depending on the initial risk category. Even without considering growth or revenues, the outcomes of a state-level treatment program are difficult to estimate. This implies that at a minimum, forest-level, if not state-level analyses including overall measures of risk reduction, costs, revenues and long-term effects need to be conducted in concert with setting priorities for treating timberlands.

TITLE: Partnering with planners to develop tools for financial analysis of fuel treatments

Author(s): Barbour RJ, Fight RD

Source: JOURNAL OF FORESTRY Volume: 105 Issue: 5 Pages: 252-256

Published: JUL-AUG 2007

Abstract: The financial analysis component of the fuel synthesis project was guided by the general specifications of the broader project. The project was requested on behalf of specific users (fuel treatment planners), to address specific questions (how to design and implement fuel treatments), and with specific attributes (easily learned and used by people with little or no background in economics or financial analysis). The strategy for designing analysis and information to meet this need was to involve the target user group and managers in design, testing, and implementation of the tools. The result is a set of tools that appear to be being adopted more quickly and more widely than any previous financial analysis tools that the authors have developed.

TITLE: Modeling fuel treatment costs on forest service lands in the western United States

Author(s): Calkin D, Gebert K

Source: WESTERN JOURNAL OF APPLIED FORESTRY Volume: 21 Issue: 4

Pages: 217-221 **Published:** OCT 2006

Abstract: Years of successful fire suppression have led to high fuel loads on the nation's forests, and steps are being taken by the nation's land management agencies to reduce these fuel loads. However, to achieve desired outcomes in a fiscally responsible manner, the cost and effectiveness in reducing losses due to wildland fire of different fuel treatments in different forest settings must be understood. Currently, prioritizing fuel treatment activities and planning budget expenditures is limited by a lack of accurate cost data. The primary objective of this research was to develop regression models that may be used to estimate the cost of hazardous fuel reduction treatments based on USDA Forest Service Region, biophysical setting, treatment type, and design. A survey instrument was used to obtain activity-specific information directly from fire management officers at Forest Service Ranger Districts for treatments occurring between 2001 and 2003. For both prescribed burns and mechanical activities, treatment size described the largest amount of variation in cost per acre, with increased size reducing cost per acre, on average. We confirmed that data on Forest Service fuel treatment activities maintained in the National Fire Plan Operations and Reporting System were not sufficiently accurate for reasonable cost analysis and modeling.

TITLE: Harvesting system simulation using a systems dynamic model

Author(s): McDonagh KD, Meller RD, Visser RJM, et al.

Source: SOUTHERN JOURNAL OF APPLIED FORESTRY Volume: 28 Issue: 2

Pages: 91-99

Published: MAY 2004

Abstract: To compete in the current work environment in the southeastern United States, forestry companies and logging contractors must manage their harvest systems to ensure efficient production. Efficiency in this case can be defined in terms of tons of wood produced per unit of system cost. Site and system factors affect the output from a stand and affect the efficiency of different harvesting systems. A model was developed that can simulate harvesting system production efficiency with changing stand and terrain parameters. Four common southeastern US harvesting systems were included in the model. The model includes functions, adjustable by the user, that quantify the efficiency of each harvest system is measured with respect to terrain parameters (slope and average extraction distance), as well as stand parameters (average tree diameter, stocking intensity, and harvest intensity). By adjusting any of these parameters, it is possible to compare the four harvest systems and to perform various sensitivity analyses. Result examples presented in the article include change in productivity with increasing tree size, productivity changes of a cut-to-length system in varied silvicultural conditions, as well as the associated evaluation of the cost of inefficiency of each system. South. J. Appl. For. 28(2):91-99.

TIMBER HARVEST OUTPUTS/SUPPLY CHAIN

TITLE: Productivity and costs of an integrated mechanical forest fuel reduction operation in southwest Oregon

Author(s): Bolding MC, Kellogg LD, Davis CT

Source: FOREST PRODUCTS JOURNAL Volume: 59 Issue: 3 Pages: 35-46

Published: MAR 2009

Abstract: Mechanical forest fuel reduction treatments that harvest and extract small, non-merchantable trees are often integrated into commercial thinning operations. Harvesting system feasibility and/or costs from such operations has been sparsely reported in the literature. To broaden the knowledge of

mechanical approaches of harvesting and utilizing small trees, this study assessed the productivity and cost from an integrated forest harvesting/mechanical forest fuel reduction operation in southwest Oregon. The study was conducted in a fuel reduction thinning of a 20-acre mixed conifer stand on gentle terrain. A tracked swing-boom feller-buncher, two rubber-tired grapple skidders, a swing-boom grapple processor, an in-woods chipper, and a tub grinder were used to fell, extract, and process non-merchantable stems and limbs and tops from felled merchantable trees into fuel (energy-wood) chips. Thinned merchantable trees were also extracted and processed into log lengths. Results indicate that harvesting and processing non-merchantable trees increased total costs by \$1,193.43 per acre. From a biomass harvesting perspective, removing only the non-merchantable portion of the stand would have resulted in a net cost of \$968.96 per acre. Thinning merchantable trees added value to the operation, subsidized costs, and decreased the net loss by \$872.00 per acre, resulting in a net cost of \$96.96 per acre.

TITLE: Biomass utilization for bioenergy in the Western United States

Author(s): Nicholls DL, Monserud RA, Dykstra DP

Source: FOREST PRODUCTS JOURNAL Volume: 58 Issue: 1-2 Pages: 6-16

Published: JAN-FEB 2008

Abstract: Wildfires, hazardous fuel buildups, small-diameter timber, wildland- urban interface zones, biomass. These are some of the terms becoming familiar to communities throughout the Western United States after the record-breaking fire seasons of the past decade. Although small-diameter stems are generally expensive to remove and often have limited utilization options, the need to reduce wildfire hazard has become increasingly important with the expansion of the wildland- urban interface across the Western United States. An estimated 73 million acres of national forest land in Western States (397 million acres across all ownerships) have been identified as high-priority treatment areas. Nearly 3,800 communities near federal lands in Western States are considered to be at high risk of wildfire.

TITLE: Transaction evidence analysis: stumpage prices and risk in central Georgia

Author(s): Sydor T, Mendell BC

Source: CANADIAN JOURNAL OF FOREST RESEARCH-REVUE CANADIENNE DE RECHERCHE FORESTIERE Volume: 38 Issue: 2 Pages: 239-246

Published: FEB 2008

Abstract: This paper uses hedonic regression techniques to analyze timber bid transactions in central Georgia. Softwood stumpage prices from pay-as-cut transactions are regressed against timber sale and stand characteristics. We identify observable factors that are statistically associated with the volatility of pine sawtimber stumpage prices in the market. The remaining price volatility, defined as market risk, characterizes undiversifiable price volatility in the market. Isolating market risk in this way has implications for relative price risk across predefined timber markets. Applications of these techniques suggest that analyzing market price variability with total measures alone, such as standard deviation, may provide false senses of timber price risk.

TITLE: Forest measurement and biometrics in forest management: Status and future needs of the Pacific Northwest USA

Author(s): Temesgen H, Goerndt ME, Johnson GP, et al.

Source: JOURNAL OF FORESTRY Volume: 105 Issue: 5 Pages: 233-238

Published: JUL-AUG 2007

Abstract: Forest measurement and biometrics (FMB) programs have been at the heart of forestry education in North America since its beginnings at the Biltmore Forest School more than 100 years ago. Over the intervening period, the field of forestry has changed in critical ways. There are many forest

management and policy issues that, at first glance, do not appear to involve FMB but which, on further examination, are found to be closely linked. In this regard, FMB has both an “inside” and “outside.” The outside part faces interactions with its clients and front-line sciences (e.g., forest ecology, silviculture, etc.) which bring new data-analytic ideas to FMB. The clients and professionals in these allied sciences need solutions to pressing quantitative questions. The inside face relates to the need to extend the structure of statistical inference, integrate emerging technologies, and adapt mathematical and statistical precepts to FMB needs. In this essay, we provide a brief overview of the current diversity of FMB applications using examples from business, policy analysis, and ecosystem and landscape analysis; offer our views on the most critical challenges facing FMB researchers and practitioners in the 21st Century; and outline ways how FMB professionals and academic forestry programs might cooperate to meet these challenges. We assert that FMB needs to be responsive to contemporary resource management challenges and address the many land management challenges in the Pacific Northwest and around the world.

TITLE: The impact of timber harvesting guidelines and timber sale attributes on stumpage bidding behavior

Author(s): Kilgore MA, Blinn CR

Source: NORTHERN JOURNAL OF APPLIED FORESTRY Volume: 22 Issue: 4

Pages: 275-280 Published: DEC 2005

Abstract: Twenty-seven public timber tracts were auctioned in Minnesota where bidders were required to submit two sealed bids for a tract—one with and the other without the use of timber harvesting guidelines. After the auctions, bidders were mailed a questionnaire requesting information about their logging business, the sources of information consulted in developing their bids, and perceptions of how various tract- and sale-specific factors and guidelines influenced their bidding behavior. The majority of responding timber harvesters did not consult any special sources and only one-half visited the tract before submitting their bids. Although bidding behavior was influenced by several factors, a tract's physical characteristics (e.g., volume of merchantable timber) had a greater influence on their bidding behavior than did any guidelines. Of the guidelines evaluated, those that required leaving merchantable trees (e.g., for wildlife or visual purposes) were reported to have the greatest influence on stumpage bids. Sale-specific variables (e.g., timber harvester's need for timber) had only a minimal to moderate influence on bidding behavior. The findings suggest that timber sale design can help mitigate the cost associated with implementing forest management guidelines.

TITLE: Supporting wood supply chain decisions with simulation for a mill in northwestern BC

Author(s): Myers J, Richards EW

Source: INFOR Volume: 41 Issue: 3 Pages: 213-234

Published: AUG 2003

Abstract: Seasonal restrictions on harvesting and transportation operations have traditionally forced mill managers to maintain high levels of inventory in the log-yard to ensure continuous operation of the mill. We propose two technologies which may prolong the operating season, potentially reducing inventory handling and holding costs: Central tire inflation (CTIS) and cable-based harvest systems. To evaluate the effect of the CTIS-equipped trucks and cable-based harvesting on the wood supply chain, a discrete event simulation model was developed and was validated. The simulation model estimates the total cost of the system with each technology included, both separately and in ...

TITLE: Evaluation of consecutive skylines yarding and gravity skidding systems in primary forest transportation on steep terrain

Author(s): Gumus S, Acar HH

Source: JOURNAL OF ENVIRONMENTAL BIOLOGY Volume: 31 Issue: 1-2

Special Issue: Sp. Iss. SI Pages: 213-218

Published: JAN-MAR 2010

Abstract: Land degradation and soil loss is a global event. Human induced pressures on the natural ecosystems are still in progress as well as conservation efforts. The need for sufficient knowledge and data for decision makers is obvious hence the present study was carried out. The study area, the A_lasun district, is in the middle west of Turkey and is characterized by a cold and sub-humid Mediterranean climate. The mountainous area is mostly covered with average low canopy closure of 11 - 40% of different forest species (52% of the study area). Universal soil loss equation (USLE) simulation model was used to predict the soil loss amounts in the study area. The results show that the predicted average soil loss amount is 7.38 (ton/ha/year). The average soil depth is about 35 cm and the soil loss tolerance limit is widely exceeded in the study area.

TITLE: Relationships between the stocking levels of live trees and dead tree attributes in forests of the United States

Author(s): Woodall CW, Westfall JA

Source: FOREST ECOLOGY AND MANAGEMENT Volume: 258 Issue: 11 Pages:

2602-2608 Published: NOV 10 2009

Abstract: There has been little examination of the relationship between the stocking of live trees in forests and the associated attributes of dead tree resources which could inform large-scale efforts to estimate and manage deadwood resources. The goal of this study was to examine the relationships between the stocking of standing live trees and attributes of standing dead and downed dead trees using a national inventory of forests in the United States. Results indicated that from the lowest to the highest class of live tree relative stand density, the mean biomass/ha of live trees increased over 2000% while standing dead and downed dead trees biomass/ha increased 295 and 75%, respectively. Correlations between downed deadwood biomass and stand/site attributes increased as live tree stocking increased.

TITLE: Silviculture for old-growth attributes

Author(s): Bauhus J, Puettmann K, Messier C

Source: FOREST ECOLOGY AND MANAGEMENT Volume: 258 Issue: 4 Special Issue: Sp. Iss. SI Pages: 525-537

Published: JUL 30 2009

Abstract: Silviculture to maintain old-growth forest attributes appears to be an oxymoron since the late developmental phases of forest dynamics, described by the term old-growth, represent forests that have not experienced human intervention or timber removal for a long time. In the past, silvicultural systems applied to old- growth aimed to convert it into simplified, more productive regrowth forests substantially different in structure and composition. Now it is recognised that the maintenance of biodiversity associated with structural and functional complexity of late forest development successional stages cannot rely solely on old-growth forests in reserves. Therefore, in managed forests, silvicultural systems able to develop or maintain old-growth forest attributes are being sought. The degree to which old-growth attributes are maintained or developed is called "old-growthness". In this paper, we discuss silvicultural approaches that promote or maintain structural attributes of old-growth forests at the forest stand level in (a) current old-growth forests managed for timber production to retain structural elements, (b) current old-growth forests requiring regular, minor disturbances to maintain their structure, and (c) regrowth and secondary forests to restore old-growth structural attributes. While the functions of

different elements of forest structure, such as coarse woody debris, large veteran trees, etc., have been described in principle, our knowledge about the quantity and distribution, in time and space, of these elements required to meet certain management objectives is rather limited for most ecosystems. The risks and operational constraints associated with managing for structural attributes create further complexity, which cannot be addressed adequately through the use of traditional silvicultural approaches. Silvicultural systems used in the retention and restoration of old-growthness can, and need, to employ a variety of approaches for managing spatial and temporal structural complexity. We present examples of silvicultural options that have been applied in creative experiments and forestry practice over the last two decades. However, these largely comprise only short-term responses, which are often accompanied by increased risks and disturbance. Much research and monitoring is required still to develop and optimise new silvicultural systems for old-growthness for a wide variety of forest ecosystem types.

TITLE: International bioenergy synthesis-Lessons learned and opportunities for the western United States
Author(s): Nicholls D, Monserud RA, Dykstra DP
Source: FOREST ECOLOGY AND MANAGEMENT Volume: 257 Issue: 8 Pages: 1647-1655
Published: MAR 31 2009

Abstract: This synthesis examines international opportunities for utilizing biomass for energy at several different scales, with an emphasis on larger scale electrical power generation at stand-alone facilities as well as smaller scale thermal heating applications such as those at governmental, educational, or other institutional facilities. It identifies barriers that can inhibit bioenergy applications, and considers international cases of successful bioenergy production with a focus on Europe and Brazil. Based on the review of international bioenergy applications, important ecosystem service issues having relevance to western U.S. forests are discussed, including hazardous fuel reduction, community development, and sustainability of the wood products industry.

TITLE: Timber product output implications of a program of mechanical fuel treatments applied on public timberland in the western United States
Author(s): Barbour RJ, Zhou XP, Prestemon JP
Source: FOREST POLICY AND ECONOMICS Volume: 10 Issue: 6 Pages: 373-385
Published: AUG 2008

Abstract: This study reports the results from a 5 year simulation of forest thinning intended to reduce fire hazard on publicly managed lands in the western United States. A state simulation model of interrelated timber markets was used to evaluate the timber product outputs. Approximately 84 million acres (34 million hectares), or 66% of total timberland in the western United States, is publicly managed; of this 78 million acres (31.6 million hectares) are managed by the federal agencies. We considered three budget scenarios using a least-expensive highest-hazard area first policy. Our intention with this simulation is not to definitively answer questions about where or how to conduct treatments to reduce fire hazard on public lands but rather to begin to develop tools that can be used to inform such a policy debate. Considerable development of this tool is still needed before it will be useful for that purpose. Our initial simulations nonetheless provide insight into what might happen if available funds were allocated to the least-expensive highest-hazard areas across the west. Using assumptions of (1) an annual "subsidy" (payments for treatments), (2) the treatment costs, (3) the priority ranking by forest type, (4) fire hazard level, and (5) the wildland-urban interface (WUI) status, the simulation suggests that lodgepole pine (*Pinus contorta*), ponderosa pine (*Pinus ponderosa*), spruce (*Picea* spp.)-fir (*Abies* spp.) and Douglas-fir (*Pseudotsuga menziesii*) are projected to be major forest types treated in the West. A combination of our treatment ranking assumptions and the low total treatable WUI acres on public timberland caused the model to concentrate almost exclusively on all the WUI stands and non-WUI ponderosa pine forest type at the budget of \$150 million and \$300 million. With the further increase of

budget, a large proportion of treated acres are lodgepole pine and spruce–fir forest types using the thin-from-below approach. About 41% of the volume removals are sawtimber for all the public timberland treated under the low budget scenario (\$150 million/year), 58 for moderate budget (\$300 million/year), 50 for the high budget scenario (\$1500 million/year). Under the moderate budget case (\$300 million a year), about 19% of the total wood removed is projected to come from trees less than 5-inches (12.7 cm) in diameter at breast height (dbh), and another 16% of the biomass is expected from trees 20-inches (50.8 cm) dbh and above.

TITLE: Analysis of mechanical thinning productivity and cost for use at the wildland urban interface

Author(s): Folegatti BS, Smidt MF, Loewenstein EF, et al.

Source: FOREST PRODUCTS JOURNAL Volume: 57 Issue: 11 Pages: 33-38

Published: NOV 2007

Abstract: Forest management in many parts of the urbanizing Southeastern U.S. is becoming more difficult due to fragmentation, alternative management objectives, and social conflicts with management activities. However, the public benefits from management of these are still high. This study compared the productivity and costs of mechanical thinning treatments using conventional thinning and two alternative thinning approaches in even-aged loblolly pine plantations. The alternative treatments removed more stand basal area and were intended to promote transition to uneven-aged stand management. Production studies and cost analysis were completed for conventional, heavy, and strip measurements. The conventional treatment was a fifth row and select removals to 16 m²ha⁻¹ residual basal area. The heavy treatment was a fifth row and select removals to 9 m²ha⁻¹ residual basal area. The strip treatment included a conventional thinning treatment with alternating reserve and clearcut strips established on the contour. The resulting residual basal area was 11.5 m²ha⁻¹. The alternative treatments provided substantially lower costs and higher residual values (\$1 to 3 m⁻³) in the 4 ha stands but smaller advantages in 8 and 12 ha stands. The difference from lower harvest costs for the alternative treatments may enable landowners to attract interest in small acreage sales that result from fragmentation.

TITLE: Influence of site characteristics and costs of extraction and trucking on logging residue utilization in southern West Virginia

Author(s): Grushecky ST, Wang JX, McGill DW

Source: FOREST PRODUCTS JOURNAL Volume: 57 Issue: 7-8 Pages: 63-67

Published: JUL-AUG 2007

Abstract: The increased utilization of logging residues has received considerable attention as a potential source of renewable biomass and as a raw material for engineered and conventional wood products. We investigated the relationship between logging residue accumulations and site characteristics on 70 timber harvests that occurred during 2000 to 2001 in southern West Virginia. Logging residue estimates were obtained using logged area analysis methodologies. The average overall weight of wood residue remaining after timber harvest in the 14- county region was 10.4 tons/acre. We found little relationship between distance to landings or average slope with residue accumulations. Likewise, relationships among distance to markets and residue accumulations did not exist for a number of potential residue buyers in the region. Scenarios of residue extraction and trucking indicated a cost range of \$58.20/cunit or \$94.30 per thousand board feet (MBF) to \$193.10/cunit (\$312.80/MBF Doyle). These results suggest that extracting residues to the landing during harvesting would be most cost-effective. Likewise, the use of grapple skidders and appropriate loading and trucking equipment would be more economical than other systems modeled.

TITLE: Effects of alternative silvicultural treatments on cable harvesting productivity and cost in western Washington

Author(s): Hartley DS, Han HS

Source: WESTERN JOURNAL OF APPLIED FORESTRY Volume: 22 Issue: 3 Pages: 204-212

Published: JUL 2007

Abstract: Increasingly, alternative silvicultural methods have been considered to meet the demand for nontimber values such as visual quality and biodiversity in the Pacific Northwest. The successful implementation of these alternative silviculture treatments requires careful consideration of economics and operational efficiencies in timber harvesting. This study used detailed time study and shift-level data to assess the effect of alternative silvicultural treatments on the production and cost of cable harvesting in western Washington. Four silvicultural treatments were examined: clearcut, two-age, patch cut and thin, and group selection. Silvicultural treatments greatly affected the production and cost of timber harvesting, especially in felling and yarding processes. The average yarding cycle time (3.74 minutes/cycle) in the clearcut unit was shorter than those in other partial cutting treatment units because there were no residual trees to work around and higher harvest volumes per acre, compared with the partial cut units. The average tree size greatly affected yarding cost: the clearcut unit had the second-highest yarding cost (\$52.38/thousand board feet [mbf]) because of the smallest piece size (69.6 board feet/piece). Stump-to-truck cost for this study ranged from \$70.49/mbf for the patch cut and thin to \$120.19/mbf for the group selection. Carriage types and yarding direction also had an impact on yarding productivity.

TITLE: Impact of the thinning regime on the mean diameter of the largest stems by diameter at breast height in even-aged *Picea abies* stands

Author(s): Karlsson K

Source: SCANDINAVIAN JOURNAL OF FOREST RESEARCH Volume: 21 Issue: 1 Pages: 20-31

Published: FEB 2006

Abstract: The increases in the arithmetic mean diameter at breast height (dbh) of the 100, 200, 300 and 400 largest stems ha^{-1} by dbh associated with six different thinning regimens for periods up to 35 years were compared, by analyses of variance, to the corresponding stem fractions in unthinned stands using permanent sample plot data. In addition, the expected mean dbh of these stand fractions at future points in time was modelled, based on site and stand data obtained at the time of the first thinning. Thirty-five years after the first thinning, the thinning from below regimens resulted in actual increases (a measure affected by both the thinning intensity and the thinning method), compared with the unthinned stands, in the mean dbh for the 100, 200, 300 and 400 largest stems ha^{-1} of 2.6-9.0 cm. The corresponding genuine increases (a measure principally affected solely by the thinning intensity) were 4-11 cm. The functions predicting the future dbh of these stand fractions yielded good fits.

TITLE: Comparing mechanized and non-mechanized logging firms in Wisconsin: Implications for a dynamic ownership and policy environment

Author(s): Rickenbach M, Steele TW

Source: FOREST PRODUCTS JOURNAL Volume: 55 Issue: 11 Pages: 21-26

Published: NOV 2005

Abstract: Wisconsin's logging sector, like many across North America, is changing. Although manual, chainsaw-based systems are still widely used, fully mechanized harvest systems are becoming more prevalent. In 2003, we surveyed 173 Wisconsin logging contractors, inquiring about their annual production, sources of supply, and distribution of timber ownership within their wood basket. Respondents were also asked to evaluate the impacts of forest ownership parcelization on their business. Seventy-six respondents (44%) indicated they had adopted a mechanized harvesting system whereas 97

(56%) used chainsaws and skidders or forwarders. Mechanized and non-mechanized logging firms were significantly different from each other ($\alpha = 0.05$). Mechanized firms reported average annual production over three times that of non-mechanized firms. Mechanized firms indicated higher proportions of their stumpage came from county and state forests, while non-mechanized firms reported a higher portion from non-industrial private forests (NIPFs). Relatedly, mechanized firms were more likely to have a higher portion of county and municipal timberland in their wood basket. Respondents from mechanized firms were also more likely to see parcelization as a potential problem. Based on these findings, we hypothesize that division by source or by timber sale size is occurring, with mechanized firms tending toward larger, public sales, while non-mechanized firms tend toward those NIPF stumpage. In light of changing timberland ownership patterns, two implications are discussed. First, continued timberland parcelization may provide an important niche for non-mechanized firms. Second, given differences between mechanized and non-mechanized firms, changes in forest and land use policy may differentially affect logging firms.

TITLE: Costs and regional impacts of restoration thinning programs on the national forests in eastern Oregon

Author(s): Adams DM, Latta GS

Source: CANADIAN JOURNAL OF FOREST RESEARCH-REVUE CANADIENNE DE RECHERCHE FORESTIERE Volume: 35 Issue: 6 Pages: 1319-1330

Published: JUN 2005

Abstract: An intertemporal spatial equilibrium model of the eastern Oregon softwood log market was employed to estimate the market and economic welfare impacts of restoration thinning programs established on national forests in the region. Programs treated only lands with sawtimber thinning volume and varied by the extent of public subsidies for costs, the types of costs that could be subsidized, and the form of the subsidy payment. Impacts on private harvest timing, numbers of mills, and postprogram log prices in the region were found to vary markedly with the form of the program. Log consumers (lumber mills) consistently realized relatively large surplus gains, while private log producers' surplus showed smaller but consistent losses. For a comparable subsidy budget, programs that subsidized only hazard removal costs, on sites where net unsubsidized sawtimber returns promised to be less than these costs, led to a larger area treated than did programs with more flexible subsidy conditions. Across all programs, net agency receipts from sawtimber sales were estimated to be insufficient to cover the costs of all areas in need of thinning treatment (lands with and without sawtimber thinning volume).

TITLE: Predicting the future diameter of stems in Norway spruce stands subjected to different thinning regimes

Author(s): Karlsson K, Norell L

Source: CANADIAN JOURNAL OF FOREST RESEARCH-REVUE CANADIENNE DE RECHERCHE FORESTIERE Volume: 35 Issue: 6 Pages: 1331-1341

Published: JUN 2005

Abstract: The future diameter of stems in even-aged Norway spruce (*Picea abies* (L.) Karst.) stands subjected to different thinning regimes was modelled, using data from a thinning experiment established in 25 localities in southern Sweden. Separate models were developed for stands thinned from below, stands thinned from above, and unthinned stands. A bivariate approach was used to construct the models, based on DBH data from the initial stand and from the same trees at future points in time. The approach entails that the dependency between initial and future DBHs can be directly used to predict the future DBH. Also, the modelling used stand and site characteristics together with information about the stand density management regime. The initial stands were assumed to be unthinned, and the dominant height was assumed to be 12–18 m. A logistic function was used to predict which individual trees would remain at future points in time. The mean and standard deviation of the differences between observed

and predicted future diameters were used to validate the models. When the prediction period was approximately 33 years, the mean was typically underestimated by 4 mm, and the standard deviation was approximately 40 mm.

TITLE: Effects of spatial scale on the perception and assessment of risk of natural disturbance in forested ecosystems: Examples from Northeastern Oregon Author(s): Barbour RJ, Hemstrom M, Ager A, et al.
Source: FOREST ECOLOGY AND MANAGEMENT Volume: 211 Issue: 1-2
Special Issue: Sp. Iss. SI Pages: 210-225
Published: JUN 6 2005

Abstract: The perception and measurement of the risk of natural disturbances often varies depending on the spatial and temporal scales over which information is collected or analyzed. This can lead to conflicting conclusions about severity of current or past disturbances or the risk of future ones. Failure to look across scales also complicates local implementation of policies developed from broad-scale perceptions of risk because perception of risk is relative and depends on context. Methods that help policymakers, managers, and the public look across spatial and temporal scales can improve their understanding of the long-term dynamics of disturbances like wildfire and insect outbreaks. This capability provides a foundation for prioritizing restoration management activities, especially in forest types prone to frequent or severe disturbances. Although techniques for estimating risk over increasingly large spatial scales are becoming more widespread, the connection of risk assessments from broad to fine scales is not well established. We use a synthesis of five existing analyses to illustrate how scale affects the perception and interpretation of risk as information, models, and findings are stepped down from broad scale (interior Columbia basin) to mid scale (parts of a river basins) to fine scale (watersheds). We present results from the Interior Columbia Basin Ecosystem Management Project (ICBEMP) and the Interior Northwest Landscape Analysis System (INLAS) efforts that compare wildfire risk and other resource attributes. Our findings compare action and no-action alternatives to illustrate the use of multiple-scale step-down analysis for understanding the relation of broad- scale policy to the feasibility and impact of local management.

TITLE: Effects of a forest health thinning program on land and timber values in eastern Oregon
Author(s): Adams DM, Latta GS
Source: JOURNAL OF FORESTRY Volume: 102 Issue: 8 Pages: 9-13
Published: DEC 2004

Abstract: The Healthy Forests Restoration Act authorizes programs of thinning on public forest lands to reduce fire hazard and improve the vigor of residual stands. These programs could generate significant volumes of merchantable sawtimber, potentially altering supply-demand conditions in local sawtimber markets and the values of private timberland. We examine the effects of two hypothetical programs on timberland prices in eastern Oregon using a model of the region's market. We find both reductions and increases in the values of various types of private timberland due to changes in the output of the region's industry, the timing of private harvests, and long-term sawtimber prices. Thinning programs in other western regions with comparable conditions of private inventory and a declining sawtimber processing industry could produce similar changes.

TITLE: Ground skidding and harvested stand attributes in Appalachian hardwood stands in West Virginia
Author(s): Egan AF, Baumgras JE
Source: FOREST PRODUCTS JOURNAL Volume: 53 Issue: 9 Pages: 59-63
Published: SEP 2003

Abstract: A statewide logging-in-progress study was conducted in West Virginia to examine the associations among several ground skidding and harvested stand attributes. There was a strong positive association between skidding distance and cycle time, and a significant negative relationship between the percent of trees removed in the stand and total cycle time. The number of residual trees per acre and number of trees per acre in the preharvest stand were not significant in explaining total skidding cycle time. In addition, the number of trees and volume skidded per cycle were positively associated with cycle time, as was the number of turn bunching moves. Additional results suggested that differences in operator behavior may be more important in explaining the size of payloads per cycle than, for example, the size of the skidder used.

TITLE: Estimating and validating ground-based timber harvesting production through computer simulation
Author(s): Wang JX, LeDoux CB
Source: FOREST SCIENCE Volume: 49 Issue: 1 Pages: 64-76
Published: FEB 2003

Abstract: Estimating ground-based timber harvesting systems production with an object oriented methodology was investigated. The estimation model developed generates stands of trees, simulates chain saw, drive-to-tree feller-buncher, swing- to-tree single-grip harvester felling, and grapple skidder and forwarder extraction activities, and analyzes costs and productivity. It also measures the traffic intensity level of extraction machines across sites. The model components were validated using data from several independent field studies. The model was used to evaluate the interaction of stand variables, harvest treatments, machines, and extraction patterns. Using two main skid trails to harvest a block minimized traffic intensity.

TITLE: Stand, harvest, and equipment interactions in simulated harvesting prescriptions
Author(s): Wang JX, Greene WD, Stokes BJ
Source: FOREST PRODUCTS JOURNAL Volume: 48 Issue: 9 Pages: 81-86
Published: SEP 1998

Abstract: The productivity, cost and fuel-consumption rates for two wood-chip production systems were tested using computer simulation. Both systems included the same terrain-going chip harvester. In the first system, it was supported by a bin forwarder, whereas in the second system, the chip harvester had to cease operations and extract the load once the bin was filled. A largely deterministic base simulation was carried out to illustrate the effects of machine interaction, bin size, chipper productivity, in-field extraction distance, and forest-road haulage distance. Very low turnaround times and increased bin size (10, 15 and 20 m³) were beneficial to the single machine system, while increased chipper productivity (40, 50 and 60 m³ h⁻¹) improved the feasibility of the two-machine system, irrespective of bin size. An applied simulation included a larger stochastic component, and showed that for a 15 m³ bin, there was a 95% probability that the single-machine system was between and 0.41 € m⁻³ [loose volume, l.v.] more costly than the two-machine system under typical Danish conditions. Fuel consumption also exceeded that for the two- machine system by between 0.24 and 0.30 l m⁻³ [l.v].

ECONOMICS/MARKET IMPACTS

TITLE: Production economics of harvesting small-diameter hardwood stands in central Appalachia

Author(s): Li YX, Wang JX, Miller G, et al.

Source: FOREST PRODUCTS JOURNAL Volume: 56 Issue: 3 Pages: 81-86

Published: MAR 2006

Abstract: Three harvesting systems of chainsaw/cable skidder, feller- buncher/grapple skidder, and harvester/forwarder were simulated in harvesting three hardwood stands 30 to 50 years old in central Appalachia. Stands were generated by using a 3D stand generator. Harvesting prescriptions included clearcut, shelterwood cut, selective cut, diameter limit cut, and crop tree release cut. The interactions among stands, harvest prescriptions, and harvesting systems were evaluated statistically in terms of production, cost, and traffic intensity. The weekly production of the chainsaw/cable skidder system was 5,773 ft³ (163 m³) with a unit cost of \$38 per 100 cubic feet (cunit) (\$13.4/m³). The feller-buncher/grapple skidder and harvester/forwarder systems could produce 22,153 ft³ (627 m³), and 8,423 ft³ (239 m³) with the unit cost of \$34.3/cunit (\$12/m³) and \$46.8/cunit (\$17/m³), respectively. Results indicated that the feller-buncher/grapple skidder system was the most productive and cost-effective system for harvesting small-diameter hardwood stands in central Appalachia under the simulated harvesting prescriptions. Compared to harvesting mature stands, harvesting small-diameter hardwood stands was about 15 percent (felling) and 14 percent (extraction) less productive, and 29 percent (felling) and 13 percent (extraction) more expensive. Results should help planners, loggers, and foresters efficiently manage and utilize small-diameter materials in the region.

TITLE: Economic feasibility of an integrated harvesting system for small-diameter trees in southwest Idaho

Author(s): Han HS

Source: FOREST PRODUCTS JOURNAL Volume: 54 Issue: 2 Pages: 21-27

Published: FEB 2004

Abstract: Mechanical thinning in dense, small-diameter stands is being increasingly considered to reduce the risk of wildfire in the Interior Northwest of the United States. Economic feasibility of small wood thinning and utilization is in question due to the low market value of thinning materials and high costs for thinning and transportation. Two cost models were used to estimate thinning costs for various harvesting systems. Tree volume and potential product recovery (roundwood, clean chip, and biomass fuel) were computed and used to analyze the economic feasibility of small wood thinning and transportation in southwest Idaho. Harvesting costs for small-diameter trees increased with decrease of tree size, especially with skyline and helicopter systems. At average 10-inch diameter at breast height (DBH), skyline and helicopter stump-to-truck logging and chipping costs were about three and six times more expensive, respectively, compared with a mechanized whole-tree harvesting system that showed the lowest cost at \$34.23/100 ft. A sawlog harvest only option with a mechanical whole-tree harvesting system showed a positive return (\$/acre) when hauling distances were less than 53 miles. Other harvest options that included clean chip and/or biomass fuel as well as sawlogs were not financially viable, indicating that transportation of low market value materials (clean chip and biomass fuel) resulted in more cost than revenue. The factors affecting economic feasibility of small wood harvesting include forest harvesting systems used, road accessibility and conditions, hauling distance to manufacturing facilities, and market price of thinning materials.

TITLE: The effect of site quality on economically optimal stand management

Author(s): Marutani T

Source: JOURNAL OF FOREST ECONOMICS Volume: 16 Issue: 1 Pages: 35-46

Published: 2010

Abstract: This paper proposes a discrete-time type timber harvesting model for simultaneously determining (i) the optimal quantity of seedlings to be planted, (ii) the optimal quantities of timber harvested by thinnings, and (iii) the optimal rotation age. With the help of Microsoft Excel Solver, a generalized reduced gradient algorithm, numerical examples are developed to evaluate the impact of the variations in the quality level of a forest site on the optimal harvest strategy. It is shown that the level of optimal rotation age and optimal quantity of seedlings to be planted can individually exhibit non-monotonicity to the increase in site quality.

TITLE: Global climate change

Author(s): [Anon]

Source: JOURNAL OF FORESTRY Volume: 106 Issue: 3 Pages: 125-171

Published: APR-MAY 2008

Abstract: Global temperatures have fluctuated over the past 400,000 years (Figure 1- 1) (US EPA 2007b). Nevertheless, Earth is currently warmer than it has been in its recent past. The Intergovernmental Panel on Climate Change (IPCC) found that “eleven of the last twelve years (1995–2006) rank among the 12 warmest years in the instrumental record of global surface temperature (since 1850)” (Solomon et al. 2007, 5). The National Research Council concluded “with a high level of confidence that global mean surface temperature was higher during the last few decades of the 20th century than during any comparable period during the preceding four centuries” and, with less confidence, that “temperatures at many, but not all, individual locations were higher during the past 25 years than during any period of comparable length since a.d. 900” (NRC 2006, 3)

TITLE: The economics of alternative fuel reduction treatments in western United States dry forests:

Financial and policy implications from the national Fire and Fire Surrogate study Author(s): Hartsough BR, Abrams S, Barbour RJ, et al.

Source: FOREST POLICY AND ECONOMICS Volume: 10 Issue: 6 Pages: 344-354

Published: AUG 2008 We

Abstract: collected data at seven sites in the western US, on the costs of fuel reduction operations (prescribed fire, mechanical treatment, mechanical plus fire), and measured the effects of these treatments on surface fuel and stand parameters. We also modeled the potential behavior of wildfire in the treated and control stands. Gross costs of mechanical treatments were more expensive than those of prescribed fire, but net costs of mechanical treatments after deducting the values of harvested products were, on most sites, less than those of fire. The fire-only treatment reduced surface fuels, while most mechanical treatments (with the probable exception of whole-tree removal) increased these loads. Most mechanical-plus-fire treatments had little net effect on surface fuels. All treatments reduced the number of live trees, on average by about 300, 500 and 700 stems per hectare respectively for fire-only, mechanical, and mechanical-plus-fire. As intended by prescription, the mechanical treatments reduced basal area per hectare significantly. In most cases the fires – either alone or following mechanical treatment – killed mostly small trees, having essentially no impact on basal area. The mechanical-plus-fire treatment was the most effective, followed by fire-only, at reducing the modeled severity of wildfire effects under extreme weather conditions. The effectiveness of mechanical-only treatments depended on how much surface fuel remained on site. A whole-tree harvesting system removed the tops and limbs along with the felled trees, thereby reducing potential fire severity more than methods which left slash and/or masticated material within the stands. The various treatments created different conditions, and

therefore the treatment intervals needed to maintain desired fire resilience would probably differ as well, being shorter for fire-only than for mechanical-only or mechanical-plus-fire treatments. Decisions about which treatments to prescribe, where, and when, will generally consider not only the financial costs and entry intervals, but other societal benefits and costs of the treatments and of wildfires as well.

TITLE: Market impacts of hypothetical fuel treatment thinning programs on federal lands in the western United States

Author(s): Ince PJ, Spelter H, Skog KE, et al.

Source: FOREST POLICY AND ECONOMICS Volume: 10 Issue: 6 Pages: 363-372

Published: AUG 2008

Abstract: This paper addresses the economics of forest fuel thinning programs on federal lands in the U.S. West, and presents a model of regional timber and product market impacts. The issue of economics is vital to the debate about fire management, and this paper presents market implications of two alternative silvicultural strategies, even-aged and uneven-aged thinning. Projections are based on a regional market model called FTM—West (*Fuel Treatment Market model—West*), which uses the method of price-endogenous linear programming to project annual market equilibria for softwood timber and wood products in the western United States from 1997 to 2020. The model takes into account variability in tree and log size, as well as economic effects of variable size class on harvest costs, log value, product recovery and mill capacity. Results show large potential market impacts from expanded thinning on federal lands, but impacts vary by silvicultural regime due to differences in size-class distributions of trees available under different thinning regimes. A hypothetical even-aged thinning program (“thin-from-below” strategy) results in net negative market welfare over the projection period (2005–2020), while a hypothetical uneven-aged thinning program (thinning based on stand density index) results in positive net market welfare. Net welfare results are the same over a range of different subsidy and administrative fee assumptions. An implication is that even-aged thinning regimes on federal lands in the U.S. West are less economical and therefore will be less effective.

TITLE: Market impacts of a multiyear mechanical fuel treatment program in the US

Author(s): Prestemon JP, Abt KL, Huggett RJ

Source: FOREST POLICY AND ECONOMICS Volume: 10 Issue: 6 Pages: 386-399

Published: AUG 2008

Abstract: We describe a two-stage model of global log and chip markets that evaluates the spatial and temporal economic effects of government-subsidized fire-related mechanical fuel treatment programs in the U.S. West and South. The first stage is a goal program that allocates subsidies according to fire risk and location priorities, given a budget and a feasible, market-clearing market solution. The second stage is a quadratic welfare maximization spatial equilibrium model of individual State and global product markets, subject to the fuel treatment allocation. Results show that the program enhances timber market welfare in regions where treatments occur and globally but has an overall negative economic impact, once fuel treatment program costs are included. The overall cost of a mechanical fuel treatment program, when considering timber market welfare, transport costs, treatment costs, and timber receipts, exceeds \$1000 per acre, implying that the long run fire effects and ecosystem net benefits of a treatment program would need to exceed this figure in order to justify widespread implementation.

TITLE: An integrated approach to evaluating the economic costs of wildfire hazard reduction through wood utilization opportunities in the southwestern United States Author(s): Lowell EC, Becker DR, Rummer R, et al.

Source: FOREST SCIENCE Volume: 54 Issue: 3 Pages: 273-283

Published: JUN 2008

Abstract: This research provides an important step in the conceptualization and development of an integrated wildfire fuels reduction system from silvicultural prescription, through stem selection, harvesting, in-woods processing, transport, and market selection. Decisions made at each functional step are informed by knowledge about subsequent functions. Data on the resource characteristics of small-diameter ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.), harvest equipment productivity, lumber recovery, and net profit (loss) by level of fuels reduction achieved were collected from four 8.1-ha (20-ac) sites in northern Arizona. These data were used to develop a Windows-based, financial and engineering software program, the harvest cost-revenue (HCR) estimator, to identify the economic costs of wildfire fuel reduction treatments that may be used to evaluate cost per acre thresholds for logging contractors, appraise contract bid rates, or assess stumpage values for ponderosa pine stands in the Southwestern United States. Application of the model illustrates variability in fuels reduction costs owing to the level of fuels reduction achieved, the volume of merchantable wood removed from different forest stands, and the availability of markets for removed material. Machine productivity helps predict differences in harvest costs but is secondary to market constraints and the volume of wood harvested.

TITLE: Conventional and mechanized logging compared for Ozark hardwood forest thinning: productivity, economics, and environmental impact

Author(s): Becker P, Jensen J, Meinert D

Source: NORTHERN JOURNAL OF APPLIED FORESTRY Volume: 23 Issue: 4 Pages: 264-272

Published: DEC 2006

Abstract: Replicate 4-ac plots in a 70-year-old upland oak forest on slopes averaging 30 percent in southeastern Missouri were harvested by conventional (chainsaw + skidder) and mechanized (small tracked skid steer + feller-buncher and harvester + forwarder) logging equipment. The heavy thinning prescribed by a crop tree management approach removed an average of 1,300 ft³ or 40 tons per acre of pole wood and sawlogs, leaving an average basal area of 36 ft²/ac. The harvester/forwarder was the most productive (ft³/production hour), and the small feller-buncher the least, being the only system whose (unreplicated) production cost exceeded revenue. Production costs (excluding mobilization, overhead, and profit) of the conventional and harvester/forwarder systems were not statistically different on average, but the lowest cost of the latter was 14% less than that of the conventional system. The frequency of residual trees experiencing substantial bole damage was not significantly different among logging technologies, but the harvester/forwarder did have a higher incidence of substantial crown damage. The area of exposed mineral soil did not differ significantly among technologies, and soil compaction sufficient to impede rooting was rare. Lack of site and operator replication and incomplete cost analyses over a limited time prohibit generalization of these conclusions.

TITLE: Determinants of timber bid prices in Arkansas

Author(s): Dahal P, Mehmood SR

Source: FOREST PRODUCTS JOURNAL Volume: 55 Issue: 12 Pages: 89-94

Published: DEC 2005

Abstract: A large number of private and public timber sales occur through competitive bidding. The price in such bids is likely to be affected by a variety of factors including site characteristics, seasonality, geographic region, contractual provisions, and ownership type. A timber bid price model was constructed for timber sales data collected from industrial, non-industrial private (NIP), and public

timber sales in Arkansas. A regression model was estimated to establish functional relationships between winning bid prices per acre and a number of other variables. The model for the three ownership types was significant with an adjusted r^2 of 0.68. Per-acre bid price in the model increased with increasing sawtimber volume, but decreased with increasing pulpwood volume. Timber sold by NIP and public owners received a lower bid price per acre compared to industrial private landowners. Various seasons and regional variables were found to have significant impacts on per-acre bid price. This study identified the determining factors for timber bid prices in Arkansas. This information will be useful to non-industrial forest landowners, forest industries, timber producers, and policy makers.

TITLE: Wildfire in Montana: Potential hazard reduction and economic effects of a strategic treatment program

Author(s): Keegan CE, Fiedler CE, Morgan TA

Source: FOREST PRODUCTS JOURNAL Volume: 54 Issue: 7-8 Pages: 21-25

Published: JUL-AUG 2004

Abstract: This paper addresses the economics of forest fuel thinning programs on federal lands in the U.S. West, and presents a model of regional timber and product market impacts. The issue of economics is vital to the debate about fire management, and this paper presents market implications of two alternative silvicultural strategies, even-aged and uneven-aged thinning. Projections are based on a regional market model called FTM—West (*Fuel Treatment Market model—West*), which uses the method of price-endogenous linear programming to project annual market equilibria for softwood timber and wood products in the western United States from 1997 to 2020. The model takes into account variability in tree and log size, as well as economic effects of variable size class on harvest costs, log value, product recovery and mill capacity. Results show large potential market impacts from expanded thinning on federal lands, but impacts vary by silvicultural regime due to differences in size-class distributions of trees available under different thinning regimes. A hypothetical even-aged thinning program (“thin-from-below” strategy) results in net negative market welfare over the projection period (2005–2020), while a hypothetical uneven-aged thinning program (thinning based on stand density index) results in positive net market welfare. Net welfare results are the same over a range of different subsidy and administrative fee assumptions. An implication is that even-aged thinning regimes on federal lands in the U.S. West are less economical and therefore will be less effective.

TITLE: A bid price equation for national forest timber sales in western Arkansas and southeastern Oklahoma

Author(s): Huebschmann MM, Lynch TB, Lewis DK, et al.

Source: SOUTHERN JOURNAL OF APPLIED FORESTRY Volume: 28 Issue: 2 Pages: 100-108

Published: MAY 2004

Abstract: An equation relating bid price to timber sale characteristics was developed using regression techniques on the basis of data from 150 timber sales that occurred between June 1992 and Dec. 1998 in the Ozark and Ouachita National Forests in Arkansas and southeastern Oklahoma. Predicted values of the real winning bid price are based on total sawtimber volume per sale, total pulpwood volume per sale, average sawtimber volume per acre, average sawtimber volume per tree, and the ratio of southern yellow pine #2 dimension lumber producer price index (PPI) to pine sawlog PPI. Sawtimber and pulpwood in these sales are mainly shortleaf pine (*Pinus echinata* Mill.). The most highly significant variables were total sawtimber volume and the ratio of southern yellow pine #2 dimension lumber PPI to pine sawlog PPI. The equation explains 95% of the variation in the total bid price data. South. J. Appl. For. 28(2):100–108.

TITLE: Productivity and cost of marking activities for single-tree selection and thinning treatments in Arkansas

Author(s): Sydor T, Kluender RA, Busby RL, et al.

Source: FOREST PRODUCTS JOURNAL Volume: 54 Issue: 3 Pages: 59-65

Published: MAR 2004

Abstract: An activity algorithm was developed for standard marking methods for natural pine stands in Arkansas. For the two types of marking methods examined, thinning (selection from below) and single-tree selection (selection from above), cycle time and cost models were developed. Basal area (BA) removed was the major influencing factor in both models. Marking method was significant in predicting the total time of the activity but not significant in estimating the cost per 10 ft.²/acre of BA removed.

TITLE: Economic aspects of thinning and harvest for forest health improvement in eastern Oregon and Washington

Author(s): Haynes R, Fight R, Lowell E, et al.

Source: NORTHWEST SCIENCE Volume: 75 Special Issue: Sp. Iss. SI Pages: 199- 207

Published: 2001

Abstract: Management activities that affect forest health and productivity are driven by social, political, and economic processes. Economic feasibility is important in determining the extent to which various treatments proposed to improve forest health will actually be applied. Three socioeconomic institutions create incentives that are important determinants: markets, land uses, and the processing industry. We have extensive information on timber markets, and land uses have been studied at broad scales. Thinning undertaken for forest health improvement provides mostly small-diameter and dead material, but markets for products from small and dead logs are limited. Harvesting and manufacturing costs, resource characteristics, and lumber prices influence the way timber is processed (i.e. what products are made); design of timber sales (i.e. amount and size of raw materials offered) influences harvest cost. Processing equipment that scans logs and processes them according to shape can greatly improve product yield. Decision tools that incorporate these factors into financial evaluations can assist in harvest and other treatment decisions.

TITLE: Effects of uneven-aged silviculture on the stand structure, species composition, and economic returns of loblolly pine stands

Author(s): Schulte BJ, Buongiorno J

Source: FOREST ECOLOGY AND MANAGEMENT Volume: 111 Issue: 1 Pages: 83-101

Published: NOV 2 1998

Abstract: Uneven-aged silviculture in loblolly pine (*Pinus taeda* L.) stands has many economic and ecological benefits. Here, the consequences of various uneven-aged management regimes are predicted with the SouthPro simulator. Results indicate that target distributions for pines with residual merchantable basal areas of $\approx 12.5 \text{ m}^2 \text{ ha}^{-1}$, maximum diameters of ca. 40 cm, and q -ratios of 1.2–1.25 for 2.5 cm DBH classes are likely to provide high economic returns on good sites when combined with hardwood control. Increasing this maximum diameter would enhance tree-size diversity, but reduce sawtimber production and profits. Retaining a hardwood component with $1.15\text{--}2.3 \text{ m}^2 \text{ ha}^{-1}$ of basal area could enhance tree- species diversity, but this too would result in moderate reductions in income. Insisting on maximizing tree-size diversity or tree-species diversity among softwoods, soft hardwood, and hard hardwoods would be quite costly in terms of lost income and production. Results also illustrate how short-term economic incentives can lead to high-grading practices, despite substantial reductions in stand productivity and net returns in the long term.

Sub-Task B3: Evaluation of Forest Biomass Processability

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Final Report

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1. Executive Summary

Reasons for renewed interest in biofuels production include new policy and legislation such as sustainable biofuel targets in the US Energy Policy Act (EPC, 2005), foreign oil dependence reduction, reduction in harmful environmental impacts, and the ability to create a more diverse product industry. This study provides a technical screening of biofuels production feasibility from forest-based feedstock that can be implemented in Michigan. These feedstocks studied include poplar, willow, aspen, switchgrass, red maple, and balsam.

Two conversion pathways were considered within this work: dilute acid hydrolysis followed by enzymatic hydrolysis (biochemical mechanisms), and pyrolysis (thermal degradation mechanisms). These processes were evaluated on their production of valuable bio-fuels intermediates. The dilute acid pretreatment and enzymatic hydrolysis was evaluated on the production of sugars that can be fermented into fuels such as ethanol. Pyrolysis was evaluated based on the yield of liquid and gaseous phase products.

From study, we found that our results agree well with existing literature, and indicate that Michigan grown woody feedstocks can be processed into valuable products through either investigated method. This work found that yields of greater than 50% of biomass-embodied sugars can be extracted when processing woods such as poplar and willow, through dilute acid pretreatment and enzyme hydrolysis. Additionally, this study found that combined bio-oil and gas phase yields of greater than 50% mass can be obtained from fast pyrolysis, within a 500-700°C range.

2. Introduction

The production of biofuels from biomass has gained accelerated interest in recent years as these fuels are increasingly economically-viable, renewable, and carbon-neutral energy sources. One reason for this renewed interest derives from new policy and legislation such as sustainable biofuel targets in the US Energy Policy Act (EPC, 2005) and Energy Independence and Security Act (EISA, 2007). In addition to these policies, renewable energy/fuel sources are substantially better for the environment because they are renewable, reduce environmental burdens over petroleum fuels, and provide a broader range of products marketable from Michigan's natural resources.

Currently the largest effort (and only well reviewed in the literature) comes from the production of corn ethanol, displacing over 4,600 million equivalent gallons of gasoline and fueling almost 5.5 million flexible fuel vehicles (Ethanol Market Penetration, 2011). These fuels, however, could be produced from any material that is rich in fermentable sugars such as lignocellulosic biomass. Because wood is an abundant, and sustainably managed resource in Michigan, it is an excellent candidate for such an alternative feedstock. Michigan feedstocks considered in this study include poplar, willow, aspen, balsam, red maple, and switchgrass.

A primary concern within assessing the processability of woody biomass for ethanol production is determining the quantity of fermentable monomer sugars that are recoverable from raw samples, as these sugars are then fermented to ethanol. It has been shown (Jensen et al., 2010, Morinelly et al., 2009, and Yat et al., 2006), that monomerization of complex molecules within woody biomass is effectively obtained through acid pretreatment and enzymatic hydrolysis. In

partial-fulfillment of the proposed objectives, Michigan-viable feedstocks were analyzed for monomer sugar recovery.

In addition to using Michigan's woody feedstocks for fermentable sugar extraction, they can also be utilized through a process called pyrolysis. Pyrolysis is the thermal degradation of wood in the absence of oxygen. The process creates three products: a dense bio-oil, a low quality gas stream, and bio-char. The bio-oil is usually a dark and viscous oil, not unlike heavy petrol-oil, and can have faint smoky odors depending on the original feedstock (Czernik and Bridgwater, 2004). This oil is usually very acidic (pH around 2.5) and contains mostly water (15-30 wt%) and polar organics (75-80wt%) (Bridgwater et al., 1999 and Mohan et al., 2006). Within these polar organic compounds, common components, as demonstrated in this research, include: hydroxylaldehydes (such as glycolaldehyde), hydroxyketones, monomer sugars (such as glucose and xylose), sugar varients (such as levoglucosan), carboxylic acids (such as acetic and formic acid), and phenolics or cyclic compounds.

The bio-oil can be directly used for heating and electricity generation, or undergo further refining to a true hydrocarbon transportation fuel. The gas-phase product stream usually contains a mixture of low-value gases (CO, CO₂) with small amounts of higher-value combustibles (methane, ethane). The solid residue remaining after pyrolysis (or torrefaction at low temperatures, 200-300°C), is referred to as char, bio-char, or bio-coal. Bio-coal has similar properties to traditional coal, and in many cases can be used as a 'drop-in' replacement in existing infrastructure. In addressing the proposed objectives, Michigan-viable feedstocks were analyzed through pyrolysis for: (1) phase-distribution data (oil-gas-char), (2) detailed speciation of the oil and gas phase products, and (3) quantification of some major components detected with the bio-oil.

3. Methods

Detailed descriptions of experimental procedures are included in this section of the report. Equipment descriptions, along with the manufacture and model, are also included

3.1. Dilute Acid Hydrolysis and Enzymatic Hydrolysis

The work performed to fulfill the Dilute Acid Hydrolysis and Enzymatic Hydrolysis (DAH-EH) requirements consisted of four major experimental steps: preparation of the biomass samples, dilute acid pretreatment, total pretreatment monomer analysis, and enzymatic hydrolysis. These methods were adopted from previous work carried out at Michigan Technological University (Jensen et al., 2010). A simplified block diagram was developed to visually represent and demonstrate the experimental stages, and is shown as Figure 1. The equipment utilized in DAH-EH includes: a W.S. Tyler Rotap (model RX-29, serial 9774) for particle size differentiation, a Marathon 21K centrifuge by FisherScientific for solid-liquid separation, an AC-48 Autoclave by New Brunswick Scientific for oligomer analysis, a 1200 series HPLC by Agilent for sugar detection and quantification, and an Orbit Environ-Shaker by Lab-Line Industries Inc. used during enzymatic hydrolysis.

Figure 2: Simplified block diagram for the dilute acid pretreatment and enzymatic hydrolysis experiments.

3.1.1. Preparation of Biomass Samples

Prior to acid pretreatment or enzymatic hydrolysis within the experiments, each biomass sample is dried and milled into small pieces. Drying was performed through heating the sample in a drying oven at 105°C until a difference in mass was no longer detected. The drying was performed in accordance with NREL's LAPS (Report NREL/TP-510-42620, 2008). A small scale hammer mill, located at MTU, was used to grind the dried biomass to an appropriate range of sizes. A rotap equipped with a range of analytical sieves was used in the particle size differentiation. The sampling was performed in accordance with NREL's LAPs (Report 2NREL/TP-510-42620, 2008) with modifications to adjust for appropriate sieve sizes (sizes larger than 28 Tyler Mesh, but smaller than 20 Tyler Mesh or approximately 599-853 microns).

3.1.2. Acid Pretreatment

Acid pretreatment is performed once the samples are dried and sorted. The optimum conditions for monomer extraction during dilute acid hydrolysis occur around 160°C and 0.5 wt/wt% acid (Jensen et al., 2010). Individual samples are weighed and placed into a set of 9 stainless steel cylindrical reactor tubes, each containing 4.5mL of 0.5 wt/wt% sulfuric acid aqueous solution. After letting the dilute acid solution properly diffuse into the wood particles (no substantial reaction takes place due to low ambient conditions), the reactors tubes are submerged into a silicon oil constant temperature bath, which is initially set to 175°C. The bath and reactors come to thermal equilibrium around 160°C in approximately 3 minutes. The acid pretreatment reaction occurs as the temperature and pressure within the reaction vessels rise. The tubes are

removed from the oil bath at varying points in time for analysis. In order to stop the reaction, the tubes are immediately submerged in an ice-water bath. The contents of each reactor tube is removed and collected when it has sufficiently cooled.

The subsequent liquid and solid portions are separated (the solid portion is carried onto enzymatic hydrolysis). A liquid sample from each reactor is rapidly centrifuged at 13,000RPM for 5 minutes. From the liquid fraction, 1mL is collected for High Performance Liquid Chromatography (HPLC) to analyze monomer sugar concentrations obtained directly from dilute acid pretreatment. Another 1mL of the liquid product is passed through a 20 micron filter and carried onto oligomer analysis (total monomer analysis).

The HPLC analysis delivers results in terms of retention time and peak area of detection. These data are correlated with monomer standard solutions; solutions with known concentrations of glucose, xylose, galactose, arabinose, and mannose. This method of analysis will result in an accurate representation of the monomer content within the samples. Dilution factors for acidification and neutralization are taken into account when performing all calculations. The sugar extracted in the greatest abundance during pretreatment is xylose, a 5-carbon sugar. Examples of sugar calibration curves are within Appendix A.

3.1.3. Total Pretreatment Monomer Analysis

In addition to direct monomer extraction from pretreatment, some sugars are extracted in their native disaccharide or polysaccharide (oligomer) forms. The quantification of these sugars requires introducing additional sulfuric acid to bring the concentration to 4 wt/wt% acid, followed by autoclaving (121°C for 1 hour). All existing oligomer sugars should be degraded to their monomer form or other degradation products after this process is complete. A 1mL liquid aliquot of the resulting liquid fraction from each sample is used for oligomer sugar content analysis. The 1ml HPLC analysis aliquots are neutralized to a pH between 5 and 6, tested with litmus paper, and passed through a 20 micron filter prior to being run through the HPLC. Similar to the previous section, the monomer sugar content is obtained through standard curves. Sugar Recovery Standards (SRS) are also used along with the acid pretreatment samples during oligomer analysis. These SRS are premade sugar solutions with known concentrations. Processing these will yield an amount of monomer sugars that are degraded to unwanted inhibitory products such as fufural and hydroxymethyl furfural. Similar to the acid pretreatment samples, the SRS are acidified to 4 wt/wt% acid prior to processing. SRS liquid samples are also neutralized to a pH between 5 and 6, tested with litmus paper, centrifuged, and analyzed with the HPLC for monomer concentration. Analysis of the SRS allows for determination of the concentration of monomer sugars that are degraded during autoclaving. The total sugars, expressed in total monomer equivalence, can be obtained by combining the initial monomer analysis of the pretreatment liquid and the oligomer analysis results. For all calculations care was taken to account for the level of monomer degradation in addition to dilution factors.

3.1.4. Enzymatic Hydrolysis

The solid portion of the biomass samples resulting from the acid pretreatment is introduced to enzymatic hydrolysis. During this procedure, enzymatic saccharification of cellulose from the pretreated lignocellulosic biomass to glucose occurs, with a minor xylose contribution as well. This allows for calculating the maximum extent of enzyme digestibility for biomass samples.

For enzymatic hydrolysis to take place the post acid pretreatment sample solids are rinsed with distilled water and then vacuum filtered to remove any excess liquid. The solids, still individual samples from their reactors, are each placed into a flask. A pre-enzymatic hydrolysis mixture added to the flasks includes: 47mL of distilled water, 2.5mL of 1M sodium citrate buffer, 200 μ L of tetracycline, and 150 μ L of cycloheximide. Tetracycline and cycloheximide are antibiotics utilized to prevent the growth of other organisms that might inhibit or consume the produced sugars. A control flask is also prepared to determine the impact of the biomass-accompanying liquids. The control flask is prepared in an identical fashion, but without and biomass.

Each flask of pre-enzymatic hydrolysis mixture is tightly sealed and introduced to an incubated bench-top shaker for 1 hour at 50°C. After reaching thermal equilibrium within the shaker, *Accellerase*® 1500 enzyme is added to each flask. An enzyme loading of 125 μ L *Accellerase*® 1500 has shown to be effective in performing enzymatic hydrolysis (Jensen et al., 2010). Samples were taken to be analyzed every 24 hours, starting with an immediate sample withdraw. The samples are passed through a 20 micron filter prior to HPLC analysis. Similar to previous sections, the HPLC results are correlation to monomer sugar standard curves. The control flask is also analyzed via HPLC to determine any levels of incidental detection within a blank sample. The monomer content within the post enzymatic hydrolysis samples is calculated for the solid portion of the acid pretreated biomass sample, taking into account any contribution within the control as well as dilution factors.

3.2. Fast Pyrolysis and Gas Chromatography/Mass Spectroscopy

The use of GC/MS analysis to analyze the products of pyrolysis has had promising results, in terms of speciation and quantification, and become a popular method (Patwardhan et al., 2009, Patwardhan et al., 2010, Patwardhan et al., 2011, Jackson et al., 2009, Dzhbiter et al., 2011). Figure 2 shows a simplified flow diagram for the Pyrolysis-GasChromatography-MassSpectroscopy (PY-GC-MS) experiment described below. The micro-pyrolysis reactor used in this work was a model 5200HP Pyroprobe created by CDS Analytical. The gas chromatograph was a Trace GC Ultra (Model K8880181) created by Thermo-Finnigan (now ThermoFisher) and was operated with a 30 meter Rxi-5ms fused silica capillary column by Restek. The mass spectrometer was also created by ThermoFinnigan (now ThermoFisher) and is a model Trace DSQ. The microbalance used during the experiments is a model CM5 created by Citizen Scales Inc. and has a readability of 1 μ g.

Figure 3: Simplified flow diagram for the PY-GC-MS experimental setup.

3.2.1. Pyrolysis and GC/MS Analysis

An experimental trial begins when an empty quartz vial (to hold the wood biomass sample for fast pyrolysis) is loaded into the sample probe along with two quartz wool plugs. The wool acts as a filter on either end of the vial, which is a hollow cylinder, allowing gases to flow through it while retaining the biomass and solid residues. After the empty vial is loaded into the micropyrolysis reactor with the probe, the materials undergo a pyrolysis cycle identical to that which is run on the biomass samples. This procedure is referred to as a *blank* and is performed before each experimental trial as a quality control method. With a process identical to that which is run on the biomass, it can be demonstrated that the materials are perfectly clean and there is no residual matter anywhere in the system. Once it is established from the resulting chromatogram that the only signal is representative of noise, and low bleed from the fused silica column in the GC, the feedstock trial can begin.

Once a successful blank is obtained, biomass particles (further sieved with the rotap as before to a particle size range between 500 and 599microns) are loaded into the clean quartz reactor vial between the two quartz wool plugs. The vial containing the biomass sample is then inserted into the pyrolysis reactor via the sample probe. Once inside, the atmosphere is immediately purged with inert helium gas. When the sample is pyrolyzed it is very rapidly ($>999^{\circ}\text{C}/\text{second}$) heated up to an experimental temperature (500, 600, or 700°C) and held there for 15 seconds. There is an interface time (2 minutes) after the heating begins where the inert gas passes through the sample probe and carries any resulting vapors through a heated transfer line to the mass spectrometer for analysis.

The GC/MS analysis conditions were modified from a published analysis method (Patwardhan et al., 2009). The GC oven temperature is initially set to a low temperature to allow the gases and vapors to condense and adsorb to the fused silica surface within the column. The oven is then slowly heated to remove the compounds at retention times, which are sent to the mass

spectrometer with the helium carrier gas. Here, the molecules are fragmented using electrons generated with a heated filament. The resulting fragments are recorded as a mass spectrum. These mass spectra are then related to spectra of known compounds in the National Institute of Standards and Technology (NIST) libraries (contained in the GC/MS software), and the compounds are identified. The probability of a match is also reported. This probability determines the accuracy of the library search. From this analysis, the identity of major pyrolysis species is obtained. Furthermore, the GM/MS integrates the area under each identified peak, which is used to estimate the relative mass of each compound identified.

3.2.2. Gravimetric Analysis

Throughout the experiment, measurements are taken to obtain a gravimetric mass balance. For this procedure, some of the biomass sample is placed into a weighing tin and a mass is recorded. One of the wool plugs from a clean blank is then removed so the massed sample can be loaded into the vial. The discrete particles are carefully placed into the vial. The wool plug is placed back into the vial after the sample is loaded. The mass of the weighing tin and feedstock sample is then taken again, to get the mass of wood added to the vial by difference. The mass of sample added to the vial is then converted to a dry basis with the moisture content of the feedstock (determination of moisture is explained in the following section). At this point the sample vial can be placed into the probe and the pyrolysis-GC/MS portion of the experiment can continue. The vial is then weighed again to obtain the mass of the sample that was pyrolyzed (representative of the pyrolysis oil and gases) by mass difference of the vial before and after the pyrolysis trial. The difference between the dry biomass added to the sample vial and mass of sample leaving during pyrolysis is representative of the pyrolysis char.

3.2.3. Moisture Content Analysis

The moisture contents of the feedstocks are determined with a drying oven. In this procedure, the oven is held at a constant temperature of 105°C and the sample masses are recorded over time. When the mass stops decreasing, the material is determined to be completely dry and the moisture content can be found. The moisture content is calculated as the difference between the samples initial weight minus its final weight, assuming that the entire sample mass loss is water moisture. These results are important, because when the samples are prepared for pyrolysis they contain moisture, whereas when they are weighed after the pyrolysis cycle they are completely dry. This allows the mass balance to account for the bound moisture leaving the feedstock, that isn't from dehydration reactions. The moisture content of the feedstocks range from 5.0-8.5%, and are shown in the results section.

4. Results

4.1. Dilute Acid Hydrolysis and Enzymatic Hydrolysis Results

For assessing the processability of biomass feedstocks, it is necessary to compile data for the sugar content available within the feedstocks of interest. A large portion of biomass feedstock consists of carbohydrates. Table 1 summarizes raw feedstock carbohydrate composition and moisture content. The carbohydrate composition analysis was performed prior to the FBSCC project, and was done independently of the moisture analysis using bone-dry materials.

Table 2: Sugar and lignin compositional analysis of raw biomass samples (wt%) (Yat et al.,2006). Carbohydrate composition is displayed as wt% of bone-dry sample.

	Moisture	Glucan	Xylan	Galactan	Araban	Mannan	Lignin
Aspen	7.5	52.43	14.60	3.52	2.41	5.32	26.69
Balsam	6.3	47.09	623	5.45	5.41	11.49	36.04
Basswood	8.5	43.99	15.31	3.41	3.49	2.91	28.44
Red Maple	7.1	43.18	17.69	5.71	4.13	5.37	36.49
Swithgrass	7.0	47.72	19.06	4.18	8.11	6.30	26.04
Willow	5.0						
Poplar	5.5						

4.1.1. Dilute Acid Hydrolysis and Enzymatic Hydrolysis Results from Previous Work

Using the acid pretreatment and enzymatic hydrolysis methods described above, the total sugar yield of different feedstocks were analyzed under different conditions. Acid concentrations from 0.25-0.75% and temperatures from 150-175°C were considered. The results of percent theoretical yield captured are shown in Figure 3. More detailed data are tabulated along with their experimental conditions in Table 2.

Figure 4: Total monomer sugar equivalence for Aspen, Balsam and Switchgrass. (A) 150°C, 0.25% H₂SO₄, (B) 150°C, 0.50% H₂SO₄, (C) 150°C, 0.75% H₂SO₄, (D) 160°C, 0.25% H₂SO₄, (E) 160°C, 0.50% H₂SO₄, (F) 160°C, 0.75% H₂SO₄, (G) 175°C, 0.25% H₂SO₄, (H) 175°C, 0.50% H₂SO₄, (I) 175°C, 0.75% H₂SO₄. (Jensen et al., 2010)

Table 3: A-Aspen, BM-Balsam, and SG-Switchgrass dilute acid hydrolysis and enzymatic hydrolysis % yields for varying reaction conditions (Jensen et al., 2010).

Dilute Acid Hydrolysis Reaction Conditions				% Theoretical Yields from Acid Hydrolysis (g sugar/g dry initial biomass)				Enzymatic Hydrolysis	
Species	Acid (wt %)	Temperature (°C)	Reaction Time (min)	Xylose Yield (%)	Xylan Oligomer (%)	Glucose Yield (%)	Glucan Oligomer (%)	Glucose Yield (%)	Xylose Yield (%)
A	0.25	150	150.5	12.4	1.6	1.6	0.3	36.8	1.0
A	0.50	150	70	12.6	1.6	1.8	0.1	35.8	0.7
A	0.75	150	45	12.6	2.1	1.8	0.2	37.3	0.7
A	0.25	160	70	12.3	1.7	1.8	0.4	39.2	0.8
A	0.50	160	24	12.1	2.3	1.5	0.3	37.8	0.9
A	0.75	160	18	12.6	2.3	1.8	0.2	37.9	0.8
A	0.25	175	30	11.9	1.4	2.8	0.3	42.3	0.5
A	0.50	175	12	12.6	2.7	2.5	0.3	40.3	0.6
A	0.75	175	8	12.9	1.5	2.6	0.2	39.6	0.4
BM	0.25	150	170	4.1	0.6	3.0	0.2	0.0	0.0
BM	0.50	150	60	4.1	0.7	3.0	0.1	0.1	0.0
BM	0.75	150	36	4.2	0.7	3.1	0.4	1.8	0.0
BM	0.25	160	71	4.3	0.6	3.2	0.2	2.8	0.0
BM	0.50	160	20	4.1	0.8	3.3	0.1	1.8	0.0
BM	0.75	160	12	4.2	0.0	3.2	0.0	1.8	0.0
BM	0.25	175	29	4.4	0.4	3.6	0.0	2.7	0.0
BM	0.50	175	10	4.3	0.8	3.4	0.2	2.5	0.0
BM	0.75	175	6	3.7	0.7	3.3	0.0	1.8	0.0
SG	0.25	150	320	6.7	5.0	2.2	1.3	19.8	2.3
SG	0.50	150	160	10.5	1.5	2.7	0.5	23.1	2.0
SG	0.75	150	60	16.2	2.9	3.6	1.0	23.1	1.5
SG	0.25	160	210	6.9	3.3	2.4	1.6	22.2	2.2
SG	0.50	160	72	13.0	2.8	3.1	1.0	22.7	2.3
SG	0.75	160	24	16.1	3.3	3.4	0.9	24.4	1.7
SG	0.25	175	40	6.2	8.4	2.1	1.2	23.1	2.4
SG	0.50	175	20	13.1	4.0	2.8	1.1	26.3	1.6

SG	0.75	175	14	16.0	3.0	4.0	0.9	25.1	0.9
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In addition to taking experimental data, considerable effort has been placed into developing kinetic models for the reactions. The fact that the carbohydrate portion of biomass can be converted to a more usable monomer, from the hydrolysis of hemicelluloses, is of significant interest for interpreting the data collected in past studies. A linear four-step kinetic model is shown in Equation 1. This equation represents the degradation of xylose in hemicelluloses (XH). In this process, the original large and branched structure that exists in hemicelluloses is first broken down into much smaller chains of oligomer xylose (XO). The oligomers are then further degraded to monomer xylose (X). As sugars emerge in their monomer forms, they begin to degrade to unwanted products, such as furfural (F) and to other degradation products (D).

Each of the kinetic rate constants, k_i , can be calculated as function of absolute temperature (T) and acid concentration (C^{m_i}). The Arrhenius expression demonstrates this as shown in Equation 2.

$$k_i = A_{oi} C^{m_i} \exp\left(-\frac{E_i}{RT}\right) \quad (2)$$

where T is the absolute temperature (K), C is the acid concentration (wt %), A_{oi} is the pre-exponential factor (min^{-1}), m_i is the acid concentration exponent (unitless), E_i is the activation energy (kJ/mol), and R is the ideal gas constant ($8.3143 \times 10^{-3} \text{ kJ/mol} \cdot \text{K}$). A summary of best fit kinetic rate constants is shown in Table 3. Arrhenius parameters were calculated using kinetic constants from Table 3. The fitted Arrhenius parameters for Equation 3 are shown in Table 4.

Table 4: Fitted Kinetic Constants to Experimental Data. (Morinelly et al., 2009)

k_i (min^{-1})	wt % H ₂ SO ₄	Aspen			Balsam			Switchgrass		
		150 °C	160 °C	175 °C	150 °C	160 °C	175 °C	150 °C	160 °C	175 °C
k_1	0.25	0.055	0.127	0.300	0.014	0.044	0.119	0.008	0.017	0.069
	0.50	0.129	0.242	0.666	0.050	0.119	0.250	0.028	0.068	0.260
	0.75	0.190	0.275	0.666	0.075	0.150	0.324	0.151	0.211	0.554
k_2	0.25	0.047	0.086	0.151	0.122	0.264	0.593	0.005	0.011	0.022
	0.50	0.130	0.223	0.317	0.407	0.461	1.020	0.033	0.057	0.149
	0.75	0.182	0.284	0.642	0.433	1.800	2.110	0.089	0.140	0.344
k_3	0.25	0.001	0.003	0.015	0.003	0.007	0.018	0.004	0.007	0.025
	0.50	0.004	0.013	0.022	0.008	0.028	0.051	0.004	0.006	0.020
	0.75	0.006	0.010	0.042	0.012	0.036	0.114	0.004	0.010	0.021
k_4	0.25	0.003	0.002	0.031	0.036	0.085	0.171	0.005	0.008	0.034
	0.50	0.017	0.027	0.064	0.156	0.596	0.352	0.010	0.019	0.081
	0.75	0.029	0.047	0.086	0.211	1.070	0.720	0.028	0.114	0.149

Table 5: Fitted Arrhenius parameters to Equation 2 from kinetic constants in Table 3. (Morinelly et al., 2009)

	Acid (%wt.) Exponent		Pre-exponential Parameter	Activation Energy	Arrhenius Fit
	k_i	m_i (unitless)	A_{oi} (min^{-1})	E_i (kJ/mol)	R^2
Aspen	k1	0.88	1.94E+11	97	0.97
	k2	1.22	9.88E+07	69	0.98
	k3	1.20	1.38E+14	132	0.94
	k4	2.06	5.70E+11	106	0.86
Balsam	k1	1.21	2.07E+12	108	0.97
	k2	1.33	2.25E+10	84	0.91
	k3	1.55	5.65E+13	125	0.97
	k4	1.77	2.79E+08	70	0.81
Switchgrass	k1	2.24	1.04E+14	120	0.97
	k2	2.47	1.96E+10	89	0.99
	k3	0.06	4.75E+10	106	0.99
	k4	1.72	2.59E+13	120	0.98

4.1.2. Dilute Acid Hydrolysis and Enzymatic Hydrolysis Results from FBSCC Work

The major results for the DAH-EH for the FBSCC work are concentrated around the extraction of sugars from willow and poplar tree samples. The sugars considered here are glucose, xylose, galactose, and combined arabinose and mannose. Figures 4 and 5 show the average monomer sugar concentrations (g/L) obtained after dilute acid pretreatment for poplar and willow respectively. Figures 6 and 7 show the average oligomer concentration following dilute acid pretreatment expressed and monomer equivalence for poplar and willow respectively. Figures 8 and 10 show the total monomer extraction for glucose and xylose respectively, through all processing stages, assuming 72 hours of enzymatic hydrolysis for poplar. Figures 9 and 11 show the monomer values as percentages of their theoretical maximum extraction amount. Similarly, Figures 12, 13, 14, and 15 show the results for willow. Average enzymatic sugar liberation versus treatment time diagrams are located in Appendix B.

Figure 5: Average monomer concentrations versus reaction time obtained from poplar following dilute acid (0.5% wt. sulfuric acid, 160°C) pretreatment monomer extraction.

Figure 6: Average monomer concentrations versus reaction time obtained from willow following dilute acid (0.5% wt. sulfuric acid, 160°C) pretreatment monomer extraction.

Figure 7: Average oligomer concentrations (expressed as monomer equivalents) versus reaction time obtained from poplar following dilute acid (0.5% wt. sulfuric acid, 160°C) pretreatment monomer extraction.

Figure 8: Average oligomer concentrations (expressed as monomer equivalents) versus reaction time obtained from willow following dilute acid (0.5% wt. sulfuric acid, 160°C) pretreatment monomer extraction.

Figure 9: Total glucose monomer mass yields obtained from poplar with acid pretreatment monomer extraction, oligomer extraction, and enzymatic hydrolysis.

Figure 10: Total glucose monomer yields (% of theoretical) obtained from poplar with acid pretreatment monomer extraction, oligomer extraction, and enzymatic hydrolysis.

Figure 11: Total xylose monomer mass yields obtained from poplar following acid pretreatment monomer extraction, oligomer extraction, and enzymatic hydrolysis.

Figure 12: Total xylose monomer yields (% of theoretical) obtained from poplar following acid pretreatment monomer extraction, oligomer extraction, and enzymatic hydrolysis.

Figure 13: Total glucose monomer mass yields obtained from willow following acid pretreatment monomer extraction, oligomer extraction, and enzymatic hydrolysis.

Figure 14: Total glucose monomer yields (% of theoretical) obtained from willow following acid pretreatment monomer extraction, oligomer extraction, and enzymatic hydrolysis

Figure 15: Total xylose monomer mass yields obtained from willow following acid pretreatment monomer extraction, oligomer extraction, and enzymatic hydrolysis.

Figure 16: Total xylose monomer yields (% of theoretical) obtained from willow following acid pretreatment monomer extraction, oligomer extraction, and enzymatic hydrolysis.

4.2. Fast Pyrolysis and Gas Chromatography/Mass Spectroscopy Results

As mentioned previously, the main focus for pyrolysis processing results has been split into three categories: (1) phase distribution for targeting desired phase production, (2) bio-oil speciation to identify major components, and (3) product quantification to establish the most abundant compounds.

4.2.1. Fast Pyrolysis Phase Distribution

Figure 16 shows the combined distribution of pyrolysis oil and gas for different feedstocks over a large range of experimental temperatures. The remaining weight percent represents the mass remaining in the experimental vial as bio-coal. Also included in the figure is a literature trend for biomass between 400 and 600°C (Bridgwater et al., 1999). The feedstocks shown were chosen to represent Michigan hardwoods (aspen), Michigan softwoods (balsam), and Michigan energy crops (switchgrass). Figure 17 shows the data for aspen with an S-curve fit to the data.

Figure 17: Average weight percents of combined bio-oil and gas products for aspen, balsam, and switchgrass.

Figure 18: Average weight percents of combined bio-oil and gas products for aspen.

4.2.2. Fast Pyrolysis Product Speciation and Quantification

Many of the fast pyrolysis trials yielded very similar compounds. Because of this, a chromatogram of aspen will be displayed here as a common representative. Full experimental trial data from this section will be included as Appendix C. Figure 18 shows a chromatogram from a trial of aspen at 600°C. Table 5 is a listing of NIST library results of some of the major peaks in addition to relative area. The tables (6-10) following that form a summary for all feedstock at different temperatures.

Figure 19: Chromatogram for an aspen trail at 600°C.

Table 6: Peak identification and quantification for aspen.

Retention Time (Min)	Name	Peak Area		
		500	600	700
6.2	CO, CO2, H2O	20.0%	38.8%	53.4%
6.7	Propanal, 2,3-dihydroxy-	1.3%		
7.0	Acetaldehyde, hydroxy-	5.7%	7.7%	10.3%
7.6	Acetic acid	3.1%	12.1%	5.2%
7.8	2-Propanone, 1-hydroxy-	9.6%	11.9%	11.9%
9.6	Acetic acid, methyl ester		2.8%	3.0%
10.1	Acetic anhydride	3.1%		2.8%
10.8	3-Furaldehyde	2.3%	3.5%	2.6%
11.4	2-Furanmethanol	1.4%	1.5%	
11.6	1,2-Ethanediol, diacetate	0.3%		
12.8	Cyclopentanone, 2-methyl-			1.7%
13.7	Phenol			1.2%
14.6	2-Cyclopenten-1-one, 2-hydroxy-3-methyl-	1.6%	2.0%	
15.3	Phenol, 3-methyl-			1.1%
15.5	Phenol, 2-methoxy-	2.4%	1.9%	1.4%
16.7	Benzaldehyde, 3-ethoxy-2-hydroxy-	1.1%		
17.0	Phenol, 2-methoxy-4-methyl-	1.9%	1.5%	0.7%
17.4	4H-Pyran-4-one, 5-hydroxy-2-(hydroxymethyl)-	1.4%		
18.4	2,4-Dimethoxytoluene	1.2%	1.0%	
19.4	Eucalyptol	3.6%	2.9%	1.1%
20.9	Phenol, 2-methoxy-4-(1-propenyl)-, (E)-	3.3%	2.3%	1.0%
22.6	3,4-Dimethoxy-5-hydroxybenzaldehyde	1.1%		
23.5	3-Hydroxycarbofuran	6.7%	0.8%	
24.2	à-D-Glucopyranoside, à-D-glucopyranosyl	5.2%		
25.2	Benzaldehyde, 4-hydroxy-3,5-dimethoxy-	1.8%		
		77.9%	90.7%	97.5%

Table 7: Peak identification and quantification for balsam.

Retention Time (Min)	Name	Peak Area		
		500	600	700
6.2	CO, CO ₂ , H ₂ O	44.5%	49.9%	49.7%
7.0	Acetaldehyde, hydroxy-	10.9%	9.4%	9.9%
7.6	Acetic acid	2.8%	3.8%	2.4%
7.8	2-Propanone, 1-hydroxy-	4.8%	7.3%	3.6%
9.6	Acetic acid, methyl ester	2.2%		1.6%
10.8	3-Furaldehyde	1.7%	1.7%	1.4%
11.4	2-Furanmethanol	1.0%		0.7%
12.8	Cyclopentanone, 2-methyl-	1.9%	1.8%	1.4%
13.7	Phenol			1.1%
14.6	2-Cyclopenten-1-one, 2-hydroxy-3-methyl-	1.2%	1.4%	
15.3	Phenol, 3-methyl-	1.2%	2.0%	2.8%
15.5	Phenol, 2-methoxy-	6.5%	4.8%	2.9%
17.0	Phenol, 2-methoxy-4-methyl-	4.8%	3.7%	2.2%
19.4	Eucalyptol	1.5%	1.4%	1.7%
20.9	Phenol, 2-methoxy-4-(1-propenyl)-, (E)-	2.6%	2.1%	2.7%
		87.5%	89.1%	84.2%

Table 8: Peak identification and quantification for poplar.

Retention Time (Min)	Name	Peak Area		
		500	600	700
1.0	CO, CO ₂ , H ₂ O	12.6%	14.9%	17.3%
1.7	Acetaldehyde, hydroxy-	4.1%	3.3%	4.9%
2.2	Acetic acid	4.4%	4.8%	5.6%
2.5	2-Propanone, 1-hydroxy-	3.9%	3.1%	2.9%
4.8	Acetic acid, methyl ester	1.3%	1.3%	2.7%
5.7	3-Furaldehyde	1.2%	1.3%	1.3%
6.2	2-Furanmethanol	1.2%	1.0%	0.9%
8.6	Phenol		3.5%	2.9%
9.5	2-Cyclopenten-1-one, 2-hydroxy-3-methyl-	1.0%	1.0%	0.9%
10.2	Phenol, 3-methyl-			0.7%
10.4	Phenol, 2-methoxy-	0.9%	1.5%	1.1%
12.1	Phenol, 2-methoxy-4-methyl-	0.9%		1.4%
15.0	Eucalyptol	0.4%	0.7%	4.4%
15.2	Phenol, 2-methoxy-4-(1-propenyl)-	0.1%		
16.0	Phenol, 2-methoxy-4-propyl-	0.2%		
17.1	à-D-Glucopyranoside, à-D-glucopyranosyl	4.5%		
17.6	Phenol, 2-methoxy-4-propyl-	0.4%	0.5%	0.6%
18.3	3-Hydroxycarbofuran	2.9%	3.5%	3.2%
		40.0%	40.4%	47.1%

Table 9: Peak identification and quantification for red maple.

Retention Time (Min)	Name	Peak Area		
		500	600	700
6.2	CO, CO ₂ , H ₂ O	53.9%	53.2%	53.2%
7.0	Acetaldehyde, hydroxy-	5.2%	2.2%	2.0%
7.6	Acetic acid	6.6%	5.3%	4.8%
7.8	2-Propanone, 1-hydroxy-	8.6%	6.4%	8.2%
9.6	Acetic acid, methyl ester	1.5%	2.3%	1.4%
10.8	3-Furaldehyde	2.4%	2.8%	2.6%
11.4	2-Furanmethanol	1.6%		
12.8	Cyclopentanone, 2-methyl-	2.1%		1.6%
13.7	Phenol			1.2%
14.6	2-Cyclopenten-1-one, 2-hydroxy-3-methyl-	1.5%		1.2%
15.3	Phenol, 3-methyl-		0.9%	1.5%
15.5	Phenol, 2-methoxy-	2.5%	2.3%	1.9%
17.0	Phenol, 2-methoxy-4-methyl-	1.2%	1.2%	0.9%
18.4	Phenol, 2-methoxy-4-propyl-	0.5%	1.0%	1.4%
19.4	Eucalyptol	1.8%	2.5%	2.7%
20.9	Phenol, 2-methoxy-4-(1-propenyl)-, (E)-	0.6%	1.3%	2.2%
23.4	3-Hydroxycarbofuran			0.7%
		90.0%	81.5%	87.2%

Table 10: Peak identification and quantification for willow.

Retention Time (Min)	Name	Peak Area		
		500	600	700
1.2	CO, CO ₂ , H ₂ O	11.4%	14.1%	13.9%
1.7	Acetaldehyde, hydroxy-	3.9%	3.6%	4.8%
2.4	Acetic acid	3.7%	3.6%	3.5%
2.5	2-Propanone, 1-hydroxy-	4.2%	2.6%	1.8%
4.9	Acetic acid, methyl ester	0.8%	1.4%	1.5%
5.7	3-Furaldehyde	1.5%	1.5%	1.2%
6.2	2-Furanmethanol	1.0%	0.9%	0.7%
7.6	Cyclopentanone, 2-methyl-	2.1%	2.4%	1.7%
8.7	Phenol	0.8%	1.4%	1.0%
9.5	2-Cyclopenten-1-one, 2-hydroxy-3-methyl-	0.8%	1.0%	0.7%
9.9	Phenol, 3-methyl-	0.2%	1.5%	2.0%
10.5	Phenol, 2-methoxy-	1.1%	1.8%	1.5%
12.1	Phenol, 2-methoxy-4-methyl-	1.4%	2.1%	1.8%
14.4	Eucalyptol	5.7%	6.0%	6.3%
15.18	Phenol, 2-methoxy-4-(1-propenyl)-, (E)-	0.3%	0.3%	
17.85	à-D-Glucopyranoside, à-D-glucopyranosyl		1.5%	
18.5	3-Hydroxycarbofuran	7.5%	5.3%	10.3%
		46.3%	50.9%	52.5%

Table 11: Peak identification and quantification for switchgrass.

Retention Time (Min)	Name	Peak Area		
		500	600	700
6.2	CO, CO ₂ , H ₂ O	50.6%	54.1%	49.3%
7.0	Acetaldehyde, hydroxy-	2.1%	1.6%	1.7%
7.6	Acetic acid	6.8%	7.4%	6.1%
7.8	2-Propanone, 1-hydroxy-	8.3%	6.7%	8.0%
9.6	Acetic acid, methyl ester	1.6%		1.4%
10.8	3-Furaldehyde	2.7%	2.9%	2.2%
12.8	Cyclopentanone, 2-methyl-	1.5%	0.6%	
13.7	Phenol			2.5%
14.6	2-Cyclopenten-1-one, 2-hydroxy-3-methyl-	2.0%	1.6%	1.9%
15.3	Phenol, 3-methyl-	1.8%	1.2%	2.6%
15.5	Phenol, 2-methoxy-	3.6%	2.9%	2.6%
17.0	Phenol, 2-methoxy-4-methyl-	0.9%	0.8%	0.9%
19.4	Eucalyptol	0.9%	0.9%	1.4%
20.9	Phenol, 2-methoxy-4-(1-propenyl)-, (E)-	0.5%	0.6%	0.8%
		83.3%	81.1%	81.4%

Biomass gasification takes place with increasing pyrolysis temperature. Gasification is generally considered to take place at temperature of 700°C or greater. Figure 19 shows the shift in products as pyrolysis temperature approach and enter the gasification range for aspen. Figures 20 through 25 show the average composition of the gas phase for each feedstock. Gasification of aspen to a very high temperature (900C) is shown in Figure 21 to establish a trend to high gasification temperatures. Hydrogen was excluded from most figures due to it very minimal contribution (<1%).

Figure 20: Change in product distribution for varying fast pyrolysis temperatures.

Figure 21: Effect of temperature on gaseous species yield for aspen.

Figure 22: Aspen gasification at 900C

Figure 23: Effect of temperature on gaseous species yield for poplar.

Figure 24: Effect of temperature on gaseous species yield for balsam.

Figure 25: Effect of temperature on gaseous species yield for red maple.

Figure 26: Effect of temperature on gaseous species yield for willow.

Figure 27: Effect of temperature on gaseous species yield for switchgrass.

5. Discussion

5.1. Hydrolysis Discussion

The hydrolysis results shown in Figures 4-15 are similar to results we have obtained previously using other forest feedstocks, but the overall sugar yields are lower in comparison. Dilute acid pretreatment of poplar and willow both display xylose as being the most prevalent monomer sugar. Xylose concentrations peak increase with pretreatment time for poplar, and then decline as monomer xylose is converted to furfural byproduct. This behavior of the xylose concentration is similar to that observed for other forest feedstocks and is consistent with the known reaction mechanisms for dilute acid hydrolysis. For willow, concentration of xylose continues to increase with reaction time and does not show indication of producing byproduct furfural from monomer xylose. Xylose accounts for more than half of the total monomer sugar concentration for both feedstocks. This compositional dominance is particularly evident at reaction times greater than 24 minutes in willow, and 8 minutes for poplar. Maximum xylose concentrations reach nearly 12 g/L at a reaction time of and 48 minutes for willow, and 24 minutes for poplar. It is generally understood that xylose is the main monomer component of hemicelluloses, which is the portion of biomass most readily attacked by dilute acid treatment.

Another important feature of our dilute acid hydrolysis results is the change in concentration of oligomer sugars over time during the reaction (Figures 6 and 7). Oligomer sugars are incomplete products of hydrolysis from the hemicelluloses (predominantly) and cellulose (minor) fractions of the wood. These molecules are intermediates between the native hemicelluloses and cellulose and the monomer sugars. Oligomer concentrations peak at early reaction times during dilute acid hydrolysis as carbohydrate break-down is initiated, these concentrations then decline as reaction time increases. Understanding oligomer sugar changes during a reaction is important because oligomers are not as fermentable as monomer sugars; reaction conditions should be adjusted to minimize oligomer sugar production and maximize monomer sugar generation.

Products of enzymatic hydrolysis of pre-treated poplar and willow are also shown in Appendix B. Glucose is the only monomer product of significance for enzymatic hydrolysis in these samples. This is expected because hemicellulose is nearly completely consumed and converted to monomer sugars after dilute acid hydrolysis. The only surprising result from these dilute acid and enzymatic hydrolysis experiments on poplar and willow is the relatively low total sugar yields (monomer and oligomer sugars) following the combined hydrolysis treatments. One reason for this might be that we do not know the composition of these feedstocks with high enough accuracy to complete a valid mass balance. Another explanation could be that the carbohydrate fractions of these feedstocks are more recalcitrant than for other forest feedstocks. Which of these reasons is correct is not yet understood and is beyond the scope of our preliminary processability analysis for the FBSCC project.

From these hydrolysis experiments, we conclude that poplar and willow exhibit similar reaction behavior compared to other forest feedstocks studied previously with our experimental process (aspen, balsam, switchgrass, basswood, red maple), but that the yields are somewhat lower than previously expected for hardwood samples.

5.2. Pyrolysis Discussion

Figure 16 shows that there are large amounts (50-70%) of bio-oil and gas products that can be produced from the investigated feedstocks at the targeted experimental conditions. While our data suggests that the yields are lower than previous studies have found, the same general trend

is observed in the temperature regions of interest for bio-oil production (500-700°C). In addition, Figure 17 illustrates how the char formation (thus oil and gas) is affected by pyrolysis temperature through the degradation stages of cellulose, hemicelluloses, and lignin. At temperatures at or below 200°C there is very little activity in the biomass, and the change in mass can be attributed to initial feedstock moisture. This moisture would appear in the collectable bio-oil. Over the hemicelluloses decomposition range, the mass appears to decrease another 5-10% which agrees well with the previously cited 14.6% xylan content of aspen (Table 1). Similarly, the area around the cellulose decomposition range can have an impact of 30-50% which is close to the glucan concentration of 52%.

With over 300 compounds (Mohan et al, 2006) expected to reside in the bio-oil, it is a daunting task to characterize and quantify the product distribution. From this work, however, it is noticed that the majority (approximately 75%) of mass appears in only a small number of components. Based on the relative peak areas as detected by the GC/MS, it was found that approximately 30% of the oil phase is comprised of glycolaldehyde, acetic acid, acetol, aldehydes (such as 3-furaldehyde), and other well-known heavy products (such as 3-hydroxycarbofuran). The calculated acetic acid contribution is in agreement with another study done on hemicellulosic decomposition in rice husks which cites 14.5% acetic acid content in the resulting bio-oil (Isa et al., 2011). The calculated area for the combined CO, CO₂, and H₂O peak is also in agreement with combined water and gas literature values ranging from 35-45% (Bridgwater et al., 1999).

As the pyrolysis temperatures approach gasification ranges, the products were observed to shift more towards light oxygenated compounds and gaseous species. As Figure 19 clearly demonstrates, many of the heavier molecules such as phenolics or poly-phenolics (that would normally reside in the bio-oil) are further broken down into gaseous species. The figures that follow (20-26) show the gaseous breakdown for the investigated species as temperature increases. In addition to the aforementioned trends, these figures also illustrate that the species most affected by the temperature are the formation of carbon monoxide and methane. Hydrogen was also observed, but at very low quantities (<1%) even at the highest pyrolysis temperature. Because of this it was included in Figure 20 for completeness, but excluded from the others.

6. Conclusions

For the purposes of this preliminary study, our results agree well with existing literature, indicating that Michigan grown woody feedstocks can be processed to valuable product intermediates through either investigated method. This work found that processing woods such as poplar and willow through dilute acid pretreatment and enzyme hydrolysis yields greater than 50% of the total biomass-embodied sugars. These sugars can then be utilized for such processes as fermentation to ethanol. Secondly, this study found that within the investigated 500-700°C fast pyrolysis temperature range, yields of greater than 50% mass can be expected for the combined bio-oil and gas phases. In addition, the bio-oil was found to be comprised mostly of hydroxyaldehydes (such as glycolaldehyde), hydroxyketones, sugar variants (such as levoglucosan), carboxylic acids (such as acetic and formic acid), and phenolics or cyclic compounds.

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Appendix A: Example HPLC Sugar Calibration Curve

The sugar standards are prepared prior to experiments and have known quantities of monomer sugars. The sugar standards' names are descriptive of their xylose concentration, i.e. a sugar standard with a xylose concentration of 2g/L is SS 2. The values used are integrated peak signal intensities obtained from the HPLC detector. The effective peak area obtained from integrating signal over time is then correlated to the standards' known concentrations.

Table 1: Concentrations of monomer Sugar Standards (SS) used in HPLC calibration.

Sugar Standard Composition					
Sample	Xylose (g/L)	Glucose (g/L)	Galactose (g/L)	Arabinose (g/L)	Mannose (g/L)
SS 2	2.0	0.8	0.4	0.4	0.8
SS 5	5.0	2.0	1.0	1.0	2.0
SS 10	10.0	4.0	2.0	2.0	4.0
SS 15	15.0	6.0	3.0	3.0	6.0

Table 2: HPLC monomer sugar calibration curve values. Data Values are Refractive Index Signal Area [nRIU*s].

Sugar Standards 1, Before DAH Analysis

	Glucose	Xylose	Galactose	Ar. + Man.
Retention Time (min)	12.54	13.69	14.71	16.40
Sample				
SS 2	1.19E+05	2.82E+05	5.51E+04	1.75E+05
SS 5	2.95E+05	7.05E+05	1.45E+05	4.37E+05
SS 10	5.92E+05	1.41E+06	2.94E+05	8.73E+05
SS 15	8.82E+05	2.10E+06	4.40E+05	1.30E+06
Fit Slope	5.89E+04	1.41E+05	2.93E+04	8.69E+04

Figure 1: HPLC monomer sugar calibrations. Refractive Index Signal Area obtained from the HPLC detector is correlated to the known sugar concentrations.

Appendix B: Enzymatic Hydrolysis Production Curves

Glucose

Figure 1: This figure represents glucose liberated from poplar through enzymatic hydrolysis as a function of reaction time . Samples were taken at approximately 0, 24, 48, and 72 hours for the peak acid pretreatment time(24mins) along with its half(12min) and double time(48min).

Figure 2: This figure represents xylose liberated from poplar through enzymatic hydrolysis as a function of reaction time. Samples were taken at approximately 0, 24, 48, and 72 hours for the peak acid pretreatment time(24mins) along with its half(12min) and double time(48min).

Figure 3: This figure represents glucose liberated from willow through enzymatic hydrolysis as a function of reaction time. Samples were taken at approximately 0, 24, 48, and 72 hours for the pretreatment time of 24mins along with its half(12min) and double time(48min).

Figure 4: This figure represents xylose liberated from willow through enzymatic hydrolysis as a function of reaction time. Samples were taken at approximately 0, 24, 48, and 72 hours for the pretreatment time of 24mins along with its half(12min) and double time(48min).

Appendix C: Additional Fast Pyrolysis Product Speciation and Quantification Data

Data contained within this appendix are representative of experimental trials for all feedstocks. The data presented are the individual chromatograms (Figures1-36) and NIST database matches (Tables 2-37) for compounds in large abundance. Note that if a database match has a low probability, this is likely due to multiple compounds eluting at the same time point as the libraries are developed for pure species. In these instances, further investigation would be needed to determine the likely species. The figures and tables that are associated with each species are summarized in Table 1.

Table 1: Location designation for experimental data within Appendix B.

	Aspen	Balsam	Poplar	Red maple	Willow	Switchgrass
500°C	Fig. 1,2 Table 2,3	Fig. 7,8 Table 8,9	Fig. 13,14 Table 14,15	Fig. 19,20 Table 20,21	Fig. 25,26 Table 26,27	Fig. 31,32 Table 32,33
600°C	Fig. 3,4 Table 4,5	Fig. 9,10 Table 10,11	Fig. 15,16 Table 16,17	Fig. 21,22 Table 22,23	Fig. 27,28 Table 28,29	Fig. 33,34 Table 34,35
700°C	Fig. 5,6 Table 6,7	Fig. 11,12 Table 12,13	Fig. 17,18 Table 18,19	Fig. 23,24 Table 24,25	Fig. 29,30 Table 30,31	Fig. 35,36 Table 36,37

Figure 1: Chromatogram for aspen fast pyrolysis trial at 500°C.

Figure 2: Chromatogram for aspen fast pyrolysis trial at 500°C.

Figure 3: Chromatogram for aspen fast pyrolysis trial at 600°C.

Figure 4: Chromatogram for aspen fast pyrolysis trial at 600°C.

Figure 5: Chromatogram for aspen fast pyrolysis trial at 700°C.

Figure 6: Chromatogram for aspen fast pyrolysis trial at 700°C.

Figure 7: Chromatogram for balsam fast pyrolysis trial at 500°C.

Figure 8: Chromatogram for balsam fast pyrolysis trial at 500°C.

Figure 9: Chromatogram for balsam fast pyrolysis trial at 600°C.

Figure 10: Chromatogram for balsam fast pyrolysis trial at 600°C.

Figure 11: Chromatogram for balsam fast pyrolysis trial at 700°C.

Figure 12: Chromatogram for balsam fast pyrolysis trial at 700°C.

Figure 13: Chromatogram for poplar fast pyrolysis trial at 500°C.

Figure 14: Chromatogram for poplar fast pyrolysis trial at 500°C.

Figure 15: Chromatogram for poplar fast pyrolysis trial at 600°C.

Figure 16: Chromatogram for poplar fast pyrolysis trial at 600°C.

Figure 17: Chromatogram for poplar fast pyrolysis trial at 700°C.

Figure 18: Chromatogram for poplar fast pyrolysis trial at 700°C.

Figure 19: Chromatogram for red maple fast pyrolysis trial at 500°C.

Figure 20: Chromatogram for red maple fast pyrolysis trial at 500°C.

Figure 21: Chromatogram for red maple fast pyrolysis trial at 600°C.

Figure 22: Chromatogram for red maple fast pyrolysis trial at 600°C.

Figure 23: Chromatogram for red maple fast pyrolysis trial at 700°C.

Figure 24: Chromatogram for red maple fast pyrolysis trial at 700°C.

Figure 25: Chromatogram for willow fast pyrolysis trial at 500°C.

Figure 26: Chromatogram for willow fast pyrolysis trial at 500°C.

Figure 27: Chromatogram for willow fast pyrolysis trial at 600°C.

Figure 28: Chromatogram for willow fast pyrolysis trial at 600°C.

Figure 29: Chromatogram for willow fast pyrolysis trial at 700°C.

Figure 30: Chromatogram for willow fast pyrolysis trial at 700°C.

Figure 31: Chromatogram for switchgrass fast pyrolysis trial at 500°C.

Figure 32: Chromatogram for switchgrass fast pyrolysis trial at 500°C.

Figure 33: Chromatogram for switchgrass fast pyrolysis trial at 600°C.

Figure 34: Chromatogram for switchgrass fast pyrolysis trial at 600°C.

Figure 35: Chromatogram for switchgrass fast pyrolysis trial at 700°C.

Figure 36: Chromatogram for switchgrass fast pyrolysis trial at 700°C.

Table 2: NIST library matches for aspen fast pyrolysis trial at 500°C.

Area	Area %	Molecular Formula	Molecular Weight	Name	Probability	RT
2.421E+09	10.44	C8H19N	129	2-Octanamine	63.22	6.22
182263218	0.79	C3H6O3	90	Propanal, 2,3-dihydroxy-	41.72	6.68
766978582	3.31	C2H4O2	60	Acetaldehyde, hydroxy-	66.63	6.98
722778691	3.12	C2H4O2	60	Acetic acid	94.05	7.58
464023420	2	C3H6O2	74	2-Propanone, 1-hydroxy-	84.68	7.81
293658738	1.27	C3H6O2	74	2-Propanone, 1-hydroxy-	49.94	9.65
235259735	1.01	C7H14O	114	Pentanal, 2,3-dimethyl-	21.43	9.89
361385700	1.56	C4H6O3	102	Acetic anhydride	30.46	10.13
287057445	1.24	C5H4O2	96	3-Furaldehyde	63.18	10.76
224059115	0.97	C5H6O2	98	2-Furanmethanol	67.7	11.37
37978769	0.16	C6H10O4	146	1,2-Ethanediol, diacetate	55.22	11.6
96621139	0.42	C6H10O2	114	2-Pentenoic acid, 2-methyl-, (E)-	25.53	12.23
186046992	0.8	C6H12	84	2-Hexene	25.74	12.6
497921059	2.15	C6H10O	98	Cyclopentanone, 2-methyl-	33.23	12.9
291732915	1.26	C11H20O2	184	Undecanoic acid, hydroxy-, lactone	21.23	13.39
358087462	1.54	C6H10O2	114	2-Pentenoic acid, 2-methyl-, (E)-	38.8	13.66
218976334	0.94	C5H10N2O	114	Piperidine, 1-nitroso-	20.05	14.13
329423831	1.42	C6H8O2	112	1,2-Cyclopentanedione, 3-methyl-	45.27	14.67
66850727	0.29	C6H10O2	114	2-Pentenoic acid, 2-methyl-, (E)-	47.49	14.87
492924174	2.13	C7H8O2	124	Phenol, 2-methoxy-	43.36	15.52
373399262	1.61	C11H22O	170	Undecanal	43.26	15.89
169992443	0.73	C7H6O5	170	2,4,6-Trihydroxybenzoic acid	36.96	16.08
175849119	0.76	C11H20O2	184	Oxacyclododecan-2-one	52.55	16.42
302354630	1.3	C11H20O2	184	Undecanoic acid, hydroxy-, lactone	46.33	16.77
238909936	1.03	C8H10O2	138	Phenol, 2-methoxy-4-methyl-	50.19	17.13
313141090	1.35	C6H6O4	142	4H-Pyran-4-one, 5-hydroxy-2-(hydroxymethyl)-	72.19	17.39
380335735	1.64	C12H22O2	198	ε Dodecalactone	22.86	17.76
349468704	1.51	C11H20O2	184	Undecanoic acid, hydroxy-, lactone	15.76	17.96
289691048	1.25	C9H12O2	152	2,4-Dimethoxytoluene	62.19	18.38

937488738	4.04	C10H14O	150	Phenol, 2,3,5,6-tetramethyl-	27.01	18.9
958942427	4.13	C10H18O	154	Eucalyptol	63.92	19.47
70658244	0.3	C11H20O2	184	Oxacyclododecan-2-one	32.01	19.63
381222346	1.64	C9H12O2	152	2,4-Dimethoxytoluene	15.93	20.21
1.061E+09	4.57	C9H12O3	168	1,2,3-Trimethoxybenzene	58.62	20.94
133584418	0.58	C8H8O4	168	Ethanone, 1-(2,3,4-trihydroxyphenyl)-	38.87	21.02
56922096	0.25	C9H10O3	166	Ethanone, 1-(4-hydroxy-3-methoxyphenyl)-	42.27	21.77
91196322	0.39	C9H10O3	166	Ethanone, 1-(4-hydroxy-3-methoxyphenyl)-	38.25	21.93
257760865	1.11	C9H10O4	182	3,4-Dimethoxy-5-hydroxybenzaldehyde	66.09	22.57
81543404	0.35	C10H14O2	166	Phenol, 2-methoxy-4-propyl-	48.22	22.77
295476133	1.27	C11H14O3	194	4-Butoxybenzoic acid	38.46	23.16
1.554E+09	6.7	C12H15NO4	237	3-Hydroxycarbofuran	78.25	23.51
672339033	2.9	C12H22O11	342	à-D-Glucopyranoside, à-D-glucopyranosyl	43.14	23.8
396042106	1.71	C15H15N	209	Acridine, 9,10-dihydro-9,9-dimethyl-	53.89	24.16
669617811	2.89	C11H21BrO2	264	11-Bromoundecanoic acid	31.94	24.27
532724377	2.3	C12H22O11	342	à-D-Glucopyranoside, à-D-glucopyranosyl	74.86	24.67
88546987	0.38	C15H15N	209	Acridine, 9,10-dihydro-9,9-dimethyl-	74.7	25.02
294763935	1.27	C9H10O4	182	Benzaldehyde, 4-hydroxy-3,5-dimethoxy-	87.64	25.24
107007434	0.46	C14H20O2	220	2,5-Cyclohexadiene-1,4-dione, 2,6-bis(1,1-dimethylethyl)-	40.26	25.46
963839214	4.16	C15H15N	209	Acridine, 9,10-dihydro-9,9-dimethyl-	70.87	25.87
306661642	1.32	C10H12O4	196	Benzaldehyde, 2,4,5-trimethoxy-	41.57	26.38
334205406	1.44	C12H8N2O	196	9H-Carbazole, 9-nitroso-	28.43	26.9
56787378	0.24	C41H64O13	764	Digitoxin	24.01	27.14
128838891	0.56	C9H10O4	182	Benzaldehyde, 4-hydroxy-3,5-dimethoxy-	53.35	27.57
158809433	0.68	C41H64O13	764	Digitoxin	37.92	27.92
92598277	0.4	C15H24O	220	4a,7-Methano-4aH-naphth[1,8a-b]oxirene, octahydro-4,4,8,8-tetramethyl-	29.19	28.57
147558072	0.64	C16H32O2	256	n-Hexadecanoic acid	70.69	29.56
318418096	1.37	C19H22O6	346	Gibberellic acid	32.9	30.16
110403927	0.48	C18H36O2	284	Octadecanoic acid	75.72	33.48
33376733	0.14	C13H17F3N4O4	350	1,3-Benzenediamine, 2,4-dinitro-N3,N3-dipropyl-6-(trifluoromethyl)-	31.73	34.61

Table 3: NIST library matches for aspen fast pyrolysis trial at 500°C.

Area	Area %	Molecular Formula	Molecular Weight	Name	Probability	RT
3.027E+09	29.46	C8H19N	129	2-Octanamine	68.42	6.19
132018407	1.28	C3H6O3	90	Propanal, 2,3-dihydroxy-	73.87	6.67
837493324	8.15	C2H4O2	60	Acetaldehyde, hydroxy-	62.83	6.92
1.774E+09	17.26	C3H6O2	74	2-Propanone, 1-hydroxy-	90.03	7.75
314375370	3.06	C3H6O2	74	2-Propanone, 1-hydroxy-	34.82	9.64
188424890	1.83	C7H14O	114	Pentanal, 2,3-dimethyl-	32.7	9.85
322793213	3.14	C4H6O3	102	Acetic anhydride	43.41	10.09
341301733	3.32	C5H4O2	96	3-Furaldehyde	78.59	10.75
178029651	1.73	C5H6O2	98	2-Furanmethanol	71.49	11.35
40775235	0.4	C6H10O4	146	1,2-Ethanediol, diacetate	65.01	11.59
74517177	0.73	C14H28O	212	9-Tetradecen-1-ol, (E)-	22.86	12.22
124173136	1.21	C6H12	84	2-Hexene	37.49	12.52
348558211	3.39	C5H6O2	98	2-Furanmethanol	30.12	12.82
156445242	1.52	C12H24O	184	Dodecanal	15.65	13.36
159672896	1.55	C6H7O4P	174	Phosphonic acid, (p-hydroxyphenyl)-	52.4	13.73
265999235	2.59	C5H10N2O	114	Piperidine, 1-nitroso-	52.26	14.07
165520210	1.61	C6H8O2	112	2-Cyclopenten-1-one, 2-hydroxy-3-methyl-	56.4	14.61
134441325	1.31	C7H8O	108	Phenol, 3-methyl-	37.74	15.29
244735322	2.38	C7H8O2	124	Phenol, 2-methoxy-	52.64	15.5
169802687	1.65	C12H22O11	342	à-D-Glucopyranoside, à-D-glucopyranosyl	31.89	15.77
108720299	1.06	C9H10O3	166	Benzaldehyde, 3-ethoxy-2-hydroxy-	52.7	16.72
35805978	0.35	C8H10O2	138	Phenol, 2-methoxy-4-methyl-	54.63	16.88
241341940	2.35	C8H10O2	138	Phenol, 2-methoxy-4-methyl-	49.86	17.12
110682207	1.08	C9H12O2	152	2,4-Dimethoxytoluene	67.38	18.35
171365822	1.67	C10H14O	150	Phenol, 2-methyl-5-(1-methylethyl)-	22.06	18.87
316311626	3.08	C10H18O	154	Eucalyptol	46.44	19.39
40767854	0.4	C10H12O2	164	Phenol, 2-methoxy-4-(1-propenyl)-	56.54	20.18
211028648	2.05	C10H12O2	164	Phenol, 2-methoxy-4-(1-propenyl)-, (E)-	45.85	20.9
40006487	0.39	C12H15NO4	237	3-Hydroxycarbofuran	74.76	23.31

Table 4: NIST library matches for aspen fast pyrolysis trial at 600°C.

Area	Area %	Molecular Formula	Molecular Weight	Name	Probability	RT
4.867E+09	45.64	C8H19N	129	2-Octanamine	80.99	6.16
815538689	7.65	C2H4O2	60	Acetaldehyde, hydroxy-	68.05	6.94
1.291E+09	12.11	C2H4O2	60	Acetic acid	95.38	7.61
324475227	3.04	C3H6O2	74	2-Propanone, 1-hydroxy-	89.07	7.78
298380339	2.8	C3H6O2	74	Acetic acid, methyl ester	59.52	9.64
156235387	1.47	C7H14O	114	Pentanal, 2,3-dimethyl-	26.69	9.85
310087209	2.91	C4H6O3	102	Acetic anhydride	34.22	10.09
329036915	3.09	C5H4O2	96	3-Furaldehyde	72.86	10.8
138608447	1.3	C5H6O2	98	2-Furanmethanol	61.91	11.35
252874693	2.37	C5H6O2	98	2-Furanmethanol	34.13	12.8
139609640	1.31	C12H24O	184	Dodecanal	21.61	13.36
124771064	1.17	C6H7O4P	174	Phosphonic acid, (p-hydroxyphenyl)-	56	13.73
269933761	2.53	C5H10N2O	114	Piperidine, 1-nitroso-	47.63	14.1
188673447	1.77	C6H8O2	112	2-Cyclopenten-1-one, 2-hydroxy-3-methyl-	64.05	14.59
126223901	1.18	C7H8O	108	Phenol, 3-methyl-	39.67	15.29
182106416	1.71	C7H8O2	124	Phenol, 2-methoxy-	44.83	15.49
83438570	0.78	C8H10O2	138	2-Methoxybenzyl alcohol	36.31	16.72
156836004	1.47	C8H10O2	138	Phenol, 2-methoxy-4-methyl-	52.62	17.11
42541766	0.4	C9H12O2	152	2,4-Dimethoxytoluene	54.93	18.35
133967941	1.26	C12H17NO2	207	Phenol, 3-methyl-5-(1-methylethyl)-, methylcarbamate	32.12	18.86
246138093	2.31	C10H18O	154	Eucalyptol	45.32	19.38
185896071	1.74	C10H12O2	164	Phenol, 2-methoxy-4-(1-propenyl)-, (E)-	46.13	20.89

Table 5: NIST library matches for aspen fast pyrolysis trial at 600°C.

Area	Area %	Molecular Formula	Molecular Weight	Name	Probability	RT
2.249E+09	32.03	CO2	44	Carbon dioxide	39.3	6.15
87835835	1.25	C3H6O3	90	Propanal, 2,3-dihydroxy-	22.41	6.64
543593169	7.74	C2H4O2	60	Acetaldehyde, hydroxy-	69.77	6.96
1.059E+09	15.08	C3H6O2	74	2-Propanone, 1-hydroxy-	90.64	7.81
190106995	2.71	C3H6O2	74	2-Propanone, 1-hydroxy-	41.09	9.65
104028998	1.48	C3H8O2	76	1,3-Propanediol	28.63	9.85
206892459	2.95	C3H6O2	74	2-Propanone, 1-hydroxy-	47.03	10.12
274432646	3.91	C5H4O2	96	3-Furaldehyde	74.78	10.81
120211066	1.71	C5H6O2	98	2-Furanmethanol	67.87	11.36
207839067	2.96	C5H6O2	98	2-Furanmethanol	26.33	12.82
122669459	1.75	C12H24O	184	Dodecanal	17.56	13.36
102565716	1.46	C6H7O4P	174	Phosphonic acid, (p-hydroxyphenyl)-	51.74	13.73
255439401	3.64	C4H6N2O2	114	2,4-Imidazolidinedione, 1-methyl-	27.17	14.11
150420193	2.14	C6H8O2	112	2-Cyclopenten-1-one, 2-hydroxy-3-methyl-	66.8	14.59
84572472	1.2	C7H8O	108	Phenol, 3-methyl-	38.72	15.29
152185555	2.17	C7H8O2	124	Phenol, 2-methoxy-	50.99	15.49
163620627	2.33	C8H10O	122	Phenol, 2,6-dimethyl-	14.17	15.76
105398179	1.5	C9H10O3	166	Benzaldehyde, 3-ethoxy-2-hydroxy-	38.71	16.72
104874112	1.49	C8H10O2	138	2-Methoxy-5-methylphenol	48.39	17.11
114770217	1.63	C9H12O2	152	2,4-Dimethoxytoluene	71.1	18.35
124554110	1.77	C10H14O	150	Phenol, 2,3,5,6-tetramethyl-	26.57	18.86
242531372	3.45	C10H18O	154	Eucalyptol	45.05	19.38
199892166	2.85	C9H12O3	168	1,2,3-Trimethoxybenzene	75.61	20.83
55870648	0.8	C12H15NO4	237	3-Hydroxycarbofuran	75.67	23.31

Table 6: NIST library matches for aspen fast pyrolysis trial at 700°C.

Area	Area %	Molecular Formula	Molecular Weight	Name	Probability	RT
5.709E+09	53.07	C8H19N	129	2-Octanamine	80.6	6.15
186404247	1.73	C3H6O3	90	Propanal, 2,3-dihydroxy-	32.71	6.64
939672434	8.73	C2H4O2	60	Acetaldehyde, hydroxy-	72.22	6.96
1.521E+09	14.14	C3H6O2	74	2-Propanone, 1-hydroxy-	91.17	7.82
324706083	3.02	C3H6O2	74	Acetic acid, methyl ester	57.64	9.66
128296154	1.19	C3H8O2	76	1,3-Propanediol	26.66	9.85
305876705	2.84	C3H6O2	74	2-Propanone, 1-hydroxy-	44	10.11
272066014	2.53	C5H4O2	96	3-Furaldehyde	54.55	10.82
116179772	1.08	C5H6O2	98	2-Furanmethanol	30.87	11.35
177529694	1.65	C6H10O	98	Cyclopentanone, 2-methyl-	41.55	12.81
143378219	1.33	C6H6O	94	Phenol	51.56	13.74
226694978	2.11	C5H10N2O	114	Piperidine, 1-nitroso-	34.64	14.09
122514769	1.14	C7H8O	108	Phenol, 3-methyl-	50.27	15.29
130870875	1.22	C7H8O2	124	Phenol, 2-methoxy-	46.95	15.48
74049037	0.69	C8H10O2	138	2-Methoxy-5-methylphenol	48.07	17.1
103254706	0.96	C10H14O	150	Phenol, 2-methyl-5-(1-methylethyl)-	23.93	18.86
166434978	1.55	C10H18O	154	Eucalyptol	54.39	19.38
110002755	1.02	C10H12O2	164	Phenol, 2-methoxy-4-(1-propenyl)-	51.6	20.9

Table 7: NIST library matches for aspen fast pyrolysis trial at 700°C.

Area	Area %	Molecular Formula	Molecular Weight	Name	Probability	RT
5.874E+09	53.75	C8H19N	129	2-Octanamine	78.78	6.15
1.304E+09	11.93	C2H4O2	60	Acetaldehyde, hydroxy-	78.87	7
568378848	5.2	C2H4O2	60	Acetic acid	91.59	7.54
1.064E+09	9.74	C3H6O2	74	2-Propanone, 1-hydroxy-	92.01	7.86
332760392	3.04	C3H6O2	74	Acetic acid, methyl ester	50.51	9.7
159053210	1.46	C3H8O2	76	1,3-Propanediol	29.19	9.89
255192230	2.33	C4H6O3	102	Acetic anhydride	38.19	10.15
295025329	2.7	C5H4O2	96	3-Furaldehyde	56.11	10.83
121537016	1.11	C5H6O2	98	2-Furanmethanol	38.07	11.38
170487887	1.56	C6H10O	98	Cyclopentanone, 2-methyl-	32.18	12.81
111690056	1.02	C6H6O	94	Phenol	49.23	13.74
185394535	1.7	C4H6N2O2	114	2,4-Imidazolidinedione, 1-methyl-	39.74	14.1
121551282	1.11	C7H8O	108	Phenol, 3-methyl-	43.38	15.29
165156058	1.51	C7H8O2	124	Phenol, 2-methoxy-	49.27	15.48
73158990	0.67	C8H10O2	138	Phenol, 2-methoxy-4-methyl-	57.11	17.09
58266974	0.53	C10H14O	150	Phenol, p-tert-butyl-	26.05	18.85
69024289	0.63	C10H18O	154	Eucalyptol	48.72	19.36

Table 8: NIST library matches for balsam fast pyrolysis trial at 500°C.

Area	Area %	Molecular Formula	Molecular Weight	Name	Probability	RT
1.198E+09	42.68	C8H19N	129	2-Octanamine	45.81	6.17
367159206	13.08	C2H4O2	60	Acetaldehyde, hydroxy-	83.01	6.7
61194639	2.18	C2H4O2	60	Acetic acid	93.6	7.17
106907051	3.81	C3H6O2	74	2-Propanone, 1-hydroxy-	84.89	7.47
61155663	2.18	C3H6O2	74	Acetic acid, methyl ester	41.03	9.42
70595088	2.52	C3H8O2	76	1,3-Propanediol	32.75	9.62
58220253	2.07	C4H6O3	102	Acetic anhydride	39.95	9.85
46998976	1.67	C5H4O2	96	3-Furaldehyde	52.61	10.68
23918107	0.85	C5H6O2	98	2-Furanmethanol	68.82	11.2
50785147	1.81	C5H7ClO	118	Cyclobutanecarboxylic acid chloride	31.23	12.33
46723099	1.67	C6H10O	98	Cyclopentanone, 2-methyl-	71.65	12.57
35879216	1.28	C4H6N2O2	114	2,4-Imidazolidinedione, 1-methyl-	33.2	13.88
28277017	1.01	C6H8O2	112	2-Cyclopenten-1-one, 2-hydroxy-3-methyl-	55.54	14.42
165875345	5.91	C7H8O2	124	Phenol, 2-methoxy-	54.71	15.47
123271329	4.39	C8H10O2	138	Phenol, 2-methoxy-4-methyl-	51.87	17.09
32941976	1.17	C10H14O2	166	Phenol, 2-methoxy-4-propyl-	57.46	18.33
163685746	5.83	C12H17NO2	207	Phenol, 3-methyl-5-(1-methylethyl)-, methylcarbamate	32.18	18.85
39993398	1.43	C10H12O2	164	Eugenol	48.73	19.42
41896125	1.49	C8H8O3	152	Vanillin	52.1	20.03
82976049	2.96	C10H12O2	164	Phenol, 2-methoxy-4-(1-propenyl)-, (E)-	49.79	20.88

Table 9: NIST library matches for balsam fast pyrolysis trial at 500°C.

Area	Area %	Molecular Formula	Molecular Weight	Name	Probability	RT
2.716E+09	46.4	C ₈ H ₁₉ N	129	2-Octanamine	91.77	6.17
505127836	8.63	C ₂ H ₄ O ₂	60	Acetaldehyde, hydroxy-	72.13	6.82
199428333	3.41	C ₂ H ₄ O ₂	60	Acetic acid	90.07	7.39
234758278	4.01	C ₃ H ₆ O ₂	74	2-Propanone, 1-hydroxy-	90.83	7.61
110500620	1.89	C ₃ H ₆ O ₂	74	2-Propanone, 1-hydroxy-	38.51	9.51
128134362	2.19	C ₃ H ₆ O	58	Propylene oxide	26.18	9.75
105140332	1.8	C ₃ H ₆ O ₂	74	2-Propanone, 1-hydroxy-	62	9.94
95762738	1.64	C ₅ H ₄ O ₂	96	3-Furaldehyde	59.11	10.71
64299198	1.1	C ₅ H ₆ O ₂	98	2-Furanmethanol	75.84	11.27
125488226	2.14	C ₆ H ₁₀ O	98	Cyclopentanone, 2-methyl-	68.14	12.68
83427819	1.43	C ₆ H ₈ O ₂	112	2-Cyclopenten-1-one, 2-hydroxy-3-methyl-	55.44	14.52
70787168	1.21	C ₇ H ₈ O	108	Phenol, 3-methyl-	48.27	15.26
410294275	7.01	C ₇ H ₈ O ₂	124	Phenol, 2-methoxy-	47.18	15.51
21455864	0.37	C ₈ H ₁₀ O ₂	138	Phenol, 2-methoxy-4-methyl-	43.37	16.86
286437083	4.89	C ₈ H ₁₀ O ₂	138	2-Methoxy-5-methylphenol	49.07	17.1
89740020	1.53	C ₁₀ H ₁₄ O ₂	166	Phenol, 2-methoxy-4-propyl-	77.44	18.34
339116015	5.79	C ₁₂ H ₁₇ NO ₂	207	Phenol, 3-methyl-5-(1-methylethyl)-, methylcarbamate	42.92	18.86
91122054	1.56	C ₁₀ H ₁₂ O ₂	164	Eugenol	46.71	19.43
49706521	0.85	C ₁₀ H ₁₂ O ₂	164	Phenol, 2-methoxy-4-(1-propenyl)-	42.56	20.17
126185736	2.16	C ₁₀ H ₁₂ O ₂	164	Phenol, 2-methoxy-4-(1-propenyl)-, (E)-	51.57	20.88

Table 10: NIST library matches for balsam fast pyrolysis trial at 600°C.

Area	Area %	Molecular Formula	Molecular Weight	Name	Probability	RT
3.974E+09	49.89	C8H19N	129	2-Octanamine	75.64	6.15
658061840	8.26	C2H4O2	60	Acetaldehyde, hydroxy-	68.76	6.86
312999189	3.93	C2H4O2	60	Acetic acid	91.13	7.46
267657110	3.36	C3H6O2	74	2-Propanone, 1-hydroxy-	91.62	7.67
145579688	1.83	C3H6O2	74	2-Propanone, 1-hydroxy-	42.71	9.53
113882969	1.43	C3H8O2	76	1,3-Propanediol	31.97	9.77
160281199	2.01	C3H6O2	74	2-Propanone, 1-hydroxy-	44.85	9.97
134688454	1.69	C5H4O2	96	3-Furaldehyde	56.57	10.69
67653926	0.85	C8H16O	128	2-Hexanone, 3,4-dimethyl-	36.85	11.27
146931220	1.84	C6H10O	98	Cyclopentanone, 2-methyl-	52.12	12.72
142461306	1.79	C6H8O2	112	2-Cyclopenten-1-one, 2-hydroxy-3-methyl-	55.71	14.55
44472790	0.56	C7H8O	108	Phenol, 3-methyl-	37.67	14.92
129482093	1.63	C7H8O	108	Phenol, 3-methyl-	53.24	15.27
377038956	4.73	C7H8O2	124	Phenol, 2-methoxy-	64.46	15.49
44346416	0.56	C8H10O	122	Phenol, 3,4-dimethyl-	27.82	16.39
250597257	3.15	C8H10O2	138	Phenol, 2-methoxy-4-methyl-	52.82	17.1
79398144	1	C6H6O2	110	1,2-Benzenediol	66.93	17.27
87244517	1.1	C10H14O2	166	Phenol, 2-methoxy-4-propyl-	75.92	18.34
417964503	5.25	C12H17NO2	207	Phenol, 3-methyl-5-(1-methylethyl)-, methylcarbamate	23.12	18.88
121594291	1.53	C10H12O2	164	Eugenol	50.47	19.43
85714259	1.08	C10H12O2	164	Phenol, 2-methoxy-4-(1-propenyl)-	50.18	20.17
203195360	2.55	C10H12O2	164	Phenol, 2-methoxy-4-(1-propenyl)-, (E)-	50.08	20.89

Table 11: NIST library matches for balsam fast pyrolysis trial at 600°C.

Area	Area %	Molecular Formula	Molecular Weight	Name	Probability	RT
3.502E+09	49.91	CO2	44	Carbon dioxide	44.09	6.14
732308060	10.44	C2H4O2	60	Acetaldehyde, hydroxy-	77.88	6.85
260657732	3.72	C2H4O2	60	Acetic acid	85.09	7.43
251288441	3.58	C3H6O2	74	2-Propanone, 1-hydroxy-	91.48	7.64
134324733	1.91	C3H6O2	74	2-Propanone, 1-hydroxy-	51.18	9.52
127977952	1.82	C3H6O	58	Propylene oxide	21.25	9.77
127166674	1.81	C3H6O2	74	2-Propanone, 1-hydroxy-	45.27	9.97
116906572	1.67	C5H4O2	96	3-Furaldehyde	69.52	10.69
66135651	0.94	C5H6O2	98	2-Furanmethanol	23.83	11.27
121800300	1.74	C6H10O	98	Cyclopentanone, 2-methyl-	63.83	12.68
69071959	0.98	C6H7O4P	174	Phosphonic acid, (p-hydroxyphenyl)-	49.81	13.67
63596404	0.91	C6H8O2	112	1,2-Cyclopentanedione, 3-methyl-	46.67	14.52
40016315	0.57	C7H8O	108	Phenol, 3-methyl-	40.32	14.91
119297697	1.7	C7H8O	108	Phenol, 3-methyl-	55.53	15.26
336731135	4.8	C7H8O2	124	Phenol, 2-methoxy-	73.88	15.49
302668925	4.31	C8H10O2	138	Phenol, 2-methoxy-4-methyl-	57.42	17.1
63823648	0.91	C10H14O2	166	Phenol, 2-methoxy-4-propyl-	56.2	18.33
303644114	4.33	C12H17NO2	207	Phenol, 3-methyl-5-(1-methylethyl)-, methylcarbamate	24.3	18.86
90473173	1.29	C10H12O2	164	Eugenol	43.5	19.42
65758519	0.94	C10H12O2	164	Phenol, 2-methoxy-4-(1-propenyl)-	47.86	20.16
120550444	1.72	C10H12O2	164	Phenol, 2-methoxy-4-(1-propenyl)-, (E)-	55.24	20.88

Table 12: NIST library matches for balsam fast pyrolysis trial at 700°C.

Area	Area %	Molecular Formula	Molecular Weight	Name	Probability	RT
3.692E+09	51.06	C8H19N	129	2-Octanamine	69.04	6.15
691391323	9.56	C2H4O2	60	Acetaldehyde, hydroxy-	67.58	6.81
175890719	2.43	C2H4O2	60	Acetic acid	61.31	7.31
186973313	2.59	C3H6O2	74	2-Propanone, 1-hydroxy-	84.53	7.57
134993496	1.87	C3H6O2	74	Acetic acid, methyl ester	41.02	9.49
65130386	0.9	C3H6O	58	Propylene oxide	28.03	9.7
110913096	1.53	C3H6O2	74	2-Propanone, 1-hydroxy-	51.76	9.92
105571616	1.46	C5H4O2	96	3-Furaldehyde	59.01	10.69
47843969	0.66	C5H6O2	98	2-Furanmethanol	63.71	11.25
104450041	1.44	C6H10O	98	Cyclopentanone, 2-methyl-	63.61	12.64
71145737	0.98	C6H6O	94	Phenol	72.08	13.65
66667309	0.92	C2H2N4O2	114	1H-1,2,4-Triazole, 3-nitro-	54.8	13.95
40983155	0.57	C7H8O	108	Phenol, 3-methyl-	42.28	14.89
146111994	2.02	C7H8O	108	Phenol, 3-methyl-	49.95	15.25
168224464	2.33	C7H8O2	124	Phenol, 2-methoxy-	50.29	15.47
75457807	1.04	C8H10O	122	Phenol, 3,4-dimethyl-	27.98	16.39
171192368	2.37	C8H10O2	138	Phenol, 2-methoxy-4-methyl-	45.56	17.09
152225264	2.11	C6H6O2	110	1,2-Benzenediol	84.44	17.27
71716266	0.99	C9H12O	136	Phenol, 2-ethyl-5-methyl-	28.11	17.73
60449063	0.84	C7H8O2	124	1,2-Benzenediol, 3-methyl-	90.95	18.11
51418707	0.71	C10H14O2	166	Phenol, 2-methoxy-4-propyl-	55.14	18.34
103650900	1.43	C7H8O2	124	1,2-Benzenediol, 3-methyl-	95.03	18.53
278022656	3.85	C12H17NO2	207	Phenol, 3-methyl-5-(1-methylethyl)-, methylcarbamate	39.81	18.86
142150703	1.97	C10H12O2	164	Eugenol	40.02	19.43
125468996	1.74	C8H8O3	152	Vanillin	52.46	20.09
190423480	2.63	C10H12O2	164	Phenol, 2-methoxy-4-(1-propenyl)-, (E)-	46.3	20.89

Table 13: NIST library matches for balsam fast pyrolysis trial at 700°C.

Area	Area %	Molecular Formula	Molecular Weight	Name	Probability	RT
4.895E+09	48.3	C ₈ H ₁₉ N	129	2-Octanamine	68.11	6.14
1.04E+09	10.27	C ₂ H ₄ O ₂	60	Acetaldehyde, hydroxy-	75.97	6.87
316249895	3.12	C ₃ H ₆ O ₂	74	2-Propanone, 1-hydroxy-	90.9	7.71
163906773	1.62	C ₃ H ₆ O ₂	74	Acetic acid, methyl ester	43.61	9.55
125746362	1.24	C ₃ H ₈ O ₂	76	1,3-Propanediol	26.56	9.77
136455696	1.35	C ₃ H ₆ O ₂	74	2-Propanone, 1-hydroxy-	50.21	10
143519301	1.42	C ₅ H ₄ O ₂	96	3-Furaldehyde	54.17	10.71
101845729	1.01	C ₈ H ₁₆ O	128	2-Hexanone, 3,4-dimethyl-	36	11.28
130367006	1.29	C ₆ H ₁₀ O	98	Cyclopentanone, 2-methyl-	47.08	12.73
133205558	1.31	C ₆ H ₆ O	94	Phenol	55.58	13.71
127431986	1.26	C ₆ H ₈ O ₂	112	2-Cyclopenten-1-one, 2-hydroxy-3-methyl-	51.45	14.57
162781735	1.61	C ₇ H ₈ O	108	Phenol, 3-methyl-	44.25	14.92
192667640	1.9	C ₇ H ₈ O	108	Phenol, 3-methyl-	56.97	15.29
352605035	3.48	C ₇ H ₈ O ₂	124	Phenol, 2-methoxy-	54.88	15.49
138560292	1.37	C ₈ H ₁₀ O	122	Phenol, 2,6-dimethyl-	13.06	15.75
81601572	0.81	C ₈ H ₁₀ O	122	Phenol, 3,4-dimethyl-	25.64	16.41
77511522	0.76	C ₈ H ₁₀ O	122	Phenol, 3,4-dimethyl-	23.86	16.72
207121996	2.04	C ₈ H ₁₀ O ₂	138	2-Methoxy-5-methylphenol	46.82	17.1
296280706	2.92	C ₆ H ₆ O ₂	110	1,2-Benzenediol	70.3	17.32
58590273	0.58	C ₉ H ₁₂ O	136	Phenol, 2-ethyl-5-methyl-	21.86	17.74
85638909	0.85	C ₁₀ H ₁₄ O ₂	166	Phenol, 2-methoxy-4-propyl-	69.07	18.36
113262983	1.12	C ₇ H ₈ O ₂	124	1,2-Benzenediol, 3-methyl-	93.89	18.57
472882121	4.67	C ₁₂ H ₁₇ NO ₂	207	Phenol, 3-methyl-5-(1-methylethyl)-, methylcarbamate	33.55	18.89
153864895	1.52	C ₁₀ H ₁₂ O ₂	164	Eugenol	37.52	19.45
143261354	1.41	C ₁₀ H ₁₂ O ₂	164	Phenol, 2-methoxy-4-(1-propenyl)-	52.72	20.18
283030681	2.79	C ₁₀ H ₁₂ O ₂	164	Phenol, 2-methoxy-4-(1-propenyl)-, (E)-	65.77	20.92

Table 14: NIST library matches for poplar fast pyrolysis trial at 500°C.

Area	Area %	Molecular Formula	Molecular Weight	Name	Probability	RT
626606150	12.69	CO ₂	44	Carbon dioxide	71.86	1.15
187958462	3.81	C ₂ H ₄ O ₂	60	Acetaldehyde, hydroxy-	77.37	1.67
62731538	1.27	C ₄ H ₆ O ₃	102	Butanoic acid, 2-oxo-	44.71	1.86
221409507	4.48	C ₂ H ₄ O ₂	60	Acetic acid	95.21	2.24
172284329	3.49	C ₃ H ₆ O ₂	74	2-Propanone, 1-hydroxy-	81.5	2.47
34194148	0.69	C ₄ H ₉ NO ₅	151	1,3-Propanediol, 2-(hydroxymethyl)-2-nitro-	21.63	3.14
24384797	0.49	C ₅ H ₈ O	84	1-Pentyn-3-ol	47.92	3.95
12067038	0.24	C ₄ H ₆ O ₃	102	Butanoic acid, 2-oxo-	17.24	4.3
99623496	2.02	C ₄ H ₆ O ₃	102	Acetic anhydride	30.48	4.4
103879088	2.1	C ₇ H ₁₄ O	114	Pentanal, 2,3-dimethyl-	15.4	4.6
75184721	1.52	C ₄ H ₆ O ₃	102	Acetic anhydride	62.85	4.82
56349596	1.14	C ₅ H ₄ O ₂	96	3-Furaldehyde	69.69	5.65
62593621	1.27	C ₅ H ₆ O ₂	98	2-Furanmethanol	64.06	6.19
19669473	0.4	C ₆ H ₁₀ O ₄	146	1,2-Ethanediol, diacetate	44.09	6.44
17793820	0.36	C ₅ H ₈ O ₂	100	2-Butenoic acid, methyl ester, (E)-	52.87	7.09
62960590	1.28	C ₆ H ₁₂	84	2-Hexene	27.95	7.31
22853409	0.46	C ₅ H ₆ O ₂	98	1,3-Butadiene-1-carboxylic acid	40.04	7.41
133888120	2.71	C ₆ H ₁₀ O	98	Cyclohexanone	58.1	7.57
27058001	0.55	C ₁₄ H ₂₈ O	212	9-Tetradecen-1-ol, (E)-	19.96	8.24
167257559	3.39	C ₆ H ₇ O ₄ P	174	Phosphonic acid, (p-hydroxyphenyl)-	48.38	8.62
83319583	1.69	C ₄ H ₆ N ₂ O ₂	114	2,4-Imidazolidinedione, 1-methyl-	35.14	8.88
11227308	0.23	C ₆ H ₈ O ₂	112	2-Cyclopenten-1-one, 2-hydroxy-3-methyl-	35.73	9.13
47860666	0.97	C ₆ H ₈ O ₂	112	2-Cyclopenten-1-one, 2-hydroxy-3-methyl-	52.41	9.4
27414178	0.56	C ₆ H ₁₀ O ₂	114	2-Pentenoic acid, 2-methyl-, (E)-	67.97	9.66
15720173	0.32	C ₉ H ₁₆ O ₂	156	2(3H)-Furanone, dihydro-5-pentyl-	14.49	9.86
56502943	1.14	C ₉ H ₁₆ O ₂	156	2(3H)-Furanone, dihydro-5-pentyl-	31.99	9.95
12847627	0.26	C ₁₁ H ₂₀ O ₂	184	Undecanoic acid, hydroxy-, lactone	32.48	10.19
18444260	0.37	C ₆ H ₆ O ₃	126	Methyl 2-furoate	89.59	10.31
45104823	0.91	C ₇ H ₈ O ₂	124	Phenol, 2-methoxy-	54.57	10.43
182363209	3.69	C ₄ H ₈ O	72	Butanal	29.66	10.57

11188603	0.23	C6H6O3	126	1,3,5-Benzenetriol	43.38	10.81
14752011	0.3	C11H20O2	184	Undecanoic acid, hydroxy-, lactone	14.29	10.92
26373877	0.53	C5H10N2O	114	Piperidine, 1-nitroso-	69.77	11.01
42197843	0.85	C6H10O	98	Cyclopentanone, 2-methyl-	12.81	11.44
27259678	0.55	C8H10O2	138	2-Methoxybenzyl alcohol	49.3	11.63
21904408	0.44	C7H6O2	122	Benzenecarboxylic acid	88.59	11.74
67151246	1.36	C8H10O2	138	Phenol, 2-methoxy-4-methyl-	53.4	12.06
37160987	0.75	C6H6O2	110	1,2-Benzenediol	70.63	12.16
14685102	0.3	C6H10O2	114	2-Pentenoic acid, 2-methyl-, (E)-	20.49	12.36
18492694	0.37	C12H22O2	198	ç Dodecalactone	22.83	12.47
51763336	1.05	C5H6O2	98	2-Furanmethanol	11.84	12.6
14522437	0.29	C12H22O11	342	à-D-Glucopyranoside, à-D-glucopyranosyl	23.96	12.93
58023557	1.18	C7H8O3	140	Flamenol	71.4	13.1
25760457	0.52	C9H12O2	152	2,4-Dimethoxytoluene	62.17	13.32
19456338	0.39	C7H6O2	122	Benzaldehyde, 3-hydroxy-	16.9	13.69
121295203	2.46	C12H17NO2	207	Phenol, 3-methyl-5-(1-methylethyl)-, methylcarbamate	22.72	13.82
193122531	3.91	C10H18O	154	Eucalyptol	44.12	14.34
34058823	0.69	C6H6O3	126	1,3,5-Benzenetriol	48.34	14.7
23571101	0.48	C11H20O2	184	Undecanoic acid, hydroxy-, lactone	28.87	14.81
22876913	0.46	C8H8O3	152	Vanillin	48.25	15.03
7177652.4	0.15	C10H12O2	164	Phenol, 2-methoxy-4-(1-propenyl)-	68.62	15.15
21528609	0.44	C9H12O2	152	2,4-Dimethoxytoluene	23.49	15.38
176037226	3.57	C9H12O3	168	1,2,3-Trimethoxybenzene	70.84	15.8
12687750	0.26	C10H14O2	166	Phenol, 2-methoxy-4-propyl-	95.14	16.03
8370636.1	0.17	C12H18	162	Benzene, 1,3-bis(1-methylethyl)-	28.8	16.41
13346056	0.27	C11H12O4	208	4-Acetoxy-3-methoxyacetophenone	54.58	16.56
13246080	0.27	C9H10O3	166	Ethanone, 1-(4-hydroxy-3-methoxyphenyl)-	17.92	16.71
204734933	4.15	C12H22O11	342	à-D-Glucopyranoside, à-D-glucopyranosyl	51.53	17.12
59581105	1.21	C10H12O3	180	Propylparaben	49.45	17.28
56200167	1.14	C10H12O3	180	Propylparaben	60.01	17.39
19852793	0.4	C10H14O2	166	Phenol, 2-methoxy-4-propyl-	82.75	17.57
148827195	3.01	C12H15NO4	237	3-Hydroxycarbofuran	56.09	18.33

17997740	0.36	C20H22N8O5	454	Methotrexate	34.71	18.69
12197467	0.25	C11H21BrO2	264	11-Bromoundecanoic acid	38.38	18.92
20224846	0.41	C10H10O2	162	4-Methoxycinnamaldehyde	18.43	19.04
21480463	0.44	C41H64O13	764	Digitoxin	25.6	19.55
18603136	0.38	C20H28O	284	Vitamin A aldehyde	16.44	19.92
20735348	0.42	C9H10O4	182	3,4-Dimethoxy-5-hydroxybenzaldehyde	49.1	20.07
12280298	0.25	C20H28O	284	Vitamin A aldehyde	21.44	20.36
96497614	1.95	C10H10O2	162	4-Methoxycinnamaldehyde	22.69	20.74
111638188	2.26	C12H18O	178	6-tert-Butyl-2,4-dimethylphenol	19.74	21.23
41026101	0.83	C13H11Br	246	Benzene, 1,1'-(bromomethylene)bis-	38.52	21.76
80146276	1.62	C12H24O2	200	Dodecanoic acid	30.2	24.51
70448569	1.43	C12H15NO4	237	3-Hydroxycarbofuran	27.91	24.96
13568626	0.27	C19H22O6	346	Gibberellic acid	19.49	25.08
70946794	1.44	C16H32O2	256	n-Hexadecanoic acid	37.89	28.43
17896360	0.36	C16H34	226	Hexadecane	20.88	35.54
16464753	0.33	C20H42	282	Eicosane	23.51	37.63
16013793	0.32	C16H34	226	Hexadecane	27.58	39.6

Table 15: NIST library matches for poplar fast pyrolysis trial at 500°C.

Area	Area %	Molecular Formula	MolecularWeight	Name	Probability	RT
11116331	0.24	CO2	44	Carbon dioxide	78.17	0.88
574375604	12.34	CO2	44	Carbon dioxide	71.61	1.16
107326292	2.31	C3H4O3	88	Propanoic acid, 2-oxo-	29.02	1.38
202795352	4.36	C2H4O2	60	Acetaldehyde, hydroxy-	78.08	1.69
58817262	1.26	C4H6O3	102	Butanoic acid, 2-oxo-	52.7	1.87
198450510	4.26	C2H4O2	60	Acetic acid	95.16	2.22
154008465	3.31	C3H6O2	74	2-Propanone, 1-hydroxy-	79.21	2.48
29492392	0.63	C4H9NO5	151	1,3-Propanediol, 2-(hydroxymethyl)-2-nitro-	33.87	3.14
22022694	0.47	C5H7ClO	118	Cyclobutanecarboxylic acid chloride	27.52	3.96
12787905	0.27	C4H6O3	102	Butanoic acid, 2-oxo-	29.78	4.3
91758111	1.97	C3H6O2	74	2-Propanone, 1-hydroxy-	34.43	4.41
100242616	2.15	C7H14O	114	Pentanal, 2,3-dimethyl-	30.48	4.6
53170005	1.14	C4H6O3	102	Acetic anhydride	65.4	4.82
16254221	0.35	C6H8N2O	124	Propanenitrile, 3,3'-oxybis-	73.73	4.93
57606691	1.24	C5H4O2	96	3-Furaldehyde	75.5	5.66
55376691	1.19	C5H6O2	98	2-Furanmethanol	72.43	6.18
18034188	0.39	C6H10O4	146	1,2-Ethanediol, diacetate	63.03	6.44
14832023	0.32	C5H8O2	100	2-Butenoic acid, methyl ester, (E)-	58.67	7.09
57053450	1.23	C6H12	84	2-Hexene	25.02	7.3
19525026	0.42	C5H6O2	98	1,3-Butadiene-1-carboxylic acid	38.61	7.4
117850753	2.53	C6H10O	98	Cyclohexanone	49.91	7.56
22531048	0.48	C14H28O	212	9-Tetradecen-1-ol, (E)-	25.6	8.23
11545913	0.25	C6H6O2	110	Resorcinol	62.27	8.5
104947665	2.25	C6H6O	94	Phenol	48.13	8.61
71157688	1.53	C4H6N2O2	114	2,4-Imidazolidinedione, 1-methyl-	24.47	8.87
11532067	0.25	C6H8O2	112	2-Cyclopenten-1-one, 2-hydroxy-3-methyl-	45.25	9.13
47540245	1.02	C6H8O2	112	2-Cyclopenten-1-one, 2-hydroxy-3-methyl-	54.96	9.4
27025908	0.58	C6H10O2	114	2-Pentenoic acid, 2-methyl-, (E)-	66.05	9.66
73662172	1.58	C7H8O	108	Phenol, 3-methyl-	18.18	9.85

12519574	0.27	C7H8O2	124	Benzenemethanol, 4-hydroxy-	21.46	10.19
19662111	0.42	C6H6O3	126	Methyl 2-furoate	92.43	10.31
45667393	0.98	C7H8O2	124	Phenol, 2-methoxy-	51.74	10.43
142911487	3.07	C4H8O	72	Butanal	32.25	10.55
10578578	0.23	C6H6O3	126	1,3,5-Benzenetriol	46.22	10.81
14814428	0.32	C11H20O2	184	Undecanoic acid, hydroxy-, lactone	14.76	10.92
24715473	0.53	C5H10N2O	114	Piperidine, 1-nitroso-	70.25	11
8885350.2	0.19	C14H28O	212	9-Tetradecen-1-ol, (E)-	28.58	11.24
35515688	0.76	C19H37NO	295	Octadecane, 1-isocyanato-	30.65	11.49
28766865	0.62	C8H10O2	138	2-Methoxybenzyl alcohol	51.36	11.63
20474323	0.44	C7H6O2	122	Benzenecarboxylic acid	87.33	11.73
24931932	0.54	C6H6O4	142	4H-Pyran-4-one, 5-hydroxy-2-(hydroxymethyl)-	37.15	11.98
40367854	0.87	C8H10O2	138	Phenol, 2-methoxy-4-methyl-	51.49	12.06
37552277	0.81	C6H6O2	110	1,2-Benzenediol	78.99	12.16
13296236	0.29	C6H10O2	114	2-Pentenoic acid, 2-methyl-, (E)-	15.1	12.36
21187675	0.46	C12H24O	184	Dodecanal	27.48	12.51
51606117	1.11	C5H6O2	98	2-Furanmethanol	14.66	12.6
17432786	0.37	C11H20O2	184	Undecanoic acid, hydroxy-, lactone	24.2	12.93
64604667	1.39	C7H8O3	140	Flamenol	75.68	13.1
28253482	0.61	C9H12O2	152	2,4-Dimethoxytoluene	73.61	13.32
19161978	0.41	C8H10O2	138	1,3-Benzenediol, 4-ethyl-	39.38	13.47
6425480.8	0.14	C12H22O11	342	à-D-Glucopyranoside, à-D-glucopyranosyl	36.42	13.6
19684173	0.42	C7H6O2	122	Benzaldehyde, 3-hydroxy-	14.38	13.69
106283936	2.28	C12H17NO2	207	Phenol, 3-methyl-5-(1-methylethyl)-, methylcarbamate	24.11	13.83
22643970	0.49	C9H11NO4	197	Levodopa	22.95	14.22
167510775	3.6	C10H18O	154	Eucalyptol	43.24	14.34
20617062	0.44	C10H12O2	164	Phenol, 2-methoxy-4-(1-propenyl)-	42.54	14.42
40129448	0.86	C6H6O3	126	1,3,5-Benzenetriol	62.73	14.7
20662334	0.44	C11H20O2	184	Undecanoic acid, hydroxy-, lactone	32.88	14.81
19350336	0.42	C8H8O3	152	Vanillin	50.46	15.03
5501583.5	0.12	C10H12O2	164	Phenol, 2-methoxy-4-(1-propenyl)-	64.7	15.15
20451270	0.44	C9H12O2	152	2,4-Dimethoxytoluene	31.88	15.36

161070353	3.46	C9H12O3	168	1,2,3-Trimethoxybenzene	60.33	15.8
9054806	0.19	C10H14O2	166	Phenol, 2-methoxy-4-propyl-	94.71	16.03
8343685.2	0.18	C11H14O	162	Ethanone, 1-(2,4,6-trimethylphenyl)-	28	16.41
10354162	0.22	C11H12O4	208	4-Acetoxy-3-methoxyacetophenone	55.8	16.56
14984543	0.32	C9H10O3	166	Ethanone, 1-(4-hydroxy-3-methoxyphenyl)-	41.86	16.71
222533417	4.78	C12H22O11	342	à-D-Glucopyranoside, à-D-glucopyranosyl	49.8	17.11
55706641	1.2	C10H12O3	180	Propylparaben	53.78	17.28
62056313	1.33	C10H12O3	180	Propylparaben	66.36	17.38
17550363	0.38	C10H14O2	166	Phenol, 2-methoxy-4-propyl-	79.42	17.57
135241359	2.91	C12H15NO4	237	3-Hydroxycarbofuran	54.12	18.32
16619272	0.36	C20H22N8O5	454	Methotrexate	57.15	18.69
12701919	0.27	C12H22O11	342	à-D-Glucopyranoside, à-D-glucopyranosyl	31.89	18.92
16205589	0.35	C15H24O	220	1,4-Methanoazulen-7(1H)-one, octahydro-1,5,5,8a-tetramethyl-	17.64	19.05
21333354	0.46	C41H64O13	764	Digitoxin	21	19.55
17002628	0.37	C20H28O	284	Vitamin A aldehyde	20.71	19.92
15719581	0.34	C9H10O4	182	3,4-Dimethoxy-5-hydroxybenzaldehyde	51.01	20.06
10998122	0.24	C20H28O	284	Vitamin A aldehyde	22.86	20.36
77962999	1.67	C10H10O2	162	4-Methoxycinnamaldehyde	29.2	20.73
100984722	2.17	C12H18O	178	6-tert-Butyl-2,4-dimethylphenol	18.48	21.23
39930514	0.86	C13H11Br	246	Benzene, 1,1'-(bromomethylene)bis-	39.15	21.76
44985748	0.97	C12H24O2	200	Dodecanoic acid	28.99	24.47
67301385	1.45	C12H15NO4	237	3-Hydroxycarbofuran	34.49	24.95
17513997	0.38	C19H22O6	346	Gibberellic acid	13.6	25.09
23838396	0.51	C16H32O2	256	n-Hexadecanoic acid	29.17	28.38

Table 16: NIST library matches for poplar fast pyrolysis trial at 600°C.

Area	Area %	Molecular Formula	MolecularWeight	Name	Probability	RT
1.086E+09	15.3	CO2	44	Carbon dioxide	89.51	1.12
163700348	2.31	C5H8O2	100	1-Propen-2-ol, acetate	30.86	1.37
183324727	2.58	C2H4O2	60	Acetaldehyde, hydroxy-	80.22	1.72
155518911	2.19	C4H6O2	86	2,3-Butanedione	44.66	1.78
254491730	3.58	C2H4O2	60	Acetic acid	96.57	2.3
219749090	3.09	C3H6O2	74	2-Propanone, 1-hydroxy-	79.14	2.54
128677403	1.81	C3H6O2	74	Acetic acid, methyl ester	28.28	4.45
128872384	1.81	C7H14O	114	Pentanal, 2,3-dimethyl-	23.44	4.66
84947118	1.2	C4H6O3	102	Acetic anhydride	66.96	4.87
24926286	0.35	C6H8N2O	124	Propanenitrile, 3,3'-oxybis-	71.06	4.97
85602055	1.21	C5H4O2	96	3-Furaldehyde	63.85	5.68
67178104	0.95	C5H6O2	98	2-Furanmethanol	67.45	6.21
31288315	0.44	C6H10O4	146	1,2-Ethanediol, diacetate	70.83	6.47
36191139	0.51	C5H8	68	1,3-Butadiene, 2-methyl-	31.97	7.15
78235358	1.1	C6H12	84	2-Hexene	23.63	7.34
186211270	2.62	C6H10O	98	Cyclopentanone, 2-methyl-	49.18	7.61
50757978	0.71	C14H28O	212	9-Tetradecen-1-ol, (E)-	43.44	8.26
16780021	0.24	C6H6O2	110	Resorcinol	38.43	8.52
248060703	3.49	C6H6O	94	Phenol	50.29	8.64
73028681	1.03	C4H6N2O2	114	2,4-Imidazolidinedione, 1-methyl-	20.8	8.93
80171159	1.13	C6H8O2	112	2-Cyclopenten-1-one, 2-hydroxy-3-methyl-	67.56	9.47
24174617	0.34	C7H8O	108	Phenol, 3-methyl-	43.67	9.89
40155912	0.57	C7H8O	108	Phenol, 3-methyl-	45.52	10.23
128611449	1.81	C7H8O2	124	Phenol, 2-methoxy-	58.47	10.47
168407256	2.37	C9H18O	142	Nonanal	22.6	10.66
18175370	0.26	C14H30O	214	1-Tetradecanol	14.46	10.96
24268989	0.34	C8H10O2	138	2-Methoxybenzyl alcohol	60.14	11.67
42495006	0.6	C7H6O2	122	Benzenecarboxylic acid	52.79	11.8
116795673	1.64	C8H10O2	138	Phenol, 2-methoxy-4-methyl-	44.65	12.09

120562567	1.7	C6H6O2	110	1,2-Benzenediol	72.6	12.23
22834510	0.32	C6H10O2	114	2-Pentenoic acid, 2-methyl-, (E)-	21.85	12.45
23840911	0.34	C11H20O2	184	Undecanoic acid, hydroxy-, lactone	17.45	12.59
57340781	0.81	C11H20O2	184	Undecanoic acid, hydroxy-, lactone	13.24	12.69
181214864	2.55	C7H8O3	140	Flamenol	76.06	13.15
94715119	1.33	C9H12O2	152	2,4-Dimethoxytoluene	71.59	13.35
46684840	0.66	C7H8O2	124	1,2-Benzenediol, 3-methyl-	87.47	13.51
214178519	3.02	C10H14O	150	Phenol, 2,3,5,6-tetramethyl-	23.14	13.86
469412221	6.61	C10H18O	154	Eucalyptol	46.92	14.39
47838500	0.67	C7H6O4	154	2,4,6-Trihydroxybenzaldehyde	27.57	14.51
72881405	1.03	C8H10O2	138	1,3-Benzenediol, 4-ethyl-	64.75	14.8
38280819	0.54	C8H8O3	152	Vanillin	48.78	15.07
17016251	0.24	C10H12O2	164	Phenol, 2-methoxy-4-(1-propenyl)-	49.78	15.18
312006659	4.39	C9H12O3	168	1,2,3-Trimethoxybenzene	73.45	15.85
211975228	2.99	C11H14O3	194	4-Butoxybenzoic acid	14.74	17.35
51654988	0.73	C13H11Br	246	Benzene, 1,1'-(bromomethylene)bis-	30.83	17.48
34653424	0.49	C10H14O2	166	Phenol, 2-methoxy-4-propyl-	86.5	17.64
284659890	4.01	C12H15NO4	237	3-Hydroxycarbofuran	66.86	18.39
47479858	0.67	C15H24O	220	1,4-Methanoazulen-7(1H)-one, octahydro-1,5,5,8a-tetramethyl-	12.15	19.09
33332222	0.47	C20H28O	284	Vitamin A aldehyde	13.85	19.96
29640568	0.42	C9H10O4	182	3,4-Dimethoxy-5-hydroxybenzaldehyde	36.47	20.11
141634497	1.99	C10H10O2	162	4-Methoxycinnamaldehyde	19.61	20.78
230179799	3.24	C12H18O	178	6-tert-Butyl-2,4-dimethylphenol	17.59	21.28
77017481	1.08	C13H11Br	246	Benzene, 1,1'-(bromomethylene)bis-	33.05	21.81
91878916	1.29	C16H32O2	256	n-Hexadecanoic acid	29.28	24.53
105930086	1.49	C12H15NO4	237	3-Hydroxycarbofuran	38.07	25.03
26661390	0.38	C19H22O6	346	Gibberellic acid	18.67	25.16
68192103	0.96	C16H32O2	256	n-Hexadecanoic acid	41.35	28.45

Table 17: NIST library matches for poplar fast pyrolysis trial at 600°C.

Area	Area %	Molecular Formula	Molecular Weight	Name	Probability	RT
1.114E+09	14.55	CO2	44	Carbon dioxide	86.61	1.12
203932668	2.66	C4H6O3	102	Acetic anhydride	34.85	1.37
314530892	4.11	C2H4O2	60	Acetaldehyde, hydroxy-	75.7	1.73
64623778	0.84	C4H6O3	102	Butanoic acid, 2-oxo-	60.99	1.87
32149033	0.42	C2H4O2	60	Acetic acid	63.04	1.96
423590268	5.53	C2H4O2	60	Acetic acid	92.71	2.37
232080707	3.03	C3H6O2	74	2-Propanone, 1-hydroxy-	80.57	2.55
32450887	0.42	C5H8O	84	1-Pentyn-3-ol	32.73	3.97
167390831	2.19	C3H6O2	74	Acetic acid, methyl ester	35.48	4.45
142106265	1.86	C7H14O	114	Pentanal, 2,3-dimethyl-	25.22	4.67
109221985	1.43	C4H6O3	102	Acetic anhydride	64.26	4.89
33886389	0.44	C6H8N2O	124	Propanenitrile, 3,3'-oxybis-	69.28	4.98
104931639	1.37	C5H4O2	96	3-Furaldehyde	73.01	5.68
77292570	1.01	C5H6O2	98	2-Furanmethanol	53.24	6.22
36087762	0.47	C6H10O4	146	1,2-Ethandiol, diacetate	70.51	6.47
85499149	1.12	C6H12	84	2-Hexene	27.92	7.35
186537039	2.44	C6H10O	98	Cyclopentanone, 2-methyl-	61.1	7.63
69175360	0.9	C12H24O	184	Dodecanal	23.09	8.25
21165980	0.28	C6H6O2	110	Resorcinol	35.09	8.53
219585636	2.87	C6H7O4P	174	Phosphonic acid, (p-hydroxyphenyl)-	48.27	8.65
141351435	1.85	C2H2N4O2	114	1H-1,2,4-Triazole, 3-nitro-	45.94	8.95
71992339	0.94	C6H8O2	112	2-Cyclopenten-1-one, 2-hydroxy-3-methyl-	67.77	9.47
19696568	0.26	C7H8O	108	Phenol, 3-methyl-	46.88	9.88
103154198	1.35	C7H8O	108	Phenol, 3-methyl-	32.32	10.23
97627282	1.27	C7H8O2	124	Phenol, 2-methoxy-	53.58	10.46
103321580	1.35	C11H22O	170	Undecanal	30.62	10.65
17236455	0.23	C11H20O2	184	Undecanoic acid, hydroxy-, lactone	22.03	10.96
31425616	0.41	C9H10O3	166	Benzaldehyde, 3-ethoxy-2-hydroxy-	42.65	11.67
129727294	1.69	C8H10O2	138	Phenol, 2-methoxy-4-methyl-	46.78	12.08
100978935	1.32	C6H6O2	110	1,2-Benzenediol	48.12	12.24

28287761	0.37	C6H10O2	114	2-Pentenoic acid, 2-methyl-, (E)-	16.8	12.47
85848085	1.12	C11H22O	170	Undecanal	14.1	12.7
174165772	2.27	C7H8O3	140	Flamenol	67.7	13.16
70848617	0.93	C9H12O2	152	2,4-Dimethoxytoluene	76.66	13.34
196215970	2.56	C12H17NO2	207	Phenol, 3-methyl-5-(1-methylethyl)-, methylcarbamate	24.78	13.85
364888594	4.77	C10H18O	154	Eucalyptol	49.39	14.38
43823158	0.57	C10H18O	154	3-Cyclohexen-1-ol, 4-methyl-1-(1-methylethyl)-	26.4	14.51
63439727	0.83	C7H6O5	170	2,4,6-Trihydroxybenzoic acid	34.11	14.86
50456558	0.66	C8H8O3	152	Vanillin	52.84	15.07
15964553	0.21	C10H12O2	164	Phenol, 2-methoxy-4-(1-propenyl)-	59.29	15.17
316494455	4.13	C9H12O3	168	1,2,3-Trimethoxybenzene	69.79	15.84
28880596	0.38	C10H14O2	166	Phenol, 2-methoxy-4-propyl-	93.73	16.08
32781047	0.43	C9H10O3	166	Ethanone, 1-(4-hydroxy-3-methoxyphenyl)-	54.64	16.63
259033288	3.38	C11H14O3	194	4-Butoxybenzoic acid	33.61	17.46
264856149	3.46	C10H12O3	180	Propylparaben	25.19	17.63
185570208	2.42	C10H12O3	180	Propylparaben	27.96	17.72
231955538	3.03	C12H15NO4	237	3-Hydroxycarbofuran	60.27	18.37
55649105	0.73	C20H28O	284	Vitamin A aldehyde	23.18	19.08
38668743	0.5	C12H15NO4	237	3-Hydroxycarbofuran	24.72	19.94
40222274	0.53	C9H10O4	182	3,4-Dimethoxy-5-hydroxybenzaldehyde	38.35	20.12
158615065	2.07	C10H10O2	162	4-Methoxycinnamaldehyde	22.9	20.77
138544758	1.81	C12H18O	178	6-tert-Butyl-2,4-dimethylphenol	18.94	21.28
62212662	0.81	C12H8N2O	196	9H-Carbazole, 9-nitroso-	30.17	21.8
91967103	1.2	C16H32O2	256	n-Hexadecanoic acid	30.91	24.52
110572930	1.44	C12H15NO4	237	3-Hydroxycarbofuran	34.83	25.03
60988621	0.8	C16H32O2	256	n-Hexadecanoic acid	42.88	28.44

Table 18: NIST library matches for poplar fast pyrolysis trial at 700°C.

Area	Area %	Molecular Formula	Molecular Weight	Name	Probability	RT
1.046E+09	18.42	CO2	44	Carbon dioxide	87.93	1.13
207624810	3.66	C5H8O2	100	1-Propen-2-ol, acetate	29.63	1.38
291870423	5.14	C2H4O2	60	Acetaldehyde, hydroxy-	79.59	1.73
61379984	1.08	C4H6O3	102	Butanoic acid, 2-oxo-	53.49	1.9
347563155	6.12	C2H4O2	60	Acetic acid	85.04	2.36
154091013	2.71	C3H6O2	74	2-Propanone, 1-hydroxy-	86.01	2.55
140972292	2.48	C3H6O2	74	Acetic acid, methyl ester	39.63	4.46
92984386	1.64	C7H14O	114	Pentanal, 2,3-dimethyl-	33.63	4.65
86879296	1.53	C4H6O3	102	Acetic anhydride	65.53	4.87
24662558	0.43	C6H8N2O	124	Propanenitrile, 3,3'-oxybis-	75.03	4.97
74770256	1.32	C5H4O2	96	3-Furaldehyde	68.42	5.68
52547302	0.93	C5H6O2	98	2-Furanmethanol	63.92	6.21
54904277	0.97	C6H12	84	2-Hexene	33.95	7.33
128278265	2.26	C6H10O	98	Cyclopentanone, 2-methyl-	44.85	7.6
52315494	0.92	C14H28O	212	9-Tetradecen-1-ol, (E)-	45.13	8.25
16029497	0.28	C6H6O2	110	Resorcinol	22.27	8.52
175757228	3.1	C6H6O	94	Phenol	49.34	8.63
123071609	2.17	C4H6N2O2	114	2,4-Imidazolidinedione, 1-methyl-	20.83	8.92
46399995	0.82	C6H8O2	112	1,2-Cyclopentanedione, 3-methyl-	47.65	9.44
23486951	0.41	C7H8O	108	Phenol, 2-methyl-	36.1	9.88
29021650	0.51	C7H8O	108	Phenol, 3-methyl-	41.6	10.22
50280064	0.89	C7H8O2	124	Phenol, 2-methoxy-	55.05	10.44
53718647	0.95	C5H10O	86	2-Penten-1-ol, (Z)-	11.64	10.57
78982701	1.39	C8H10O2	138	Phenol, 2-methoxy-4-methyl-	52.96	12.08
83370415	1.47	C6H6O2	110	1,2-Benzenediol	72.52	12.2
60321500	1.06	C11H20O2	184	Undecanoic acid, hydroxy-, lactone	11.99	12.67
119300653	2.1	C7H8O3	140	Flamenol	70.69	13.13
37704480	0.66	C9H12O2	152	2,4-Dimethoxytoluene	70.81	13.33
44541354	0.78	C7H8O2	124	1,2-Benzenediol, 3-methyl-	88.49	13.5
114125255	2.01	C10H14O	150	Phenol, p-tert-butyl-	26.06	13.84

225571785	3.97	C10H18O	154	Eucalyptol	50.7	14.36
43183836	0.76	C10H18O	154	3-Cyclohexen-1-ol, 4-methyl-1-(1-methylethyl)-	26.64	14.49
65720531	1.16	C8H10O2	138	1,3-Benzenediol, 4-ethyl-	58.09	14.78
34991085	0.62	C8H8O3	152	Vanillin	48.66	15.06
186967060	3.29	C9H12O3	168	1,2,3-Trimethoxybenzene	70.88	15.82
22627245	0.4	C11H12O4	208	4-Acetoxy-3-methoxyacetophenone	68.22	16.74
240399527	4.23	C11H14O3	194	4-Butoxybenzoic acid	38.31	17.45
100720773	1.77	C10H12O3	180	Propylparaben	27.66	17.54
176027956	3.1	C12H15NO4	237	3-Hydroxycarbofuran	72.29	18.35
46242895	0.81	C10H10O2	162	4-Methoxycinnamaldehyde	12.26	19.07
35334714	0.62	C9H10O4	182	3,4-Dimethoxy-5-hydroxybenzaldehyde	38.84	20.11
99537686	1.75	C10H10O2	162	4-Methoxycinnamaldehyde	15.72	20.76
165401087	2.91	C12H18O	178	6-tert-Butyl-2,4-dimethylphenol	17.57	21.26
41331507	0.73	C13H11Br	246	Benzene, 1,1'-(bromomethylene)bis-	28.41	21.78
114588851	2.02	C16H32O2	256	n-Hexadecanoic acid	28.56	24.53
80744811	1.42	C12H15NO4	237	3-Hydroxycarbofuran	39.37	25
43370892	0.76	C19H22O6	346	Gibberellic acid	22.83	25.16
81729775	1.44	C16H32O2	256	n-Hexadecanoic acid	29	28.46

Table 19: NIST library matches for poplar fast pyrolysis trial at 700°C.

Area	Area %	Molecular Formula	Molecular Weight	Name	Probability	RT
1.005E+09	16.25	CO ₂	44	Carbon dioxide	87.78	1.1
202366997	3.27	C ₄ H ₆ O ₃	102	Acetic anhydride	30.25	1.35
288370477	4.66	C ₂ H ₄ O ₂	60	Acetaldehyde, hydroxy-	79.35	1.7
97424251	1.57	C ₄ H ₆ O ₃	102	Butanoic acid, 2-oxo-	59.1	1.85
317247881	5.13	C ₂ H ₄ O ₂	60	Acetic acid	96.09	2.29
185019501	2.99	C ₃ H ₆ O ₂	74	2-Propanone, 1-hydroxy-	78.97	2.51
149397983	2.42	C ₃ H ₆ O ₂	74	Acetic acid, methyl ester	55.38	4.43
111496711	1.8	C ₇ H ₁₄ O	114	Pentanal, 2,3-dimethyl-	38.18	4.63
88758408	1.43	C ₄ H ₆ O ₃	102	Acetic anhydride	66.24	4.86
26581353	0.43	C ₆ H ₈ N ₂ O	124	Propanenitrile, 3,3'-oxybis-	72.68	4.95
83660357	1.35	C ₅ H ₄ O ₂	96	3-Furaldehyde	73.77	5.66
58004130	0.94	C ₅ H ₆ O ₂	98	2-Furanmethanol	47.73	6.2
63761916	1.03	C ₆ H ₁₂	84	2-Hexene	43.8	7.33
150948823	2.44	C ₆ H ₁₀ O	98	Cyclopentanone, 2-methyl-	44.27	7.59
49199229	0.8	C ₁₄ H ₂₈ O	212	9-Tetradecen-1-ol, (E)-	34.2	8.25
16573697	0.27	C ₆ H ₆ O ₂	110	Resorcinol	38.57	8.52
181115367	2.93	C ₆ H ₆ O	94	Phenol	50.24	8.63
132772657	2.15	C ₂ H ₂ N ₄ O ₂	114	1H-1,2,4-Triazole, 3-nitro-	23.12	8.92
57645778	0.93	C ₆ H ₈ O ₂	112	2-Cyclopenten-1-one, 2-hydroxy-3-methyl-	72.64	9.44
26714934	0.43	C ₇ H ₈ O	108	Phenol, 3-methyl-	41.88	9.88
42447032	0.69	C ₇ H ₈ O	108	Phenol, 3-methyl-	55.58	10.22
77524109	1.25	C ₇ H ₈ O ₂	124	Phenol, 2-methoxy-	52.27	10.45
75773162	1.22	C ₅ H ₁₀ O	86	2-Penten-1-ol, (Z)-	8.57	10.58
28255843	0.46	C ₉ H ₁₀ O ₃	166	Benzaldehyde, 3-ethoxy-2-hydroxy-	35.65	11.66
106511468	1.72	C ₈ H ₁₀ O ₂	138	Phenol, 2-methoxy-4-methyl-	48.3	12.08
89032168	1.44	C ₆ H ₆ O ₂	110	1,2-Benzenediol	62.21	12.22
69877644	1.13	C ₁₁ H ₂₀ O ₂	184	Undecanoic acid, hydroxy-, lactone	15.03	12.68
167747835	2.71	C ₇ H ₈ O ₃	140	Flamenol	70.44	13.14
75445188	1.22	C ₉ H ₁₂ O ₂	152	2,4-Dimethoxytoluene	69.5	13.34
38956310	0.63	C ₇ H ₈ O ₂	124	1,2-Benzenediol, 3-methyl-	88.68	13.51

169155076	2.73	C10H14O	150	Phenol, 2-methyl-5-(1-methylethyl)-	21.05	13.85
301835306	4.88	C10H18O	154	Eucalyptol	50.48	14.36
38300167	0.62	C10H18O	154	3-Cyclohexen-1-ol, 4-methyl-1-(1-methylethyl)-	25.83	14.5
68698470	1.11	C8H10O2	138	1,3-Benzenediol, 4-ethyl-	58.12	14.79
41543622	0.67	C8H8O3	152	Vanillin	45.84	15.07
237010034	3.83	C9H12O3	168	1,2,3-Trimethoxybenzene	49.5	15.83
39237950	0.63	C10H14O2	166	Phenol, 2-methoxy-4-propyl-	93	16.07
241985020	3.91	C11H14O3	194	4-Butoxybenzoic acid	32.73	17.46
166611844	2.69	C10H12O3	180	Propylparaben	31.92	17.57
200125487	3.24	C12H15NO4	237	3-Hydroxycarbofuran	58.71	18.36
41693644	0.67	C20H28O	284	Vitamin A aldehyde	14.01	19.07
31358133	0.51	C9H10O4	182	3,4-Dimethoxy-5-hydroxybenzaldehyde	42.83	20.11
118402464	1.91	C10H10O2	162	4-Methoxycinnamaldehyde	21.02	20.76
134162081	2.17	C12H18O	178	6-tert-Butyl-2,4-dimethylphenol	22	21.26
50311274	0.81	C13H11Br	246	Benzene, 1,1'-(bromomethylene)bis-	27.41	21.79
82294487	1.33	C16H32O2	256	n-Hexadecanoic acid	33.02	24.51
94185161	1.52	C12H15NO4	237	3-Hydroxycarbofuran	35.98	25
65325222	1.06	C16H32O2	256	n-Hexadecanoic acid	34.67	28.43

Table 20: NIST library matches for red maple fast pyrolysis trial at 500°C.

Area	Area %	Molecular Formula	Molecular Weight	Name	Probability	RT
4.281E+09	51.87	C9H13N	135	Dextroamphetamine	42.43	6.15
133581622	1.62	CH6N2	46	Hydrazine, methyl-	53.83	6.66
643511098	7.8	C2H4O2	60	Acetaldehyde, hydroxy-	70.91	6.96
523703814	6.34	C2H4O2	60	Acetic acid	93.68	7.56
332178914	4.02	C2H4O2	60	Acetic acid	94.33	7.73
322341008	3.91	C3H6O2	74	2-Propanone, 1-hydroxy-	93.16	7.83
205009768	2.48	C3H6O2	74	Acetic acid, methyl ester	42.26	9.63
211912636	2.57	C3H6O	58	Propylene oxide	27.6	9.89
200216919	2.43	C3H6O2	74	2-Propanone, 1-hydroxy-	39.95	10.11
200789284	2.43	C5H4O2	96	3-Furaldehyde	59.31	10.75
130632104	1.58	C5H6O2	98	2-Furanmethanol	61.12	11.36
175019671	2.12	C6H10O	98	Cyclopentanone, 2-methyl-	50.93	12.81
149413023	1.81	C5H10N2O	114	Piperidine, 1-nitroso-	31.06	14.06
107096894	1.3	C6H8O2	112	2-Cyclopenten-1-one, 2-hydroxy-3-methyl-	56.42	14.59
194314964	2.35	C7H8O2	124	Phenol, 2-methoxy-	59.95	15.51
97215940	1.18	C8H10O2	138	Phenol, 2-methoxy-4-methyl-	52.62	17.1
35585162	0.43	C9H12O2	152	2,4-Dimethoxytoluene	57.76	18.34
101249627	1.23	C12H17NO2	207	Phenol, 3-methyl-5-(1-methylethyl)-, methylcarbamate	23.81	18.86
151241737	1.83	C10H18O	154	Eucalyptol	46.54	19.37
57494461	0.7	C10H12O2	164	Phenol, 2-methoxy-4-(1-propenyl)-, (E)-	46.8	20.88

Table 21: NIST library matches for red maple fast pyrolysis trial at 500°C.

Area	Area %	Molecular Formula	Molecular Weight	Name	Probability	RT
5.995E+09	55.89	C8H19N	129	2-Octanamine	54.51	6.17
244179132	2.28	C4H8O	72	Oxirane, 2,3-dimethyl-, trans-	33.94	6.79
275423016	2.57	C2H4O2	60	Acetaldehyde, hydroxy-	72.93	7.07
310649423	2.9	C2H4O2	60	Acetic acid	80.62	7.45
1.08E+09	10.07	C3H6O2	74	2-Propanone, 1-hydroxy-	90.85	7.98
233512250	2.18	C3H6O2	74	Acetic acid, methyl ester	38.07	9.72
201324647	1.88	C3H8O2	76	1,3-Propanediol	36.68	9.94
338056080	3.15	C3H6O2	74	2-Propanone, 1-hydroxy-	47.66	10.19
328877633	3.07	C6H8O	96	Furan, 2,5-dimethyl-	36.2	10.88
153477486	1.43	C6H12O	100	Butanal, 2-ethyl-	39.49	11.4
50418743	0.47	C4H6O2	86	Acetic acid ethenyl ester	50.48	11.65
228173756	2.13	C6H10O	98	Cyclopentanone, 2-methyl-	44.61	12.86
111791027	1.04	C12H24O	184	Dodecanal	25.62	13.39
175192558	1.63	C5H10N2O	114	Piperidine, 1-nitroso-	27.68	14.13
176197295	1.64	C6H8O2	112	1,2-Cyclopentanedione, 3-methyl-	44.52	14.66
287747448	2.68	C7H8O2	124	Phenol, 2-methoxy-	60.08	15.53
141046515	1.31	C8H10O2	138	Phenol, 2-methoxy-4-methyl-	56.65	17.13
55273899	0.52	C10H14O2	166	Phenol, 2-methoxy-4-propyl-	46.37	18.36
131910879	1.23	C10H14O	150	Phenol, p-tert-butyl-	26.27	18.88
154948604	1.44	C10H18O	154	Eucalyptol	35.73	19.38
52853459	0.49	C10H12O2	164	Phenol, 2-methoxy-4-(1-propenyl)-	50.92	20.89

Table 22: NIST library matches for red maple fast pyrolysis trial at 600°C.

Area	Area %	Molecular Formula	Molecular Weight	Name	Probability	RT
5.869E+09	53.44	C8H19N	129	2-Octanamine	55.36	6.15
215044035	1.96	C3H4O2	72	Methylglyoxal	30.87	6.77
237095788	2.16	C2H4O2	60	Acetaldehyde, hydroxy-	71.99	7.01
906234942	8.25	C2H4O2	60	Acetic acid	91.11	7.86
269171154	2.45	C3H6O2	74	2-Propanone, 1-hydroxy-	92.04	7.93
231763792	2.11	C3H6O2	74	Acetic acid, methyl ester	48.96	9.7
152413410	1.39	C3H6O	58	Propylene oxide	38.83	9.89
332963224	3.03	C3H6O2	74	2-Propanone, 1-hydroxy-	38.55	10.15
306205617	2.79	C5H4O2	96	3-Furaldehyde	58.85	10.75
134502082	1.22	C6H12O	100	Butanal, 2-ethyl-	35.31	11.38
40014116	0.36	C4H6O2	86	Acetic acid ethenyl ester	35.9	11.62
213914134	1.95	C6H10O	98	Cyclopentanone, 2-methyl-	39.46	12.85
110893433	1.01	C12H24O	184	Dodecanal	21.07	13.38
213961377	1.95	C2H2N4O2	114	1H-1,2,4-Triazole, 3-nitro-	32.43	14.16
173033120	1.58	C6H8O2	112	1,2-Cyclopentanedione, 3-methyl-	35.49	14.66
111342226	1.01	C7H8O	108	Phenol, 3-methyl-	60.03	15.33
273059898	2.49	C7H8O2	124	Phenol, 2-methoxy-	55.77	15.52
156375505	1.42	C8H10O	122	Phenol, 2,6-dimethyl-	21.38	15.77
74429694	0.68	C8H10O2	138	2-Methoxybenzyl alcohol	61.27	16.75
126733827	1.15	C8H10O2	138	Phenol, 2-methoxy-4-methyl-	50.63	17.12
121759124	1.11	C10H14O2	166	Phenol, 2-methoxy-4-propyl-	66.57	18.36
216521200	1.97	C12H17NO2	207	Phenol, 3-methyl-5-(1-methylethyl)-, methylcarbamate	23.93	18.88
351711691	3.2	C10H18O	154	Eucalyptol	36.27	19.41
143800000	1.31	C10H12O2	164	Phenol, 2-methoxy-4-(1-propenyl)-, (E)-	43.46	20.91

Table 23: NIST library matches for red maple fast pyrolysis trial at 600°C.

Area	Area %	Molecular Formula	Molecular Weight	Name	Probability	RT
6.151E+09	52.95	C8H19N	129	2-Octanamine	70.11	6.15
327364676	2.82	C4H8O	72	Oxirane, 2,3-dimethyl-, trans-	34.63	6.77
267282407	2.3	C2H4O2	60	Acetaldehyde, hydroxy-	69.96	7.02
281210352	2.42	C2H4O2	60	Acetic acid	74.86	7.43
1.196E+09	10.29	C3H6O2	74	2-Propanone, 1-hydroxy-	89.53	7.95
294776004	2.54	C3H6O2	74	Acetic acid, methyl ester	42.06	9.71
127846360	1.1	C3H6O	58	Propylene oxide	24.81	9.88
395791757	3.41	C3H6O2	74	2-Propanone, 1-hydroxy-	46.6	10.18
308975648	2.66	C6H8O	96	Furan, 2,5-dimethyl-	33.91	10.87
138744847	1.19	C6H12O	100	Butanal, 2-ethyl-	25.93	11.39
260012882	2.24	C6H10O	98	Cyclopentanone, 2-methyl-	37.6	12.88
143310395	1.23	C12H24O	184	Dodecanal	29.15	13.39
275967737	2.38	C4H6N2O2	114	2,4-Imidazolidinedione, 1-methyl-	45.58	14.21
151491056	1.3	C6H8O2	112	2-Cyclopenten-1-one, 2-hydroxy-3-methyl-	36.26	14.66
101173958	0.87	C7H8O	108	Phenol, 3-methyl-	44.51	15.33
255650338	2.2	C7H8O2	124	Phenol, 2-methoxy-	52.78	15.52
71689943	0.62	C8H10O2	138	2-Methoxybenzyl alcohol	58.52	16.75
137384214	1.18	C8H10O2	138	Phenol, 2-methoxy-4-methyl-	57.75	17.13
109690598	0.94	C10H14O2	166	Phenol, 2-methoxy-4-propyl-	53.16	18.36
190815340	1.64	C12H17NO2	207	Phenol, 3-methyl-5-(1-methylethyl)-, methylcarbamate	30.1	18.88
287341295	2.47	C10H18O	154	Eucalyptol	44.65	19.41
144179531	1.24	C10H12O2	164	Phenol, 2-methoxy-4-(1-propenyl)-	57.59	20.91

Table 24: NIST library matches for red maple fast pyrolysis trial at 700°C.

Area	Area %	Molecular Formula	Molecular Weight	Name	Probability	RT
6.287E+09	54.59	C8H19N	129	2-Octanamine	83	6.15
307103141	2.67	C4H6O	70	Methyl vinyl ketone	20.97	6.77
260654127	2.26	C2H4O2	60	Acetaldehyde, hydroxy-	72.39	6.98
384551369	3.34	C2H4O2	60	Acetic acid	86.3	7.46
934319438	8.11	C3H6O2	74	2-Propanone, 1-hydroxy-	92.25	7.88
269874135	2.34	C3H6O2	74	2-Propanone, 1-hydroxy-	51.88	9.68
119219383	1.04	C3H6O	58	Propylene oxide	25.34	9.85
374922204	3.26	C3H6O2	74	2-Propanone, 1-hydroxy-	40.02	10.12
306088198	2.66	C5H4O2	96	3-Furaldehyde	60.63	10.75
127397918	1.11	C6H12O	100	Butanal, 2-ethyl-	32.73	11.36
179911145	1.56	C6H10O	98	Cyclopentanone, 2-methyl-	40.35	12.82
108860505	0.95	C6H7O4P	174	Phosphonic acid, (p-hydroxyphenyl)-	33.98	13.75
300287071	2.61	C2H2N4O2	114	1H-1,2,4-Triazole, 3-nitro-	24.92	14.16
135242855	1.17	C6H8O2	112	1,2-Cyclopentanedione, 3-methyl-	46.4	14.65
118829358	1.03	C7H8O	108	Phenol, 3-methyl-	43.51	15.32
211143243	1.83	C7H8O2	124	Phenol, 2-methoxy-	45.32	15.51
88262934	0.77	C8H10O	122	Phenol, 3,4-dimethyl-	26.15	16.43
81452027	0.71	C8H10O2	138	2-Methoxybenzyl alcohol	53.95	16.75
103460954	0.9	C8H10O2	138	Phenol, 2-methoxy-4-methyl-	54.2	17.12
129080255	1.12	C9H12O2	152	2,4-Dimethoxytoluene	48.12	18.37
196371094	1.71	C10H14O	150	Phenol, 2,3,5,6-tetramethyl-	30.78	18.88
310621730	2.7	C10H18O	154	Eucalyptol	43.75	19.41
181574122	1.58	C10H12O2	164	Phenol, 2-methoxy-4-(1-propenyl)-	49.46	20.92

Table 25: NIST library matches for red maple fast pyrolysis trial at 700°C.

Area	Area %	Molecular Formula	Molecular Weight	Name	Probability	RT
6.53E+09	51.73	C8H19N	129	2-Octanamine	80.68	6.15
267609492	2.12	C3H4O2	72	Methylglyoxal	16.81	6.77
208629596	1.65	C2H4O2	60	Acetaldehyde, hydroxy-	75.26	7.01
790130193	6.26	C2H4O2	60	Acetic acid	90.72	7.84
342831911	2.72	C3H6O2	74	2-Propanone, 1-hydroxy-	88	7.94
178559520	1.41	C3H6O2	74	Acetic acid, methyl ester	46.73	9.68
158152417	1.25	C3H8O2	76	1,3-Propanediol	35.38	9.88
291904587	2.31	C3H6O2	74	2-Propanone, 1-hydroxy-	52.05	10.13
311602280	2.47	C5H4O2	96	3-Furaldehyde	65.51	10.75
144227129	1.14	C6H12O	100	Butanal, 2-ethyl-	27.96	11.38
236120736	1.87	C6H10O	98	Cyclopentanone, 2-methyl-	60.29	12.85
145789196	1.15	C14H28O	212	9-Tetradecen-1-ol, (E)-	46.31	13.37
155338156	1.23	C6H6O	94	Phenol	40.9	13.76
159452362	1.26	C4H6N2O2	114	2,4-Imidazolidinedione, 1-methyl-	35.44	14.14
204565223	1.62	C6H8O2	112	1,2-Cyclopentanedione, 3-methyl-	36.18	14.66
95645519	0.76	C7H8O	108	Phenol, 3-methyl-	47	14.98
143879368	1.14	C7H8O	108	Phenol, 3-methyl-	50	15.33
249836672	1.98	C7H8O2	124	Phenol, 2-methoxy-	50.37	15.52
95135197	0.75	C8H10O	122	Phenol, 3,4-dimethyl-	24.67	16.44
120541138	0.95	C8H10O2	138	2-Methoxybenzyl alcohol	48.57	16.76
101850918	0.81	C8H10O2	138	2-Methoxy-5-methylphenol	49.16	17.12
169981204	1.35	C6H6O2	110	1,2-Benzenediol	54.57	17.4
201757653	1.6	C9H12O2	152	2,4-Dimethoxytoluene	65.59	18.37
298340549	2.36	C12H17NO2	207	Phenol, 3-methyl-5-(1-methylethyl)-, methylcarbamate	38.75	18.89
577569606	4.58	C10H18O	154	Eucalyptol	31.38	19.44
84428425	0.67	C10H12O2	164	Phenol, 2-methoxy-4-(1-propenyl)-	42.43	20.2
274334537	2.17	C10H12O2	164	Phenol, 2-methoxy-4-(1-propenyl)-	50.41	20.94
84533331	0.67	C12H15NO4	237	3-Hydroxycarbofuran	72.73	23.36

Table 26: NIST library matches for willow fast pyrolysis trial at 500°C.

Area	Area %	Molecular Formula	Molecular Weight	Name	Probability	RT
49540528	0.5	CO2	44	Carbon dioxide	97.98	0.9
1.21E+09	12.14	C9H13N	135	Dextroamphetamine	46.74	1.14
97497501	0.98	C3H4O3	88	Propanoic acid, 2-oxo-	30.62	1.38
224376591	2.25	C2H4O2	60	Acetaldehyde, hydroxy-	42.46	1.77
106157459	1.07	C4H6O3	102	Butanoic acid, 2-oxo-	41.78	1.88
596446525	5.98	C3H6O2	74	2-Propanone, 1-hydroxy-	89.77	2.62
30759897	0.31	C15H22N2O3	278	Tolycaine	55.85	3.18
44759718	0.45	C4H6O2	86	2,2'-Bioxirane, (R*,R*)-(ñ)-	26.65	4.02
158030251	1.59	C3H6O2	74	Acetic acid, methyl ester	36	4.48
112658205	1.13	C7H14O	114	Pentanal, 2,3-dimethyl-	29.26	4.7
78680622	0.79	C4H6O3	102	Acetic anhydride	46.23	4.91
24467885	0.25	C5H7NO3	129	Pidolic Acid	67.55	5
174476638	1.75	C5H4O2	96	3-Furaldehyde	78.99	5.71
99480707	1	C5H6O2	98	2-Furanmethanol	58.1	6.25
38061163	0.38	C6H10O4	146	1,2-Ethenediol, diacetate	62.86	6.49
80086662	0.8	C6H12	84	2-Hexene	33.94	7.39
190473367	1.91	C6H10O	98	Cyclopentanone, 2-methyl-	69.95	7.68
70870190	0.71	C12H24O	184	Dodecanal	20.44	8.27
18744479	0.19	C6H6O2	110	Resorcinol	57.42	8.55
93175653	0.93	C6H7O4P	174	Phosphonic acid, (p-hydroxyphenyl)-	58.13	8.67
231066061	2.32	C2H2N4O2	114	1H-1,2,4-Triazole, 3-nitro-	40.41	8.97
42727845	0.43	C6H8O2	112	2-Cyclopenten-1-one, 2-hydroxy-3-methyl-	41.38	9.24
67678132	0.68	C6H8O2	112	1,2-Cyclopentanedione, 3-methyl-	57.24	9.5
26391531	0.26	C7H6O2	122	Benzaldehyde, 2-hydroxy-	36.81	9.67
21468921	0.22	C6H10O2	114	2-Pentenoic acid, 2-methyl-, (E)-	62.83	9.74
21971808	0.22	C7H8O	108	Phenol, 3-methyl-	40.19	9.9
75017349	0.75	C9H16O2	156	2(3H)-Furanone, dihydro-5-pentyl-	32.78	10.16
44566953	0.45	C7H8O	108	Phenol, 3-methyl-	20	10.24
108196002	1.09	C7H8O2	124	Phenol, 2-methoxy-	52.76	10.47

158680247	1.59	C9H18O	142	Nonanal	36.85	10.68
15574982	0.16	C6H6O3	126	1,3,5-Benzenetriol	33.04	10.98
33197951	0.33	C5H10N2O	114	Piperidine, 1-nitroso-	34.97	11.16
93846445	0.94	C9H10O3	166	Benzaldehyde, 3-ethoxy-2-hydroxy-	57.75	11.68
37450959	0.38	C7H6O2	122	Benzenecarboxylic acid	45.22	11.83
133429811	1.34	C8H10O2	138	Phenol, 2-methoxy-4-methyl-	51.75	12.09
117481216	1.18	C6H6O2	110	1,2-Benzenediol	47.87	12.27
40898617	0.41	C8H8O	120	Phthalan	28.98	12.46
100506273	1.01	C11H22O	170	Undecanal	14.31	12.7
94459299	0.95	C7H8O3	140	Flamenol	71.2	13.17
110902745	1.11	C9H12O2	152	2,4-Dimethoxytoluene	68.77	13.35
312751130	3.14	C10H14O	150	Phenol, 2-methyl-5-(1-methylethyl)-	24.83	13.86
576844517	5.79	C10H18O	154	Eucalyptol	47.32	14.39
45599846	0.46	C11H20O2	184	Oxacyclododecan-2-one	30.5	14.87
34052344	0.34	C15H24O	220	4a,7-Methano-4aH-naphth[1,8a-b]oxirene, octahydro-4,4,8,8-tetramethyl-	25.37	14.98
86062650	0.86	C8H8O3	152	Vanillin	48.21	15.09
33397836	0.34	C10H12O2	164	Phenol, 2-methoxy-4-(1-propenyl)-	61.95	15.18
513952366	5.16	C9H12O3	168	1,2,3-Trimethoxybenzene	70.54	15.86
26874945	0.27	C10H14O2	166	Phenol, 2-methoxy-4-propyl-	93.9	16.09
41871391	0.42	C11H12O4	208	4-Acetoxy-3-methoxyacetophenone	63.68	16.65
175382724	1.76	C13H11Br	246	Benzene, 1,1'-(bromomethylene)bis-	27.95	17.48
180481207	1.81	C10H14O2	166	Phenol, 2-methoxy-4-propyl-	71.24	17.65
611730069	6.14	C12H15NO4	237	3-Hydroxycarbofuran	65.39	18.42
27875890	0.28	C12H15NO4	237	3-Hydroxycarbofuran	80.45	18.57
41069267	0.41	C18H22O4	302	3,4-Hexanediol, 3,4-bis(4-hydroxyphenyl)-	25.96	18.72
117967726	1.18	C12H15NO4	237	3-Hydroxycarbofuran	16.57	19.1
23435330	0.24	C13H11Br	246	Benzene, 1,1'-(bromomethylene)bis-	30.03	19.21
84210004	0.84	C12H15NO4	237	3-Hydroxycarbofuran	46.14	19.96
87934164	0.88	C9H10O4	182	3,4-Dimethoxy-5-hydroxybenzaldehyde	49.33	20.15
27099225	0.27	C12H15NO4	237	3-Hydroxycarbofuran	85.6	20.32
26305910	0.26	C20H28O	284	Vitamin A aldehyde	21.14	20.4

14450542	0.14	C15H24O	220	4a,7-Methano-4aH-naphth[1,8a-b]oxirene, octahydro-4,4,8,8-tetramethyl-	25.61	20.52
416738924	4.18	C10H10O2	162	4-Methoxycinnamaldehyde	22.93	20.81
202818658	2.04	C12H18O	178	6-tert-Butyl-2,4-dimethylphenol	18.4	21.3
178131411	1.79	C12H15NO4	237	3-Hydroxycarbofuran	90.33	21.37
147633183	1.48	C13H11Br	246	Benzene, 1,1'-(bromomethylene)bis-	30.43	21.82
24747962	0.25	C15H24O	220	4a,7-Methano-4aH-naphth[1,8a-b]oxirene, octahydro-4,4,8,8-tetramethyl-	38.63	22.43
22835572	0.23	C8H11NO2	153	3-Pyridinemethanol, 5-hydroxy-4,6-dimethyl-	28.08	22.51
59572838	0.6	C13H12	168	Diphenylmethane	32.65	23.47
47125528	0.47	C19H22O6	346	Gibberellic acid	18.15	23.84
84110646	0.84	C16H32O2	256	n-Hexadecanoic acid	31.93	24.53
229741690	2.31	C12H15NO4	237	3-Hydroxycarbofuran	37.55	25.07
122125902	1.23	C15H24O	220	4a,7-Methano-4aH-naphth[1,8a-b]oxirene, octahydro-4,4,8,8-tetramethyl-	16.55	25.24
65343711	0.66	C16H32O2	256	n-Hexadecanoic acid	40.89	28.46
32636414	0.33	C10H10O2	162	Benzene, 1,2-(methylenedioxy)-4-propenyl-, (E)-	12.01	36.24
41806549	0.42	C12H11N	169	[1,1'-Biphenyl]-4-amine	49.11	38.56
29900162	0.3	C17H36	240	Heptadecane	18.46	43.29
28739500	0.29	C13H14	170	Naphthalene, 1-(1-methylethyl)-	54.71	43.42
68760146	0.69	C41H72O2	596	Cholest-5-en-3-ol (3á)-, tetradecanoate	39.04	50.25

Table 27: NIST library matches for willow fast pyrolysis trial at 500°C.

Area	Area %	Molecular Formula	Molecular Weight	Name	Probability	RT
634745062	10.52	CO2	44	Carbon dioxide	49.71	1.15
102642018	1.7	C5H8O2	100	1-Propen-2-ol, acetate	18.2	1.39
335592094	5.56	C2H4O2	60	Acetaldehyde, hydroxy-	76.5	1.72
223525764	3.7	C2H4O2	60	Acetic acid	94.12	2.35
143541556	2.38	C3H6O2	74	2-Propanone, 1-hydroxy-	86.36	2.52
25736446	0.43	C4H6O2	86	2,2'-Bioxirane, (R*,R*)-(ñ)-	30.96	3.99
101816669	1.69	C3H6O2	74	2-Propanone, 1-hydroxy-	37.93	4.44
100000249	1.66	C3H6O	58	Propylene oxide	20.53	4.66
66627282	1.1	C4H6O3	102	Acetic anhydride	35.02	4.87
19323208	0.32	C5H7NO3	129	Pidolic Acid	75.26	4.97
73886923	1.22	C5H4O2	96	3-Furaldehyde	75.7	5.68
61701453	1.02	C5H6O2	98	2-Furanmethanol	72.34	6.22
21731655	0.36	C6H10O4	146	1,2-Ethanediol, diacetate	71.77	6.47
58611512	0.97	C6H12	84	2-Hexene	41.36	7.36
139440118	2.31	C6H10O	98	Cyclopentanone, 2-methyl-	52.96	7.63
41250146	0.68	C12H24O	184	Dodecanal	19.06	8.25
16858947	0.28	C6H6O2	110	Resorcinol	63.82	8.53
48849969	0.81	C6H6O	94	Phenol	53.29	8.65
162833923	2.7	C4H6N2O2	114	2,4-Imidazolidinedione, 1-methyl-	35.53	8.93
15704540	0.26	C6H8O2	112	2-Cyclopenten-1-one, 2-hydroxy-3-methyl-	35.31	9.18
54900794	0.91	C6H8O2	112	2-Cyclopenten-1-one, 2-hydroxy-3-methyl-	72.84	9.45
34196068	0.57	C6H10O2	114	2-Pentenoic acid, 2-methyl-, (E)-	72.31	9.71
14243159	0.24	C7H8O	108	Phenol, 3-methyl-	36.89	9.89
41472822	0.69	C9H16O2	156	2(3H)-Furanone, dihydro-5-pentyl-	63.22	10.01
14984883	0.25	C12H24O	184	Dodecanal	26.82	10.14
16500044	0.27	C11H20O2	184	Oxacyclododecan-2-one	18.09	10.22
11111834	0.18	C6H6O3	126	Methyl 2-furoate	93.59	10.34
54053084	0.9	C7H8O2	124	Phenol, 2-methoxy-	66.22	10.46
105637878	1.75	C5H10O	86	Cyclobutanemethanol	18.41	10.61

13650569	0.23	C6H6O3	126	1,3,5-Benzenetriol	49.14	10.86
12785107	0.21	C11H20O2	184	Undecanoic acid, hydroxy-, lactone	17.55	10.96
32167074	0.53	C5H10N2O	114	Piperidine, 1-nitroso-	31.13	11.08
44627861	0.74	C19H37NO	295	Octadecane, 1-isocyanato-	32.07	11.55
24894901	0.41	C9H10O3	166	Benzaldehyde, 3-ethoxy-2-hydroxy-	40.51	11.66
85168709	1.41	C8H10O2	138	2-Methoxy-5-methylphenol	52.73	12.08
60455525	1	C6H6O2	110	1,2-Benzenediol	52.91	12.22
20422318	0.34	C11H20O2	184	Undecanoic acid, hydroxy-, lactone	17.71	12.42
23798649	0.39	C12H22O2	198	ç Dodecalactone	13.9	12.56
66612151	1.1	C14H30O	214	1-Tetradecanol	14.07	12.69
23444037	0.39	C11H20O2	184	Oxacyclododecan-2-one	36.08	12.98
126018349	2.09	C7H8O3	140	Flamenol	73.25	13.14
50056612	0.83	C9H12O2	152	2,4-Dimethoxytoluene	50.96	13.34
30539931	0.51	C12H22O11	342	à-D-Glucopyranoside, à-D-glucopyranosyl	28.87	13.74
132024546	2.19	C12H17NO2	207	Phenol, 3-methyl-5-(1-methylethyl)-, methylcarbamate	28.31	13.85
338906697	5.61	C10H18O	154	Eucalyptol	45.66	14.37
66851999	1.11	C11H20O2	184	Oxacyclododecan-2-one	20.86	14.85
18453668	0.31	C15H24O	220	4a,7-Methano-4aH-naphth[1,8a-b]oxirene, octahydro-4,4,8,8-tetramethyl-	31.73	14.97
36717594	0.61	C8H8O3	152	Vanillin	44.9	15.06
11170250	0.19	C10H12O2	164	Phenol, 2-methoxy-4-(1-propenyl)-	59.38	15.18
291216707	4.82	C9H12O3	168	1,2,3-Trimethoxybenzene	70.29	15.84
29885305	0.5	C10H14O2	166	Phenol, 2-methoxy-4-propyl-	93.57	16.07
19656052	0.33	C11H12O4	208	4-Acetoxy-3-methoxyacetophenone	60.29	16.61
11170976	0.19	C11H12O4	208	4-Acetoxy-3-methoxyacetophenone	74.68	16.76
125606806	2.08	C10H12O3	180	Propylparaben	20.49	17.35
77356235	1.28	C13H11Br	246	Benzene, 1,1'-(bromomethylene)bis-	32.99	17.47
68306380	1.13	C10H14O2	166	Phenol, 2-methoxy-4-propyl-	49.39	17.61
328569239	5.44	C12H15NO4	237	3-Hydroxycarbofuran	71	18.38
12910660	0.21	C12H15NO4	237	3-Hydroxycarbofuran	78	18.54
57870949	0.96	C10H10O2	162	4-Methoxycinnamaldehyde	18.61	19.08
20820109	0.34	C13H11Br	246	Benzene, 1,1'-(bromomethylene)bis-	44.88	19.2

32916149	0.55	C15H24O	220	4a,7-Methano-4aH-naphth[1,8a-b]oxirene, octahydro-4,4,8,8-tetramethyl-	20.19	19.66
36343604	0.6	C20H28O	284	Vitamin A aldehyde	12.42	19.95
46289144	0.77	C9H10O4	182	3,4-Dimethoxy-5-hydroxybenzaldehyde	43.08	20.12
18744152	0.31	C20H28O	284	Vitamin A aldehyde	18.94	20.39
200916063	3.33	C10H10O2	162	4-Methoxycinnamaldehyde	28.52	20.77
194235973	3.22	C12H18O	178	6-tert-Butyl-2,4-dimethylphenol	16.82	21.27
82212739	1.36	C13H11Cl	202	Benzene, 1,1'-(chloromethylene)bis-	29.73	21.8
18740579	0.31	C15H24O	220	4a,7-Methano-4aH-naphth[1,8a-b]oxirene, octahydro-4,4,8,8-tetramethyl-	44.43	22.41
11936482	0.2	C8H11NO2	153	3-Pyridinemethanol, 5-hydroxy-4,6-dimethyl-	24.73	22.49
29296140	0.49	C13H12	168	Naphthalene, 1-(2-propenyl)-	35.01	23.44
27556303	0.46	C19H22O6	346	Gibberellic acid	19.35	23.8
32229131	0.53	C16H32O2	256	n-Hexadecanoic acid	30.2	24.47
168732200	2.8	C12H15NO4	237	3-Hydroxycarbofuran	36.4	25.02
58060380	0.96	C15H24O	220	4a,7-Methano-4aH-naphth[1,8a-b]oxirene, octahydro-4,4,8,8-tetramethyl-	22.28	25.17
19084367	0.32	C16H32O2	256	n-Hexadecanoic acid	37.69	28.39
22659839	0.38	C12H11N	169	[1,1'-Biphenyl]-4-amine	43	38.52
32676798	0.54	C41H72O2	596	Cholest-5-en-3-ol (3á)-, tetradecanoate	36.13	50.23

Table 28: NIST library matches for willow fast pyrolysis trial at 600°C.

Area	Area %	Molecular Formula	Molecular Weight	Name	Probability	RT
1.632E+09	13.91	C8H19N	129	2-Octanamine	62.76	1.13
204663674	1.74	C5H8O2	100	1-Propen-2-ol, acetate	47.88	1.37
37529006	0.32	C2H4O2	60	Acetaldehyde, hydroxy-	77.18	1.63
353079954	3.01	C2H4O2	60	Acetaldehyde, hydroxy-	55.52	1.78
62402144	0.53	C4H6O3	102	Butanoic acid, 2-oxo-	43.33	1.87
412584221	3.51	C2H4O2	60	Acetic acid	94.48	2.47
292869922	2.49	C3H6O2	74	2-Propanone, 1-hydroxy-	89.26	2.61
38489119	0.33	C5H10O	86	3-Pentanone	19.76	3.16
204256894	1.74	C3H6O2	74	2-Propanone, 1-hydroxy-	30.64	4.5
178317532	1.52	C6H12O	100	Pentanal, 2-methyl-	25.6	4.72
166885591	1.42	C4H6O3	102	Acetic anhydride	49.71	4.95
57117279	0.49	C5H7NO3	129	Pidolic Acid	45.28	5.03
178906174	1.52	C5H4O2	96	3-Furaldehyde	76.83	5.69
110689468	0.94	C5H6O2	98	2-Furanmethanol	56.47	6.25
23882354	0.2	C6H10O4	146	1,2-Ethandiol, diacetate	74.62	6.5
43446287	0.37	C14H28O	212	9-Tetradecen-1-ol, (E)-	34.71	7.16
111707285	0.95	C6H12	84	2-Hexene	39.32	7.41
306945180	2.61	C6H10O	98	Cyclopentanone, 2-methyl-	72.45	7.69
98565463	0.84	C14H28O	212	9-Tetradecen-1-ol, (E)-	35.68	8.29
39412644	0.34	C6H6O2	110	Resorcinol	60.28	8.55
161415897	1.38	C6H6O	94	Phenol	48.41	8.67
211061286	1.8	C5H10N2O	114	Piperidine, 1-nitroso-	28.21	8.96
119448615	1.02	C6H8O2	112	1,2-Cyclopentanedione, 3-methyl-	44.96	9.54
50093742	0.43	C6H10O2	114	2-Pentenoic acid, 2-methyl-, (E)-	67.64	9.76
41087478	0.35	C7H8O	108	Phenol, 3-methyl-	49.7	9.91
134742735	1.15	C7H8O	108	Phenol, 3-methyl-	46.52	10.26
253915348	2.16	C7H8O2	124	Phenol, 2-methoxy-	46.82	10.48
151199390	1.29	C9H18O	142	Nonanal	28.02	10.71
57748046	0.49	C11H20O2	184	Undecanoic acid, hydroxy-, lactone	32.17	11
81151873	0.69	C9H10O3	166	Benzaldehyde, 3-ethoxy-2-hydroxy-	36.89	11.68

75903448	0.65	C8H10O2	138	Phenol, 2-methoxy-4-methyl-	51.6	11.86
182462512	1.55	C8H10O2	138	Phenol, 2-methoxy-4-methyl-	55.97	12.1
67232148	0.57	C6H6O4	142	4H-Pyran-4-one, 5-hydroxy-2-(hydroxymethyl)-	86.41	12.19
167170943	1.42	C6H6O2	110	1,2-Benzenediol	64.09	12.31
170756860	1.45	C6H6O3	126	1,3,5-Benzenetriol	27.79	12.8
257861282	2.2	C7H8O3	140	Flamenol	66.92	13.2
110865086	0.94	C9H12O2	152	2,4-Dimethoxytoluene	51.94	13.35
129567872	1.1	C11H20O2	184	Undecylenic Acid	24.02	13.45
81917980	0.7	C7H8O2	124	1,2-Benzenediol, 3-methyl-	51.37	13.6
367565071	3.13	C12H17NO2	207	Phenol, 3-methyl-5-(1-methylethyl)-, methylcarbamate	27.76	13.87
751014935	6.4	C10H18O	154	Eucalyptol	53.07	14.41
95091374	0.81	C8H11NO3	169	dl-Noradrenaline	24.21	14.54
144262418	1.23	C8H8O3	152	Vanillin	47.55	15.12
658663255	5.61	C9H12O3	168	1,2,3-Trimethoxybenzene	55.08	15.89
104329200	0.89	C13H11Br	246	Benzene, 1,1'-(bromomethylene)bis-	31.44	17.49
154576285	1.32	C10H14O2	166	Phenol, 2-methoxy-4-propyl-	62.06	17.68
46358397	0.39	C11H14O3	194	4-Butoxybenzoic acid	55.32	17.78
133166349	1.13	C12H22O11	342	à-D-Glucopyranoside, à-D-glucopyranosyl	71.11	18.17
668967838	5.7	C12H15NO4	237	3-Hydroxycarbofuran	76.36	18.43
122491325	1.04	C12H15NO4	237	3-Hydroxycarbofuran	16.35	19.11
89626190	0.76	C12H15NO4	237	3-Hydroxycarbofuran	34.16	19.97
76796675	0.65	C9H10O4	182	3,4-Dimethoxy-5-hydroxybenzaldehyde	21.84	20.17
342367658	2.92	C10H10O2	162	4-Methoxycinnamaldehyde	18.86	20.81
271965113	2.32	C12H18O	178	6-tert-Butyl-2,4-dimethylphenol	17.83	21.32
136047232	1.16	C12H8N2O	196	9H-Carbazole, 9-nitroso-	48.34	21.83
124315108	1.06	C16H32O2	256	n-Hexadecanoic acid	30.09	24.55
237717472	2.02	C12H15NO4	237	3-Hydroxycarbofuran	37.18	25.09
112303758	0.96	C16H32O2	256	n-Hexadecanoic acid	41.35	28.48
41889024	0.36	C17H36	240	Heptadecane	18.93	43.28

Table 29: NIST library matches for willow fast pyrolysis trial at 600°C.

Area	Area %	Molecular Formula	Molecular Weight	Name	Probability	RT
1.303E+09	14.3	CO2	44	Carbon dioxide	42.64	1.13
210060338	2.31	C5H8O2	100	1-Propen-2-ol, acetate	36.94	1.37
63101425	0.69	C2H4O2	60	Acetaldehyde, hydroxy-	77.9	1.64
295310920	3.24	C2H4O2	60	Acetaldehyde, hydroxy-	80.07	1.74
58085982	0.64	C4H6O3	102	Butanoic acid, 2-oxo-	48.31	1.87
332837821	3.65	C2H4O2	60	Acetic acid	93.8	2.4
240098896	2.64	C3H6O2	74	2-Propanone, 1-hydroxy-	88.88	2.56
32808909	0.36	C4H6O2	86	2-Propenoic acid, 2-methyl-	26.82	3.15
179886160	1.97	C3H6O2	74	Acetic acid, methyl ester	42.74	4.46
145362814	1.6	C7H14O	114	Pentanal, 2,3-dimethyl-	23.85	4.67
124762892	1.37	C4H6O3	102	Acetic anhydride	59.84	4.9
42452078	0.47	C5H7NO3	129	Pidolic Acid	50.71	4.99
142408900	1.56	C5H4O2	96	3-Furaldehyde	73.87	5.68
76052150	0.83	C5H6O2	98	2-Furanmethanol	70.98	6.22
42184067	0.46	C6H10O4	146	1,2-Ethanediol, diacetate	63.41	6.48
89893496	0.99	C6H12	84	2-Hexene	43.41	7.36
205144257	2.25	C6H10O	98	Cyclopentanone, 2-methyl-	66.2	7.65
93206626	1.02	C14H28O	212	9-Tetradecen-1-ol, (E)-	39.9	8.27
28095076	0.31	C6H6O2	110	Resorcinol	56.86	8.53
96691418	1.06	C6H7O4P	174	Phosphonic acid, (p-hydroxyphenyl)-	54.6	8.65
232665237	2.55	C2H2N4O2	114	1H-1,2,4-Triazole, 3-nitro-	31.26	8.96
80391204	0.88	C6H8O2	112	1,2-Cyclopentanedione, 3-methyl-	50.82	9.49
26757335	0.29	C7H8O	108	Phenol, 3-methyl-	38.5	9.89
112561956	1.24	C7H8O	108	Phenol, 3-methyl-	35.58	10.24
122203383	1.34	C7H8O2	124	Phenol, 2-methoxy-	54.74	10.46
97376424	1.07	C11H22O	170	Undecanal	42.83	10.67
20510172	0.23	C11H20O2	184	Undecanoic acid, hydroxy-, lactone	25.06	10.97
33437698	0.37	C9H10O3	166	Benzaldehyde, 3-ethoxy-2-hydroxy-	36.74	11.67
189948840	2.09	C8H10O2	138	Phenol, 2-methoxy-4-methyl-	52.94	12.09
156222962	1.72	C6H6O2	110	1,2-Benzenediol	69.3	12.26

174597943	1.92	C11H20O2	184	Undecanoic acid, hydroxy-, lactone	14.47	12.73
235696232	2.59	C7H8O3	140	Flamenol	69.86	13.17
138333025	1.52	C9H12O2	152	2,4-Dimethoxytoluene	55.63	13.34
262154249	2.88	C10H14O	150	Phenol, 2-methyl-5-(1-methylethyl)-	32.08	13.85
511459358	5.62	C10H18O	154	Eucalyptol	52.08	14.39
83339369	0.91	C10H18O	154	3-Cyclohexen-1-ol, 4-methyl-1-(1-methylethyl)-	26.5	14.51
111827289	1.23	C11H20O2	184	Oxacyclododecan-2-one	19.13	14.89
64514385	0.71	C8H8O3	152	Vanillin	45.73	15.09
24334659	0.27	C10H12O2	164	Phenol, 2-methoxy-4-(1-propenyl)-	60.45	15.18
455418867	5	C9H12O3	168	1,2,3-Trimethoxybenzene	68.35	15.86
141862269	1.56	C12H8N2O	196	9H-Carbazole, 9-nitroso-	14.37	17.47
134105648	1.47	C10H14O2	166	Phenol, 2-methoxy-4-propyl-	64.96	17.64
81765635	0.9	C12H22O11	342	à-D-Glucopyranoside, à-D-glucopyranosyl	57.67	17.76
88821583	0.98	C12H22O11	342	à-D-Glucopyranoside, à-D-glucopyranosyl	72.5	17.93
447545359	4.91	C12H15NO4	237	3-Hydroxycarbofuran	77.36	18.4
72723001	0.8	C20H28O	284	Vitamin A aldehyde	27.81	19.09
51845612	0.57	C12H15NO4	237	3-Hydroxycarbofuran	32.84	19.95
79923346	0.88	C9H10O4	182	3,4-Dimethoxy-5-hydroxybenzaldehyde	35.63	20.14
23904255	0.26	C20H28O	284	Vitamin A aldehyde	35.74	20.39
248447351	2.73	C10H10O2	162	4-Methoxycinnamaldehyde	19.83	20.79
236095281	2.59	C12H18O	178	6-tert-Butyl-2,4-dimethylphenol	13.88	21.29
95213950	1.05	C12H8N2O	196	9H-Carbazole, 9-nitroso-	29.17	21.81
102112780	1.12	C16H32O2	256	n-Hexadecanoic acid	33.17	24.53
204620344	2.25	C12H15NO4	237	3-Hydroxycarbofuran	34.75	25.07
35143769	0.39	C19H22O6	346	Gibberellic acid	25.88	25.2
97236759	1.07	C16H32O2	256	n-Hexadecanoic acid	37.54	28.47
32146492	0.35	C16H34	226	Hexadecane	19.8	43.28

Table 30: NIST library matches for willow fast pyrolysis trial at 700°C.

Area	Area %	Molecular Formula	Molecular Weight	Name	Probability	RT
812121676	13.95	CO2	44	Carbon dioxide	92.59	1.11
141418407	2.43	C4H10	58	Butane	19.85	1.35
274929607	4.72	C2H4O2	60	Acetaldehyde, hydroxy-	81.62	1.73
186727785	3.21	C2H4O2	60	Acetic acid	89.63	2.35
85544517	1.47	C3H6O2	74	2-Propanone, 1-hydroxy-	89.82	2.53
79672976	1.37	C3H6O2	74	2-Propanone, 1-hydroxy-	21.79	4.44
66714948	1.15	C7H14O	114	Pentanal, 2,3-dimethyl-	22.51	4.65
68188437	1.17	C4H6O3	102	Acetic anhydride	58.82	4.88
78808706	1.35	C5H4O2	96	3-Furaldehyde	76.84	5.68
37370243	0.64	C5H6O2	98	2-Furanmethanol	61.34	6.22
41778121	0.72	C6H12	84	2-Hexene	25.12	7.35
88242428	1.52	C6H10O	98	Cyclopentanone, 2-methyl-	41.27	7.62
48949746	0.84	C14H28O	212	9-Tetradecen-1-ol, (E)-	28.07	8.26
58760286	1.01	C6H6O	94	Phenol	51.83	8.65
125565118	2.16	C2H2N4O2	114	1H-1,2,4-Triazole, 3-nitro-	43.47	8.95
43684211	0.75	C6H8O2	112	1,2-Cyclopentanedione, 3-methyl-	46.53	9.46
27589088	0.47	C7H8O	108	Phenol, 2-methyl-	40.49	9.89
109883159	1.89	C7H8O	108	Phenol, 3-methyl-	41.18	10.24
63124417	1.08	C7H8O2	124	Phenol, 2-methoxy-	54.35	10.46
83010657	1.43	C8H10O2	138	Phenol, 2-methoxy-4-methyl-	57.48	12.08
88157681	1.51	C6H6O2	110	1,2-Benzenediol	68.28	12.26
81268408	1.4	C11H22O	170	Undecanal	15.11	12.71
132810189	2.28	C7H8O3	140	Flamenol	69.88	13.16
65684557	1.13	C9H12O2	152	2,4-Dimethoxytoluene	59.56	13.35
156732904	2.69	C10H14O	150	Phenol, 2,3,5,6-tetramethyl-	28.52	13.86
323550806	5.56	C10H18O	154	Eucalyptol	45.81	14.38
80085979	1.38	C11H20O2	184	Oxacyclododecan-2-one	21.57	14.87
56814046	0.98	C8H8O3	152	Vanillin	40.35	15.09
264244813	4.54	C9H12O3	168	1,2,3-Trimethoxybenzene	73.68	15.85
236286854	4.06	C9H10O4	182	3,4-Dimethoxy-5-hydroxybenzaldehyde	58.23	17.47

120373266	2.07	C12H15NO4	237	3-Hydroxycarbofuran	63.66	17.63
340686427	5.85	C12H15NO4	237	3-Hydroxycarbofuran	73.42	18.38
63178469	1.08	C15H15N	209	Acridine, 9,10-dihydro-9,9-dimethyl-	62.08	19.07
43235961	0.74	C15H15N	209	Acridine, 9,10-dihydro-9,9-dimethyl-	70.75	19.94
85852435	1.47	C9H10O4	182	Benzaldehyde, 4-hydroxy-3,5-dimethoxy-	91.88	20.11
48628211	0.84	C14H20O2	220	2,5-Cyclohexadiene-1,4-dione, 2,6-bis(1,1-dimethylethyl)-	40.89	20.38
242802220	4.17	C15H15N	209	Acridine, 9,10-dihydro-9,9-dimethyl-	69.14	20.77
223927589	3.85	C10H12O4	196	Benzaldehyde, 2,3,4-trimethoxy-	74.08	21.26
93753515	1.61	C12H8N2O	196	9H-Carbazole, 9-nitroso-	27.76	21.8
67128398	1.15	C9H10O4	182	Benzaldehyde, 4-hydroxy-3,5-dimethoxy-	37.83	22.48
57700018	0.99	C16H32O2	256	n-Hexadecanoic acid	67.66	24.47
279485542	4.8	C12H15NO4	237	3-Hydroxycarbofuran	27.74	25.02
61111039	1.05	C17H21NO2	271	Desomorphine	56.95	38.49
87519512	1.5	C23H32O6	404	Hydrocortisone Acetate	56.53	43.38

Table 31: NIST library matches for willow fast pyrolysis trial at 700°C.

Area	Area %	Molecular Formula	Molecular Weight	Name	Probability	RT
1.122E+09	13.79	CO2	44	Carbon dioxide	86.32	1.11
158978057	1.95	C5H8O2	100	1-Propen-2-ol, acetate	36.86	1.37
390818883	4.8	C2H4O2	60	Acetaldehyde, hydroxy-	57.04	1.75
302481575	3.72	C2H4O2	60	Acetic acid	67.04	2.33
167984608	2.06	C3H6O2	74	2-Propanone, 1-hydroxy-	90.27	2.57
133596433	1.64	C3H6O2	74	2-Propanone, 1-hydroxy-	32.36	4.47
98073789	1.21	C3H8O2	76	1,3-Propanediol	19.58	4.68
144122116	1.77	C4H6O3	102	Acetic anhydride	61.99	4.92
89168507	1.1	C5H4O2	96	3-Furaldehyde	75.71	5.68
58322604	0.72	C5H6O2	98	2-Furanmethanol	68.19	6.24
156197232	1.92	C6H10O	98	Cyclopentanone, 2-methyl-	70.06	7.67
78972622	0.97	C6H7O4P	174	Phosphonic acid, (p-hydroxyphenyl)-	50.26	8.66
174347058	2.14	C5H10N2O	114	Piperidine, 1-nitroso-	13.93	8.94
56842683	0.7	C6H8O2	112	2-Cyclopenten-1-one, 2-hydroxy-3-methyl-	58.21	9.52
44393065	0.55	C7H8O	108	Phenol, 2-methyl-	42.15	9.9
136153231	1.67	C7H8O	108	Phenol, 3-methyl-	46.5	10.26
163004881	2	C7H8O2	124	Phenol, 2-methoxy-	56.39	10.48
175204353	2.15	C8H10O2	138	Phenol, 2-methoxy-4-methyl-	51.66	12.1
181507584	2.23	C6H6O2	110	1,2-Benzenediol	55.25	12.32
176462402	2.17	C7H8O3	140	Flamenol	66.9	13.2
248934111	3.06	C10H14O	150	Phenol, 2-methyl-5-(1-methylethyl)-	24.56	13.87
565568716	6.95	C10H18O	154	Eucalyptol	44.06	14.41
101424312	1.25	C8H8O3	152	Vanillin	42.47	15.12
454219065	5.58	C9H12O3	168	1,2,3-Trimethoxybenzene	69.13	15.88
135859003	1.67	C9H10O4	182	3,4-Dimethoxy-5-hydroxybenzaldehyde	69.39	17.48
226763709	2.79	C12H15NO4	237	3-Hydroxycarbofuran	65.39	17.65
797277289	9.8	C12H15NO4	237	3-Hydroxycarbofuran	74.91	18.42
128619891	1.58	C15H15N	209	Acridine, 9,10-dihydro-9,9-dimethyl-	56.24	19.1
81313397	1	C15H15N	209	Acridine, 9,10-dihydro-9,9-dimethyl-	68.33	19.95
128678034	1.58	C9H10O4	182	Benzaldehyde, 4-hydroxy-3,5-dimethoxy-	91.6	20.14

75104543	0.92	C ₁₄ H ₂₀ O ₂	220	2,5-Cyclohexadiene-1,4-dione, 2,6-bis(1,1-dimethylethyl)-	42.11	20.39
347354584	4.27	C ₁₅ H ₁₅ N	209	Acridine, 9,10-dihydro-9,9-dimethyl-	80.67	20.78
198551822	2.44	C ₁₃ H ₁₀ O ₂	198	2-Biphenylcarboxylic acid	47.71	22.49
97736869	1.2	C ₁₆ H ₃₂ O ₂	256	n-Hexadecanoic acid	70.22	24.5
309493127	3.8	C ₁₂ H ₁₅ NO ₄	237	3-Hydroxycarbofuran	27.08	25.06
87182978	1.07	C ₁₇ H ₂₁ NO ₂	271	Desomorphine	56.69	38.5
143017297	1.76	C ₂₃ H ₃₂ O ₆	404	Hydrocortisone Acetate	50.32	43.39

Table 32: NIST library matches for switchgrass fast pyrolysis trial at 500°C.

Area	Area %	Molecular Formula	Molecular Weight	Name	Probability	RT
5.073E+09	49.3	C9H13N	135	Dextroamphetamine	40.59	6.17
173915948	1.69	C4H6O2	86	2,3-Butanedione	45.3	6.78
190556691	1.85	C2H4O2	60	Acetaldehyde, hydroxy-	72.75	7.04
1.209E+09	11.75	C3H6O2	74	2-Propanone, 1-hydroxy-	92.11	7.99
154190551	1.5	C8H10N2O2	166	Hydrazinecarboxylic acid, phenylmethyl ester	46.29	9.29
153930552	1.5	C4H6O3	102	Butanoic acid, 2-oxo-	47.3	9.62
125572129	1.22	C7H14O	114	Pentanal, 2,3-dimethyl-	27.65	9.89
86198542	0.84	C3H6O2	74	2-Propanone, 1-hydroxy-	38.37	10.09
280209437	2.72	C5H4O2	96	3-Furaldehyde	64.79	10.74
157544272	1.53	C6H12O	100	Butanal, 2-ethyl-	35.93	11.35
76274722	0.74	C6H10O4	146	1,2-Ethanediol, diacetate	70.21	11.62
167406357	1.63	C14H28O	212	9-Tetradecen-1-ol, (E)-	33.18	12.24
149196596	1.45	C6H10O	98	Cyclopentanone, 2-methyl-	65.93	12.74
112491820	1.09	C14H28O	212	9-Tetradecen-1-ol, (E)-	48.23	13.34
232622624	2.26	C6H7O4P	174	Phosphonic acid, (p-hydroxyphenyl)-	42.07	13.84
223694238	2.17	C6H8O2	112	2-Cyclopenten-1-one, 2-hydroxy-3-methyl-	46.86	14.61
68798892	0.67	C7H8O	108	Phenol, 3-methyl-	42.88	14.98
111648624	1.08	C7H8O	108	Phenol, 3-methyl-	52.69	15.3
392067923	3.81	C7H8O2	124	Phenol, 2-methoxy-	54.13	15.54
76012954	0.74	C14H28O	212	9-Tetradecen-1-ol, (E)-	21.14	15.7
48078009	0.47	C6H6O3	126	1,3,5-Benzenetriol	55.15	16.03
58908140	0.57	C8H10O	122	Phenol, 4-ethyl-	30.07	16.71
96473212	0.94	C8H10O2	138	Phenol, 2-methoxy-4-methyl-	51.28	17.1
200682327	1.95	C8H8O	120	Phthalan	37.8	17.5
81605466	0.79	C9H12O2	152	2,4-Dimethoxytoluene	52.78	18.36
452489188	4.4	C12H17NO2	207	Phenol, 3-methyl-5-(1-methylethyl)-, methylcarbamate	31.46	18.89
94269589	0.92	C10H18O	154	Eucalyptol	61.31	19.37
44393532	0.43	C10H12O2	164	Phenol, 2-methoxy-4-(1-propenyl)-, (E)-	40.99	20.88

Table 33: NIST library matches for switchgrass fast pyrolysis trial at 500°C.

Area	Area %	Molecular Formula	Molecular Weight	Name	Probability	RT
4.346E+09	51.83	C8H19N	129	2-Octanamine	40.14	6.15
138781066	1.66	C4H6O2	86	Acetic acid ethenyl ester	35.84	6.78
204315241	2.44	C2H4O2	60	Acetaldehyde, hydroxy-	71.58	6.96
112521273	1.34	C2H8N2	60	Hydrazine, ethyl-	71.39	7.2
566298076	6.75	C2H4O2	60	Acetic acid	93.44	7.78
404767861	4.83	C3H6O2	74	2-Propanone, 1-hydroxy-	92.26	7.88
143998236	1.72	C4H6O3	102	Butanoic acid, 2-oxo-	49.75	9.55
103137964	1.23	C7H14O	114	Pentanal, 2,3-dimethyl-	22.07	9.84
67864489	0.81	C3H6O2	74	2-Propanone, 1-hydroxy-	30.85	10.04
218852017	2.61	C5H4O2	96	3-Furaldehyde	63.48	10.72
141540340	1.69	C8H16O	128	2-Hexanone, 3,4-dimethyl-	41.37	11.31
61126772	0.73	C6H10O4	146	1,2-Ethandiol, diacetate	75.09	11.58
129135148	1.54	C6H10O	98	Cyclopentanone, 2-methyl-	66.87	12.73
84597769	1.01	C14H28O	212	9-Tetradecen-1-ol, (E)-	53.66	13.31
202718075	2.42	C6H7O4P	174	Phosphonic acid, (p-hydroxyphenyl)-	39.35	13.83
153897785	1.84	C6H8O2	112	1,2-Cyclopentanedione, 3-methyl-	48.85	14.58
92308519	1.1	C7H8O	108	Phenol, 3-methyl-	40.09	15.29
290798661	3.47	C7H8O2	124	Phenol, 2-methoxy-	62.53	15.51
54857443	0.65	C8H10O	122	Phenol, 4-ethyl-	26.73	16.69
70942708	0.85	C8H10O2	138	Phenol, 2-methoxy-4-methyl-	54.5	17.1
182517294	2.18	C8H8O	120	Phthalan	41.06	17.49
69170149	0.82	C9H12O2	152	2,4-Dimethoxytoluene	49.77	18.36
424513641	5.06	C12H17NO2	207	Phenol, 3-methyl-5-(1-methylethyl)-, methylcarbamate	30.77	18.89
74862775	0.89	C10H18O	154	Eucalyptol	47.9	19.35
45181190	0.54	C10H12O2	164	Phenol, 2-methoxy-4-(1-propenyl)-	61.05	20.88

Table 34: NIST library matches for switchgrass fast pyrolysis trial at 600°C.

Area	Area %	Molecular Formula	Molecular Weight	Name	Probability	RT
5.677E+09	57.15	C8H19N	129	2-Octanamine	31.17	6.17
184509312	1.86	C4H6O2	86	Acetic acid ethenyl ester	18.07	6.82
207797365	2.09	C2H4O2	60	Acetaldehyde, hydroxy-	73.37	7.05
731850337	7.37	C2H4O2	60	Acetic acid	86.89	7.86
410020441	4.13	C3H6O2	74	2-Propanone, 1-hydroxy-	91.45	7.98
63704232	0.64	C4H6O3	102	Butanoic acid, 2-oxo-	44.14	9.6
230705288	2.32	C7H14O	114	Pentanal, 2,3-dimethyl-	19.09	9.9
76507254	0.77	C3H6O2	74	2-Propanone, 1-hydroxy-	33.49	10.11
306872839	3.09	C5H4O2	96	3-Furaldehyde	66.71	10.76
144646584	1.46	C8H16O	128	2-Hexanone, 3,4-dimethyl-	30.33	11.35
72963203	0.73	C6H10O4	146	1,2-Ethanediol, diacetate	76.4	11.61
124694504	1.26	C6H10O	98	Cyclopentanone, 2-methyl-	36.35	12.74
101488485	1.02	C14H28O	212	9-Tetradecen-1-ol, (E)-	46.31	13.34
218007614	2.19	C6H7O4P	174	Phosphonic acid, (p-hydroxyphenyl)-	39.04	13.82
137773515	1.39	C6H8O2	112	1,2-Cyclopentanedione, 3-methyl-	52.88	14.58
71318954	0.72	C7H8O	108	Phenol, 3-methyl-	41.56	14.96
109835632	1.11	C7H8O	108	Phenol, 3-methyl-	55.48	15.3
279384974	2.81	C7H8O2	124	Phenol, 2-methoxy-	55.97	15.52
73935136	0.74	C8H10O2	138	Phenol, 2-methoxy-4-methyl-	53.13	17.1
166117373	1.67	C8H8O	120	Phthalan	45.66	17.5
49398050	0.5	C9H12O2	152	2,4-Dimethoxytoluene	48.47	18.36
372121136	3.75	C10H14O	150	Phenol, 2,3,5,6-tetramethyl-	29.81	18.89
74130869	0.75	C10H18O	154	Eucalyptol	56.74	19.37
48227993	0.49	C10H12O2	164	Phenol, 2-methoxy-4-(1-propenyl)-	48.08	20.89

Table 35: NIST library matches for switchgrass fast pyrolysis trial at 600°C.

Area	Area %	Molecular Formula	Molecular Weight	Name	Probability	RT
5.079E+09	50.95	CO2	44	Carbon dioxide	36.45	6.15
186776355	1.87	C4H6O2	86	Acetic acid ethenyl ester	43.83	6.78
112677497	1.13	C2H4O2	60	Acetaldehyde, hydroxy-	71.87	7.04
310541753	3.12	C4H9NO2	103	sec-Butyl nitrite	7.86	7.46
928373066	9.31	C3H6O2	74	2-Propanone, 1-hydroxy-	91.43	8.02
188829939	1.89	C7H8	92	1,3,5-Cycloheptatriene	51.57	9.29
73250289	0.73	C4H6O3	102	Butanoic acid, 2-oxo-	45.73	9.62
147110446	1.48	C7H14O	114	Pentanal, 2,3-dimethyl-	32.69	9.88
97034700	0.97	C3H6O2	74	2-Propanone, 1-hydroxy-	38.36	10.11
263745133	2.65	C5H4O2	96	3-Furaldehyde	61.4	10.75
167141613	1.68	C5H6O2	98	2-Furanmethanol	21.03	11.44
74630686	0.75	C6H10O4	146	1,2-Ethandiol, diacetate	71.65	11.62
121835198	1.22	C6H10O	98	Cyclopentanone, 2-methyl-	54.51	12.75
124875504	1.25	C14H28O	212	9-Tetradecen-1-ol, (E)-	47.29	13.35
313696559	3.15	C7H7NO2	137	Carbamic acid, phenyl ester	33.88	13.9
184091646	1.85	C6H8O2	112	1,2-Cyclopentanedione, 3-methyl-	54.36	14.62
78700545	0.79	C7H8O	108	Phenol, 3-methyl-	39.32	14.98
125994564	1.26	C7H8O	108	Phenol, 3-methyl-	43.98	15.32
292420488	2.93	C7H8O2	124	Phenol, 2-methoxy-	55.19	15.52
70835994	0.71	C8H10O	122	Phenol, 4-ethyl-	34.9	16.71
82983132	0.83	C8H10O2	138	Phenol, 2-methoxy-4-methyl-	54.79	17.1
192441203	1.93	C8H8O	120	Phthalan	41.73	17.51
71957558	0.72	C9H12O2	152	2,4-Dimethoxytoluene	51.05	18.36
521874738	5.24	C12H17NO2	207	Phenol, 3-methyl-5-(1-methylethyl)-, methylcarbamate	38.34	18.9
94434185	0.95	C10H18O	154	Eucalyptol	53.34	19.37
62534030	0.63	C10H12O2	164	Phenol, 2-methoxy-4-(1-propenyl)-	56.49	20.89
310541753	3.12	C4H9NO2	103	sec-Butyl nitrite	7.86	7.46

Table 36: NIST library matches for switchgrass fast pyrolysis trial at 700°C.

Area	Area %	Molecular Formula	Molecular Weight	Name	Probability	RT
7.191E+09	49.16	C ₈ H ₁₉ N	129	2-Octanamine	84.07	6.17
278510533	1.9	C ₄ H ₆ O ₂	86	Acetic acid ethenyl ester	37.13	6.77
180502674	1.23	C ₂ H ₄ O ₂	60	Acetaldehyde, hydroxy-	65.76	7.12
134821331	0.92	C ₅ H ₁₂ O	88	1-Butanol, 3-methyl-	21.31	7.38
1.416E+09	9.68	C ₃ H ₆ O ₂	74	2-Propanone, 1-hydroxy-	93.86	8.1
236669683	1.62	C ₇ H ₈	92	1,3,5-Cycloheptatriene	29.25	9.33
73864256	0.5	C ₄ H ₆ O ₃	102	Butanoic acid, 2-oxo-	44.3	9.67
198234400	1.36	C ₃ H ₈ O ₂	76	1,3-Propanediol	23.67	9.94
198856759	1.36	C ₃ H ₆ O ₂	74	2-Propanone, 1-hydroxy-	44.01	10.18
326331578	2.23	C ₅ H ₄ O ₂	96	3-Furaldehyde	54.97	10.78
211558250	1.45	C ₈ H ₁₀	106	Benzene, 1,3-dimethyl-	31.86	11.44
89899768	0.61	C ₆ H ₁₀ O ₄	146	1,2-Ethandiol, diacetate	70.45	11.66
71436015	0.49	C ₈ H ₈	104	1,3,5,7-Cyclooctatetraene	53.94	11.88
177487390	1.21	C ₅ H ₆ O ₂	98	2-Furanmethanol	24.05	12.79
133800913	0.91	C ₁₄ H ₂₈ O	212	9-Tetradecen-1-ol, (E)-	42.97	13.37
388066580	2.65	C ₆ H ₆ O	94	Phenol	50.68	13.78
288273223	1.97	C ₆ H ₈ O ₂	112	1,2-Cyclopentanedione, 3-methyl-	43.12	14.66
124165974	0.85	C ₇ H ₈ O	108	Phenol, 3-methyl-	45.51	15
232454269	1.59	C ₇ H ₈ O	108	Phenol, 3-methyl-	53.55	15.34
330708539	2.26	C ₇ H ₈ O ₂	124	Phenol, 2-methoxy-	60.46	15.54
128465819	0.88	C ₈ H ₁₀ O	122	Phenol, 2,6-dimethyl-	25.61	15.78
55473566	0.38	C ₆ H ₆ O ₃	126	1,3,5-Benzenetriol	42.53	16.05
78995069	0.54	C ₈ H ₁₀ O	122	Phenol, 2,3-dimethyl-	22.15	16.45
183518096	1.25	C ₈ H ₁₀ O	122	Phenol, 4-ethyl-	42.84	16.74
120179429	0.82	C ₈ H ₁₀ O ₂	138	Phenol, 2-methoxy-4-methyl-	51.98	17.12
521073684	3.56	C ₈ H ₈ O	120	Phthalan	50.08	17.55
95766726	0.65	C ₉ H ₁₂ O ₂	152	2,4-Dimethoxytoluene	51.76	18.37
846571105	5.79	C ₁₂ H ₁₇ NO ₂	207	Phenol, 3-methyl-5-(1-methylethyl)-, methylcarbamate	35.59	18.93
190063916	1.3	C ₁₀ H ₁₈ O	154	Eucalyptol	57.38	19.4
125044523	0.85	C ₁₀ H ₁₂ O ₂	164	Phenol, 2-methoxy-4-(1-propenyl)-	46.11	20.91

Table 37: NIST library matches for switchgrass fast pyrolysis trial at 700°C.

Area	Area %	Molecular Formula	Molecular Weight	Name	Probability	RT
5.739E+09	49.42	C8H19N	129	2-Octanamine	77.24	6.17
210838192	1.82	C4H6O2	86	2,3-Butanedione	37.4	6.77
262298543	2.26	C2H4O2	60	Acetaldehyde, hydroxy-	74.03	7.01
95825130	0.83	C2H8N2	60	Hydrazine, ethyl-	38.46	7.24
711753827	6.13	C2H4O2	60	Acetic acid	87.22	7.82
451419953	3.89	C3H6O2	74	2-Propanone, 1-hydroxy-	92.5	7.93
157351840	1.35	C3H6O2	74	2-Propanone, 1-hydroxy-	50.99	9.67
170549400	1.47	C3H8O2	76	1,3-Propanediol	26.07	9.89
128418732	1.11	C3H6O2	74	2-Propanone, 1-hydroxy-	47.09	10.09
248426790	2.14	C5H4O2	96	3-Furaldehyde	62.87	10.75
163435641	1.41	C8H16O	128	2-Hexanone, 3,4-dimethyl-	31.77	11.35
64907799	0.56	C6H10O4	146	1,2-Ethandiol, diacetate	48.53	11.62
153589245	1.32	C6H10O	98	Cyclopentanone, 2-methyl-	36.22	12.74
264533129	2.28	C6H6O	94	Phenol	55.63	13.73
62980827	0.54	C2H2N4O2	114	1H-1,2,4-Triazole, 3-nitro-	43.7	14.03
215689616	1.86	C6H8O2	112	2-Cyclopenten-1-one, 2-hydroxy-3-methyl-	58.68	14.62
128069551	1.1	C7H8O	108	Phenol, 3-methyl-	46.65	14.98
184547192	1.59	C7H8O	108	Phenol, 3-methyl-	51.29	15.32
332756532	2.87	C7H8O2	124	Phenol, 2-methoxy-	56.55	15.52
59583270	0.51	C8H10O	122	Phenol, 3,4-dimethyl-	21.22	16.44
129822265	1.12	C8H10O	122	Phenol, 4-ethyl-	41.55	16.71
109126842	0.94	C8H10O2	138	Phenol, 2-methoxy-4-methyl-	53.18	17.12
100472508	0.87	C6H6O2	110	1,2-Benzenediol	64.5	17.32
402514332	3.47	C8H8O	120	Phthalan	39.96	17.53
94212069	0.81	C9H12O2	152	2,4-Dimethoxytoluene	50.96	18.37
699365197	6.02	C12H17NO2	207	Phenol, 3-methyl-5-(1-methylethyl)-, methylcarbamate	33.51	18.92
174354948	1.5	C10H18O	154	Eucalyptol	53.74	19.38
97394229	0.84	C10H12O2	164	Phenol, 2-methoxy-4-(1-propenyl)-	53.51	20.91

Sub-Task B4: Extended Supply Chain Model and Access Economic Business Viability Project.

Reported by:

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Units of measurement: Biomass feedstock is measured in green, short tons. A rough estimate of the ratio between *green tons* and *dry tons* is 2:1. The system performance indicators are measured based on the units of biomass feedstock. For example, the delivered feedstock cost is measured in U. S. dollar per green, short ton of biomass being transported to a biofuel facility. Energy consumption is measured in Btu by delivering per green, short ton of biomass. Greenhouse gas emissions are measured in lbs. of CO₂e per green, short ton of biomass being delivered.

EXECUTIVE SUMMARY

The supply chain models were developed in conjunction with the Forestry Biofuel Statewide Collaboration Center exploring the option of a biorefinery in the upper portion of the Lower Peninsula of Michigan. The models integrated information from several of the project tasks and allowed for an evaluation of cost, emissions, and energy consumption impacts of forest resources as feedstocks for potential biofuels facilities in Michigan. The initial project intent was to apply the models in relation to biorefineries only. In reality, the feedstock supply chain would be the same for biomass supplied to a biorefinery, biomass fired or co-fired power plant, or torrefaction/pelletization operations.

Project Scope

A literature summary was conducted to identify gaps and investigate why the optimization models are unique from what has been completed in the past. A Geographic Information Systems (GIS)-based approach was used to select potential biofuel facility locations in Michigan. Two models were developed for the biofuel supply chain: the optimization model and the simulation model. The two models focused on different areas and addressed different issues in the supply chain.

Literature Review

The complexity of a biomass supply chain has been a significant challenge that hinders increased biomass utilization for energy production due to the distributed nature of biomass feedstock. A literature review allowed for the development of a comparative

analysis to a unique biomass supply chain designed for the FBSCC project in Michigan. Based on the current literature, there are a number of research gaps filled by the biomass feedstock supply chain research for the FBSCC project. The literature from existing cellulosic ethanol supply chains served as a basis for the development of supply chain management decision support tools.

Candidate Location Selection

To implement cost-effective biofuel production, the selection of the best location for a processing facility becomes a critical concern. This is because biomass feedstock is geographically dispersed, and the location of a biofuel facility significantly influences transportation costs. Through the use of Geographic Information Systems (GIS), nine candidate locations were selected based on a set of evaluation criteria. The criteria are:

- county boundaries,
- a railroad transportation network,
- a state/federal road transportation network,
- water body (rivers, lakes, etc.) distribution,
- city and village distributions,
- a population census,
- biomass production, and
- no co-location with co-fired power plants

Optimization Modeling

The optimization model and supporting information is provided after the biofuel facility candidate location selection. The optimization model was developed using single location and three multi-location configurations. For the single location models, cost, emissions, and energy were minimized to optimize the individual attributes. In the case of the multi-location configurations, only cost was evaluated. Since the project scope was limited, there were no estimates regarding the future transportation costs, emissions data, and energy inputs. The optimization model is a static, Excel-based application which allows for sensitivity analysis by changing inputs to evaluate different scenarios. The optimization model can also be applied to multiple years and can changes in data inputs.

Simulation Modeling

The simulation model, with an easy-to-use graphical user interface, has been designed and implemented using the Arena Simulation Software, available from Rockwell Automation²⁴. The simulation model confirms the one year look conducted by the optimization model. Compared with the optimization model, the simulation model represents a more dynamic look at a 20-year operation by considering the impacts associated with building inventory at the biorefinery to address the limited availability of biomass feedstock during the spring breakup period. Since the simulation model cannot capture all the features of a supply chain system, a series of assumptions were made to simplify the supply chain and the constraints and limitations introduced by the assumptions are discussed.

Infrastructure Analysis

²⁴ Arena Simulation Software. <http://www.arenasimulation.com/>

An initial assessment of the infrastructure needs for the top couple of locations is addressed in the final section. An infrastructure analysis was conducted to investigate the feasibility of growing the transportation infrastructure in order to realize the necessary network system needed to transport sufficiently large volumes of biomass in the Lower Peninsula of Michigan. The analysis is conducted on the road transportation network and equipment by examining existing roads and truck fleets as well as comparing with the needs for road and truck infrastructure forecasted for the supply chain model. The capital investment on road and truck infrastructure is also discussed.

ABSTRACT

Work on subtask B4 commenced in Fall 2009 with only minor progress until it was restarted in mid May 2010 and the work was completed by April 30, 2011. Given the limited time for this project, prototype optimization and simulation models were developed with emphasis on biorefinery location(s) in the upper portion of the Lower Peninsula of Michigan. Through the use of Geographic Information Systems (GIS), nine candidate locations were selected based on a set of evaluation criteria. The optimization model was developed using single location and three multi-location configurations while the simulation model only used single locations. For the single location models, cost, emissions, and energy were minimized to optimize the individual attributes. In the case of the multi-location configurations, only cost was evaluated. Preliminary capital investment infrastructure requirements were briefly discussed. These models and the infrastructure analysis can be extended to a larger study area at a point in time when additional funding becomes available.

PROJECT OVERVIEW

Overview

The supply chain model was developed in conjunction with the Forestry Biofuel Statewide Collaboration Center to encompass all forest regions in Michigan. However, because of the limited time and funding for this subtask, the work completed was limited to the upper portion of the Lower Peninsula of Michigan. The model integrated information from several of the project tasks and allowed for an evaluation of cost, emissions, and energy consumption impacts of forest resources as feedstocks for potential biofuels facilities in Michigan. The initial project intent was to apply the models in relation to biorefineries only. In reality, the feedstock supply chain would be the same for biomass supplied to a biorefinery, biomass fired or co-fired power plant, or torrefaction/pelletization operation. Because of limited travel distance (100 mile radius) from the woody biomass feedstock source to the biorefinery locations, the only transportation method considered in the models was truck transportation for inbound woody biomass feedstock. Optimization and simulation models were developed. The optimization model is a static model that focuses on a single time period; whereas the simulation model focuses on the operation of a biorefinery over a 20 year period. Further, the latter model takes into consideration an assumed starting inventory along with

increased inventory prior to spring break up to deal with limited supply during that time period.

If the volumes of woody biomass required exceed the current removals of the supply chain, the supply system can be modified to meet the increased requirement for roads, trucks, and other equipment. Thus, additional significant capital investment is required by biorefinery investors, harvesting/processing operators, loggers, developers of the infrastructure (i.e., roads, water treatment, utility connections, etc.), and transportation companies. Preliminary recommendations in relationship to the top three locations identify some of the infrastructure requirements necessary to begin operations from a macro level perspective. A critical ingredient is to sufficiently identify the optimal costs associated with capital investment along with the required maintenance and operational costs for longer-term viability and sustainability. The capital investment costs will be split between infrastructure (i.e., roads, railways, utilities, etc.) and equipment (i.e., harvesting, processing, and transportation). These two components are addressed by other subtasks. Specifically, *Task B1: Evaluation Michigan Biomass Transportation Systems*, which evaluates different modes of transportation. The focus for the supply chain model was to use truck transportation only. Different configurations are noted in Task B1. Task B2.5 *Select feasible processing technologies* and B2.6 *Analyze supply chain cost of processing technologies* both include capital investment costs information as well as other data that will be available in the future and can be entered into the model. Due to uncertainty in the information and the lack of a cohesive set of numbers, it was not possible to complete the economic evaluation using traditional financial tools to identify the net present value (NPV) and payback periods. Since total cost information for a longer period of time would be required and there is much uncertainty surrounding the configuration of any specific location (i.e., size, location, etc.) we were unable to complete an economic/business viability analysis of different alternatives other than to identify the least costly location for transportation of woody biomass. This discussion was enhanced by not only computing the transportation cost differential but taking into consideration the emissions generated on pounds basis and energy consumption computed in Btus.

It is unlikely that there will be a statistically significant difference in the price of biomass feedstock (harvesting/processing and stumpage price) from one location to another or between ownership types. The major differentiator in location is the transportation cost. In other words, the locations that are closest to dense forestation are the preferred locations. This is an assumption that has been made at this point in time. As the demand for woody biomass grows, it is likely that there will be price differentials between the different ownership classes, specifically public versus private land ownership. As the size of the facility grows, the feedstock supply radius from the facility will increase. Although the current radius is 100 miles, for each of the optimized locations it is less. It can be observed that on a per ton basis for transportation cost, the larger the facility size, the further the distance, and the longer the haul, with transportation cost per ton that is higher.

The report covers the literature summary gap identification and why these models are unique and different from what has been completed in the past. The optimization model and supporting information is provided after the literature summary. The optimization model represents a one year snapshot but can be applied to multiple years

assuming there are no changes in data inputs. Since the project scope was limited, there were no estimates regarding the future transportation costs, emissions data, and energy inputs. The model is a static, Excel-based application which allows for sensitivity analysis by changing inputs to evaluate different scenarios. It provides information on each of the nine locations and presents three possible multi-location configurations. The simulation model represents a more dynamic look at a twenty year operation by considering the impacts associated with building inventory at the biorefinery to address the limited availability of biomass feedstock during the spring breakup period. Finally an initial assessment of the infrastructure needs for the top couple of locations is addressed in the final section.

GAPS IDENTIFIED IN LITERATURE

The original information provided in the first status report has been modified and is now under review for the Decision Sciences Institute Conference. The information is outlined below and also included in the publications section of the report. The title of the paper is *Comparative Review of Biofuels Supply Chains*.

Abstract

The complexity of a biomass supply chain has been a significant challenge that hinders increased biomass utilization for energy production due to the distributed nature of biomass feedstock. A literature review allowed for the development of a comparative analysis to a unique biomass supply chain designed for the Forestry Biofuel Statewide Collaboration Center (FBSCC) project in Michigan. Research gaps were used to develop models for the FBSCC.

Keywords: cellulosic ethanol, biomass supply chain, comparative analysis, literature review

Introduction

Numerous studies have been conducted to develop models for cellulosic ethanol supply chains, which included a wide variety of different types and forms of biomass feedstock. The Forestry Biofuel Statewide Collaboration Center (FBSCC) project has focused supply chain research and modeling on the use of woody biomass feedstock, including both hard and soft wood species. The main purpose of the FBSCC supply chain is to develop a supply chain model specific to the FBSCC facilities. The model developed by the FBSCC project incorporates other biomass supply chains and mathematical models as its foundation but is tailored to meet local criteria and demands for operating in Michigan. The potential biorefinery in the FBSCC project performs secondary processing at their facility, which differs from other supply chains. This unique supply chain model focused on key activities and characteristics of supply chains. The main goal of the FBSCC supply chain system is to develop a supply chain specific for the FBSCC facilities.

A literature review was performed to compare current models and their attributes. Specific models used for comparison are described in greater detail to allow for clearer

understanding. The literature review allowed the unique aspects of the FBSCC model to be identified clearly and addressed. The synopsis in this paper is a summary of a much larger overall detailed report. We focused on the most salient points in the remainder of the discussion.

Comparison Description of the Selected Literature

Based on the current literature, there are a number of research gaps filled by the biomass feedstock supply chain research for the FBSCC project. The literature from existing cellulosic ethanol supply chains served as a basis for the development of supply chain management decision support tools. A unique supply chain model was tailored for the FBSCC. Information from previously developed biomass supply chains and mathematical models formed the foundation for the development of a unique biomass feedstock supply chain model.

National Biofuels Plan

The National Biofuels Plan developed by the Biomass R&D Board (2008) includes sustainability as an action area for successful development of the supply chain. This is similar to the FBSCC facilities because sustainability issues are one of the key drivers behind why the facility will be built. The Biomass R&D Board (2008) includes environment, health, and safety into an action area of its biofuels plan. The addition of these elements ensures that the supply chain can operate in a manner that is safe and compliant with energy policies, procedures, laws, and regulations. The FBSCC facilities relates to this part of the plan from an environmental and sustainability policy prospective.

The Biomass R&D Board (2008) also focuses on feedstock logistics because of its effect on the finished cost of cellulosic ethanol. These same feedstock logistics costs will be considered when developing the supply chain for the FBSCC facilities. The areas of focus for feedstock logistics in the biofuels plan that relate to the FBSCC project are harvesting process, storage facilities, and transportation of the feedstock.

The supply chain model for the FBSCC facilities differs from the National Biofuels Plan in that it uses woody biomass (including logs, forest residues or chips) for its feedstock. National Biofuel Plan considered agricultural residues and energy crops as the feedstock. Also, the FBSCC facilities supply chain will be tailored to meet the local criteria and demands of operating in Michigan, as opposed to a nationwide scale supply chain like the National Biofuels Plan. The Biomass R&D Board (2008) also focuses on conversion science and technology, distribution technology for the ethanol, and blending of the ethanol, which are all out of the scope of the project for the FBSCC supply chain team. Since there are a number of government agencies and researchers conducting research concurrently, we uncovered several other relevant models.

Idaho National Laboratory

Idaho National Laboratory (INL) also developed a biomass supply chain for ethanol. Hess et al. (2007) proposed a uniform-format feedstock supply chain that can be implemented at a nationwide level. This is different from the scope of the supply chain team for the FBSCC facilities. Also, unlike the supply chain model that uses woody

biomass (including logs, forest residues or chips), the Idaho National Laboratory mainly uses wheat straw and agricultural residues as primary feedstocks. One of the variables identified by Hess et al. (2007) is the different demands of varying products that compete for biomass to use in energy production. This is similar to the FBSCC facilities. Some of the forest products will also be used by mills in the pulp and paper industry. Another recent source of demand for wood resources is the increasing number of combined heat and power (CHP) operations using co-firing of coal and woody biomass or complete operation with woody biomass. There will be a limited amount available for conversion to ethanol. Preprocessing of the biomass is moved prior to the transportation and handling in the INL report. This allows the transportation and handling procedures to be uniform no matter what type of feedstock is used. This differs from the FBSCC facilities supply chain since all of the preprocessing and chipping will occur at the biorefinery. Because of this unique feature, it will be not included in the supply chain model for FBSCC. Hess et al. (2007) also highlight that transportation and handling costs account for nearly 30% of the annual cost for feedstock. The supply chain team will work to minimize transportation costs through the use of simulation and optimization to the nine potential FBSCC facilities to ensure the system is cost effective.

The INL (2009) study included some critical success factors for a supply chain feedstock model using wheat and barley straw. One of the critical success factors includes the ability to contract straw from a specified distance. Even though the feedstock type is different from that of the FBSCC facilities, the issue outlined is very relevant. Woody biomass need to be harvested from specific harvest areas within a 100-mile radius of the facility. INL (2009) highlighted areas of concern for the feedstock supply chain system. The areas that relate to the FBSCC facilities include: (1) the cost of feedstock will vary with demand; (2) the logistics of moving the feedstock are complicated; (3) storage of feedstock may be subject to fire codes; (4) unloading the feedstock after transportation will vary with each case; and (5) the amount of field energy used while handling and transporting the feedstock.

Sandia National Laboratory

Sandia National Laboratories (SNL) performed a study assessing the feasibility of achieving national goals to produce 90 billion gallons of biofuels by 2030 (SNL, 2009; West et al., 2008). The study considered corn-based ethanol to support the national goal. The ethanol in this study is cellulosic ethanol from energy crops and agricultural and forest residues. This is different from the FBSCC facilities since the supply chain will only incorporate woody biomass supplied from the forest. Corn-based or agricultural residues-based ethanol will not be in the scope of the supply system. SNL developed a model with inputs such as conversion yield, capital investment/annual capacity per cellulosic plant, energy prices, and feedstock yield improvements. However, the supply chain model developed for FBSCC includes supply chain inputs such as feedstock inventory and availability, harvesting/processing, storage at biorefinery, transportation, and environmental policy considerations.

Oak Ridge National Laboratory

The Oak Ridge National Laboratory (ORNL) investigated the feasibility of expanding the ethanol industry. Reynolds, R.E. (2002) studied two different cases for this expansion

scenario. Costs associated with building additional infrastructure were estimated. Similarly, the FBSCC supply chain will consider building infrastructure to meet the demand and the associated cost. The ORNL also calculated transportation costs, which is also an important consideration to the supply chain team for the FBSCC facilities. However, these ORNL costs will differ from those observed by the supply system for FBSCC. The FBSCC facilities only include woody biomass primarily in Michigan within a 100 mile radius of an ethanol plant studied other regions and included more sources of feedstock including agricultural residues and grasses. The supply chain team will fill the research gap of producing a woody biomass supply system for ethanol plants in Michigan.

Mathematical Models

Preprocessing at the facility will vary and be dependent on the technological process used to produce cellulosic ethanol. There are different preprocessing steps that can occur. One of those steps is chipping. The chipping of debarked logs may be necessary to reduce the size of the woody biomass to meet the input specifications for feedstock size to more efficiently produce cellulosic ethanol. Gronalt and Rauch (2007) investigated the issue of centralized and decentralized chipping when designing a forest fuel network. The work described by Gronalt and Rauch (2007) solved the supply system problem for several plants at once using numerous storage facilities and terminals to meet the varying demands of each plant. This accumulation of materials from multiple locations is similar to the work that will be done with the FBSCC facilities. The FBSCC model will identify 3-4 best locations for biorefinery facilities by concurrently using simulation and optimization models to minimize cost, emissions, and energy consumption in the transportation process to the mill gate. In another study, mixed integer programming models were used to optimize cost. Gunnarsson et al. (2004) proposed a solution to the supply chain problem involving a forest fuel network structure through a large mixed integer linear programming (MLP) model. The main product used is forest fuels, which are forest residues from harvest areas or byproducts from sawmills. The destination for the forest fuel is a combined heat and power (CHP) plant instead of a biorefinery. This is different from the FBSCC facilities because the primary demand for feedstock is for use in the biorefinery process, with a secondary use for providing power through co-generation of residues from the preprocessing and waste in the production of cellulosic ethanol. The study also raised the issue of forests that are owned by the CHP plant as opposed to contracted forests. Feedstock coming from forests owned by the plant would not have to be purchased; while contracted forests would have to be purchased. All the woody biomass feedstock from the FBSCC facilities will have to be purchased, differentiating it from the Gunnarsson model.

Another study by De Mol et al. (1997) created both simulation and optimization models for the logistics of biomass fuel collection. The network structure associated with the models includes nodes that correspond to source locations, collection sites, transshipment sites, pre-treatment sites, and the energy plant itself. Arcs connect the nodes that represent road, water, or rail transportation. This network structure is similar to the FBSCC facilities structure; but water and rail transportation modes are not included in the FBSCC study. The simulation model created by De Mol et al. (1997) is similar to the simulation model being developed for the FBSCC facilities. Both simulation models

include a similar network structure. The model for the FBSCC facilities investigates a variety of different facility locations for an ethanol biorefinery, which is the same as the De Mol et al.'s (1997) simulation model. The optimization model created by De Mol et al. (1997) combines different types of biomass, different nodes, and pre-treatments scenarios to develop the optimal network structure. The fact that the optimization model includes different pre-treatment situations differentiates it from the FBSCC optimization model. The overall goals of supplying an ethanol plant with biomass are the same for both.

In another study, McNeil Technologies, Inc. (2005) investigated the feasibility of building a biomass plant in Jefferson County, Colorado. Several scenarios were considered including centralized and decentralized facilities, various conversion techniques, and different harvesting processes. Similarly, the goal of the FBSCC model is to investigate the feasibility of building one or more biorefineries across Michigan by conducting sensitivity analysis of different plant sizes. Urban wood waste and forest biomass travels through the supply chain from procurement to storage and finally to the energy plant (2005). Woody biomass is used to fuel heating and power plants throughout Jefferson and nearby counties (2005). While this study considers the feasibility of a biomass facility, an optimum facility or process is not chosen. This decision remains in the hands of Jefferson county officials. Different from this study, the FBSCC model will give one or more best locations for biorefinery in Michigan as one of the model outputs.

Sokhansanj, et al. (2006) examined an integrated biomass supply analysis and logistics model (IBSAL). This model examines the supply chain of corn stover through harvesting, storage, and transportation to the biorefinery. The IBSAL model examines costs and optimum conditions for harvesting and transportation logistics of biomass material. Weather conditions and routine equipment maintenance are entered in the model to calculate moisture content of the stover and equipment performance. This is similar with the FBSCC model since the FBSCC supply chain also considers cost, energy use and GHG emissions involved in equipment maintenance. The IBSAL model only considers flatbed trucks which are similar with the FBSCC supply chain by considering truck transportation only. This similarity offers valuable information for the design of the FBSCC supply chain.

The FBSCC supply chain is greatly affected by policy related constraints. This gap was reviewed and constraints addressed in the simulation model. The literature reviewed provides guidance expanding the body of knowledge and application to develop an efficient and cost effective biomass feedstock supply chain model.

Comparison Summary of Key Features of Biomass Supply Chain

Based on the comparison description in previous paragraphs, a comparison summary of the key features involved in biomass feedstock supply chain was illustrated in Table 1. The key features include feedstock type, harvesting procedures, transportation methods, storage facilities, preprocessing facilities, biorefinery distribution, and model outputs.

	Idaho National Laboratory Hess, et al. (2007); Hess, et al. (2009); Idaho National Laboratory (2006)	Sandia National Laboratory Sandia National Laboratories (2009); West, et al. (2009)	National Biofuels Plan Biomass Research and Development Board (2008)	Oak Ridge National Laboratory Reynolds (2002)
Feedstock Type	Wheat Straw	Corn-based/agricultural and forest residues	Corn, crop residues, woody residues	Corn stover, forest residues/thinnings, agricultural residue, urban waste
Harvesting Procedures	Industrial harvesting (Crop harvesting, residue collection)	Not Identified	Industrial harvesting (Feller-buncher, skidder, crop harvesting, residue collection)	Not Identified
Transportation Methods	Truck/Rail/Water	Truck/Rail	Truck/Rail/Water	Truck/Rail/Water
Locations and Facilities	Harvesting and collection sites, storage facilities, preprocessing locations, ethanol plant	Source locations, storage sites, conversion plants, blending locations, distribution facilities	Harvesting and collection sites, storage facilities, preprocessing locations, ethanol plant	Source locations, terminals, ethanol plant
Preprocessing Facilities	Reports suggest moving preprocessing of the biomass to early on in the supply chain	Not Identified	Various locations along the supply chain specific in each case	Not Identified
Biorefinery or Energy Operations	Numerous ethanol plants	Numerous ethanol plants	Numerous ethanol plants	Single plant destinations
Output	Cellulosic Ethanol	Cellulosic Ethanol	Cellulosic Ethanol	Cellulosic Ethanol

Table 1 Comparison Summary of Key Features of the Selected Literature

	Simulation and Optimization De Mol et al. (1997)	Forest fuel network design Gronalt and Rauch (2007)	Supply chain Optimization in the Forest Industry Gunnarsson (2007)	Jefferson County Biomass Facility Feasibility Study McNeil Technologies, Inc. (2005)	Integrated biomass supply analysis and logistics model (IBSAL) Sokhansanj et al. (2006)	FBSCC Model
Feedstock Type	Thinnings, prunings, waste wood, sewage sludge, waste paper	Forest Fuel	Forest fuel, pulp products	Urban wood waste, forest biomass	Corn stover	Woody biomass
Harvesting Procedures	Not Identified	Industrial harvesting (Feller-buncher, skidder)	Not Identified	Industrial Harvesting (chainsaw, feller-buncher, harvester, skid steer, masticator)	Shredding, Baling, Stacking	Industrial harvesting (Feller-buncher, skidder)
Transportation Methods	Truck/Rail/Water	Truck	Truck/Rail/Vessels/Barges	Truck	Truck (flatbed trailers)	Truck
Locations and Facilities	Source locations, collection sites, transshipment sites, pre-treatment sites, the energy plant	Harvesting site, regional terminals, industrial terminals, energy plant	Storage terminals, saw mill, pulp mill, paper mill, heating plant	Harvesting site, landing, energy plant	Harvesting site, satellite storage, biorefinery	Harvesting site, storage at biorefinery
Preprocessing Facilities	Optimization and simulation found preprocessing can best be done at the plant	A central terminal where all the chipping can occur and mobile chipping options were analyzed	Chipping occurs at the forest or at the mill prior to transport to the heating plant	Chipping occurs at the landing	Grinding occurs at the biorefinery	Chipping occurs at biorefinery
Biorefinery or Energy Operations	One central location	Numerous energy plants	Numerous CHP facilities	Central facility, semi-mobile plant, existing facility, heating and cooling system	Biorefinery	Numerous ethanol plants
Output	Some type of fuel from Biomass	Fuel for heating and bioenergy plants	Saw wood, paper, forest fuels	Fuel for heating and power plants	Biorefinery	Cellulosic ethanol

Table 1 Comparison Summary of Key Features of the Selected Literature (continued)

Conclusion

A series of studies regarding existing biomass supply chains were reviewed and compared with the supply chain developed for the FBSCC facilities in Michigan. The FBSCC supply chain has similarities with existing biomass supply chain models, including the output of the supply chain (cellulosic ethanol), the method of transportation (truck), and land ownership (i.e., federal, state, private) issues. The FBSCC supply chain differs from existing feedstock supply chains in biomass feedstock types and activities (i.e. storage along the supply chain and chipping) along the supply chain. The FBSCC facilities supply chain uses only woody biomass as the type of feedstock. The combination of these differences from existing supply chains creates a unique opportunity to develop a new supply chain using woody biomass as the primary feedstock to support the FBSCC facilities.

The detailed literature review is contained in Appendix B4-A.

IDENTIFICATION OF CANDIDATE LOCATION

Nine potential locations to construct and operate an ethanol facility were identified in the upper portion of the Lower Peninsula of Michigan. This analysis was based on criteria used in a renewable assessment report (Jenkins, 2008) and additional items. The criterion includes:

- 1) Location within one mile of a major state road (Jenkins, 2008);
- 2) Location within one mile of railway (Jenkins, 2008);
- 3) Location within a community size of at least 1,000 (Jenkins, 2008);
- 4) Location within ¼ mile of a water body (rivers, lakes, etc.);
- 5) The minimum residues within a 100 mile radius of any select community have to be at least 0.7 million dry tons / 1.4 million green tons (a rough estimate of the ratio between *green tons* and *dry tons* is 2:1²⁵) to support a facility producing 50 million gallons of fuel each year; and
- 6) Location does not have a co-fired power plant around (there are co-fired power plants in Grayling, Mancelona and Cadillac).

The list of the nine potential sites for biorefinery in the lower peninsula of Michigan, as well as the distance (miles) to a closest co-fired power plant, is shown in Table 2. The map in Figure 1 shows the distribution of the nine potential sites.

²⁵ Minnesota Woody Biomass Facility Survey. Minnesota Department of Natural Resources Division of Forestry Forest Products Utilization & Marketing Program.
http://files.dnr.state.mn.us/forestry/um/biomass/minnesotawoodybiomassutilization_report.pdf; 2008

City / Village	Distance to a Nearest Biomass Power Plant (miles)
Manton City	11.19
Roscommon Village	12.81
Kingsley Village	23.86
Kalkaska Village	23.94
Gaylord City	25.49
Clare City	33.97
West Branch City	35.29
Traverse City	36.03
Boyne City	41.24

Table 2 Potential Site for Biorefinery in Lower Peninsula of Michigan

Nine Potential Biorefinery Sites in L.P.

Figure 1 Map of Nine Candidate Locations for Biorefinery Plant in Lower Peninsula of Michigan

Each of the candidate locations and the 100 mile radius are shown in Appendix B4-C *Counties within 100 mile radius of each location.*

Existing/Approved Wood-Fueled Biomass Power Plants in Michigan

There are several electric power generation facilities using wood fuel as feedstock in Michigan. These utilities have a combined capacity of 173,000 kW, or approximately half of Michigan's wood-based energy production capability. Table 3 shows each facility's information, including the name of the power plants, locations, capacities, and approximate wood fuel consumption in tons per year. In order to avoid competition, e.g., pulpwood, workforce, and other resources, with the power facilities listed in the table, potential ethanol conversion plants will not be located in adjacent areas. The exact type and mix of woody biomass used for firing these operations is unknown and varies by each location.

Power Plants	Location	Capacity (kW)	Wood Fuel Consumption (tons/yr)
Grayling Generating Station	Grayling	38,000	250,000-300,000
Viking Energy--McBain ^a	McBain	18,000	150,000
Cadillac Renewable Energy ^a	Cadillac	39,600	375,000
Hillman Power Co. ^a	Hillman	20,000	230,000
Viking Energy--Lincoln ^a	Lincoln	18,000	150,000
Genesee Power Station ^a	Flint	39,500	300,000
Mancelona Biomass Plant ^b	Mancelona	36,000	Approximately 300,000

Table 3 Existing/Approved Wood-Fueled Biomass Power Plants in Michigan

^aSource: REPIS, <http://www.nrel.gov/analysis/repis/>

^bSource: McWhirter S., "Mancelona biomass plant awaits utility deal."

Overlap in Study Area

There is an overlap in the study area with the Frontier Renewable Resources biorefinery to be constructed in Kinross, MI. Figure 2 is a map of the overlapping counties under consideration for both projects. The radial lines in Figure 2 identify the zone distances (60-150 miles) from the Kinross plant.

Figure 2 Overlapping Counties with Frontier Renewable Resource for Competing

Also, there are special considerations that need to be noted for some of the overlapping counties. This information is detailed in Figure 3. The special considerations do not apply to FBSCC because FBSCC considers a county as a harvesting area while one county is split into several harvesting areas for the Frontier Renewable Resources biorefinery.

Figure 3 Overlapping Counties with Special Considerations

Modification of Original Approach

The original intent was to use a two-step methodology to identify the cost optimal locations, however, this approach proved to not be the best method for identifying candidate locations. Two papers outlining this approach titled, Zhang, F., Johnson, D.M., and Sutherland, J.W. (May 2010) “GIS-based approach of identification of the optimal pulpwood-to-biofuel facility location in Michigan’s Upper Peninsula,” 2010 Production and Operations Management Society (POMS) Conference, Vancouver, British Columbia, CA and Zhang, F., Johnson, D.M., and Sutherland, J.W. (June 2011) “A GIS-Based Method for Identifying the Optimal Location for a Facility to Convert Forest Biomass to Biofuel,” *Biomass and Bioenergy*, discussed this approach.

SUMMARY OF DATA INPUTS

Information was obtained from other subtasks that have specific assumptions and limitations which go beyond those that apply specifically to each of the models.

Analysis of Spring Breakup Data

Data Collection

In Michigan, there are weight restrictions to prevent damage to roads during the freeze-thaw cycle from winter to spring. All the weight restriction dates (including start dates and end dates) from 2006 to 2010 for all harvesting areas are identified according to the maps provided by Michigan Department of Transportation (MDOT) (Appendix B4-D). The start and end dates are clearly colored in the map. We identified the start as the day one county is colored and the end as the day the color disappears. The duration calculation required adding one day to the difference between the start and end dates to determine the total number of days.

Statistical Analysis

Statistical analysis was conducted for the weight restriction dates in order to describe the data using a mathematical model (either theoretical or empirical). Statistical analysis can also help to find the correlation between weight dates for different harvesting areas. Two methods are used for analysis. First, a normal probability plot is generated to graphically assess whether the sampling data could come from a normal distribution. Second, the Lilliefors tests were performed as a supplement for the normal probability plots to further check whether the samples come from normal distributions. The Lilliefors test was utilized because it is appropriate for small sample size. An example analysis of Ogemaw County (a harvesting area) was performed. The original data for Ogemaw County is shown in Table 4. The transformed data (representing Number of Days from Jan. 1) is shown in Table 5. The normalized numerical data in Table 6 is calculated based on the transformed data in Table 5.

Spring Break	2002	2003	2004	2005	2006	2007	2008	2009	2010
Start	18-Feb	17-Mar	1-Mar	9-Mar	8-Mar	9-Mar	17-Mar	6-Mar	8-Mar
End	17-Apr	24-Apr	19-Apr	18-Apr	7-Apr	13-Apr	23-Apr	22-Apr	1-Apr
# of Days	59	39	50	41	31	36	38	48	25

Table 4 Original Data

Spring Break	2002	2003	2004	2005	2006	2007	2008	2009	2010	Average	Standard Deviation
Start	49	76	61	68	67	68	77	65	67	66	8.25
End	107	114	110	108	97	103	114	112	91	106	7.90
# Of Days	59	39	50	41	31	36	38	48	25	41	10.29

Table 5 Numerical Dates (Representing Number of Days from Jan. 1)

Spring Break	2002	2003	2004	2005	2006	2007	2008	2009	2010
Start	-2.12	1.16	-0.66	0.19	0.07	0.19	1.28	-0.18	0.07
End	0.10	0.98	0.48	0.22	-1.17	-0.41	0.98	0.73	-1.93
# of Days	1.77	-0.17	0.90	0.02	-0.95	-0.46	-0.27	0.70	-1.53

Table 6 Normalized Numerical Dates

Normal Probability Plot

The purpose of the normal probability plot is to graphically assess whether the sampling data could come from a normal distribution. If the data are normal the plot will be linear. Other distribution types will introduce curvature in the plot. Normal probability plots were created for the spring break duration (Figure 4), start (Figure 5), and end (Figure 6) for Ogemaw County separately. There is strong evidence that the three plots are linear, except some outliers in the start and end plots. The identified outliers may be the result of irregular warm climate or data error.

Figure 4 Normal Probability Plot of Spring Break Duration for Ogemaw County

Figure 5 Normal Probability Plot of Spring Break Start for Ogemaw County

Figure 6 Normal Probability Plot of Spring Break End for Ogemaw County

Lilliefors Test

The Lilliefors tests were performed as a supplement to the normal probability plots to validate whether the samples come from normal distributions. The Lilliefors test was utilized because it is appropriate for small sample size. The tests failed to reject the null hypothesis that the values come from a normal distribution. Figures 7-9 graphically illustrate the comparison between empirical and theoretical distributions (standard normal distribution was used in this study).

Figure 7 Comparison of Spring Break Duration Empirical CDF with Standard Normal CDF

Figure 8 Comparison of Spring Break Start Empirical CDF with Standard Normal CDF

Figure 9 Comparison of Spring Break End Empirical CDF with Standard Normal CDF

Goodness-of-Fit Test Using Arena Input Analyzer

The goodness-of-fit test was applied using Arena Input Analyzer. The results are shown in Table 7 and confirm the prior analysis.

<i>Spring Break Start Distribution Summary</i>	
Distribution:	Normal
Expression:	NORM(66.4, 7.78)
Square Error:	0.11992
<i>Spring Break End Distribution Summary</i>	
Distribution:	Normal
Expression:	NORM(106, 7.45)
Square Error:	0.097101
<i>Spring Break Duration Distribution Summary</i>	
Distribution:	Normal
Expression:	NORM(40.8, 9.7)
Square Error:	0.082609

Table 7 Goodness-of-Fit Test Results

Conclusion

For Ogemaw County normal distributions can describe the spring break data, including start, end, and number of days. However, for most of the supplier counties, limited data is available for accurate statistical analysis. The analysis was not included in the report for all counties. Ogemaw County was used to provide an example.

Michigan state law indicates that the months of March, April and May are automatically reduced loading months, but the statute also allows the Michigan Department of Transportation (MDOT) and the county road commission to implement those restrictions earlier or suspend reduced loading, depending upon weather conditions (MSP, 2004). Since the area under study is the upper portion of the Lower Peninsula of Michigan where spring breakup ends earlier, an assumption of using March and April as the spring breakup months was made.

Forest Biomass Data

The forest biomass data is characterized by ownership type: federal forests (national), state forests, and private landowner including corporate. The forest biomass data was provided by Dr. Robert Froese from the Forest Service Inventory EVALIDator web application version 4.01 (Miles, 2011) (Task A1: *Develop a Geospatial Forest Based Biomass Inventory* Task A2: *Develop a Forest Biomass Information System (FBIS)*).

Ownership

There were three broad land ownership categories for the forest biomass data. These included federal (national) forests, state forests, and private forests. The private forests are in aggregate and do not delineate between corporate ownership or large or small ownership.

Species

The species are aggregated by soft and hard wood but are not separated in any greater detail. The user of the models should exercise caution as the mix of species and the proportion of each type are not included. Also, the data input for the model allows for determining the percentages of roundwood versus forest residues.

Availability

Net growth after removals was calculated. In other words, the net growth accumulating in the forest on an annual basis, after accounting for losses to mortality, timber harvesting, reversion (land becoming forest) and conversion (land becoming nonforest). This is a straightforward query using the EVALIDATOR interface. The fraction of net growth, that is net growth after removals, is equal to 1 minus the fraction of net growth of current removals was used. The forest biomass data is located in Appendices B4-F through B4-H by ownership type, soft and hardwood, and availability factors. These represent data input cells in the models and can be modified if the data and/or assumptions regarding availability change. Figure 10 (Leatherberry and Spencer, 1996) shows the four regions in Michigan. There are the two regions where counties are located within a 100-mile radius of the nine selected locations: Northern Lower Peninsula (N) and Southern Lower Peninsula (L). Because of the competing uses in the Upper Peninsula (U.P.) of Michigan, we did not use feedstock from the U.P. so Eastern and Western U.P. are not relevant at this point.

Figure 10 Michigan Map Showing Regions

Adjustment Factors

The ability to adjust the quantities for known, planned uses of forest biomass has been included. This includes an adjustment of hardwood information for overlapping counties for the planned biorefinery plant in the eastern portion of the Upper Peninsula of Michigan. Additionally, an adjustment can be made to the resource availability for the planned combined heat and power (CHP) of a fully biomass fired operation in

Mancelona, MI, in the eastern portion of the upper, Lower Peninsula of Michigan. In Michigan there are currently six wood-based electricity generating plants (as indicated earlier in the report). These operations use mostly logging residues, chips, sawmill or other mill residues, and municipal or industrial wood waste, listed in highest to lowest consumption pattern.

Distance Data

The distances from the centroid of the counties within a 100-mile radius to each of the candidate locations calculated using the latitude and longitude for rectilinear distance are shown in Appendix B4-I. The level of detail is aggregate and is not specifically linked to road networks.

Cost Data

The cost data includes the transportation cost only. The table was computed by using the rectilinear distance for latitude and longitude (Appendix B4-I) of the centroid for each of the counties within a 100-mile radius of the specific location and the selected biorefinery location. The cost model included a fixed and variable portion and is calculated as follows: Variable cost = 0.074 \$/ton-mile and Fixed cost = 3.72 \$/ton. The final models allow for inputs for harvesting/processing and stumpage costs. The transportation cost for each candidate location by county within a 100 mile radius is shown in Appendix B-4J.

Emissions and Energy Data

Greenhouse gas (GHG) emissions and fossil energy demand due to forest feedstock production (harvesting/processing) and transportation have been calculated using the assumptions and literature values (Tables 8 and 9). In both supply chain stages, diesel fuel use was the primary driver of environmental burdens. Forest feedstock production was assumed to take place with a full processor and forwarder equipment configuration. Truck transportation of forest biomass was assumed using Michigan log trucks which are typically “truck + trailer” units capable of hauling much larger loads (45 - 50 ton average assumed) than is typical in neighboring states. Emissions factors and energy demand factors have been normalized to one ton of biomass production, assumed to be a ‘green’ ton containing roughly 50% moisture.

<i>Item</i>	<i>Data</i>	<i>Source</i>
Harvesting and Forwarding		
Gallons diesel / hr	30 L / hr, full processor and forwarder	White 2005
Productivity / hr	4 cords/hr , 2.35 tons/cord	Logger interviews (Handler 2010)
Diesel emissions factors	13.63 kg CO ₂ e / gal 30.05 lb CO ₂ e / gal	GREET 1 upstream production (Wang 2009); US LCI combustion (U.S. Life-Cycle Inventory Database 2009)
Diesel energy impact factor	40.5 MJ / L 38,387 Btu / L	Klvac 2003
Emissions factors for machine production, maintenance	0.1 kg CO ₂ e / ton timber 0.2 lb CO ₂ e / ton timber	Assumed burden for lifetime of production, normalized to 1 ton
Energy impact factor for machine production, maintenance	15.7 MJ / ton 14,881 Btu / ton	Athanassiadis 2002 , lubricant use from logger interviews (Handler 2010)
<i>Total GHG emissions (Harv. & Forw.)</i>	<i>11.6 kg CO₂e / ton</i> <i>25.6 lb CO₂e / ton</i>	
<i>Total Fossil Energy Demand (Harv. & Forw.)</i>	<i>145 MJ / ton</i> <i>137,433 Btu / ton</i>	

Table 8 Data and assumptions for roundwood harvesting/forwarding (Zhang, Handler et al., 2011)

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Item	Data	Source
Truck transportation		
Diesel emissions factor	13.63 kg CO ₂ e / gal 30.05 lb CO ₂ e / gal	REET upstream production (Wang 2009); US LCI combustion (U.S. Life-Cycle Inventory Database 2009)
Log truck fuel use per ton-mile	4 miles / gallon 45 ton loaded average 50% loaded miles 0.0111 gal / ton-mile	Logger interviews (Handler 2010)
Emissions for log truck production, maintenance	290,000 kg CO ₂ e 639,341 lb CO ₂ e Must normalize to lifetime ton-miles of truck operation	REET 2 vehicle analysis (Athanasiadis 2000), scaled to log truck weight
Lifetime ton-miles of log truck	8 yr productive life 70,000 miles / yr 45-50 ton loads, 50% loaded miles	Assumed
Diesel Energy Impact factor	40.5 MJ / L 38,387 Btu / L	Klvac 2003
<i>Total Log Truck GHGs / ton-mile</i>	<i>0.174 kg CO₂e / ton-mile</i> <i>0.384 lb CO₂e / ton-mile</i>	
<i>Total Fossil Energy Demand, Log Truck</i>	<i>1.68 MJ / ton-mile</i> <i>1592 Btu / ton-mile</i>	

Table 9 Data and assumptions for truck transportation (Zhang, Handler et al., 2011)

The energy and emissions values used in the optimization model are located in Appendices B4-K and B4-L respectively.

Data Requirements Summary Tables

The summary tables showing the data requirements for the optimization and simulation models are shown in Appendix B4-M.

Plant Size and Conversion Ratio

For this study, three different plant sizes were evaluated: 50 million gallons per year (50 MGY), as well as 30 MGY and 40 MGY. Numerous studies indicate varying levels of conversion of forest biomass to fuels. This variance is based on the moisture content of wood and ranges from a low of 40 gallons per ton to a high of 75 gallons per ton. The low end of the spectrum is assumed to use biomass that has higher moisture content (approximately 40-50%) and is typically referred to as “green tons”, whereas the higher end of the spectrum would be characteristic of wood that has a much lower moisture content in the range of 15-25% (Maker, 2004; Aerts and Ragland, 2000; Ragland, et. Al, 1991). In this study, green tons were assumed with an approximate conversion factor of 1 green (short) ton could produce 40 gallons of fuel (Aden et al., 2002).

OPTIMIZATION MODEL

Overview

The optimization model was designed to be utilized by any user who has an interest in exploring the option of a biorefinery in the upper portion of the Lower Peninsula of Michigan. The same feedstock supply chain would exist for a wood-fired or co-fired power plant so the model serves multiple users. This section provides information on the purpose/objectives of using optimization models, model assumptions, model description, model constraints/limitations, Microsoft Excel™ 2007 Solver model, discussion of results, overall limitations, summary, and identification of future work.

Purpose/Objectives

Optimization is a modeling technique designed to identify optimal decisions and is used as a management decision support system. For example, minimize total system cost, select the best location for a biofuel production facility or facilities, or minimize emissions or energy consumption, are representative of decisions made through optimization. Optimization provides an integrated tool for several interrelated planning situations. The model can be used both as a tool for tactical planning, and as a strategic tool to analyze the effects on the current planning in various situations (Gunnarsson, et. al., 2004). We used single objective optimization to identify the optimum location or locations for a biorefinery. *In other words, the question to be addressed is can the study area support more than one biorefinery and what is the optimum location?* The three decision criteria for the optimization model are characterized as cost, emissions, and energy. Evaluation of each of the nine locations based on the three criterion along with three multiple location configurations were completed. In conjunction with the optimization results, a weighted-average approach was conducted to determine ranking of the nine locations.

The optimization model of the woody biomass supply chain was developed using Microsoft Excel. Although Excel does have some limitations regarding model size, it is a widely used software package that is readily available. The intent was to allow the optimization model to be downloaded by users who can then modify the input parameters to allow for decision making and sensitivity analysis. Although it is limited to the nine selected locations and three multi-location configurations, it is an aggregate tool that requires little knowledge on using Excel or any other package.

The optimization model was designed to answers some of the following potential questions:

- What is the cost for harvesting/processing, stumpage, and transportation?
- How many plants can be supported with the existing and future woody biomass resources and given there are other competing sources for the same feedstock?
- What is the best location?

Model Assumptions

The assumptions are divided into several categories: biorefinery locations, biorefinery

operations, transportation, and biomass availability and inventory.

Assumptions for identifying initial prospective biorefinery locations

- Accessibility to the state/federal road and county road (road must be paved – either concrete or asphalt) transportation networks (i.e., the facility is within one mile of a network) is required. This guarantees the input (pulpwood feedstock) and output (biofuel products) can be easily transported;
- The biorefinery is also required to be within one mile of rail access;
- Only cities, villages and township with populations greater than 1,000 will be considered for locating biorefinery, to ensure the availability of a workforce;
- Accessibility to water connections within ¼ mile of location;
- Accessibility to sewer/water connections or would required to add a septic system and well; and
- Accessibility to electricity infrastructure.

Assumptions for biorefinery operation

- The biorefinery will operate 20 years continuously;
- The biorefinery operates 24/7, 50 weeks per year with 2 weeks shutdown for maintenance;
- The biorefinery production is level (i.e., same production volumes each week); and
- The biorefinery will not have a dedicated supply source for any of the feedstock requirement; all biomass will be purchased from multiple sources and the optimum price.

Assumptions for transportation

- Transportation radius is less than 100 miles;
- The centroid of the county is used as the origin for the feedstock to the facility location; and
- Truck carrying capacity is 50 tons.

Assumptions for biomass availability and inventory

- The biorefinery(ies) will not have a dedicated supply source for any of the feedstock requirement; all biomass will have to be purchased.;
- The land area within the 100-mile radius will be subdivided into harvesting areas to incorporate county level information;
- The harvest areas have a target size that allows a suitable balance between having detailed information about the resource locations;
- During spring break, the only access to feedstock for the biorefinery will be from its own storage yard;
- Delivery of feedstock will remain constant during the periods of June 1 through November 30 while December 1 through the end of February will have increased delivered quantities for inventory build up to address road load restrictions during spring break up;
- Woody biomass feedstock includes logs and forest residues;
- One green ton is used to produce 40 gallons of biofuel. A green ton is defined as

woody biomass that is less than 90 days old;

- For a 30 million gallon facility the total green tons required is 750,000.
- For a 40 million gallon facility the total green tons required is 1,000,000.
- For a 50 million gallon facility the total green tons required is 1,250,000.
- No feedstock will be transported over the Mackinaw Bridge (hereafter referred to as “bridge”²⁶). It is assumed that all feedstock in the Upper Peninsula is not available for transport over the bridge and will be consumed by others in the Upper Peninsula; and
- Reduced by a percentage to be determined based on the biomass combined heat and power facilities and mill consumption for operations that are not currently consumers of feedstock. This includes the Frontier Renewable Resources biorefinery and the planned 36MW combined heat and power plant planned for Mancelona, MI. For both of these planned operations, it is anticipated that they will require a combined total of approximately 800,000 green tons per year for steady-state operation.

Constraints/Limitations

One of the most challenging issues that confront FBSCC biorefinery(ies) is securing woody biomass when unusually warm weather forces road weight restrictions to be imposed much earlier than expected. The wood must be in areas that can be logged rapidly and directly from Class A highways. The land ownership data will greatly facilitate this process. The large non-public owners are the most likely partners for FBSCC facilities to develop relationships with to secure wood. Some of the constraints/limitations may include the following:

- Biomass supplied cannot exceed the biomass production at each harvesting area.
- Use of same feedstock for CHP facilities, biorefinery, etc. There is a need to locate and use underutilized woody biomass, specifically forest residues where an existing supply chain is rather limited because of minimal demand for this form of feedstock.
- The amount available from private landowners is largely unknown and subject to a high level of uncertainty and variability. There are numerous factors that impact the availability which were not fully evaluated in this report.
- The total supply of biomass is equal to the demand at biorefinery(ies).
- Demand for biomass at biorefinery(ies) must be satisfied.
- The transportation distance may be more than 100 miles based on the transportation networks.
- All storage will be at the biorefinery whereas in practice, there may be multiple storage locations or roadside landing storage.
- Transport capacity for each time period varies. We assume constant.
- Policy constraints may include GHG emissions and Forbidden areas/reserve areas
- Sustainability constraints that were not factored into the model:
 - [1] Sustainable harvesting (percentage of harvestable);

²⁶ The Mackinac Bridge is a suspension bridge spanning the Straits of Mackinac to connect the non-contiguous Upper and Lower peninsulas of the U.S. State of Michigan. Opened in 1957, the bridge (familiarily known as "Big Mac" and "Mighty Mac") is the third longest in total suspension in the world and the longest suspension bridge between anchorages in the Western hemisphere. The Mackinac Bridge carries Interstate 75 across the straits and connects the city of St Ignace on the north end with the village of Mackinaw City on the south. (Wikipedia, 2010)

- [2] Traffic congestion;
- [3] Damage to roads as a result of higher volumes of traffic;
- [4] Noise;
- [5] Air quality; and
- [6] Water quality.

Model Description

Objective Functions

The optimization models optimize the following items associated with activities including harvesting/processing, transportation, and storage on site for the biomass feedstock supply chain system for biofuel production. Each variable was optimized individually.

- Minimize delivered feedstock cost
- Minimize energy use; and
- Minimize GHG emissions.
-

Inputs

- Stumpage cost (\$/ton);
- Harvesting cost (\$/ton);
- Transportation cost, including cost (\$/ton) and cost (\$/ton-mile);
- GIS-based data describing the annual yields of feedstock of each type (forest residues and roundwood) in aggregate (hardwood and softwood) and not by species;
- Distances between harvesting sites (centroid of county) and biorefineries for transporting feedstock by trucks (rail was not included because it is not economically feasible for a 100 mile radius used in this study);
- Latitude and longitude of the centroid of each county to the latitude and longitude of the biorefinery location to determine the transportation distances;
- GHG emissions of harvesting/processing (lbs/ton green biomass) and transporting (lbs/ton-mile) of feedstock;
- Energy use of harvesting/processing (Btu/ton green biomass) and transporting (Btu/ton-mile) of feedstock;
- Amount (tons) of biomass available at a harvesting area in a time period; and
- Conversion rate (gallon/green ton) of biomass to ethanol, which is 40 gallons per 1 green, short ton of biomass. Green ton has an approximate moisture content of 50%.

Decisions/Outputs

- The minimum total delivered feedstock cost (\$) for supplying woody biomass feedstock for ethanol production;
- The minimum system energy use (Btu);
- The minimum GHG emissions (lbs/ton green biomass);
- Numbers, locations and sizes (gallons per year) of new biorefinery(ies); and
- The optimal allocation of biomass resources to biorefinery.

Constraints/Limitations

- *Constraints at harvesting sites*

- Delivered amount (tons) of biomass feedstock at each harvesting area cannot exceed its corresponding maximum yearly availability; and
- Amount available for biorefineries after other competing uses are met. All current uses are assumed to be in the existing data. Other uses, such as a new 40MGY biorefinery in the eastern portion of the Upper Peninsula of Michigan in Kinross, and the 36 MW wood-fired power plant expected to be operational in 2013 in Mancelona, Michigan, have been factored into by using adjustment factors to reduce the potential amount available for a biorefinery.
- *Constraints at biorefineries*
 - Total gallons of ethanol produced at a biorefinery in a time period equals the amount (tons) of feedstock transported to that biorefinery multiplied by the associated energy conversion rates (gallons/ton);
 - There is no fuel production capacity unless there is a refinery opened; and
 - The designed biorefinery capacity (gallons/yr) must not exceed the maximum allowable biorefinery capacity.
- *Nonnegativity constraints*
 - The amount (tons) of feedstock harvested at a harvesting site in a time period is nonnegative;
 - The amount (tons) of feedstock transported from a harvesting site to a biorefinery in a time period is nonnegative;
 - The designed biorefinery capacity (gallon/yr) is nonnegative; and
 - Ethanol production at a biorefinery in a time period is nonnegative.

Network Representation of Biomass Supply Chain

There are three important components in the biomass supply chain for a biorefinery: harvesting, transportation, and storage at the biomass processing facility. Truck is the only form of transportation utilized in this project. The abstract representation of this supply chain is given in Figure 11.

Figure 11 Segment of Network Representation of Biomass Supply Chain

Indices

- I Set of harvesting sites, indexed by i
- K Set of potential locations for biorefineries, indexed by k

Model Parameters

- s Unit stumpage price (\$/ton) of biomass
- h Unit harvesting price (\$/ton) of biomass
- t_d Truck variable mileage cost (\$/ton/mile)
- t_{lu} Truck fixed cost (\$/ton), includes one loading and unloading routine
- d_{ik} Distance (miles) between harvesting site i and biorefinery k
- Q_i Amount of biomass available at harvesting area i
- γ Conversion rate (gallon/green ton) of biomass to ethanol
- w_h CO₂ emission (lbs/ton green biomass) for harvesting / forwarding feedstock
- f_h Energy use (Btu/ton green biomass) for harvesting / forwarding feedstock
- w_{tr} CO₂ emission (lbs/ton-mile) for truck transportation
- f_{tr} Energy use (Btu/ton-mile) for truck transportation
- CAP_k Capacity (gallons of ethanol per year) of biorefinery k

Decision Variables

- q_i Amount (tons) of biomass harvested at site i

Objective Functions

Three objective functions are: (1) minimize the annual supply chain system cost of: stumpage, harvesting, and transportation (C_s), (2) minimize the energy use across the supply chain, (EU_s), and (3) minimize CO₂ emissions (EM_s) across the supply chain. Note: The mathematical model is based on one year operation for a single biomass processing facility.

$$C_{\text{tot}} = \sum_{k=1}^K \sum_{i=1}^I (s + h + t_{lu} + t_d \cdot d_{ik}) \cdot q_{ik}$$

(1)

$$F_{\text{tot}} = \sum_{k=1}^K \sum_{i=1}^I (f_h + f_{tr} \cdot d_{ik}) \cdot q_{ik}$$

(2)

$$W_{\text{tot}} = \sum_{k=1}^K \sum_{i=1}^I (w_h + w_{tr} \cdot d_{ik}) \cdot q_{ik}$$

(3)

Constraints/Limitations

- The sum of the amount of biomass harvested at a harvesting site i and sent to a

biorefinery k cannot exceed the harvesting site's maximum yield per year

$$\sum_{k=1}^K q_{ik} \leq Q_i, i \in I \quad (4)$$

- Total biomass amount of biomass delivered to a biomass processing facility meets the demand for biomass feedstock at the biomass processing facility

$$\sum_i q_{ik} \geq \frac{CAP_k}{\gamma}, k \in K \quad (5)$$

- Amount (tons) of biomass harvested at harvesting area i is nonnegative

$$q_{ik} \geq 0, i \in I, k \in K \quad (6)$$

Microsoft Excel™ Model

Microsoft Excel™ using Excel Solver was the software used to develop and solve the optimization models. Solver does have size limitations regarding the number of changing cells and number of decisions. The underlying model is a linear optimization model based on transportation networks. Solver applies the simplex method to rapidly solve larger scale problems. This problem is characterized as a minimization problem so as to minimize cost, energy, or emissions. Sensitivity and “what-if” scenario analysis can be easily conducted with this model.

The Master page of the workbook shows all the inputs required and buttons to update the model after each change. The input screen is split into multiple views to provide a brief explanation of each of the different data areas. Information for cost, energy, emissions, feedstock availability factors, percentages of residue and roundwood, and adjustments for Frontier Renewable Resources as well as other adjustments (i.e., biomass fired power plant in Mancelona) are included in this initial screen. This input screen is shown in Table 10. A key is provided to indicate which cells are inputs, calculated, and results. The same key is used for all entry screens.

	Stumpage		Harvest		Transport		Total	
Cost	0.00	\$/ton	0.00	\$/ton	3.72	\$/ton	3.72	\$/ton
					0.074	\$/ton-mile	0.074	\$/ton-mile
Energy			137.4330	1000 Btu/ton	1.5924	1000 Btu/ton-mile		
Emissions			25.6	lb GHG/ton	0.377	lb GHG/ton-mile		
Federal		Region	Factor		Residue	Roundwood	Total	
Availability	Soft	N	0.93288219		0%	100%	100%	
		S	0.93288219		0%	100%		
	Hard	N	0.90959717		0%	100%	100%	
		S	0.90959717		0%	100%		
State		Region	Factor		Residue	Roundwood	Total	
Availability	Soft	N	0.54210441		0%	100%	100%	
		S	0.89363253		0%	100%		
	Hard	N	0.48138431		0%	100%	100%	
		S	0.88568285		0%	100%		
Private		Region	Factor		Residue	Roundwood	Total	
Availability	Soft	N	0.68544762		0%	100%	100%	
		S	0.95282162		0%	100%		
	Hard	N	0.56189444		0%	100%	100%	
		S	0.75485393		0%	100%		
FRR	500,000	tons hardwood (roundwood)						
Soft adjust	Species			Hard adjust	Species			
	Residue	80%			Residue	100%		
	Roundwood	80%			Roundwood	100%		
								KEY:
								INPUT CELLS
								CALCULATED CELLS
								MODEL RESULTS

Table 10 Data entry screen for cost, energy, emissions, feedstock availability factors by ownership type, and adjustment factors for other planned uses of woody biomass feedstock

The next screen shot shows the input for the biorefinery size in million gallons per year (MGY). Results will be provided in the results section for 50 MGY, 40 MGY, and 30 MGY per year facilities. As indicated earlier the conversion rate is 40 gallons per green, short ton. Table 11 also shows the summary of Model Output for the selected biorefinery size (in this case it is for 50 MGY) and details the total and average per ton in the specified units. After entering data and to update the Model Output, select the Cost, Energy, and Emissions buttons and the Model Output table will be updated with the changes. This allows for performing a sensitivity analysis.

[illegible]

Table 11 Input for biorefinery size, conversion rate, biomass feedstock requirements calculation, and optimization results for cost, energy, and emissions

Because of size limitations, one possible configuration of three possible multiple locations were selected. The first configuration is for three plants that are spaced and not close to one another. The next two configurations are four possible locations each. However, this hits the maximum of the Solver limitations and will give an error message that it will not process results. When you select the Solve button when the error appears, it completes the calculation and gives an accurate result. The multiple location figures were only evaluated using cost optimization (minimizing cost) and to demonstrate the maximum number of locations at the maximum size. Given the current feedstock availability, no more than four plants (biorefinery) can be supported. There are limitations with Excel Solver and also limitations with feedstock availability that limits the maximum number and size of possible biorefineries. The details of the multiple location models are located in Table 12.

MULTIPLE LOCATIONS									
			Conversion Rate (gal/tons)	Biomass Feedstock (tons)					
Configuration 1		Size (MGY)							
	Roscommon	50	40	1,250,000				KEY:	
	Clare	50	40	1,250,000				INPUT CELLS	
	Boyne City	50	40	1,250,000					
Configuration 2								CALCULATED CELLS	
	Roscommon	50	40	1,250,000					
	Clare	50	40	1,250,000				MODEL RESULTS	
	Boyne City	50	40	1,250,000					
	Traverse City	50	40	1,250,000					
Configuration 3									
	Traverse City	50	40	1,250,000					
	Kalkaska	50	40	1,250,000					
	Kingsley	50	40	1,250,000					
	Manton	50	40	1,250,000					
Update									
Model	Multi Cost	Note: For Multiple Locations, the model exceeds the Solver parameters and will request that you click Solve. It will result in an optimal solution.							

Table 12 Input for three selected multiple location configurations, including inputs for biorefinery size, conversion rate, and calculations of biomass feedstock

Table 13 shows the model output for the cost optimization for the three selected multiple location configurations. The total cost by configuration as well as the average dollar cost per ton is summarized in the table.

MODEL OUTPUT									
Configuration 1		Total Cost by Location	Average (\$/ton)	Total Cost by Configuration	Average (\$/ton)				
	Roscommon	\$ 11,609,108	\$ 9.28729						
	Clare	\$ 11,583,556	\$ 9.26684						
	Boyne City	\$ 11,354,180	\$ 9.08334						
Total Configuration 1				\$ 34,546,844	\$ 9.21249				
Configuration 2									
	Roscommon	\$ 11,894,912	\$ 9.51593						
	Clare	\$ 11,682,077	\$ 9.34566						
	Boyne City	\$ 12,475,818	\$ 9.98065						
	Traverse City	\$ 11,905,801	\$ 9.52464						
Total Configuration 2				\$ 47,958,609	\$ 9.59172				
Configuration 3									
	Traverse City	\$ 15,615,295	\$ 12.49224						
	Kalkaska	\$ 16,806,034	\$ 13.44483						
	Kingsley	\$ 15,653,106	\$ 12.52248						
	Manton	\$ 15,834,518	\$ 12.66761						
Total Configuration 3				\$ 63,908,953	\$12.78179				

KEY:	
	INPUT CELLS
	CALCULATED CELLS
	MODEL RESULTS

Table 13 Cost optimization model output for three selected multiple locations

Discussion of Results

The results for each of the nine candidate locations are summarized in this section with supporting details relating to the specific counties that would supply feedstock for each of the locations in the Appendices. Each of the different variables, transportation cost, energy, and emissions are summarized and include individual as well as combined rankings.

Transportation Cost

The transportation cost per green ton delivered by each candidate location by size is shown in Table 14. The details related to which counties will supply each location by size are located in Appendices B4-N to B4-P.

MGY/Green Tons	Transportation Cost Per Green Ton Delivered								
	Manton	Roscommon	Kingsley	Kalkaska	Gaylord	Clare	West Branch	Traverse City	Boyne City
50MGY - 1,250,000	\$8.02924	\$ 8.35383	\$8.40309	\$8.47558	\$7.77808	\$8.88795	\$8.58456	\$9.08841	\$8.99179
40MGY - 1,000,000	\$7.54038	\$ 8.11689	\$7.84365	\$7.91999	\$7.19287	\$8.32781	\$8.05903	\$8.45935	\$8.34225
30MGY - 750,000	\$7.02973	\$ 7.74899	\$7.19957	\$7.11791	\$6.47805	\$7.78447	\$7.54163	\$7.66297	\$7.86804

Table 14 Transportation Cost Per Green Ton Delivered by Candidate Location by Size

In reviewing the transportation costs, as the plant size grows, the cost per ton increases. This is because more feedstock is required and transporters have to travel a longer distance to bring the feedstock to the biorefinery. Cost per ton by plant size was ranked from lowest to highest cost, with the lowest cost receiving a ranking of “1” and the highest cost receiving a ranking of “9”. The rankings are shown in Table 15. The rankings were summed and an overall cost ranking was developed. The best location overall is Gaylord. The worst location (in terms of highest transportation cost per ton) is Boyne City. This in part can be attributed to the fact that feedstock is assumed to not be transported over the bridge, even though counties in the Upper Peninsula of Michigan are within the 100 mile radius of this location. This limitation likely added to the increased costs. There was a tie between West Branch and Roscommon. Because West Branch had two plant sizes ranked at 5, this location was arbitrarily chosen as the 5th ranked overall.

	<i>Rank by Lowest to Highest - Transportation Cost Per Green Ton Delivered</i>								
<i>MGY/Green Tons</i>	<i>Manton</i>	<i>Roscommon</i>	<i>Kingsley</i>	<i>Kalkaska</i>	<i>Gaylord</i>	<i>Clare</i>	<i>West Branch</i>	<i>Traverse City</i>	<i>Boyne City</i>
50MGY - 1,250,000	2	3	4	5	1	7	6	9	8
40MGY - 1,000,000	2	6	3	4	1	7	5	9	8
30MGY - 750,000	2	7	4	3	1	8	5	6	9
SUM	6	16	11	12	3	22	16	24	25
Overall Rank - Cost	2	6	3	4	1	7	5	8	9

Table 15 Ranking by Transportation Cost Per Green Ton Delivered by Candidate Location by Size and Overall Ranking

Energy

The energy per green ton delivered (1000 Btu) by each candidate location by size is shown in Table 16. The details related to which counties will supply each location by size are located in Appendices B4-Q to B4-S.

	<i>Energy Per Green Ton Harvested/Processed and Delivered (1000 Btu)</i>								
<i>MGY/Green Tons</i>	<i>Manton</i>	<i>Roscommon</i>	<i>Kingsley</i>	<i>Kalkaska</i>	<i>Gaylord</i>	<i>Clare</i>	<i>West Branch</i>	<i>Traverse City</i>	<i>Boyne City</i>
50MGY - 1,250,000	230.163	237.148	238.208	239.768	224.759	248.642	242.113	252.955	250.876
40MGY - 1,000,000	219.643	232.049	226.169	227.812	212.165	236.588	230.804	239.419	236.899
30MGY - 750,000	208.655	224.132	212.310	210.552	196.783	224.896	219.670	222.281	226.694

Table 16 Energy Per Green Ton Harvested/Processed and Delivered (1000 Btu) by Candidate Location by Size

In reviewing the energy consumption data, as the plant size grows, the energy consumed per ton increases. This is because more feedstock is required and transporters have to travel a longer distance to bring the feedstock to the biorefinery. There is no change in the energy consumption on a per ton basis associated with the energy consumption, only

in total because of the higher volume. Energy per ton by plant size was ranked from lowest to highest cost, with the lowest cost receiving a ranking of “1” and the highest cost receiving a ranking of “9”. The rankings are shown in Table 17. The rankings were summed and an overall cost ranking was developed. The best location overall is Gaylord. The worst location (in terms of highest transportation cost per ton) is Boyne City. This in part can be attributed to the fact that feedstock will not be transported over the bridge, even though counties in the Upper Peninsula of Michigan are within the 100 mile radius of this location. This limitation likely added to the increased energy consumption because of greater distance traveled. Traverse City is a close 8 and likely experiences the same issues as Boyne City, with an additional factor of being positioned close to water. If marine transportation is considered at some point in time to transport biomass from the Upper Peninsula to the Lower Peninsula of Michigan, this alternatives ranking would like be more favorable. There was a tie between West Branch and Roscommon. Because West Branch had two plant sizes ranked at 5, this location was arbitrarily chosen as the 5th ranked overall.

<i>Rank Lowest to Highest - Energy Per Green Ton Harvested/Processed and Delivered (1000 Btu)</i>									
<i>MGY/Green Tons</i>	<i>Manton</i>	<i>Roscommon</i>	<i>Kingsley</i>	<i>Kalkaska</i>	<i>Gaylord</i>	<i>Clare</i>	<i>West Branch</i>	<i>Traverse City</i>	<i>Boyne City</i>
50MGY - 1,250,000	2	3	4	5	1	7	6	9	8
40MGY - 1,000,000	2	6	3	4	1	7	5	9	8
30MGY - 750,000	2	7	4	3	1	8	5	6	9
SUM	6	16	11	12	3	22	16	24	25
Overall Rank-Energy	2	6	3	4	1	7	5	8	9

Table 17 Ranking Energy Per Green Ton Harvested/Processed and Delivered (1000 Btu) by Candidate Location by Size and Overall Ranking

Emissions

The emissions per green ton delivered (in pounds) by each candidate location by size is shown in Table 18. The details related to which counties will supply each location by size are located in Appendices B4-T to B4-V.

<i>Emissions Per Green Ton Harvested/Processed and Delivered in Pounds</i>									
<i>MGY/Green Tons</i>	<i>Manton</i>	<i>Roscommon</i>	<i>Kingsley</i>	<i>Kalkaska</i>	<i>Gaylord</i>	<i>Clare</i>	<i>West Branch</i>	<i>Traverse City</i>	<i>Boyne City</i>
50MGY - 1,250,000	47.55381	49.20749	49.45843	49.82775	46.27428	51.92862	50.38295	52.94988	52.45763
40MGY - 1,000,000	45.06329	48.00036	46.60830	46.99726	43.29286	49.07492	47.70560	49.74509	49.14848
30MGY - 750,000	42.46171	46.12606	43.32699	42.91099	39.65114	46.30681	45.06965	45.68781	46.73256

Table 18 Emissions Per Green Ton Harvested/Processed and Delivered in Pounds by Candidate Location by Size

In reviewing the emissions data, as the plant size grows, the emissions generated per ton increases. This is because more feedstock is required and transporters have to travel a longer distance to bring the feedstock to the biorefinery. There is no change in the emissions on a per ton basis associated with the energy consumption, only in total because of the higher volume. Energy per ton by plant size was ranked from lowest to

highest cost, with the lowest cost receiving a ranking of “1” and the highest cost receiving a ranking of “9”. The rankings are shown in Table 19. The rankings were summed and an overall cost ranking was developed. The best location overall is Gaylord. The worst location (in terms of highest transportation cost per ton) is Boyne City. This in part can be attributed to the fact that feedstock will be transported over the bridge, even though counties in the Upper Peninsula of Michigan are within the 100 mile radius of this location. This limitation likely added to the increased energy consumption because of greater distance traveled. Traverse City is a close 8 and likely experiences the same issues as Boyne City, with an additional factor of being positioned close to water. If marine transportation is considered at some point in time to transport biomass from the Upper Peninsula to the Lower Peninsula of Michigan, this alternatives ranking would like be more favorable. There was a tie between West Branch and Roscommon. Because West Branch had two plant sizes ranked at 5, this location was arbitrarily chosen as the 5th ranked overall.

<i>Rank Lowest to Highest - Emissions Per Green Ton Harvested/Processed and Delivered in Pounds</i>									
<i>MGY/Green Tons</i>	<i>Manton</i>	<i>Roscommon</i>	<i>Kingsley</i>	<i>Kalkaska</i>	<i>Gaylord</i>	<i>Clare</i>	<i>West Branch</i>	<i>Traverse City</i>	<i>Boyne City</i>
50MGY - 1,250,000	2	3	4	5	1	7	6	9	8
40MGY - 1,000,000	2	6	3	4	1	7	5	9	8
30MGY - 750,000	2	7	4	3	1	8	5	6	9
SUM	6	16	11	12	3	22	16	24	25
Overall Rank-Emissions	2	6	3	4	1	7	5	8	9

Table 19 Ranking Emissions Per Green Ton Harvested/Processed and Delivered in Pounds by Candidate Location by Size and Overall Ranking

Comparative Table - Overall Rank

Because the overall rankings for each of the locations came up to be the same, there is no real need at this point to change the weighting factors for each of the three variables. However, this option is available. Table 20 shows the comparative analysis. The best location choice is Gaylord with the least desirable location identified as Boyne City.

		<i>Manton</i>	<i>Roscom mon</i>	<i>Kingsley</i>	<i>Kalkaska</i>	<i>Gaylord</i>	<i>Clare</i>	<i>West Branch</i>	<i>Traverse City</i>	<i>Boyne City</i>
Overall Rank - Cost		2	6	3	4	1	7	5	8	9
Overall Rank-Energy		2	6	3	4	1	7	5	8	9
Overall Rank-Emissions		2	6	3	4	1	7	5	8	9
Total Average		2.0	6.0	3.0	4.0	1.0	7.0	5.0	8.0	9.0
Total Ranking		2	6	3	4	1	7	5	8	9
Cost Weight	60%									
Energy Weight	20%									
Emission Weight	20%									
Total Weighted		0.8	2.4	1.2	1.6	0.4	2.8	2	3.2	3.6
Total Weighted Ranking		2	6	3	4	1	7	5	8	9

Table 20 Comparative Overall Ranking

Sensitivity Analysis

The extent of the sensitivity analysis was based on looking at three different sized biorefinery plants. However, more extensive sensitivity analysis can occur by varying the model inputs, allowing for many different variants on the variables that were presented in this report.

Maps Showing Feedstock Requirements for 50 MGY Facility

As indicated in earlier discussion of results, individual plants and multi location configurations indicate there is sufficient feedstock to supply candidate biorefineries within a 100-mile radius. A visual depiction of each candidate location optimal cost supply by county is shown in Appendix B4-W. The shading depicts the counties to supply the candidate location sufficient feedstock for a 50 million gallon per year facility. In most cases it would appear that the feedstock is readily available in somewhere between 50-75 mile radiuses of the candidate facility.

Hardware Requirements

The minimum system requirements (Microsoft Office, 2009) to install Microsoft Office Professional Plus 2007 system products are:

- Computer and processor: 500 megahertz (MHz) processor or higher
- Memory: 256 megabyte (MB) RAM or higher
- Hard disk: 2 gigabyte (GB); a portion of this disk space will be freed after installation if the original download package is removed from the hard drive.
- Drive: CD-ROM or DVD drive
- Display: 1024x768 or higher resolution monitor

The details of the requirements can be found at:

<http://www.microsoft.com/officebusiness/products/technical-requirements.aspx>

Summary

The optimization model, selected locations, and results of study provide one tool for a decision maker to determine the optimal cost, energy consumption, and emissions for candidate locations. Because the optimization model is a static look for a single period of time, it should be utilized in conjunction with the simulation model. The simulation model confirms the one year look but also extends the analysis to consider multiple years of operations. The simulation model considers the operations of a biorefinery over a 20 year period of time and is presented in the next section.

SIMULATION MODEL

Overview

To facilitate the exploration of a wide variety of conditions that promise profitable biomass utilization, a biomass supply chain model has been designed for biofuel production. The model considers key supply chain activities including biomass harvesting/processing, transportation, and storage. In order to have a visual depiction of the proposed supply chain and allow for a comprehensive analysis of the key elements and components to be addressed, an activity model was developed using Integrated DEfinition (or IDEF). This activity model aids in the formulation of the simulation of the biomass supply chain. The simulation model with an easy-to-use graphical user interface has been designed and implemented using the Arena Simulation Software, available from Rockwell Automation. Since the simulation model cannot capture all the features of a supply chain system, a series of assumptions were made to simplify the supply chain and the constraints and limitations introduced by the assumptions are discussed. The model was applied to the potential biofuel facility locations identified in the previous sections and the results are discussed. Finally, future work and possible improvement opportunities regarding the model are identified.

Purpose/Objectives

As previously stated, the model is a simulation of the biomass supply chain for biofuel production in the Lower Peninsula of Michigan. The model simulates the flow of biomass from harvesting areas to the onsite storage at a biomass processing facility. The simulation operates on a set of prescribed rules for harvesting, transporting, and storing biomass. Using the simulation model can better address some uncertainties (e.g., timing of spring breakup) and includes the following capabilities:

- Optimize the location of plant(s) through minimum total cost,
- Minimize energy consumption,
- Minimize emissions,
- Additional outputs may include to:
- Provide dynamic information about daily inventory of the biorefinery;
- Provide cost information, including total cost per year;
- Provide data about energy usage;

- Provide GHG emissions information;
- Examine the reliability of the supply chain to satisfy the daily demand, especially during the spring break-up;
- Find improvement opportunities, simulate alternatives and make comparison. Find the best alternative.

Activity Model

The activity model was developed using a standardized format to aid in the formulation of the biomass feedstock supply chain simulation. Integrated DEFinition (or IDEF) provides a visual depiction of the biomass feedstock supply chain activities and related inputs, outputs, controls, mechanisms, and metrics (Hanrahan, 1995). With a visual depiction of the proposed simulation model, a comprehensive analysis of the key elements and components can be addressed through the entire supply chain. An overview of the model (the first level) is shown in Figure 12. A detailed second level model is shown in Figure 13. The detailed transportation model (third level) is illustrated in Figure 14.

Figure 12 Overview Activity Model

Figure 13 Complete Biomass Feedstock Supply Chain Model

Figure 14 Transportation Model

Model Assumptions

The supply chain activities include harvesting, transportation, and storage at the biomass processing facility. A series of assumptions were made associated with each activity to simplify the supply chain (Zhang, Johnson, Johnson et al., 2011).

Harvesting

- Harvesting areas are defined on a county-basis. The centroid of each county is the starting point of transportation;
- No feedstock will be transported over the bridge from the Upper Peninsula of Michigan. It is assumed that all feedstock in the Upper Peninsula is not available for transport over the bridge and will be consumed by others in the Upper Peninsula;

Biorefinery

- For a biorefinery that produces 50 million gallons of ethanol per year (MGY), the biomass feedstock required is 1,250,000 green tons with a conversion factor of 40 gallons of biofuel per green ton of biomass. The daily demand for biomass feedstock would be about 3,572 green tons assuming that the biorefinery operates 350 days (50 weeks) per year with 2 weeks for maintenance;
- The biorefinery operates on a 24/7 schedule;
- The biorefinery operates 20 years continuously;
- The starting inventory quantity required to commence operations is 25,000 tons of woody biomass for a biorefinery that produces 50 million gallons of ethanol per year;

Transportation

- The transportation radius is assumed to be less than 100 miles;
- Biomass feedstock is delivered by diesel truck. This is important in order to estimate energy consumption and GHG emissions associated with biomass transportation;
- No rail transportation is considered;
- All trucks are initially located at the harvesting areas;
- Trucks have a carrying capacity of 50 tons;
- Trucks are fully loaded for each trip from a harvesting area to the biorefinery;
- Outgoing trucks carry an empty load;
- The truck transportation provider will also provide loading and unloading. No additional/independent loaders/unloaders are necessary;
- Trucks work on a 5-day schedule. No transportation occurs on weekends;
- The number of hours per day that a log truck driver will operate is 5 hours of driving plus 5 hours of loading/unloading;
- During the regular/normal working days (May 1st to October 31st), 40% ($2/5 = 0.4$) more biomass than the daily demand is needed to be harvested due to the 5-day schedule of truck transportation activities; based on the daily demand of 3,572 green tons biomass feedstock at the biorefinery, 100 round trips (50 trucks) ($3,572 \text{ tons per day} * 1.4 / 50 \text{ tons per round trip} = 100 \text{ round trips per day}$) are

needed per day during the regular/normal working days (May 1st to October 31st);

Spring breakup

- Spring breakup, where road load restrictions are in place, is assumed to be March 1 through April 30²⁷ (61 days in this duration) for all the harvesting areas;
- Delivery of feedstock will remain constant during the periods of May 1st through October 31st, while the building inventory phase for spring breakup occurs November 1st through the end of February;
- From November 1st through the end of February, there are about 35 days of weekends (34.32 days on average based on a 25-year (2010-2035) data sample) when there are no transportation activities. Thus the average number of weekdays is about 85 during this period;
- Starting with November 1st, 72% ($61/85 = 0.72$) more biomass than the regular daily demand is needed every day to build up inventory;
- Based on biomass feedstock daily demand of 3,572 green tons at the biorefinery, 122 round trips (61 trucks) ($3,572 \text{ tons per day} * 1.72 / 50 \text{ tons per round trip} = 122 \text{ round trips per day}$) are needed per day from November 1st through the end of February to ensure sufficient inventory during spring breakup;
- Demand for biomass feedstock at the biorefinery during spring breakup is pulled from on site inventory only; there is no offsite storage of inventory. This assumes that there is adequate storage at the biorefinery;

Others

- The moisture content is constant throughout the supply chain (50%); therefore, biomass weight delivered from harvesting areas to the biorefinery remains the same;
- No dry matter loss is taken into account through the supply chain, for example, weight loss during storage due to insect infestation.

Model Description

As has been noted, the model is evaluated using three key performance indicators: the delivered feedstock cost, energy consumption, and GHG emissions. Mathematical models of the three indicators are now presented.

Delivered Feedstock Cost

The delivered feedstock cost consists of a stumpage cost, harvesting/processing cost, and the transportation cost (including loading cost and unloading cost). The stumpage cost is the payment made to land owners. The unit stumpage cost (s , \$/ton) and the unit harvesting/processing cost (h , \$/ton) are assumed to be constant for all the harvesting areas within the study region ($i = 1, 2, \dots, I$) in any time period ($t = 1, 2, \dots, T$). The daily biomass recovery at harvesting area i is defined as q_{it} . The stumpage cost and harvesting/processing cost (C_{sh} , \$) is calculated as:

²⁷ [Michigan State Policy, http://www.michigan.gov/msp/0,1607,7-123-1586_1710-87560--,00.html](http://www.michigan.gov/msp/0,1607,7-123-1586_1710-87560--,00.html), accessed on Sep. 26, 2010.

$$C_{sh} = \sum_{t=1}^T \sum_{i=1}^I (s + h) \cdot q_{it} \quad (7)$$

The transportation cost (C_{tr} , \$) consists of two major terms: one for truck transportation and one for rail transportation. The truck transportation cost has a fixed cost (t_{lu} , \$/ton, which includes one loading and unloading routine) and a variable (distance-dependent) cost (t_d , \$/ton-mile). The transportation cost is calculated as:

$$C_{tr} = \sum_{t=1}^T \sum_{i=1}^I (t_{lu} + t_d \cdot d_i) \cdot q_{it} \quad (8)$$

where d_i is the transportation distance from harvesting area i to the biorefinery.

The total delivered feedstock cost (C_{tot} , \$) is the sum of stumpage cost, harvesting/processing cost, and transportation cost. The calculation is

$$C_{tot} = C_{sh} + C_{tr} \quad (9)$$

Energy Consumption

Energy consumption (Btu) is assumed to only be associated with harvesting/processing and transportation activities. The energy consumed per unit of biomass (Btu/ton) for harvesting/processing is termed f_h , and the truck transportation energy intensity is termed f_{tr} (Btu/ton-mile). The energy used in harvesting/processing (F_h , Btu) is calculated as:

$$F_h = \sum_{t=1}^T \sum_{i=1}^I f_h \cdot q_{it} \quad (10)$$

Transportation energy consumption (F_{tr} , Btu) for truck is calculated as:

$$F_{tr} = \sum_{t=1}^T \sum_{i=1}^I f_{tr} \cdot d_i \cdot q_{it} \quad (11)$$

The total energy consumption (F_{tot} , Btu) is the sum of energy use associated with harvesting/processing, and transportation, and is given by Equation (12):

$$F_{tot} = F_h + F_{tr} \quad (12)$$

GHG Emissions

In terms of the processes that deliver biomass to a processing facility, GHG emissions (lb) are assumed to only be associated with harvesting/processing and transportation activities. w_h is the GHG emissions per unit of biomass (lb/ton) for harvesting/processing and w_{tr} is the truck transportation GHG emission intensity (lb/ton-mile). GHG emissions (W_h , lb) associated with harvesting/processing are then calculated as:

$$W_h = \sum_{t=1}^T \sum_{i=1}^I w_h \cdot q_{it} \quad (13)$$

And, the GHG emissions (W_{tr} , lb) associated with transportation are

$$W_{tr} = \sum_{t=1}^T \sum_{i=1}^I w_{tr} \cdot d_i \cdot q_{it} \quad (14)$$

The total GHG emissions (W_{tot} , lb) are the sum of the emissions associated with

harvesting/processing and transportation:

$$W_{\text{tot}} = W_h + W_{\text{tr}} \quad (15)$$

Simulation Model Using Arena

The development of a biomass feedstock supply chain for a facility considers a number of key activities and processes: biomass harvesting and forwarding to a roadside collection point, transportation from the roadside collection point to a biomass processing facility by truck, and storage at the biorefinery. Size reduction (chipping) activity is assumed to occur at the biofuel facility where the biomass can be processed more efficiently. The purpose of a simulation model is to evaluate the supply chain based on multiple criteria that include the delivered feedstock cost, energy consumption, and GHG emissions. The delivered feedstock cost, as stated earlier, consists of stumpage cost (payment to land owners), harvesting/processing cost, transportation cost (including loading and unloading cost). For the supply chain, energy use and GHG emissions are assumed to be associated with harvesting/processing and transportation activities. The model also tracks the inventory level at the biomass processing facility over time, and picks the most preferable harvesting sites for each facility. The other model consideration is the road restrictions associated with the spring thaw that limits use of truck transportation during that time.

The simulation model was built using Arena Simulation Software. The model consists of three sub-models: reading model inputs, supply activities (including harvesting/processing, transportation and storage at the biomass processing facility), and daily biomass processing. Sub-models communicate with each other via signals. Two types of signals are created: transportation signals (brown arrows in Figure 15) and reading data signals (green arrow in Figure 15). Transportation signals can either come from the reading model inputs sub-model or the daily biomass processing sub-model. Reading data signals are created by the supply sub-model and sent to the reading model inputs sub-model.

The two simulation model drivers are daily demand for biomass feedstock at a biorefinery and the daily biomass recovery at harvesting sites distributed across a harvesting region (the biorefinery is located at one of the nine locations). In other words, it is a combined “pull” and “make-to-order” supply chain system. Each day the biorefinery requires a specified quantity of biomass feedstock from the harvesting areas or on-site storage. Figure 15 illustrates the model logic. The detailed logic for each sub-model is described separately below.

Figure 15 Logic for Biomass Supply Chain Model

Reading Model Inputs

This sub-model (Figure 16) reads two types of data for model configuration before beginning the simulation: biomass inventory levels at a harvesting area within a given region and the transportation distance from the harvesting area to the biorefinery. As has been noted before, two types of signals (transportation signals and reading data signals) are used to exchange information between the three sub-models. On the first operation day in a year, the reading model inputs sub-model starts with initializing some model parameters, for example, the number of days the biorefinery has been operating in a year, and the inventory level at the biorefinery. After initialization, the sub-model checks the month of the year to identify if it is spring breakup. If it is spring breakup, the sub-model does nothing but delays one day and goes back to check the month of the year again. This loop continues until spring breakup ends. On the other hand, if it is not spring breakup or the loop ends, the model will check the day of the week. If it is weekend the sub-model does nothing but delays one day and goes back to check the day of week again. If it is weekday, the sub-model reads inputs for one harvesting area. After the first reading, a transportation signal is created and sent to the harvesting area to inform of the delivery. Then the reading procedure is put on hold waiting for a reading data signal. The reading data signal will be created and sent by the harvesting area when the inventory at the harvesting area is depleted. After the reading data signal is picked up by the reading procedure, it will read the next input (data for the second closest harvesting area to the biorefinery). These iterations will continue until the yearly demand for biomass at the biorefinery is met.

Figure 16 Sub-model Design for Reading Model Inputs

Supply Activities

Supply activities (Figure 17) include biomass harvesting/processing, transportation, and storage at the biomass processing facility. The transportation activity consists of loading transporters, transporting, and unloading transporters at the biorefinery.

Before any signal is received, the sub-model is put on hold. Once the transportation signal is received, the harvesting area starts to harvest a certain amount of biomass which varies based on the month of the year. After the harvesting is done, the sub-model will request a truck for transportation followed by a loading process. When the truck is fully loaded, it routes to the biorefinery. While, at the same time, the biomass inventory level at the harvesting area is updated. If there is still biomass available at the harvesting area, the harvesting procedure will start on the second day. If the harvesting area is depleted, the sub-model will send a reading data signal to the reading model inputs sub-model to shift to the next available harvesting area. The process goes on until the yearly demand for biomass feedstock at the biorefinery is met.

Figure 17 Sub-model Design for Harvesting Areas

At the biorefinery, as trucks arrive they are unloaded and the inventory at the biorefinery is updated. Total truck numbers are also updated as appropriate. The logic for the biorefinery operation is shown in Figure 18.

Figure 18 Sub-model Design for Biorefinery Operations

Daily Biomass Processing

This daily biomass processing sub-model (Figure 19) is responsible for dictating the daily biomass demand at a biorefinery. Each day a production target (control entity) is issued and then the biorefinery prepares a certain amount of biomass either from the on-site inventory or using fresh biomass (biomass that is delivered to the biorefinery on the day it is needed) to process based on the daily requirement/production target. If the biorefinery is experiencing a biomass feedstock shortage, the sub-model sends a transportation signal to inform of the supply sub-model of the low inventory situation.

Figure 19 Sub-model Design for Biomass Processing

Screen Shots of Model Input

Parameter Input

An easy-to-use graphical user interface has been developed for the simulation model. The interface (Figure 20) allows users to enter data into one or more of the model parameters before running the model. The model parameters are classified into four categories: cost coefficients, energy intensity coefficients (Btu/ton-mile), GHG emission coefficients (lbs/ton-mile), and biorefinery size options. The first three coefficients are only related to the transportation activity. The transportation cost consists of two parts: fixed cost (\$/ton, including loading and unloading cost) and distance-dependent variable cost (\$/ton-mile). Users can also select a plant size of 30 MGY, 40 MGY, or 50 MGY.

FBSCC Simulation Model V1.0

Cost Coefficient

fixed cost, truck (\$/ton) 3.72

variable cost, truck (\$/ton-mile) 0.074

Energy intensity coefficient

truck operations & maintenance (Btu/ton-mile) 1592.4

Emissions (CO₂ eq) coefficient

truck operations & maintenance (lb/ton-mile) 0.384

Biorefinery size (MGY)

☐ 30

☐ 40

☒ 50

OK

Figure 20 Graphical User Interface

Data Input

The model also reads two types of data for model configuration before beginning the simulation: biomass inventory level at a harvesting area within a given region and the transportation distance from the harvesting area to the biorefinery. The model inputs are organized in macro enabled Microsoft Excel format by harvesting area and by year. As an example, take the input file for the Manton facility location (Table 21). In Table 21, only the first three years' data are shown. The first column contains the 37 potential harvesting areas (suppliers) for the Manton facility ordered by distance. The harvesting areas are specified and will keep the same for 20 years. The transportation distance is derived using the rectilinear distance function. The initial values of the distance are calculated from the center of a harvesting area to the center of the facility location. The amount of biomass available for biofuel production in each harvesting area represents net forest growth each year. Users can enter new data or change the current data for transportation distance and biomass availability. Note that every time users make a

change to the distance values for the first year, the table will automatically sort from the smallest to the largest by distance. The distance values from the second year to the 20th year will be filled automatically according to the first year distance value. The two types of inputs for each year (20 years in all) are organized in the same way.

Harvesting Area	year1		year2		year3	
	distance (mile)	biomass (50 tons)	distance (mile)	biomass (50 tons)	distance (mile)	biomass (50 tons)
Wexford	13.862	4911	13.862	4911	13.862	4911
Missaukee	20.151	3868	20.151	3868	20.151	3868
Grand Traverse	25.728	2358	25.728	2358	25.728	2358
Osceola	33.021	2801	33.021	2801	33.021	2801
Kalkaska	34.15	3436	34.15	3436	34.15	3436
Manistee	37.986	4124	37.986	4124	37.986	4124
Roscommon	43.864	2978	43.864	2978	43.864	2978
Benzie	46.018	2027	46.018	2027	46.018	2027
Lake	48.94	4942	48.94	4942	48.94	4942
Antrim	53.136	2697	53.136	2697	53.136	2697
Clare	56.676	3089	56.676	3089	56.676	3089
Leelanau	56.721	978	56.721	978	56.721	978
Mecosta	57.339	3239	57.339	3239	57.339	3239
Crawford	58.042	2416	58.042	2416	58.042	2416
Ogemaw	67.463	2450	67.463	2450	67.463	2450
Mason	70.919	4203	70.919	4203	70.919	4203
Charlevoix	74.514	1935	74.514	1935	74.514	1935
Newaygo	78.924	5875	78.924	5875	78.924	5875
Gladwin	78.994	2418	78.994	2418	78.994	2418
Isabella	81.031	2958	81.031	2958	81.031	2958
Otsego	81.523	5498	81.523	5498	81.523	5498
Oscoda	82.053	4735	82.053	4735	82.053	4735
Montcalm	88.884	3680	88.884	3680	88.884	3680
Iosco	89.638	3187	89.638	3187	89.638	3187
Oceana	96.323	4469	96.323	4469	96.323	4469
Arenac	97.706	2377	97.706	2377	97.706	2377
Emmet	101.01	2780	101.01	2780	101.01	2780
Kent	102.064	3898	102.064	3898	102.064	3898
Midland	103.189	2104	103.189	2104	103.189	2104
Montmorency	105.497	4001	105.497	4001	105.497	4001
Alcona	109.381	4237	109.381	4237	109.381	4237
Muskegon	114.708	4524	114.708	4524	114.708	4524
Cheboygan	115.246	4506	115.246	4506	115.246	4506
Gratiot	117.374	1313	117.374	1313	117.374	1313
Bay	118.366	589	118.366	589	118.366	589
Alpena	131.073	2438	131.073	2438	131.073	2438
Presque Isle	137.05	2972	137.05	2972	137.05	2972

Table 21 Model Inputs for a Manton Facility

Discussion of Results

As main outputs, the simulation model provides estimates of the delivery cost, energy consumption, and greenhouse gas (GHG) emissions for different facility locations and different plant sizes. The delivery cost is a sum of loading cost, transportation cost, and unloading cost. No stumpage and harvesting costs are calculated in this model due to the assumption that all harvesting areas have the same stumpage and harvesting costs. Other important outputs of the model are tracking the inventory level at the biomass processing facility over time, and picking the most preferable harvesting sites for each biofuel facility.

One simulation was run for a biofuel facility of 50 million gallons per year (MGY) in the city of Gaylord, Michigan. The start date for the simulation was set as Nov 1st, 2011 and the model run length was 350 days a year, 20 years in total. The time step during the simulation was set as one day. The inventory (tons) changes as a function of time following the pattern demonstrated in Figure 21. A better look at the first year operation is shown in Figure 22. In Figure 22, it is obvious that there are three phases in the chart. For the first 4 months (Nov 1st to Feb the end), the harvesting areas provide 72% more biomass each day than the daily demand to build up the inventory. Starting with March 1st, the spring thaw starts and no biomass is allowed to be transported. The daily requirement for biomass at the biorefinery is met by pulling biomass from inventory only. When spring breakup ends at the end of April a regular operation plan (daily demand is met by daily transportation) is executed, and the inventory essentially equals to the initial inventory level (25,000 tons). Table 22 shows the eight most preferable harvesting areas (ordered by the distance from a harvesting area to the facility) for supplying the Gaylord plant.

Figure 21 Inventory level for a Facility Size of 50 MGY in Gaylord Operating 20 Years

Figure 22 A Better Look at the First Year Operation

Order	Harvesting Area	Rectlinear Distance (mile)	Biomass (green tons)
1	Otsego	4.023	274,920
2	Antrim	24.754	134,827
3	Crawford	27.196	120,789
4	Montmorency	27.607	200,041
5	Cheboygan	37.356	225,280
6	Charlevoix	40.748	96,751
7	Kalkaska	43.740	171,816
8	Emmet	44.968	28,450

Table 22 Eight Most Preferable Harvesting Areas for Supplying Gaylord Plant

A series of simulations were run for each of the nine potential biofuel facility locations. The facilities can have a size of producing 30, 40 or 50 million gallons of biofuel per year. The outputs of the three system performance indicators were shown in Table 23. The tables in the left column are total measurement and the right ones are average measurement. Based on the average measurements, it is obvious that Gaylord is the best facility location due to the lowest unit delivery cost, the lowest unit energy use, and the lowest unit GHG emissions regardless of plant size. Traverse City is the least favorable location to build a biofuel facility of producing 40 or 50 million gallons of biofuel per year, while Boyne City is the least favorable location for a 30 MGY biofuel facility. If a comparison is made among the three different facility sizes at one location, a 30 MGY biofuel facility is the best plant size due to the lowest unit delivery cost, the lowest unit energy use, and the lowest unit GHG emissions.

Gaylord	indicators	total			Indicator	Average		
		50 MGY	40 MGY	30 MGY		50 MGY	40 MGY	30 MGY
	cost (1000 \$)	9810.66	7239.59	4882.29	cost (\$/ton)	7.8485	7.2396	6.5097
	energy use (Mill Btu)	110824	75546	44884	energy use (Mill Btu/ton)	88659	75546	59845
	GHG emissions (ton)	13118.72	8942.7	5313.1	GHG emissions (lb/ton)	20.9900	17.8854	14.1683
Boyne City	indicators	total			Indicator	Average		
		50 MGY	40 MGY	30 MGY		50 MGY	40 MGY	30 MGY
	cost (1000 \$)	11318.09	8386.8	5932.23	cost (\$/ton)	9.0545	8.3868	7.9096
	energy use (Mill Btu)	143418	100356	67477	energy use (Mill Btu/ton)	114734	100356	89969
	GHG emissions (ton)	16977.07	11879.68	7987.62	GHG emissions (lb/ton)	27.1633	23.7594	21.3003
Manton	indicators	total			Indicator	Average		
		50 MGY	40 MGY	30 MGY		50 MGY	40 MGY	30 MGY
	cost (1000 \$)	10101.17	7592.22	5286.78	cost (\$/ton)	8.0809	7.5922	7.0490
	energy use (Mill Btu)	117075	83134	53668	energy use (Mill Btu/ton)	93660	83134	71557
	GHG emissions (ton)	13858.75	9840.96	6352.94	GHG emissions (lb/ton)	22.1740	19.6819	16.9412
Roscommon	indicators	total			Indicator	Average		
		50 MGY	40 MGY	30 MGY		50 MGY	40 MGY	30 MGY
	cost (1000 \$)	10472.69	8145.89	5835.68	cost (\$/ton)	8.3782	8.1459	7.7809
	energy use (Mill Btu)	125226	95192	65400	energy use (Mill Btu/ton)	100181	95192	87200
	GHG emissions (ton)	14823.6	11268.37	7741.68	GHG emissions (lb/ton)	23.7178	22.5367	20.6445
Kingsley	indicators	total			Indicator	Average		
		50 MGY	40 MGY	30 MGY		50 MGY	40 MGY	30 MGY
	cost (1000 \$)	10565.57	7900.33	5425.88	cost (\$/ton)	8.4525	7.9003	7.2345
	energy use (Mill Btu)	127225	89784	56661	energy use (Mill Btu/ton)	101780	89784	75548
	GHG emissions (ton)	15060.2	10628.18	6707.26	GHG emissions (lb/ton)	24.0963	21.2564	17.8860

Kalkaska	indicators	total			Indicator	Average		
		50 MGY	40 MGY	30 MGY		50 MGY	40 MGY	30 MGY
	cost (1000 \$)	10653.66	7977.31	5364.66	cost (\$/ton)	8.5229	7.9773	7.1529
	energy use (Mill Btu)	129120	91441	55344	energy use (Mill Btu/ton)	103296	91441	73792
Clare	GHG emissions (ton)	15284.58	10824.26	6551.33	GHG emissions (lb/ton)	24.4553	21.6485	17.4702
	indicators	total			Indicator	Average		
		50 MGY	40 MGY	30 MGY		50 MGY	40 MGY	30 MGY
	cost (1000 \$)	10847.44	8140.26	5685.37	cost (\$/ton)	8.6780	8.1403	7.5805
West Branch	energy use (Mill Btu)	133134	95031	62245	energy use (Mill Btu/ton)	106507	95031	82993
	GHG emissions (ton)	15759.71	11249.3	7368.25	GHG emissions (lb/ton)	25.2155	22.4986	19.6487
	indicators	total			Indicator	Average		
		50 MGY	40 MGY	30 MGY		50 MGY	40 MGY	30 MGY
Traverse City	cost (1000 \$)	10815.45	8125.22	5667.31	cost (\$/ton)	8.6524	8.1252	7.5564
	energy use (Mill Btu)	132446	94644	61869	energy use (Mill Btu/ton)	105957	94644	82491
	GHG emissions (ton)	15678.22	11203.41	7323.67	GHG emissions (lb/ton)	25.0852	22.4068	19.5298
	indicators	total			Indicator	Average		
		50 MGY	40 MGY	30 MGY		50 MGY	40 MGY	30 MGY
	cost (1000 \$)	11451.83	8514.55	5779.91	cost (\$/ton)	9.1615	8.5146	7.7065
	energy use (Mill Btu)	146168	103001	64280	energy use (Mill Btu/ton)	116934	103001	85706
	GHG emissions (ton)	17302.59	12192.76	7609.09	GHG emissions (lb/ton)	27.6841	24.3855	20.2909
	indicators	total			Indicator	Average		
		50 MGY	40 MGY	30 MGY		50 MGY	40 MGY	30 MGY

Table 23 System Performance Indicators for Different Facility Locations and Different Plant Sizes

Hardware Requirements

Minimum System Requirements

The minimum system requirements to run the simulation model are (Rockwell Automation, 2011):

- Arena simulation software, version 13 (or newer)
- Hard drive with 1GB free disk space (or more)
- 2GB RAM (or more)
- Intel dual-core processor (or more), 3GHz or faster

Recommended System Requirements

The recommended system requirements to run the simulation model are (Rockwell Automation, 2011):

- Arena simulation software, version 13.0 (or newer)
- Hard drive with 4GB free disk space (or more)
- 4GB RAM (or more)
- Intel dual-core processor (or more), 3GHz or faster

The details can be found at:

http://www.arenasimulation.com/Files/Requirements_13.9.pdf.

Model Constraints/Limitations

The model is a simplification of a biomass supply chain system for biofuel production. A series of assumptions were made to simulate the supply chain system. As a result, some of the processes in the model may not be able to capture all the features in the real world. The limitations produce two types of uncertainties inherent to the model: data uncertainty and model uncertainty (National Research Council, 2007).

- Due to the minimum resolution available for the harvesting areas is county, the assumption of defining a county as one harvesting area introduces uncertainties. In the real world, one county can be split into several harvesting areas;
- The starting point of transportation in real is not the county centroid;
- The amount available from private landowners is largely unknown and subject to a high level of uncertainty and variability. There are numerous factors that impact the availability which were not fully evaluated in this report.
- The conversion factor that defines gallons of biofuel per green ton of biomass could produce varies based on the conversion technology adopted at the biorefinery, the feedstock type used, and so on. And the conversion efficiency may be improved over time. In this model, the assumption of a conversion factor of 40 gallons biofuel per green ton of biomass may introduce uncertainty;
- The assumption of all trucks are initially located at the biorefinery may produce uncertainty. In real, trucks are initially located in transportation companies.
- In the model, no backhaul is considered. In reality, a certain percent of backhaul may be practical;
- Truck breakdown and weather delay are not considered in the model;

- Spring breakup, where road load restrictions are in place, is not calendar based as assumed in the model. It depends on geological locations, weather conditions, soil types and so on.
- Although road weight limits are enforced during spring breakup, transportation can still take place by reducing truck loads;
- The moisture content may keep changing throughout the supply chain;
- Dry matter loss may be caused through the supply chain due to a series of reasons, for example, weight loss during storage due to insect infestation.

Similarities and Differences

The two models (the optimization model discussed in section 6 and the simulation model described in section 7) built for the biofuel supply chain addressed different supply issues, while they also share similarities. Both models can be used to rank the nine potential biofuel facility locations identified in previous sections. In other words, the two models can be used to identify the optimal biofuel facility location in the study area. Both models used the delivered feedstock cost, GHG emissions, and energy consumption as system performance criteria. Both models can be applied to a single location for one year operation. Since both models cannot capture all the features of a supply chain system, a series of assumptions were made to simplify the supply chain and corresponding constraints and limitations applied.

The optimization model is a static, Excel-based application which allows for sensitivity analysis by changing inputs to evaluate different scenarios. The optimization model was demonstrated using single location and three multi-location configurations. For the single location models, cost, emissions, and energy were minimized to optimize the individual attributes. In the case of the multi-location configurations, only cost was evaluated. The optimization model is for a single period of time, but can be applied to multiple years assuming there are no changes in data inputs. Since the optimization model is a static model considering only one year operation, the optimization model cannot evaluate the impacts of spring breakup period on biomass supply and demand, and cannot be used to track inventory level or estimate truck requirements.

Compared with the optimization model, the simulation model represents a more dynamic look at a 20-year operation by considering the impacts associated with building inventory at the biorefinery to address the limited availability of biomass feedstock during the spring breakup period. The simulation model was developed using single location over a 20 year period of time. The assumed starting inventory along with increased inventory prior to spring break up was designed to deal with limited supply during that time period. The number of trucks required per day is estimated and the inventory level all year around was tracked. Also the potential optimal suppliers (harvesting areas) were selected based on the three system performance criteria (the delivered feedstock cost, energy consumption and GHG emissions). Through the exchange of information across different procedures (harvesting procedure, transportation procedure, and biomass feedstock processing procedure), a smooth flow of biomass from harvesting areas to a biofuel facility was implemented.

Compared with existing supply chain models discussed in the literature review section, both models considered different feedstock type, harvesting/preprocessing procedures, transportation modes and plant locations. The both models used roundwood or/and forest residue as biomass feedstock while other types of biomass (energy crops, agriculture residues etc.) can be easily added. The both models did not consider size reduction (chipping) procedures which are assumed to happen at a biorefinery. The truck transportation is the only option considered in the two models due to the lower cost, while existing supply chain models consider multiple transportation modes including water, railway and sometimes pipelines. The two models were applied in the Lower Peninsula of Michigan which is different from existing supply chain models in the literature which considers nationwide or a different study area.

Summary

To reduce carbon emissions and reduce U.S. dependence on imported oil, renewable biofuel production from biomass has received increasing interest. However, due to the distributed nature of biomass feedstock, the cost and complexity of biomass recovery operations result in significant challenges that hinder increased biomass utilization for energy production. To facilitate the exploration of a wide variety of conditions that promise profitable biomass utilization, a supply chain model has been designed and implemented using Arena Simulation Software. The model considers key activities of the supply chain, including biomass harvesting/processing, transportation, and onsite storage. The supply chain is driven by both daily demand for biomass feedstock at a biorefinery and daily biomass recovery at harvesting sites. The model is evaluated using three key performance indicators: the delivered feedstock cost, energy consumption, and GHG emissions. The model also considered road restrictions associated with spring breakup that limit use of truck transportation on certain roads. The utility of the supply chain simulation model has been demonstrated through a series of simulations that considers a supply chain for biomass feedstock for several biorefinery locations in the Lower Peninsula of Michigan.

Future Work

Future work will focus on refining the model to incorporate uncertainties listed in the model limitation section. The graphical user interface needs to be improved as well. Another consideration may include integrating inventory holding cost. The possibility of applying the model (subject to minor revisions) to other regions in the United States may be investigated.

3. Infrastructure Analysis

Overview

An infrastructure analysis was conducted to investigate the feasibility of growing the transportation infrastructure in order to realize the necessary network system needed to transport sufficiently large volumes of biomass in the Lower Peninsula of Michigan. The analysis is conducted on the road transportation network and equipment by examining existing roads and truck fleets as well as comparing with the needs for road and truck

infrastructure forecasted for the supply chain model. The capital investment on road and truck infrastructure is also discussed.

Purpose/Objective

Driven by the concern regarding the effects of greenhouse gases on global warming, biofuel production from renewable biomass has been receiving increased attention lately. Growing biofuel requirements pose considerable challenges to the infrastructure needed across all stages of the supply chain, such as biomass feedstock harvesting/processing, and transportation. The purpose of the infrastructure analysis was to address shipment routing decisions or/and biofuel facility location decisions, with the objective to minimize the total cost including the transportation costs and the cost for infrastructure investment. The analysis identifies and evaluates the existing road and truck infrastructure. The information gained through the analysis will provide direction for possible solutions that can incorporate existing transportation networks and technologies and leverage existing investments in the networks and technologies.

Discussion

To reduce carbon emissions and reduce U.S. dependence on imported oil, renewable biofuel production from biomass has received increasing interest. However, due to the distributed nature of biomass feedstock, the complexity of biofuel supply chain result in significant challenges that hinder increased biomass utilization for energy production (Iakovou et al., 2010; Rentizelas et al., 2009). One particular aspect of the biofuel supply chain is that biomass transportation (i.e., routing) should be considered endogenously with biofuel facility location decisions (Bai et al., 2011).

In the biofuel supply design literature, comprehensive mathematical models have been proposed to address shipment routing decisions or/and biofuel facility location decisions, with the objective to minimize the total cost including the transportation costs and the cost for infrastructure investment (Bai et al., 2011). The biomass and ethanol routing problems can be modeled as a traffic assignment problem, which determines traffic flow on a network that achieves certain optimal criteria (e.g., user equilibrium or system optimum) (Bai et al., 2011). Such problems can be solved efficiently by the convex combination method (Frank and Wolfe, 1965; Sheffi, 1985), the disaggregated simplicial decomposition method (Larsson and Patriksson, 1992), the gradient projection method (Jayakrishnan et al., 1994), and the origin-based assignment method (Bar-Gera, 2002), among others. The biofuel facility location problem can be modeled as a fixed-charge facility location problem, which is nonlinear (NP)-hard but can be solved effectively by techniques such as Lagrangian relaxation. Bai et al. (2011) proposed a variety of solution approaches based on combinations of Lagrangian relaxation, liner programming relaxation, branch and bound and convex combination in order to solve the integrated model of addressing both facility location and shipment routing problems.

The mathematical model proposed by Bai et al. (2011) can serve as a basis for the development of supply chain management decision support tools. Bai's model focuses on planning biofuel facility locations where the total system cost for biofuel facility investment, biomass and ethanol transportation and public travel is minimized. Bai's

model is similar to our model at finding biofuel facility locations while minimize transportation cost. The difference is our model will only consider biomass shipment routing problem, not considering ethanol distribution issues as Bai's model. Our model may consider other optimal criteria, such as minimizing energy consumption and GHG emissions, other than just transportation cost.

The biofuel facility location decision has been made based on a GIS-based method presented in Section 4: Identification of Candidate Locations. Nine potential biofuel facility locations were identified. Further analysis on ranking the nine candidate locations can be made either by the optimization model in section 6 or the simulation model in section 7. However, as has been noted, latitude and longitude coordinates are used from the related centroid of the harvesting areas to the nine potential biofuel facilities in order to estimate the transportation distances. It is necessary to examine the existing transportation networks to identify whether these infrastructures are sufficient for large volumes of biomass delivery. For the biofuel supply chain, only the road transportation network is considered. Therefore, the existing road (e.g., national highway, major road, and county road) and truck infrastructures are examined. See Appendix B4-B for the maps having information regarding the road transportation network.

In the third quarter report of FBSCC from MTU, the truck fleet size for the State of Michigan has been identified by Task B1: *Evaluation Michigan Biomass Transportation Systems*. The truck fleet was split between the Upper and Lower Peninsula's. From this report, 405 trucks are available within the Lower Peninsula region. As has been noted, to meet the demand for biomass at a biorefinery, which produces 50 million gallons of biofuel per year, 50 trucks (more than 12% of the truck fleet size) are needed on regular working days (May 1st to October 31st) and 61 trucks (more than 15% of the fleet size) needed per day from November 1st through the end of February to prepare the inventory for the coming of spring breakup. The large size of truck fleet required to transport sufficiently large volumes of biomass may be not met using current truck fleet in the Lower Peninsula region. Therefore, new investment may be required on new equipment for biomass transportation. However, the exact number is dependent on the number of roundtrips in a day and distance driven.

There is a significant capital investment that is required by developers of the infrastructure along with the transportation companies supporting the increased volumes. A critical ingredient is to sufficiently identify the optimal costs associated with capital investment along with the required maintenance and operational costs for longer-term viability and sustainability. The capital investment costs will be split between infrastructure (e.g., roads) and equipment (e.g., trucks). Identification of the associate maintenance and operating costs will also be included.

Summary

To expand the biofuel industry, it is important to examine the existing transportation networks and technologies to identify whether they are sufficient for large volumes of biomass delivery for the increasing biofuel industry. Bai's model (2011) was suggested to serve as a basis for the infrastructure analysis in order to investigate the feasibility of

growing infrastructure to be able to realize the necessary scales to transport sufficiently large volumes of biomass in the Lower Peninsula of Michigan. The analysis is made on road transportation network and equipment by examining existing roads and truck fleets and comparing with the needs for road and truck infrastructure forecasted for the supply chain model. The capital investment on road and truck infrastructure is also discussed.

4. Overall Summary and Conclusion

Summary

The data and results in this report represent a snapshot in time. Because of the flexibility of the models to accept input as new data becomes available, it allows prospective users to evaluate different scenarios and conduct sensitivity analysis to meet their needs. Each of the sections in the paper outlines the results from the optimization and simulation models. With any study, there are limitations that a decision maker needs to be aware of. The next section outlines some of the potential limitations associated with this study and report.

Limitations

This study was conducted using an aggregated approach. Although the results provide some initial insights into potential locations for a biorefinery plant, the following are limitations of this study:

- Limited to selected locations,
- Aggregate feedstock data and availability,
- Expansion of supply chain,
- Stability of feedstock supply,
- Distance calculations,
- Limited transportation modes,
- Transportation costs,
- Harvest/processing cost and stumpage prices,
- Known and unknown competing uses,
- Preprocessing unknown, and
- Processing technology for fuel production is unknown.

Each of these limitations is discussed below.

Selected Locations

The ideal situation would allow for the selection of a location based on the greatest amount of feedstock available close by. If the evaluation considered only one location, this approach would be feasible. Reviewing multiple locations at the same time required identification of desirable selection criteria for candidate locations. This approach allowed for evaluating multiple locations concurrently but does have its limitation as that the locations are fixed and so are the results from the models.

Aggregate Feedstock Data and Availability

The classification of woody biomass was at an aggregate level of hardwood and softwood without differentiation to different species within each of those classes. Most

engineering design studies have indicated specific species of hardwood and processing technologies as desirable for cellulosic ethanol production, if this is the biofuel of choice. An additional factor for consideration is the percentage of each of hardwood or softwood that is roundwood or logs and the percentage of forest residues. This is an option in the entry screens.

Much of the data on historical removals are based on actual removals. The decline in pulp and paper production does allow for sufficient availability for other uses but determining the exact quantities can only be based on historical information. The exact amount of expansion relies heavily on estimates. This information was outlined in an earlier section.

Expansion of supply chain

The woody biomass supply chain is well developed and has been in existence for many years supporting lumber, furniture, pulp and paper, and a number of other industries with fiber. The market has seen some retrenchment because housing starts are down and production in the pulp and paper industry. This has caused a reduced demand and resulted in the lowering of prices for delivered woody biomass. It is anticipated that the biofuels industry will increase demand to exceed prior levels. The question is, “How much can the supply chain expand to reliably meet the growing demand?” It is not a matter of sufficient woody biomass but more of an issue of whether the demand can be met when needed at a price that is affordable and with adequate quality to meet the producers’ or refiners’ needs.

The harvesting/processing provides two primary products: logs and forest residue. One does not exist without the other. The supply chain for logs is well developed. The supply chain for forest residue is developing as some of the residue will remain in the forests and some would be available for biomass fired electric plants or perhaps in the future, biofuels that can use the forest residues.

Stability of Feedstock Supply

The demand for roundwood and the highest quality fiber is going to initially exceed the demand for forest residues. The expansion and supply is highly dependent on a supply chain of independent operators and private owners. The loggers/transporters represent a large stakeholder in the process and also can make or break the success of the biorefinery industry. The need to develop a supply chain for forest residues that is more formalized would be useful, especially for biomass fired electric plants.

Distance calculations

The distance calculations were based on the rectilinear distance using the latitude and longitude of the centroid of each of the counties to the candidate locations. Because of the number of locations and the limited scope of the project, the results represent an estimate with limited variability. This does represent a close approximation, especially if the road system is in grids. The only possible adjustment would have been to consider adding a tortuosity factor²⁸ to take into consideration curves in the road. But since each location is unique, this could require multiple factors and many inputs into the model.

²⁸ The ratio of actual distance travelled to straight line distance.

Limited transportation modes

Exclusive use of truck transportation may be a limiting factor in this study. Prior work had indicated that transportation distances less than 100 miles will be more economically served by truck instead of multimodal truck/rail or rail (Hicks, 2009). Some counties did not have rail access, which poses further limitations. Another possible future consideration may be to consider transport by barge from the Upper Peninsula of Michigan or adjacent states such as Minnesota and Wisconsin.

Transportation costs

The transportation cost is based on a study conducted in 2009 when diesel fuel prices were lower than the current levels (Hicks, 2009). The results contained for the FBSCC study were based on the models provided. However, input cells are available in both models to update these parameters as new information becomes available.

Harvest/processing cost and stumpage prices

Task B2.5 *Select feasible processing technologies* and B2.6 *Analyze supply chain cost of processing technologies* are evaluating the potential costs associated with harvesting and processing

Known and unknown uses

There are two known future uses of woody biomass that were identified earlier in the report. The biorefinery in the eastern portion of the Upper Peninsula of Michigan will be using woody biomass from the upper portion of the Lower Peninsula of Michigan, as indicated as the overlapping area in this study. It is not known if all sources of woody biomass for the planned Mancelona biomass fired electric plant will come from Michigan or from outside of Michigan (i.e., Wisconsin). There are other potential uses that have not been confirmed. For example, there is some indication that in the upper portion of the Lower Peninsula there is consideration for a pellet operation.

Preprocessing unknown

It is likely that preprocessing, such as bark removal, will occur. It is unknown whether this preprocessing will occur at the landing, roadside, or biorefinery location. Other preprocessing such as chipping and shredding could occur. Without knowing this information, it was not included in any evaluation associated with this project.

Processing technology for fuel production is unknown

There are different processing technologies for producing biofuels. Since no specific technology was specifically indicated in this study, attributes or variables associated with processing technologies were not included as a part of this study.

5. Proposed Future Work

The pilot project was limited in scope to the upper portion of the Lower Peninsula of Michigan. Initially the project was planned to encompass the entire state of Michigan but because of the possible size of the project and the limited time span to complete the

project, a scope that was appropriate to the time and resource availability was completed. There are several possible expansions of work and include:

- 1) Differentiating feedstock species,
- 2) Identifying other possible industries to include beyond biorefineries and look at other related industries such as biomass fired or co-fired power operations,
- 3) Evaluating the impact on the expansion in the supply chain from a behavioral as well as a quantitative perspective,
- 4) Determining the maximum resource consumption of forest residues and roundwood that would allow for maintaining sustainable forest management practices,
- 5) Considering a mix of feedstock, to include agricultural residues such as corn stover,
- 6) Studying the co-location of a biorefinery with a biomass fired electric plant or pulp and paper operations to determine if there are possible synergies and whether it is feasible,
- 7) Expanding the scope to the rest of the state of Michigan,
- 8) Expanding the scope to a Midwestern focused study to include the states of Wisconsin and Minnesota,
- 9) Expanding the modes of transportation,
- 10) Identifying if there are additional decision criteria need to determine candidate locations, and
- 11) Evaluating the potential retooling of former pulp and paper locations that have been closed (i.e., Gaylord).

This represents a possible list of additional work to expand the scope of work. It is not intended to be all-inclusive but to represent a starting point for consideration of future projects to enhance the output from this study.

6. List of Publications and Presentations Associated with Research

1. Johnson, D. M., Zhang, F., Harrison, E., and Hanninen, K., (2011) "Comparative Review of Biofuel Supply Chains," Decision Sciences Institute 42nd Annual Meeting, Boston, MA, USA Nov 19 to 22, 2011 (accepted).
2. Zhang, F., Johnson, D. M., and Sutherland, J. W., (June 2011) "A GIS-Based Method for Identifying the Optimal Location for a Facility to Convert Forest Biomass to Biofuel," Biomass and Bioenergy.
3. Zhang, F., Johnson, D. M., Johnson, M. A., and Sutherland, J. W., (2011) "Development of a Biomass Supply Chain for Biofuel Production," 2011 Industrial Engineering Research Conference, Reno, Nevada May 21-25, 2011.
4. Zhang, F., Handler, R., Johnson, D. M., and Shonnard, D. R., (2011) "Comparative Analysis of Life Cycle Greenhouse Gas Emissions of Supply Chains for Biofuel and Fossil Fuel Production," Production and Operations Management Society (POMS) 22nd Annual Conference, Reno, Nevada, USA April 29 to May 2, 2011.

5. Zhang, F., Johnson, D. M., and Sutherland, J. W., (May 2010) “GIS-based Approach of Identification of the Optimal Pulpwood-to-Biofuel Facility Location in Michigan's Upper Peninsula,” POMS 21st Annual Conference, Vancouver, Canada.

Conference Presentations

6. Johnson, D. M., Zhang, F., and Sutherland, J. W., (May 2010) “GIS-based Approach of Identification of the Optimal Pulpwood-to-Biofuel Facility Location in Michigan's Upper Peninsula,” POMS 21st Annual Conference, Vancouver, Canada.
7. Johnson, D. M., Zhang, F., Handler, R., and Shonnard, D. R., (April 29 to May 2, 2011) “Comparative Analysis of Life Cycle Greenhouse Gas Emissions of Supply Chains for Biofuel and Fossil Fuel Production,” Production and Operations Management Society (POMS) 22nd Annual Conference, Reno, Nevada, USA.
8. Zhang, F., Johnson, D. M., Johnson, M. A., and Sutherland, J. W., (May 21-25, 2011) “Development of a Biomass Supply Chain for Biofuel Production,” 2011 Industrial Engineering Research Conference, Reno, Nevada.

7. Website Associated with Research

The public webpage (Figure 23) is a part of the outreach component for the FBSCC project. It includes a page that summarizes the supply chain component of the FBSCC project (Task B4). Basically we summarized the research questions and the approach employed to address the questions. We also have a section for a brief description of the project progress and results, where the literature gap analysis and initial location selection were attached. More details can be found at:

<http://biofuels.confidentialdelivery.com/research-project/feedstock-supply-chain-landing-biorefinery>

Michigan Forest Biofuels Research

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Feedstock Supply Chain from Landing to Biorefinery

We want to know how many biorefineries Michigan can support, given current and future demands on woody materials.

Research question

Woody biomass feedstock can include logs, forest residues, and energy crops. We want to know how many biorefineries can be supported by the current and future feedstock in the northern lower peninsula of Michigan, and what the optimum locations and sizes of these refineries might be. Is there sufficient material to support more biorefineries in Michigan given that biomass is currently needed by biomass-fired utility operations, pulp and paper mills, and a planned biorefinery in Michigan's Upper Peninsula? The distributed nature of biomass feedstock, and the cost and methods of biomass recovery operations add complexity to these questions, which are critical for increasing biomass energy production in Michigan.

Approach

A series of steps that we used to address these questions are outlined. First, we developed a Geographic Information System (GIS)-based multi-criteria approach to select the best facility locations for biofuel production. Second, we used a simulation tool to address uncertainties in the transportation and storage of biomass (e.g., timing of spring melt). Last, we used a multi-objective optimization technique to identify optimal decisions and evaluate the economic, environmental, and societal impacts of using forest resources as feedstock for biofuel production in Michigan. Other tools will be added, if necessary, in later phases of this project.

Progress and Results

Several products have been developed and are available below.

- Gap Analysis
- Initial Location Selection

Events & Postings

Announcement : Watch a new video on sustainable timber harvesting
Announcement : New document available on Forest Feedstock Inventory

How much forest-based biomass is available?

How can woody fuel material be sustainably produced?

How can we efficiently harvest, move and produce biofuel?

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Figure 23 The website for supply chain component of the FBSCC project (Task B4)

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USER'S DOCUMENTATION – OPTIMIZATION MODEL

Introduction

The optimization model was designed as a user-friendly, Excel-based tool to allow for selected inputs to be modified based on the user's needs. This management decision support tool was also developed to allow for quick and easy sensitivity analysis. The aggregate nature of the tool allows for a macro level view of decisions associated with nine specific potential locations for a biorefinery in the upper portion of the Lower Peninsula of Michigan. It was designed to provide fundamental information regarding optimizing cost, energy, and emissions, as outlined in the earlier sections of the report.

Entry Screen Key

The entry screen key is color coded to help denote the meaning of each of the cells. There are three different types of cells in the key: Input Cells, Calculated Cells, and Model Results. The key is shown in Figure O-1.

KEY:		
	INPUT CELLS	
	CALCULATED CELLS	
	MODEL RESULTS	

Figure O-1 Entry Screen Key

Input Screens

There are a series of input screens. These include:

- Cost
- Energy
- Emissions
- Availability
- Availability Adjustment Factors
- Facility Size, Conversion Rate, and Biomass Feedstock Requirement

Cost

The cost entry screen includes information for stumpage, harvest/processing, and transportation. The transport cost consists of two components: a cost per ton and a cost per ton per mile. At the time of the optimization model development, only transportation cost was available. There are entry boxes for stumpage and harvest.

	<i>Stumpage</i>		<i>Harvest</i>		<i>Transport</i>		<i>Total</i>	
Cost	0.00 \$/ton		0.00 \$/ton		3.72 \$/ton		3.72 \$/ton	
					0.074 \$/ton-mile		0.074 \$/ton-mile	

Figure O-2 Input Screen for Cost Data

Energy

The energy screen includes information for harvest/processing and transportation energy consumption.

	<i>Stumpage</i>		<i>Harvest</i>			<i>Transport</i>		
Energy			137.4330	1000 Btu/ton		1.5924	1000 Btu/ton-mile	

Figure O-3 Input Screen for Energy Data

Emissions

The emissions screen includes information for harvest/processing and transportation emissions.

	<i>Stumpage</i>		<i>Harvest</i>			<i>Transport</i>		
Emissions			25.6	lb GHG/ton		0.377	lb GHG/ton-mile	

Figure O-4 Input Screen for Emissions Data

Availability

The availability screen includes the region as noted in the map in Figure 10 along with the availability factor for federal, state, and private ownership. These factors can be modified and were provided from Task A1: *Develop a Geospatial Forest Based Biomass Inventory*.

Federal		Region	Factor
Availability	Soft	N	0.93288219
		S	0.93288219
	Hard	N	0.90959717
		S	0.90959717
State		Region	Factor
Availability	Soft	N	0.54210441
		S	0.89363253
	Hard	N	0.48138431
		S	0.88568285
Private		Region	Factor
Availability	Soft	N	0.68544762
		S	0.95282162
	Hard	N	0.56189444
		S	0.75485393

Figure O-5 Input Screen for Availability by General Species and Ownership Type

Availability can further be classified by general characterization of roundwood or forest residues.

<i>Residue</i>	<i>Roundwood</i>	<i>Total</i>
0%	100%	100%
0%	100%	100%
0%	100%	100%
0%	100%	100%
<i>Residue</i>	<i>Roundwood</i>	<i>Total</i>
0%	100%	100%
0%	100%	100%
0%	100%	100%
0%	100%	100%
<i>Residue</i>	<i>Roundwood</i>	<i>Total</i>
0%	100%	100%
0%	100%	100%
0%	100%	100%
0%	100%	100%

Figure O-6 Input Screen to Identify Percentages

The calculation will default the balance to roundwood for total supply of 100%. If residues are entered, the roundwood percentage would be reduced.

Availability Adjustment Factors

The adjustment factors were utilized to adjust for known competing uses that will be coming on line and operational in 2012+ timeframe. FRR stands for Frontier Renewable Resources, a biorefinery being constructed in the Eastern portion of the U.P. in Kinross, MI. FRR plans to purchase woody biomass from the upper portion of the Lower Peninsula of Michigan, and the estimated quantity is included in Figure O-7. This amount can be modified. Additionally, an adjustment factor for the planned operation of a biomass fired electric plant in Mancelona assumed to use softwood so the amount available for other uses is 80% of the softwood. Both the soft and hard wood residue and roundwood can be adjusted to account for competing uses.

FRR	500,000	tons hardwood (roundwood)				
Soft adjust	<i>Species</i>			Hard adjust	<i>Species</i>	
	<i>Residue</i>	80%			<i>Residue</i>	100%
	<i>Roundwood</i>	80%			<i>Roundwood</i>	100%

Figure O-7 Adjustment Factors for Competing Uses

Facility Size, Conversion Rate, and Biomass Feedstock Requirement

In this study we used 50 MGY, 40 MGY, and 30 MGY sized facilities. Both the size and conversion rate (gal/ton) can be modified to compute the required biomass feedstock for a particular location. Each location calculation is independent and not all locations at the same time. Multiple location configurations will be shown later.

Facility	Location	Size (MGY)	Conversion Rate (gal/ton)	Biomass Feedstock
	<i>Manton</i>	30	40	750,000
	<i>Roscommon</i>	30	40	750,000
	<i>Kingsley</i>	30	40	750,000
	<i>Kalkaska</i>	30	40	750,000
	<i>Gaylord</i>	30	40	750,000
	<i>Clare</i>	30	40	750,000
	<i>West Branch</i>	30	40	750,000
	<i>Traverse City</i>	30	40	750,000
	<i>Boyne City</i>	30	40	750,000

Figure O-8 Facility Size

Update Model

Macros and buttons were created to update the calculations in the model. Select one or more buttons to update the related information.

Update Model	☐ Cost	☐ Energy	☐ Emissions
---------------------	-------------------------------	---------------------------------	------------------------------------

Figure O-9 Buttons to Update Model

Model Output

After updating the model, the Model Output screen will be updated showing average cost (in this example it is for transportation cost only), energy consumption, and emissions.

MODEL OUTPUT							
Location	Cost		Energy (1000 Btu)		Emissions (lbs/ton)		
	Total	Average (\$/ton)	Total	Average	Total	Average	
<i>Manton</i>	\$ 5,272,294	7.02973	156,491,043	208.655	31,846,284	42.46171	
<i>Roscommon</i>	\$ 5,811,741	7.74899	168,099,340	224.132	34,594,543	46.12606	
<i>Kingsley</i>	\$ 5,399,676	7.19957	159,232,166	212.310	32,495,244	43.32699	
<i>Kalkaska</i>	\$ 5,338,434	7.11791	157,914,298	210.552	32,183,239	42.91099	
<i>Gaylord</i>	\$ 4,858,537	6.47805	147,587,434	196.783	29,738,358	39.65114	
<i>Clare</i>	\$ 5,838,350	7.78447	168,671,944	224.896	34,730,107	46.30681	
<i>West Branch</i>	\$ 5,656,221	7.54163	164,752,737	219.670	33,802,236	45.06965	
<i>Traverse City</i>	\$ 5,747,224	7.66297	166,711,018	222.281	34,265,859	45.68781	
<i>Boyne City</i>	\$ 5,901,027	7.86804	170,020,685	226.694	35,049,421	46.73256	

Figure O-10 Model Output Screen

Multiple Locations

There are three examples of possible multiple location configurations shown in Figure O-11. This allows the user to modify the size of the locations as well as the conversion rate for biomass feedstock. This is an advanced function. Given all the possible combinations, if further combinations are required, this will require additional modeling.

MULTIPLE LOCATIONS				
			<i>Conversion Rate (gal/tons)</i>	<i>Biomass Feedstock (tons)</i>
Configuration 1		<i>Size (MGY)</i>		
	<i>Roscommon</i>	50	40	1,250,000
	<i>Clare</i>	50	40	1,250,000
	<i>Boyne City</i>	50	40	1,250,000
Configuration 2				
	<i>Roscommon</i>	50	40	1,250,000
	<i>Clare</i>	50	40	1,250,000
	<i>Boyne City</i>	50	40	1,250,000
	<i>Traverse City</i>	50	40	1,250,000
Configuration 3				
	<i>Traverse City</i>	50	40	1,250,000
	<i>Kalkaska</i>	50	40	1,250,000
	<i>Kingsley</i>	50	40	1,250,000
	<i>Manton</i>	50	40	1,250,000

Figure O-11 Example Multiple Location Configurations

Update Model

Macros and a button were created to update the calculations in the model. Select the button to update the related information.

Update Model	Multi Cost	

Figure O-12 Button to Update Model

Model Output for Multiple Locations

After updating the model, the Model Output screen will be updated showing average cost (in this example it is for transportation cost only).

MODEL OUTPUT					
		<i>Total Cost by Location</i>	<i>Average (\$/ton)</i>	<i>Total Cost by Configuration</i>	<i>Average (\$/ton)</i>
Configuration 1					
	<i>Roscommon</i>	\$ 11,609,108	\$ 9.28729		
	<i>Clare</i>	\$ 11,583,556	\$ 9.26684		
	<i>Boyne City</i>	\$ 11,354,180	\$ 9.08334		
Total Configuration 1				\$ 34,546,844	\$ 9.21249
Configuration 2					
	<i>Roscommon</i>	\$ 11,894,975	\$ 9.51598		
	<i>Clare</i>	\$ 11,682,077	\$ 9.34566		
	<i>Boyne City</i>	\$ 12,475,818	\$ 9.98065		
	<i>Traverse City</i>	\$ 11,905,801	\$ 9.52464		
Total Configuration 2				\$ 47,958,672	\$ 9.59173
Configuration 3					
	<i>Traverse City</i>	\$ 15,615,295	\$ 12.49224		
	<i>Kalkaska</i>	\$ 16,806,034	\$ 13.44483		
	<i>Kingsley</i>	\$ 15,653,106	\$ 12.52248		
	<i>Manton</i>	\$ 15,834,518	\$ 12.66761		
Total Configuration 3				\$ 63,908,953	\$ 12.78179

Figure O-13 Results for Multiple Location Configurations

USER'S DOCUMENTATION – SIMULATION MODEL

Introduction

The model is a simulation of the woody biomass supply chain prepared for the FBSCC project. The model simulates the flow of biomass from harvesting areas to the inventory at a biomass processing facility. It consists of three different sub-models for reading model inputs, supplying activities (including harvesting, transportation and storage at the biomass processing facility), and daily biomass processing. As main outputs, the FBSCC simulation model estimates the delivery cost, energy consumption, and greenhouse gas (GHG) emissions for different facility locations and different plant sizes. The model also tracks the inventory level at the biomass processing facility versus time, and picks the most preferable harvesting sites for each plant. The FBSCC simulation model has been developed using the Arena Simulation Software, Version 13, available from Rockwell Automation. Arena Simulation Software is required to run the simulation and can be purchased for approximately \$2,495 (per website). This user's guide outlines the setup and running of the model.

Setup

Arena

To run the simulation model, the Arena Simulation Software has to be installed on a computer. The version that has been used to develop the model is Arena 13.0. Old versions of Arena may be not able to run the model due to compatibility issues.

Microsoft Excel

To run the simulation model, the user also needs to have Microsoft Excel 2007 installed. This is for the user's benefit to review or modify the model inputs which are stored in a Microsoft Excel file format.

File Structure

There are two types of files that should be stored in the master simulation. The model file is created using Arena 13.0 and was named FBSCC simulation model.doe. The data input files are in macro-enabled Microsoft Excel format and are identified by city name. The city name represents one of the nine potential biorefinery locations: Boyne City, Clare, Gaylord, Kalkaska, Kingsley, Manton, Roscommon, Traverse City, and West Branch.

The Excel input file for each city is structured the same. Take a 3-year input file for the Manton facility location as shown in table S-1 for example. The harvesting areas are specified and remain the same for the entire simulation length of 20 years. The areas are fixed parameters and can't be changed. The transportation distances shown in the file are derived using the rectilinear distance function. The initial values of the distance are calculated from the center of a harvesting area to the center of the facility location. The distance values from the second year to the 20th year are filled automatically according to the first year distance value. The amount of biomass available for biofuel production in each harvesting area represents net forest growth each year and is in 50 ton units. Users can enter new data or change the current data for transportation distance (only the first year) and biomass availability (for all 20 years). Note that every time users make a change to the distance values for the first year, the table will automatically sort from smallest to the largest by distance. To use the auto sort function, users need to have Macros enabled. Users will see a security warning message when opening an input file.

Users need to click on 'Options...' in the message and the Microsoft Office Security Options dialog box will be opened. Users have to have the option of 'Enable this content' selected and then click OK to finish.

Harvesting Area	year1		year2		year3	
	distance (mile)	biomass (50 tons)	distance (mile)	biomass (50 tons)	distance (mile)	biomass (50 tons)
Wexford	13.862	4911	13.862	4911	13.862	4911
Missaukee	20.151	3868	20.151	3868	20.151	3868
Grand Traverse	25.728	2358	25.728	2358	25.728	2358
Osceola	33.021	2801	33.021	2801	33.021	2801
Kalkaska	34.15	3436	34.15	3436	34.15	3436
Manistee	37.986	4124	37.986	4124	37.986	4124
Roscommon	43.864	2978	43.864	2978	43.864	2978
Benzie	46.018	2027	46.018	2027	46.018	2027
Lake	48.94	4942	48.94	4942	48.94	4942
Antrim	53.136	2697	53.136	2697	53.136	2697
Clare	56.676	3089	56.676	3089	56.676	3089
Leelanau	56.721	978	56.721	978	56.721	978
Mecosta	57.339	3239	57.339	3239	57.339	3239
Crawford	58.042	2416	58.042	2416	58.042	2416
Ogemaw	67.463	2450	67.463	2450	67.463	2450
Mason	70.919	4203	70.919	4203	70.919	4203
Charlevoix	74.514	1935	74.514	1935	74.514	1935
Newaygo	78.924	5875	78.924	5875	78.924	5875
Gladwin	78.994	2418	78.994	2418	78.994	2418
Isabella	81.031	2958	81.031	2958	81.031	2958
Otsego	81.523	5498	81.523	5498	81.523	5498
Oscoda	82.053	4735	82.053	4735	82.053	4735
Montcalm	88.884	3680	88.884	3680	88.884	3680
Iosco	89.638	3187	89.638	3187	89.638	3187
Oceana	96.323	4469	96.323	4469	96.323	4469
Arenac	97.706	2377	97.706	2377	97.706	2377
Emmet	101.01	2780	101.01	2780	101.01	2780
Kent	102.064	3898	102.064	3898	102.064	3898
Midland	103.189	2104	103.189	2104	103.189	2104
Montmorency	105.497	4001	105.497	4001	105.497	4001
Alcona	109.381	4237	109.381	4237	109.381	4237
Muskegon	114.708	4524	114.708	4524	114.708	4524
Cheboygan	115.246	4506	115.246	4506	115.246	4506
Gratiot	117.374	1313	117.374	1313	117.374	1313
Bay	118.366	589	118.366	589	118.366	589
Alpena	131.073	2438	131.073	2438	131.073	2438
Presque Isle	137.05	2972	137.05	2972	137.05	2972

Table S-1 Model Inputs for a Manton Facility

Running the Model

- Launch the model
 - Double click on the model file of FBSCC simulation model.doe to start the model.
 - Or first start Arena 13.0 from the Windows Start menu and navigate to Program > Rockwell Software > Arena. The Arena modeling environment will open with a new model window. Go to File > Open, the Open dialog box will open. Navigate to the path where the FBSCC simulation model.doe file is stored and select it to open.
- Specify replication parameters

Open the Run Setup dialog box (Figure S-1) by using the Run > Setup menu item and clicking the Replication Parameters tab.

 - # of replications
 - Start data and time
 - Replication length
 - Hours per day
 - Base time units

Click OK to close the dialog box.

Note:

1. Replication length is set as the (# of years * 365) -1 in days. In this example, the # of years equals 20 resulting in a replication length as 7299 days;
2. All the time units are in days;
3. Hours per day is suggested to set as 24 because a biofuel facility usually operates 24/7.

Figure S-1 Project Parameters Dialog Box

- Select an input file

Users can select an input file by clicking the file module in the Advanced Process panel (Figure S-2). Within the file module, users can select an input file under the Operating System File Name box. To select a file, users will need to click on the small button to the right of the input file name box. After clicking the button, a dialog box of Browse for File will appear. Users will need to click the arrow to the right of the Files of Type box and select All Files. A list of input files will appear (Figure S-3). Users can select one file as the input file.

Figure S-2 File Module in the Advanced Process Panel

Figure S-3 Select an Input file within the File Module

- Start a simulation run

Click the Go button (Figure S-4) in the main toolbar or clicking the Run > Go menu item. The input screen (Figure S-5) will open. Users can specify cost, energy use and GHG emissions coefficients, and specify the facility size in million gallons per year of 30, 40 and 50. Click OK by finishing up input.

Go
Button

Figure S-4 Go Button in the Main Toolbar

FBSCC Simulation Model V1.0

Cost Coefficient

fixed cost, truck (\$/ton)

variable cost, truck (\$/ton-mile)

Energy intensity coefficient

truck operations & maintenance (Btu/ton-mile)

Emissions (CO2 eq) coefficient

truck operations & maintenance (lb/ton-mile)

Biorefinery size (MGY)

☐ 30

☐ 40

☒ 50

Figure S-5 Input Screen

- To speed up the simulation

Users can speed up a simulation by adjusting the animation scale factor. For this users have two choices:

- Use the slide bar in the main toolbar (Figure S-6). Move the slider to the left to slow down the animation; move the slider to the right to speed up the animation; or
- Click the Fast-Forward button in the main toolbar (Figure S-6).

- Pause the simulation

Click the Pause button in the main toolbar (Figure S-6) or press the Esc key.

- Step through the simulation

Pause the simulation and then click the Step button in the main toolbar (Figure S-6) or press F10 key. Note that if a simulation is running, users have to pause the model first before stepping through it.

- Stop button

Users can stop a simulation anytime by pressing the stop button in the main toolbar (Figure S-6).

Figure S-6 Main Toolbar

View Model Outputs

At the end of each run, users will see the output window. Outputs of the model include (Figure S-7):

- End date of a simulation;
- Inventory level at the biomass processing facility against time;

- Delivery cost, energy consumption and greenhouse gas (GHG) emissions, total biomass transported in tons, and real time tracking of transportation distance and inventory level;
- The most preferable harvesting sites.
The numbers of the most preferable harvesting sites are displayed as an output. The name of the most preferable harvesting sites can be obtained by comparing those numbers with the corresponding input file.

Figure S-7 output Window of the Simulation Model

TUTORIAL – OPTIMIZATION MODEL

Tutorial for the optimization model is available and is complimentary to the user documentation.

TUTORIAL – SIMULATION MODEL

Tutorial for the simulation model is available and is complimentary to the user documentation.

APPENDIX B4-A DETAILED LITERATURE SUMMARY

Introduction

The literature review examined research to date on producing biofuel from lignocellulosic biomass and identified the gap where new research can focus. The review was organized into seven categories. In each category, a series of critical points were examined. The seven categories included the investigation of existing biomass supply chains, different types and forms of feedstock for the supply chains, key drivers of the supply chain, policy related constraints, mathematical models that have been developed for supply chains, infrastructure requirement for an expanded fuel ethanol industry and methodologies used to identify the best facility location for biofuel production. Each category has its own heading with the summaries of the corresponding literature following the heading.

Existing supply chain systems for ethanol

This section investigated the different existing supply chain systems available for ethanol. The first existing system is the National Biofuels Plan created by the Biomass Research and Development Board (BRDB) that developed a plan to reach government biofuel goals. The second system discussed involves different research studies with the uniform-format feedstock supply system produced by the Idaho National Laboratory. The third system discussed was created by Sandia National Laboratories which performed a feasibility analysis for large scale production of biofuels.

National Biofuels Plan (hereafter referred to as ‘plan’)

This Biomass Research and Development Board (2008) developed a plan that discusses specific government legislation affecting the amount of biofuels required to be in use over the next few years; 36 billion gallons per year (BGY) of biofuels by 2022. In order to accomplish this, a group called the BRDB was established. The BRDB outlined its plan of action in the study and discussed the required steps needed to reach the government goals. The first area of focus for the BRDB is sustainability.

Sustainability

The first area of action outlined by the Biomass R&D Board is to evaluate the sustainability of biofuels production and use. The plan must try to enhance economic and environmental benefits of biofuels through a successful implementation of an efficient feedstock supply chain. The board suggested to do this by reducing greenhouse gases from the different feedstocks, requiring biofuel production to not adversely impact the environment, focusing on developing cellulosic and other feedstocks that promote sustainability, and stipulating that the EPA assess and report to Congress on environmental impacts.

Feedstock Production

The second action area outlined in the plan is to review feedstock production. The plan outlined different generations of feedstock production. The first generation is ethanol and biodiesel made from corn and soybeans. The second is using residues and “left-overs” from crops and forests as feedstock for the process. The third is using R&D to

develop specific types of energy crops that have high yields for biofuels. The board is reviewing factors such as a long-term integrated feedstock research plan, information and research into new energy crops, and the promotion of knowledge sharing between select government groups and agencies involved.

Feedstock Logistics

The third action area of the plan is feedstock logistics which can count for as much as 20% of the cost of finished ethanol. However, Hess et al. (2007) reported transportation and handling compose nearly 30% of annual cost. Among the areas of focus inside this plan that relate to the project are storage facilities, preprocessing/grinding equipment, and transportation of feedstock. The board will focus on collaborating the development and deployment of logistics systems, while including the private sector as well.

Conversion Science and Technology

The fourth action area is conversion science and technology in which the need to develop a more economically viable conversion process if biofuels are going to compete in the marketplace is revealed. The board is establishing groups to investigate the different conversion processes that will lead to cost-effective and commercially viable options.

Distribution Infrastructure

The fifth area of action for the plan is the distribution infrastructure, which focuses on the need for transporting biofuels, mainly from the Midwest, to areas on the east and west coasts. If this is going to be done via pipeline, the board suggests that research is needed to know the effects of ethanol on pipeline components (e.g. gasket and sealing materials) and the cost.

Blending

The sixth area of action for the plan is blending, in which the issue of increasing the acceptable level of blended ethanol in gasoline is addressed. The board stated that research on the effects of ethanol on air quality, automobiles, and pipeline components is needed before increased blending can occur.

Environment, Health, and Safety

The seventh action area of the plan includes environment, health, and safety issues, in which the board stated that it will inventory related Federal government activities, as well as review and summarize related potential issues that may arise from the life-cycle of biofuel. The action plan ends by stating that the critical near term areas of action for biofuel success are feedstock production and logistics, conversion, and distribution and end use.

Idaho National Laboratory (INL)

Hess et al. (2009) performed a research study that identifies the need for a uniform-format, commodity driven supply system for biomass. This is to meet the goals of displacing 30% of the United States' gasoline consumption in 2004 with biofuels by 2030. In order to do this economically, the feedstock supply system cannot account for more than 25% of the total cost of biofuel production. This report introduced two types of

supply systems:

- the conventional bale feedstock supply system, representing current practice, and
- the uniform-format supply system, moving preprocessing to early stages of the system so that the biomass is a commodity.

Hess et al. (2007) discussed the pioneer feedstock supply system using cellulosic biomass. An advanced feedstock supply system would be targeted. In order to economically produce ethanol from biomass at a national level, the discussion described the different conversion processes for ethanol at the biorefinery: biochemical and thermo chemical conversion. It then described the current feedstock supply system.

Feedstock Supply System

A challenge in a feedstock supply system highlighted in the research by Hess et al. (2007) is that each supply system tends to be unique for each biorefinery based on factors like location, size, and harvesting procedures. The costs that make up the minimum cost for ethanol can be broken into feedstock costs and conversion costs. Grower payment, efficiency/capacity, and quality are all aspects of feedstock costs. The research stated that the two main challenges for the feedstock supply system are:

- Improving feedstock logistics mainly through efficiency and capacity operations; and
- Developing a uniform commodity-scale feedstock supply system that can use diverse cellulosic feedstock with standardized supply system infrastructures and biorefinery conversion processes.

From the feedstock supply system, the research introduces a pioneer supply system that can make the supply chain be more economically viable at the national level.

Pioneer Supply System

Hess et al. (2007) discusses the pioneer supply system using wheat straw as an example throughout. It begins with production where the largest variable is due to the different demands for a variety of products that compete with the amount of feedstock available for energy production. The harvesting and collection describes common practices. Storage of the biomass feedstock variables includes shrinkage and material degradation. Preprocessing occurs to enable transportation and handling in a similar fashion by all of the equipment involved. After the pioneer supply system, an advanced feedstock supply system was introduced.

Advanced Feedstock Supply System

The advanced feedstock supply system is described by Hess et al. (2007) states that technological advancement will occur in the harvesting and collection processes. This will improve the efficiency, allowing for increased and overall supply system costs can be reduced. More research is in progress to identify losses that occur during storage so that the losses can be prevented in the advanced model. Next there is a discussion regarding the advances in preprocessing equipment. This will allow transportation and handling problems to be minimized. The product is more uniform. The study reports that transporting and material handling account for nearly 30% of the annual cost for a feedstock assembly system. Evaluating new methods can possibly eliminate the need for certain types of equipment used, thus lower costs.

INL (2006) reviewed a previously written study that describes a biomass feedstock

system for wheat and barley straw. Some critical success factors identified for the feedstock model include:

- Ability to contract straw from a specified distance,
- Capability to field grind straw to customer's specifications,
- Capability to transport ground straw to meet demand, and
- Ability to design a transfer facility that can accommodate inflow of material and refinery demand.

The aspects of the INL (2006) study included harvesting, transporting and handling, inventory management, and quality assurance. Some areas of concern were highlighted in the study. These were:

- Cost of straw will increase as the demand increases substantially after the plant is operational,
- Logistics of moving the straw are very complicated,
- Storing the straw may be subject to a variety of fire codes,
- Unloading the truck and transferring the feedstock into and out of storage may not have a practical design, and
- Field fueling issues may arise so equipment might need day tanks that they can be fueled once per day at each site.

Sandia National Laboratories

A joint biofuels system analysis project, "90-Billion Gallon Biofuel Deployment Study", was conducted by Sandia National Laboratories (SNL) and General Motors' Research and Development Center between March and November 2008 (SNL, 2009; West et al., 2008). The project assessed the feasibility, implications, limitations, and enablers of large-scale production of biofuels in the United States. A 'Seed to Station' system dynamics model, Biofuels Deployment Model (BDM), was developed to explore the feasibility of producing 90 billion gallons of biofuels in US. This is a linear programming distribution optimization model. The inputs of the model were derived from previous research and imported into the model. The inputs were categorized into four major groups, including conversion yield, capital investment/annual capacity per cellulosic plant, energy prices, and feedstock yield improvements.

Sensitivity analyses were conducted to identify the most influential factors that impact the feasibility, cost-competitiveness, and greenhouse gas impact of large-scale ethanol production. Three major matrices were generated: the total volume of ethanol production by 2030; the difference of accumulated cost between the ethanol produced over the life of the simulation and the displaced gasoline; and the difference between the GHG emissions associated with ethanol production over the life of the simulation and those associated with the gasoline that it replaced. Several steps were involved to perform the sensitivity analyses: importance screening, interaction screening, and fine-tuning of the last step.

A reference/base case was set as the baseline in the sensitivity analyses. A series of assumptions were made in the reference case, such as conversion yield is 90 gallons/dry ton and short rotation woody crops (SRWC) are available for cellulosic ethanol production and so on. The results of the sensitivity analysis were discussed. For the first metric of ethanol production volume, conversion yield and the availability of SRWC play an important role in achieving the goal. The examination of the combined influence of

the two most important factors on ethanol production demonstrated that the goal of producing 90-billion gallon of ethanol per year by 2030 in U.S. is feasible over the range of the conversion yield from 74 gallons/dry ton to 115 gallons/dry ton. When SRWC and/or energy crops are not available, the goal cannot be achieved, even at the highest conversion yield. For the second metric of cost-competitiveness of ethanol relative to gasoline, energy prices were demonstrated as the most influential parameter. It was also identified that the price of crude oil influences the most of the price of energy. However, the competitiveness of price is only valid when the price of crude oil is over \$90/barrel.

Further examination shows that the capital cost, conversion yield, and feedstock cost also impact significantly the cost-competitiveness of ethanol with gasoline. For the third metric of GHG gas emission savings relative to gasoline, it was identified that the conversion yield and the boiler efficiency have the largest influence. An increase of the conversion yield at 10 gallons/dry ton would result in about a 3% increase of GHG gas emission savings while a 6% improvement in the boiler efficiency (which reduces the amount of energy generation needed) results in a similar percentage of GHG gas emission savings.

Different feedstock types involved in supply chains

This section investigates the use of different feedstocks for biomass supply chains such as agricultural residues, woodchips, forest residues, and energy crops. Searcy et al. (2007) examined two types of biomass: woodchips and agriculture residues, including stover and straw. Aden et al. (2002) developed a process design for producing ethanol using corn stover and conducted related cost estimation analysis.

Blackwelder and Wilkerson (2008) highlight the different aspects and associated supply costs (harvesting, handling, transporting, and preprocessing) for using different types of feedstocks including slash, forest thinnings, and commercial energy wood as biomass.

Slash

Blackwelder and Wilkerson (2008) describe slash as the leftover tree tops and limbs from commercial harvesting. It states that 20-30% of the total volume of woody biomass is leftover as slash when harvested. Through model simulation and estimates, the predicted cost of supplying one bone dry ton (bdt) to the plant is \$20.50 per bdt. The assumed transportation procedure for this process is to place the slash into a chipper with a loader and from there, the chipped slash gets loaded into a truck trailer. The trailer is then brought to the plant gate and unloaded so the conversion process can begin. This scenario does not require an incremental cost of piling the slash because that process is a byproduct of commercial harvesting.

Forest Thinning

Forest thinning, which involves the removal of certain trees that are small or undesirable for commercial harvesting, was also analyzed by Blackwelder and Wilkerson (2008) for supply costs. The projected cost for the plant using forest thinning was \$51.85 per bdt. The assumed procedure for moving the woody biomass is after the harvesting has occurred and the logs are moved with a forwarder. Then a loader is used to load the logs into a chipper which puts the chips directly into a truck bed. Next, the woody biomass

get transported to the plant gate and unloaded so the conversion process can begin.

Energy Crops

The third option analyzed by Blackwelder and Wilkerson (2008) was plantation energy crops that are grown specifically for high potential biofuel yield and quick growth. The supply cost associated with this method was found to be \$30.52-\$34.63 per bdt. The transportation procedures are very similar to the ones outlined in the forest thinnings section.

Stokes (1992) described the background of each country for using forest residue and small trees as energy and relative harvesting technologies at that time. Countries involved in this activity were Denmark, Finland, Norway, Sweden, United Kingdom, Italy, Switzerland, New Zealand, Canada and United States. Harvesting system databases and transportation database were built with the activity. To increase the use of forest residues and small tree for energy production, the fossil fuel price and the political decisions impacted significantly.

Forest residues

Harvesting systems for forest residues differ depending on where the forest residuals were concentrated. For residues on cutover areas, stand mobile chippers were the most popularly used because the residues had characteristics of widely spread, small size and non-uniform shapes which are difficult to compact. For residues that were more concentrated distributed, e.g., on roadsides, drum chippers, and tub grinders were commonly used for size reduction.

Small trees

Small trees were much easier to harvest compared to forest residues. Small trees can be harvested in three periods: thinnings, preharvests and postharvests of conventional forest products. Preharvestings were more efficient than the other two and harvested more materials too. The least expensive harvesting technologies involved mechanical felling and bunching, skidding of whole trees and chipping at roadside. Stand-mobile chippers were commonly used in Denmark and the United Kingdom for smaller harvest volumes. In Sweden, drum delimber/debarkers were employed, called tree-section method, to separate high value pulp chip from low value fuel products.

Mitchell (2005) reviewed two types of integrating biomass harvest system, one-pass and two-pass harvesting. The one-pass harvesting was defined as the felling and skidding of energy wood are operated at the same time when the conventional roundwood products are removed. The two-pass harvesting method involves two operations. Energy wood is felled, skidded and chipped first and merchantable roundwood products are harvested afterwards. The comparison of the two methods showed that the one-pass method is more efficient. Mitchell (2005) also presented the impact of different production. Slash and stems, which are longer portions of forest residues, are easy to grapple. The shorter limbs and tops are not easy to carry with grapplers. Mitchell (2005) also created a table to show the productivity and cost using different combination machines depending on the production type. The study also presents a new technology of bundling and a new type of machine caller bundler. Mitchell (2005) discussed the low transporting efficiency due to the physical characters

of forest residues. At last, the value of the forest residues was estimated and compared with traditional fuels.

Key drivers of the supply chain

This section discusses research involved in areas that are key drivers of the supply chain. These areas include information management, transportation, and supply chain enablers.

Information Management

Cachon and Fisher (2000) investigate, through mathematical equations, the cost effects that full information sharing versus a traditional, non-information sharing policy has on supply chain.

Supply Chain Inventory Management

The purpose of this investigation is to address the general belief in industry that capturing real-time demand information is important for improving supply chain performance. The study defines traditional information sharing is where the supplier only observes the orders, and full information sharing is where the supplier has instant access to inventory data. The investigation goes into addressing the question of how information technology improves supply chain performance, not necessarily if it does. This can be related to woody biomass systems in which the logger, the supplier, would have orders from the ethanol plant. The traditional information sharing would provide full access to all of the inventory data for the ethanol plant.

Modeling

The equations used to model the different scenarios are discussed in detail, as well as the results. The mean cost benefit that a full information policy has over the traditional policy on the supply chain is 2.2% in supply chain cost savings. The study concludes from the results that there are savings from lead time and batch size reductions, which are both caused by the implementation of information technology. Information sharing could have a much larger effect on the supply chain. If the demand of the product was unknown, full information could be used to detect shifts in the demand process. The research assumed demand was known, retailers were identical, one source of inventory, no constraints on capacity, firms could not create conflict between other supply chain firms based on incentives, and that the firms were rational in their ordering practices.

Transportation

Mahmudi and Flynn (2006) observe the cost savings between a single transportation system for straw or wood biomass via truck or rail versus a transshipment method that combines the two.

Single Shipment of Biomass

The study states that rail transportation has higher fixed cost than trucks. This is because there are both supplier and carrier components to consider for rail transportation. However, the variable costs are lower for rail than trucks. This means if a transshipment method is to be used for transporting biomass to a facility; the distance has to be such that the saving in variable costs from the second mode of transportation must be able to offset

the increase in fixed costs for the system.

Transshipment of Biomass

Mahmudi and Flynn (2006) state there is an optimum number of transshipment terminals that minimize shipping costs. There are tradeoffs between fixed and variable costs as the number of terminals increases. The study found the optimal rate of biomass per terminal to be 100,000 dry tons of boreal forest harvest residue (FHR) wood chips. The study also highlights that the minimum economic rail shipping distance for boreal FHR wood chips is 145 km (also in parenthesis include the conversion of miles). In the study, power plants in Canada that were an economic size (130 MW) and were economically capable of using transshipment were analyzed. Transshipment from truck to rail was indeed found to be an economically viable option if rail lines existed that led to the plant.

Supply chain enablers

Edward (2008) discussed the four supply chain enablers: organizational infrastructure, technology, strategic alliances, and human resources management. A group of professionals were interviewed to rank the four enablers and the associated attributes of each enabler. The results of the survey show that organizational infrastructure and its associated attributes topped the list for being the most important enabler of successful supply chain implementation.

For organizational infrastructure enabler, the attribute –a business strategy that aligns business units toward the same goal—was more significant than other attributes. The second important attribute was considered to be the need to have a sound process-management methodology in place. A top-management process flow chart was presented to illustrate how the first two important attributes are implemented in a company. The technology enabler was analyzed in two parts: IT and manufacturing and material-management technology. For IT, a list of eight categories was used to define the scope of IT in supply chain. The ready availability of coordinated internal data on operations, marketing, and logistics were pointed out to be the first important attribute. When it comes to manufacturing and material-management technology, a list of four categories was used to define the scope of the physical technologies. The design of products and physical processes for supply chain efficiencies topped the list of attributes. For strategic alliances enabler, the attribute –having expectations clearly stated, understood, and agreed to up front—was more significant than other attributes. For human resources management enabler, the most challenging enabling attribute is finding practitioners knowledgeable in supply chain management and finding facilitators to lead the implementation change process.

Policy related constraints

The following section will highlight different policies that can create constraints in a supply chain. The first area discussed is forest policies. Next, environmental policy will be reviewed. The third area of discussion relates to different public policies.

Forest Policies

Cubbage and Newman (2006) describe the reformation of forest policy over time. They suggest that forest policy is developed through a mixture of implementing reasoned laws

and decisions to resolve identified fundamental issues, making small incremental changes to existing policies as time goes on, and making short-term incremental changes while implementing new policy based on social innovation.

International Forestry

Cubbage and Newman (2006) discuss how international forestry and trade has enhanced sustainable forest management. International agreements have been developed to clearly define seven agreed upon criteria for sustainable forest management. The seven criteria include “(1) conservation of biological diversity, (2) maintenance of the productive capacity of forest ecosystems, (3) maintenance of forest ecosystem health and vitality, (4) conservation and maintenance of soil and water resources, (5) maintenance of forest contribution to global carbon cycles, (6) maintenance and enhancement of long-term socio-economic benefits to meet the needs of societies, and (7) development of the legal, institutional, and economic framework for forest conservation and sustainable management (Cubbage and Newman, 2006, pg. 263)”. Combined with international agreements, market-based-incentives for producing green products have increased the use of sustainable practices.

“Green” Policies

Cubbage and Newman (2006) also describe how intense public pressure to ensure sustainable forest practices is causing a corporate “green” revolution. There are two major U.S. certification programs, the Forest Stewardship Council (FSC) and the Sustainable Forestry Initiative (SFI). The research highlights that there are no federal or state forests that are certified by these programs. It begins to discuss the expansions being made at the federal and state level on the topic of forests.

Federal and State Policies

Cubbage and Newman (2006) highlight some of the legislation that has been passed over the past decades, such as the initiative to reduce unneeded paperwork for thinning and harvesting to take place. The topic of different state forest policy was addressed and the idea of how corporations have actively pursued environmental agendas on their own that exceed government regulations was highlighted. The future of forest policy developers have the challenge of meeting widely accepted economic, social, and environmental goals of sustainable development without decreasing the ability of forests to provide for the needs of people.

Environmental Policy

Gallagher et al. (2004) proposes three different possible scenarios for the future of the fuel industry:

- Implementing a renewable fuel standard (RFS),
- Imposing a national ban on the additive MTBE and replace with ETBE, and
- Removing oxygen standards for reformulated fuel.

These scenarios are modeled through simulation and the effects of each change are documented and compared against a baseline scenario which uses existing EPA policies. The research provides an introduction to the three natural resources used in fuel processing: petroleum, natural gas, and biomass. It also investigates the existing

emission standards and what each formulation of fuel does to the environment.

Implementing a renewable fuel standard

The implementing renewable fuel standards scenario's simulation shows growth in the additives market by 56%, specifically with growth in refined gasoline output at 20%. The ethanol industry also grows in this simulation.

National ban

Under the scenario where there is a ban on MTBE, gasoline prices are predicted to rise and ethanol demand is projected to rise moderately as well. Long-run welfare gains for corn-producers and processors raise slightly based on the slight increase in ethanol demand.

Removing Oxygen Standards

The third scenario, removing oxygen standards while still banning MTBE, efficiency is improved some while summer reformulated gasoline prices return to baseline levels. In all three scenarios, gasoline additives will continue to grow, which includes the production of ethanol. The economic costs associated with this growth are more than offset by the environmental improvement. The research states that issue leads to the potential expansion of biofuels in the future.

Public Policy

Sissine (2007) summarized the major provisions included in the Energy Independence and Security Act of 2007 and presented the legislative actions under each of the titles in the law. Three key provisions were included in the law: the Corporate Average Fuel Economy (CAFE) Standards, the Renewable Fuel Standard (RFS), and the Appliance and Lighting Efficiency Standards (Sissine, 2007). The CAFÉ provision involves a setting of an average fuel economy goal at 35 miles per gallon for the combined fleet of light trucks and cars by 2020. The RFS law is about setting standards for the availability of renewable fuels. By 2020, 36 billions of biofuels will be available arising from 9.0 billions from 2008. Especially, 21-billion out of the 36-billion biofuels are cellulosic ethanol and other advanced biofuels. The Appliance and Lighting Efficiency Standards set requirements for residential and commercial appliance equipment.

Mathematical models for supply chains

Many existing mathematical models were reviewed and summarized in the following section. The first specific area that will be discussed are simulation and optimization models. The second area involves full supply chain models that have been developed. The next section discussed focuses on models that have been developed involving the specific individual drivers of supply chain, such as transportation. The last section reviews mathematical models for different processing methods.

Simulation and Optimization

De Mol et al. (1997) discuss the results and differences in simulation models versus optimization models for the logistics of biomass fuel collection. The report first describes how the network structure is set up for the supply system.

Network Structure

The network structure is defined by De Mol et al. (1997) as having nodes, which correspond to source locations, collection sites, transshipment sites, pre-treatment sites, and the energy plant itself. There are also arcs connecting the nodes which are modes of transportation like road, water, or rail. The study also discusses how there are losses during storage that can be positive, like moisture losses, or negative like dry matter losses. All of this information was defined in a database where the simulation and optimization could be performed from. The research uses numerous different combinations of the described network structures to find the optimal design through simulation and optimization.

Simulation Model

For the simulation model by De Mol et al. (1997), the network structure is fixed, and different parameters like transportation costs, storage losses, and seasonal supply or demand are inputs into the simulation. The biomass flows for certain time periods are simulated and cost figures of variances are calculated from the results. The simulation model follows a pull model where each lot orders stock from the preceding lot to maintain at least the minimum safety level that can be used to provide for the lot that is next in line. Results of the simulation model include input and output of biomass, costs for transportation and handling, energy consumption for transportation and handling, and number of transports needed to supply the energy plant.

Optimization Model

The optimization model by De Mol et al. (1997) combines different types of biomass, different nodes, and pre-treatments situations to develop the optimal network structure. While the simulation model takes losses into account for the biomass, the optimization model does not because it only gives annual flows. It is also hard to include time-dependent effects in the optimization model like the simulation model can. The research also states that optimization of logistics structure is hard with the simulation model. The results of the modeling by De Mol et al. (1997) are as followed.

Results of the modeling

- The simulation model showed that the truck is cheapest for short distances, chipping should be done at the plant, and that costs and energy consumption from logistics is a major part of the cost for biomass fuel.
- The optimization model's results were similar to the simulation model previously listed.
- The research states that the optimization model is best for selecting what type of network structure to use when there is a lot of variation, and that the simulation model works best when the network structure is fixed or has a small number of possible variations in it.
- The research also mentions that simulation gives more detailed results on biomass logistics, and can be further detailed to make operational decisions from it.

Mathematical models for the supply chain

Gronalt and Rauch (2007) discuss the design of a forest fuel network for a region. It incorporates delivering the products to multiple energy plants, with the use of storage terminals. Different scenarios of how many terminals and where each one is located are simulated to find the most optimal network. Also, the point at which the lumber gets chipped is studied as a central location, as well as on-site chipping. Since bioenergy has to compete in harvesting the forests with logs for pulp, paper, and wood manufacturing industries, the first step for designing a regional forest fuel supply network is to identify the target forests and determine how much wood could be used as forest fuel.

Supply network for forest fuel

Gronalt and Rauch (2007) state that for Austria only 54% of the areas where mechanized harvesting systems could reach could be utilized economically for forest fuels. This is due to lumber claims on certain forests, as well as the inability to harvest specific areas. The research states that the next step is to calculate expected demand of forest fuel for the specific region. Once demand is known, the costs associated with the network including transportation to terminal, terminal costs, and transportation cost to the plants are necessary to design an optimal supply network. Based on the costs as well as the supply and demand, the network can be designed to find the best spatial allocation for the terminals that minimizes both transportation and chipping costs associated with the network. The study proposes this stepwise heuristic approach as a way to solve forest fuel supply network design problems.

Gunnarsson et al. (2004) propose a solution to the supply chain problem involved with a forest fuel network structure through a large mixed integer linear programming model. The main product used is forest fuel, which are mainly forest residues in harvest areas or from byproducts from sawmills. The destination for the forest fuel is a heat plant. The same research also raises the issues of forests that are owned by the heat plant in which the product would not have to be purchased as opposed to contracted forests in which it would have to be purchased.

Mathematical Model

The mathematical model for Gunnarsson et al. (2004) incorporates the issues associated with chipping forest residues in the forest which is more expensive than doing it at a terminal. It is cheaper to transport chipped wood and it could be delivered directly to the heating plants. Non-chipped residues can be stored at a variety of locations, but it is more expensive to transport them. The model also incorporates locations and numbers of terminals involved in the network. The demand for heat from the plant over the year can be calculated. Based on the calculations, the model shows how much wood to acquire and deliver from each terminal. The model then shows whether or not the wood should be chipped in the forest or at specific terminal locations for transportation purposes. Scenarios for Sweden were computed using the mathematical model by Gunnarsson et al. (2004). This provided the best alternatives for transportation and chipping methods of the forest fuel to the plant. This model can be used to support tactical planning and strategic analysis for the supply of forest fuel to multiple heating plants.

Models involving specific drivers of the supply chain

Kumar et al. (2006) evaluate different collection and transportation systems for biomass feedstock systems using a method called preference ranking organization method for enrichment and evaluations (PROMETHEE).

Mathematical Models

The model developed by Kumar et al. (2006) integrates economic, social, environmental, and technical factors in order to rank alternatives for collection and transportation methods of biomass feedstock. The three collection systems analyzed using PROMETHEE model were baling, loafing, and chopping & ensiling. The collection systems were analyzed using the following criteria: delivery costs, quality of material, emissions, energy consumed, and the maturity of technology. After the analysis was performed, loafing was shown to be the best alternative for collection.

For biomass transportation systems, truck, rail, and pipeline were analyzed. The evaluation criteria included cost, emissions, traffic congestion caused, and maturity of technology. Based on the analysis, rail was shown to be the best alternative for the specific criteria.

Transportation cost model

Searcy et al. (2007) estimated transportation costs for two types of biomass and two types of energy production systems from biomass transported using different modes and unique transport distances. The two types of biomass examined were woodchips and agriculture residues, including stover and straw. The two types of energy were electricity power and ethanol. Transportation modes for biomass involved truck for short distance transportation, and any combination of truck plus rail, truck plus ship and truck plus pipelines for long distance transportation. Transportation modes for ethanol involved truck and pipeline. The transportation cost model comprises two components: Distance Fixed Costs (DFC) and Distance Variable Costs (DVC). DFC included loading and unloading costs which has nothing to do with the distance traveled and DVC depends on the travel distance. The transportation cost models were built by Searcy et al. (2007) based on previous research. Transportation cost factors for each case were generated from the models and relative transportation costs were compared between each case. The results show that truck, rail, and ship have a negligible economy of scale while pipeline has a higher one. Rail and ship are not economical transportation modes until a longer distance are traveled due to the high costs incurred by transshipment. Pipeline does not show its advantage over truck until a higher production rate of ethanol is met per day. It is always a good idea to build a conversion plant closer to the biomass than to a population center or a transmission grid.

Processing models

To estimate ethanol selling price, a series of process design and plant design assumptions were made by Aden et al. (2002). To evaluate the affect of plant size, a tradeoff was examined between the savings resulting from increasing plant size/economies of scale and the increased transportation cost due to increased collect distance of biomass. A formula was presented to illustrate the relationship between plant size and area to collect

biomass. The results of the formula also show the impact of the assumed availability of harvesting acres and the yield of corn stover per acre per year.

Infrastructure requirement analysis

Reynolds (2002) investigated the feasibility of expanding the ethanol industry by studying two cases. Each case identified the potential ethanol plant location information and then estimated the demand volume of the ethanol markets. Finally, composite freight rates were developed.

Market uncertainties analysis

Market uncertainties, resulting from a series of issues that impacted the demand for ethanol and the production of ethanol, were examined. Relevant public policy issues and regulatory barriers included:

- The legislation banning the use of methyl tertiary butyl ether (MTBE) increased the opportunities of the use of ethanol as a substitute.
- U.S. Environmental Protection Agency/California Air Resources Board (USEPA/CARB) models effect on ethanol's value as a blending component could also potentially affect the demand and production of ethanol.
- Whether the tax exemption of ethanol blends sustain affects the demand for ethanol and the production of ethanol.
- Energy policy encouraged the use of renewable fuels.
- The availability and competition of cellulosic biomass affected the production of ethanol.
- The concern of reducing GHG emissions increased the use of ethanol.
- The different state regulations may affect the ethanol use positively or negatively.

Optimization model

A mathematical model that integrates spatial and temporal dimensions was proposed for strategic planning of ethanol supply chain systems. A snap shot of a bioethanol supply chain is shown in Figure 1 (Huang et al.). This model incorporates dynamics issues in long-term strategic planning of biofuel systems. In previous literature, advanced mathematical models have been proposed but seldom consider system dynamics and uncertainties. This model also considered the entire biofuel supply chain as a whole which has not been widely adopted in renewable energy planning literature (Huang et al.).

Fig. 1. A snap shot of a bioethanol supply chain.

Figure 1 A snap shot of a bioethanol supply chain (Huang et al.)

The spatial dimension represents the geographic distribution of the feedstock resources, the fuel demands and the production and transportation infrastructure (Huang et al.). The temporal dimension focuses on long-term biofuel system planning. The production and distribution infrastructure system will have to be expanded over time in response to the growing demand. To achieve an overall effectiveness of the systems expansion, the dynamics of such an evolving process needs to be taken into consideration in the system planning (Huang et al.).

The objective of the model was to minimize the cost of the entire supply chain of biofuel from biowaste feedstock field to end users. The key research questions of this study were (Huang et al.):

- Is cellulosic biofuel an economically viable solution?
- What are the infrastructure requirements to support such a biofuel supply chain system?

The model was used to evaluate the economic potential and infrastructure requirements for bioethanol production from eight waste biomass resources in California as a case study. It concluded that biowaste-based ethanol production can be sustained at a compatible cost around \$1.1 per gallon (Huang et al.).

A mathematical model was developed to design biomass-to-biorefinery supply chain and manage the logistics of a biorefinery (Eksioglu et al., 2009). Decisions about supply chain design are long-term decisions which are made every 5-10 years, or even more.

These decisions related to identifying (Eksioglu et al., 2009):

- The number, capacity and location of biorefineries needed to make use of the biomass available in the region;
- The number and location of biomass collection facilities;
- Harvesting sites that serve a particular collection facility;
- Collection facilities that serve a particular biorefinery; and
- Blending facilities used by a particular biorefinery.

On the other hand, managing the logistics of a biorefinery consists of mid-term to short-term decisions. These decisions related to identifying (Eksioglu et al., 2009):

- The amount of biomass collected in a time period;
- The amount of biomass shipped in a time period to a collection facility (or directly to a biorefinery) from each harvesting site;

- The amount of biomass shipped to a biorefinery in a time period;
- The amount of biofuel shipped in a time period from a biorefinery to a blending facility
- The amount of biomass processed in a time period in a biorefinery; and
- The amount of inventory of biomass in a facility, etc.

Due to the high transportation cost, biorefineries prefer to get their supply of biomass from within 50 miles of radius. This is the reason why 76% of ethanol produced in the USA comes from small sized biorefineries located in four major corn producing states in the Midwest (Eksioglu et al., 2009).

There is a vast literature on the area of supply-chain design and supply-chain management for industrial products. However, due to the nature of biomass, these models do not directly apply. For example, biomass supply is uncertain, seasonal, and constrained by land availability. Supply-chain design and management models for industrial products consider mainly demand (rather than supply) uncertainties, consider demand (rather than supply) seasonality, and focus on satisfying demand (rather than making good use of the supply). The literature related to supply chain management for biomass supply provides models that estimate the cost of collecting, handling and hauling biomass to biorefineries, compare different modes of delivering biomass, and identify supply chain options for biobased businesses. To our knowledge, the work of Tembo, Epplin, and Hunke (2003) is the only study that takes an integrated view of biomass harvesting, inventory, transportation processes and biorefinery location. However, the structure of the supply chain considered is different (Eksioglu et al., 2009).

The supply chain is modeled as a network design problem with additional constraints. Figure 2 gives a network representation of a supply chain model consisting of two harvesting sites, two potential locations for collection facilities, two potential locations for biorefineries, and two blending facilities. Each time period can be taken as a layer. Within each layer, nodes represent potential locations for harvesting sites, collection facilities, or biorefineries. Arcs in solid lines are transportation pathway, while the dash lines that connect the same facility in two consecutive time periods represent inventory arcs. The model assumed no inventory of biomass was held in the field side. The network representation allows modeling the dynamic nature of decisions related to supply chain design and logistics management of a biorefinery. In this network, a time period t could be as long as a day, a week, or a month. The length of the whole horizon T could be as long as one year. Decreasing the length of a time period t increases the size of the problem. Due to the availability of the data, the length of a time period used in the computational analyses is one week, and the planning horizon is one year (Eksioglu et al., 2009).

Fig. 4. Network representation of the supply chain model.

Figure 2 Network representation of the supply chain model (Eksioglu et al., 2009)

This study aims to identify the number, size and location of collection facilities and biorefineries needed to process the biomass availability in a particular region. The objective function is to minimize the annual cost of harvesting, storing, transporting and processing biomass; storing and transporting ethanol; and locating and operating biorefineries. A mixed integer programming (MIP) model was developed and the CPLEX optimization software was used to solve the problem (Eksioglu et al., 2009). The objective was to minimize the annual cost of harvesting, storing and transporting ethanol as well as locating and operating biorefineries.

Two significant bottlenecks that hinder the increased biomass utilization for energy production are the cost and complexity of its logistics operations (Iakovou et al.). Figure 3 is a graphical representation of a waste biomass supply chain.

Fig. 1. Graphical representation of a waste biomass supply chain (WSBC).

Figure 3 Graphical representation of a waste biomass supply chain (WSBC) (Iakovou et al.)

The economic potential and infrastructure requirements of hydrogen production from agricultural residues were examined by Parker et al. (2010). In general, a biorefinery

pathway includes all the facilities and operations involved in the supply chain of biorefinery from the raw feedstock supply to the end users. The efficiency of the entire pathway depends on the geography of the feedstock resources, the layout and operation of the biorefineries, and the cost of accessing the energy market. These factors are not independent of each other. In order to achieve the most efficient and economic production of hydrogen, individual components of bio-hydrogen pathway, the supplies, the production, and the delivery systems, need to be designed simultaneously as an integrated supply chain system. However, an integrated system analysis for the entire hydrogen pathway from biomass waste is still lacking in the literature (Parker et al.).

Fig. 1. A simple example of biohydrogen pathway.

Figure 4 A simple example of biohydrogen pathway (Parker et al.)

The integrated model was developed based on GIS and mathematical programming to evaluate the economic potential and infrastructure requirements of hydrogen production from agricultural residues. The model answered the two following questions (Parker et al.):

- Is bio-hydrogen production economically sustainable?
- How should we plan the production and delivery infrastructure system involved in the bio-hydrogen supply chain and allocate available biomass resources to achieve the best economic performance?

The objective is to maximize profit generated from biohydrogen production. It depends on the capacities of the infrastructure built as well as the quantities delivered or produced at each node and along each link. A mixed integer non-linear programming (MINLP) model with real word GIS data was developed. The objective was to maximize the profit generated from biohydrogen production. It is dependent on the infrastructure capacity as well as the quantities delivered or produced at each node and along each link. The model described the optimal behavior of an industry to supply vehicular hydrogen from agricultural residues in a steady-state system of hydrogen demand, selling price, and feedstock supply. If hydrogen from agricultural residues can be delivered to the refueling stations for less than the given selling price then it is profitable for the industry to supply that hydrogen and the infrastructure is built to reap that profit. Model assumptions include (Parker et al.):

- The optimality is measured by the annualized profit from hydrogen production. Most supply chain model chooses minimizing total cost as the objective. The advantage of choosing profit maximization lie in that it reflects the profit-driven industrial operation and it allows infrastructure design to respond to price differentials between demand centers.

- Hydrogen is produced from rice straw via a gasification process with co-production of a small amount of electricity. The technologies for rice straw harvest and delivery remain unchanged from current practice. Hydrogen is delivered to refueling stations using one of three modes: gaseous truck, liquid truck or via pipeline (new). The refueling stations dispense hydrogen to vehicles with 5000 psi onboard storage tanks.
- Hydrogen demand will be concentrated in areas of high population density and will be evenly distributed in those areas.
- Model parameters remain constant in the one-year study period. This model is a deterministic model (demand, supply, and technology are stabilized in the long run) which can serve as the basis for more advanced stochastic models. For example, sensitivity analysis of the deterministic model can help identify important model parameters that may need stochastic treatment.

The inputs of the model include (Parker et al.):

- GIS-based data describing biomass feedstock availability;
- Geographic distribution and projection for future hydrogen demand; and
- Engineering economic sub models for computing the production and transportation costs under different technology assumptions.

The outputs of the model include (Parker et al.):

- The maximum profit generated from biohydrogen production;
- The optimal locations and sizes of biohydrogen production plants;
- The optimal allocation of biomass resources to production plants; and
- The optimal transportation infrastructure configuration and operation for biomass and produced hydrogen.

The objective is to build an industry that will maximize profit with given demands, supplies, and hydrogen market price. Figure 5 is a network representation of biohydrogen pathway. Three types of constraints are considered, including (Parker et al.),

- Capacity constraints which restrict quantities not to exceed the maximum allowed by the built or given capacities;
- Flow conservation constraints which require that at each node the quantities going in must equal the quantities going out plus (or minus) the quantities supplied (or consumed) at the node; and
- Non-negative constraints which require that all physical quantities be positive as they cannot be negative.

Fig. 2. Network representation of biohydrogen pathway.

Figure 5 Network representation of biohydrogen pathway (Parker et al.)

A multi-biomass supply chain model for tri-generation energy (electricity, heating and cooling) production was built and optimized to maximize the financial yield of the investment for investors (Rentizelas et al., 2009). The consideration of multi-biomass supply chain presents significant potential for cost reduction, by allowing spreading of capital costs and reducing warehousing requirement, especially when seasonal biomass types are concerned (Rentizelas et al., 2009).

One of the most important barriers in increased biomass utilization in energy supply is the cost of the respective supply chain and the technology to convert biomass into useful forms of energy (electricity, heating, etc.). It is therefore natural that many attempts have been made to date to simulate and optimize a specific biomass supply chain on the understanding that significant cost reductions could originate from more efficient logistics operations (Rentizelas et al., 2009).

Two of the major characteristics of the model are (Rentizelas et al., 2009):

- Multi-biomass supply chain approach which leads to increased efficiencies in the biomass supply chain, especially when biomass types with high seasonality are concerned, according to several researchers; and
- System-wide modeling and optimization approach which ensuring that the global optimum design and operational characteristics for the system are defined.

The model aims to provide investor with optimal answers concerning the following investment issues (Rentizelas et al., 2009):

- Which is the best location to establish the biomass-to-energy facility?
- Which is the optimal relative size of the base-load CHP unit and the peak-load boiler?
- Which amount of each locally available biomass type should be used and from where should it be collected?

The simulation and the optimization model were developed in Matlab by Mathworks.

The objective function to be maximized is the net present value (NPV) of the investment for the project's lifetime. NPV was chosen not only because it is the most frequently used

investment appraisal criterion in co-generation plant investment, but also as it is considered theoretically superior to other criteria (Rentizelas et al., 2009).

The constraints considered include (Rentizelas et al., 2009):

- Energy demand constraints
- Warehousing constraints
 - A safety stock constraint was considered. The biomass safety stock in the warehouse was set as the amount of biomass adequate for at least 20 days of full load operation.
 - Another constraint is introduced, due to the rolling horizon of the model: the finishing season stock must be at least as much as the starting season stock.
- Legislation constraints
 - The legislation in Greece requires that a co-generation project may receive subsidy on investment only if at least 65% of the heat generated is exploited.
- Social constraints
 - The bioenergy conversion facility must be located at least a safety distance away from the customer's location.
- Logic constraints
 - non-negative or upper bounds constraints

In order to overcome the limitations of using a specific non-linear method, a hybrid method was applied in the model. This means that firstly, one optimization method is employed to define a good solution to the problem. This solution is used as the starting point of the second optimization method that bears the task to enhance further the solution found at the first step. The optimization method used for the first step is a genetic algorithm (GA). A sequential quadratic programming (SQP) optimization method was applied at the second step to define the optimum (Rentizelas et al., 2009).

Lam et al. (2010) proposed a novel methodology for regional energy targeting and supply chain synthesis. It is a two-level methodology. The first is a top-level supply chain network with lowest Carbon Footprint (CFP) generated. It consists of a number of zone clusters. The zones can be a village or a town. Each zone was considered as a unit. At the second level is a supply chain synthesis carried out by P-graph (process graph) based optimization with each cluster (Lam et al.).

The objective of the paper is to minimize the CFP generated in the biomass supply chain. The CFP is mainly caused by processing, transportation and burning. Especially transportation activities could contribute the major part of the CFP in the supply chain. The typical locations of biomass sources (farms, forest, etc.), the relatively low energy density, and the distributed nature of the sources require extensive infrastructure and huge transport capacities for implementing the biomass supply network. For regional biomass supply chain road transportation is the usual mode for collection and transportation. This tends to increase the CFP of the biomass based energy (Lam et al.). This paper focused on a detailed technical design combining with economic and environmental analysis of a lignocellulosic feedstock (LCF) biorefinery producing ethanol, power and high-value chemicals (succinic acid and acetic acid). The results of the economic analysis showed that the designed refinery has great potential compared to the single-output ethanol plant. The LCF biorefinery showed better environmental performance mainly in global warming potential due to CO₂ fixation during acid fermentation (Luo et al.).

Design of the biorefinery

The LCF biorefinery used corn stover as feedstock and produce multiple outputs, including ethanol, power and high-value chemicals (succinic acid and acetic acid). The stover is collected with an 80 km (50 miles) radius around the biorefinery. The harvested stover was transported by lorries. The biorefinery was designed to operate 24 hours per day, and 335 days (11 months) per year continuously. The remaining one month was used for cleaning-up and restarting the operations. As crop residues are harvested and transported at different time of the year, long-term storage is required to provide feedstocks to the plant year-round. The lifetime of the biorefinery was assumed to be 20 years. The capacity of the biorefinery was also defined from literature study (Luo et al.). On-site short-term storage was provided equivalent to 72 hours of production at an outside storage area. The stored material provides a short-term supply for weekends, holidays, and when normal direct delivery of material into the process is interrupted. The material will be rotated continuously, with a first-in, first-out inventory management strategy (Luo et al.).

Economic analysis

The economic analysis was conducted to estimate the net present value (NPV) and internal rate of return (IRR), which is based on the capital investment, and on the variable and fixed operating costs of the refinery. The discount rate was set at 10%. The construction period of the biorefinery was assumed to be three years. The first year expense is the engineering, construction and contingency costs. In the second year, 80% of the total capital investment is assumed to be made and the investment is finished in the third year. It is assumed that the refinery starts to be operated at 75% capacity in the third year, and at full capacity (11 months per year) in the rest of the life time. The results of the economic analysis were compared with the ones from the ethanol plant designed by Aden et al. (2002) from NREL. Sensitivity analyses were conducted on the capital investment, the market price of both succinic acid and ethanol, and the purchase price of the feedstock (Luo et al.).

Publications

Zhang, F, Handler, R, Johnson, D.M., and Shonnard, D.R. 2011. Comparative Analysis of Life Cycle Greenhouse Gas Emissions of Supply Chains for Biofuel and Fossil Fuel Production. IN: IN: Production and Operations Management Society - POMS 22nd Annual Conference, Reno, Nevada, April 29-2, 2011.

Zhang, F., Johnson, D.M., and Sutherland, J.W. 2010. GIS-based Approach of Identification of the Optimal Pulpwood-to-Biofuel Facility Location in Michigan's Upper Peninsula. IN: Production and Operations Management Society - POMS 22nd Annual Conference, Vancouver, Canada, May 7-10, 2010.

Zhang, F., Johnson, D.M. Johnson, M.A., and Sutherland, J.W. 2011. Development of a Biomass Supply Chain for Biofuel Production. IN: Proceedings of the 2011 Industrial Engineering Research Conference (T. Doolen and E. Van Aken, eds.), Reno, Nevada, May 21-25, 2011.

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Appendix B4-A: Publications

Zhang, F, Handler, R, Johnson, D.M., and Shonnard, D.R. 2011. Comparative Analysis of Life Cycle Greenhouse Gas Emissions of Supply Chains for Biofuel and Fossil Fuel Production. IN: IN: Production and Operations Management Society - POMS 22nd Annual Conference, Reno, Nevada, April 29-2, 2011.

Abstract

To reduce U.S. dependence on imported oil and to reduce carbon emissions, renewable biofuel production from biomass has seen emerging interest. This study focused on life cycle greenhouse gas emission impacts of forest biomass supply chain for ethanol production. The life cycle stages considered include biomass harvesting/forwarding, and transportation via truck/rail. The comparison system is a supply chain for petroleum-based fuel production, exemplified using data specific to the U.S. The results show that from feedstock supply perspective, biofuel production from forest biomass is more environmentally friendly (about 50-70% less greenhouse gas emissions) compared with petroleum based fuel production. Forest biomass supply by rail performs better (about 15 million kg less carbon emissions) than truck supply.

Keywords: LCA, biomass supply chain, greenhouse gas emissions

Zhang, F., Johnson, D.M., and Sutherland, J.W. 2010. GIS-based Approach of Identification of the Optimal Pulpwood-to-Biofuel Facility Location in Michigan's Upper Peninsula. IN: Production and Operations Management Society - POMS 22nd Annual Conference, Vancouver, Canada, May 7-10, 2010.

Abstract

One of the critical elements for promoting ethanol production from woody biomass is defining the optimal ethanol plant location. The woody biomass feedstock and transportation costs are geographically dependent. A Geographic Information System (GIS) based approach was applied to identify potential pulpwood-to-biofuel facility locations. The approach uses a county-based pulpwood distribution, a population census, and railroad and state/federal road transportation networks. The preferred location will be selected using a weighted-average transportation cost.

Keywords: GIS, biomass, biofuel, transportation cost, optimal facility location

Zhang, F., Johnson, D.M. Johnson, M.A., and Sutherland, J.W. 2011. Development of a Biomass Supply Chain for Biofuel Production. IN: Proceedings of the 2011 Industrial Engineering Research Conference (T. Doolen and E. Van Aken, eds.), Reno, Nevada, May 21-25, 2011.

Abstract

To reduce U.S. dependence on imported oil and reduce carbon emissions, biofuel production from renewable biomass is receiving increasing interest. However, due to the distributed nature of biomass feedstock, the cost and complexity of biomass recovery operations result in significant challenges that hinder the increased biomass utilization for energy production. This paper describes the development of a simulation model using Arena for the biomass supply chain for biofuel production in Michigan. The model describes the supply chain from landing sites to the biorefinery, including biomass harvesting, transportation, and on-site storage. The simulation model is driven by both the daily biomass production at harvesting sites distributed across a harvesting region and the daily demand for biomass feedstock at a biorefinery located in the center of the region. The supply chain model is evaluated using multiple criteria that include the delivered feedstock cost, energy consumption, and greenhouse gas (GHG) emissions. Other considerations include the average age of the in-field biomass inventory and road restrictions associated with spring thaw that limit use of truck transportation on certain roads. The utility of the supply chain simulation model is demonstrated by considering a biomass supply chain for a biorefinery in the lower peninsula of Michigan.

Keywords

Biomass supply chain, simulation, delivered feedstock cost, energy consumption, greenhouse gas emissions

Johnson, D.A., Zhang, F, Harrison, E, Hanninen, K. 2011. Comparative Review of Biofuel Supply Chains. IN: Proceedings of Decision Sciences Institute 42nd Annual Meeting, Boston, MA, November 19-22, 2011.

Abstract

The complexity of a biomass supply chain has been a significant challenge that hinders increased biomass utilization for energy production due to the distributed nature of biomass feedstock. A literature review allowed for the development of a comparative analysis to a unique biomass supply chain designed for the Forestry Biofuel Statewide Collaboration Center (FBSCC) project in Michigan. Research gaps were used to develop models for the FBSCC.

Keywords: cellulosic ethanol, biomass supply chain, comparative analysis, literature review

Zhang, F., Johnson, D.M. Johnson, M.A., and Sutherland, J.W. "A GIS-based method for identifying the optimal location for a facility to convert forest biomass to biofuel." *Biomass and Bioenergy*, 35 (2011) 3951-3961.

Abstract

There is growing interest in the production of biofuels from woody biomass. Critical to the financial success of producing biofuel is identifying the optimal location for the facility. The location decision is especially important for woody biomass feedstock owing to the distributed nature of biomass and the significant costs associated with transportation. This study introduces a two-stage methodology to identify the best location for biofuel production based on multiple attributes. Stage I uses a Geographic Information System approach to identify feasible biofuel facility locations. The approach employs county boundaries, a county-based pulpwood distribution, a population census, city and village distributions, and railroad and state/federal road transportation networks. In Stage II, the preferred location is selected using a total transportation cost model. The methodology is applied to the Upper Peninsula of Michigan to locate a biofuel production facility. Through the application of the two-stage methodology, the best possible location for biofuel production was identified as the Village of L'anse in Baraga County. Also investigated are the sensitivity of transportation cost and the optimal site for biofuel production to changes in several key variables. These additional variables included fuel price, transportation distance, and pulpwood availability. By applying sensitivity analysis based on limited availability of feedstock, the City of Ishpeming emerged as another viable location for the production facility.

Appendix B4-B Maps of Each of the Nine Locations and 100 Mile Radius

City of Clare

Village of Kalkaska

City of Manton

City of Traverse City

City of Boyne City

City of Gaylord

Village of Kingsley

Village of Roscommon

Transportation

- Roscommon_Buf_county
- ★ Roscommon
- Ip_county_Point
- Roscommon_Buffer
- +— railroad_lp
- roads_lp

04.59 18 27 36
Miles

Data Source: MI Geographic Data Library and FIA Forest Service
Fengli Zhang
Aug 24, 2010

City of West Branch

Transportation

- West Branch_Buf_county
- ★ West Branch
- Ip_county_Point
- West_Branch_Buffer
- +— railroad_lp
- stroads_lp

04.59 18 27 36
Miles

Data Source: MI Geographic Data Library and FIA Forest Service
Fengli Zhang
Aug 24, 2010

Appendix B4-C – Counties within 100 mile radius of each location (we excluded UP)

County (supplier)	Railway going through the county (YES/NO)	Biorefinery location (demand site)								
		Manton	Roscommon	Kingsley	Kalkaska	Gaylord	Clare	West Branch	Traverse City	Boyne City
Barry	NO						X			
Benzie	NO	X	X	X	X	X	X	X	X	X
Cheboygan	NO	X	X	X	X	X		X	X	X
Gladwin	NO	X	X	X	X	X	X	X	X	X
Leelanau	NO	X	X	X	X	X	X	X	X	X
Mecosta	NO	X	X	X	X		X	X	X	
Montmorency	NO	X	X	X	X	X	X	X	X	X
Oceana	NO	X		X	X		X		X	
Oscoda	NO	X	X	X	X	X	X	X	X	X
Presque Isle	NO	X	X	X	X	X		X	X	X
Alcona	YES	X	X	X	X	X	X	X	X	X
Alpena	YES	X	X	X	X	X		X	X	X
Antrim	YES	X	X	X	X	X	X	X	X	X
Arenac	YES	X	X	X	X	X	X	X	X	X
Bay	YES	X	X	X	X	X	X	X		
Charlevoix	YES	X	X	X	X	X		X	X	X
Clare	YES	X	X	X	X	X	X	X	X	X
Clinton	YES						X	X		
Crawford	YES	X	X	X	X	X	X	X	X	X
Eaton	YES						X			
Emmet	YES	X	X	X	X	X		X	X	X
Genesee	YES						X	X		
Grand Traverse	YES	X	X	X	X	X	X	X	X	X
Gratiot	YES	X	X				X	X		
Huron	YES		X				X	X		
Ingham	YES						X			
Ionia	YES						X			
Iosco	YES	X	X	X	X	X	X	X		X
Isabella	YES	X	X	X	X	X	X	X	X	
Kalkaska	YES	X	X	X	X	X	X	X	X	X
Kent	YES	X					X			
Lake	YES	X	X	X	X	X	X	X	X	X
Lapeer	YES						X	X		
Livingston	YES						X			
Manistee	YES	X	X	X	X	X	X	X	X	X
Mason	YES	X	X	X	X		X		X	
Midland	YES	X	X	X	X	X	X	X	X	
Missaukee	YES	X	X	X	X	X	X	X	X	X
Montcalm	YES	X	X	X	X		X	X		
Muskegon	YES	X		X			X			
Newaygo	YES	X	X	X	X		X	X	X	
Ogemaw	YES	X	X	X	X	X	X	X	X	X
Osceola	YES	X	X	X	X	X	X	X	X	X
Otsego	YES	X	X	X	X	X	X	X	X	X
Ottawa	YES						X			
Roscommon	YES	X	X	X	X	X	X	X	X	X
Saginaw	YES		X				X	X		
Sanilac	YES							X		
Shiawassee	YES						X	X		
Tuscola	YES		X				X	X		
Wexford	YES	X	X	X	X	X	X	X	X	X

NOTE: X means the county is a potential supplier for the biorefinery.

Appendix B4-D Michigan Department of Transportation Spring Break Up Maps

41706a

41806a

42106a

42406a

042506

042806

050306

050306b

050406

050806a

051006

051006

051606

051706

051706b

051906

052306

052306b

062106

3_11_08_2

3_11_08_3

3_11_08_4

3_11_08_5

3_12_08

3_12_08_2

3_12_08_3

3_12_08_4

3_12_08_5

3_12_08_6

3_13_08

3_13_08_2

3_13_08_3

3_14_08

3_14_08_2

3_17_08

3_17_08_2

3-18-02

3-24-08

4-7-08

4-8-08

4-9-08

4-9-08-2

4-11-08

4-15-08

4-16-08

4-16-08-2

4-17-08

Appendix B4-E MDOT Spring Break Up Data

County	2006			2007			2008			2009			2010		
	start	end	# of days	start	end	# of days	start	end	# of days	start	end	# of days	start	end	# of days
Alcona	9-Mar	13-Apr	36	12-Mar	23-Apr	43	17-Mar	25-Apr	40	9-Mar	24-Apr	47	8-Mar	6-Apr	30
Alpena	8-Mar	13-Apr	37	12-Mar	20-Apr	40	17-Mar	22-Apr	37	9-Mar	22-Apr	45	8-Mar	1-Apr	25
Antrim	6-Mar	9-Apr	35	9-Mar	2-Apr	25	11-Mar	18-Apr	39	9-Mar	15-Apr	38	3-Mar	25-Mar	23
Arenac	13-Mar	7-Apr	26	5-Mar	20-Apr	47	14-Mar	18-Apr	36	6-Mar	15-Apr	41	8-Mar	1-Apr	25
Barry	1-Feb	28-Mar	56	26-Feb	3-Apr	37	10-Mar	9-Apr	31	25-Feb	1-Apr	37	2-Mar	25-Mar	24
Bay	6-Mar	12-Apr	38	28-Feb	16-Apr	48	10-Mar	15-Apr	37	6-Mar	15-Apr	41	3-Mar	26-Mar	24
Benzie	8-Mar	23-Mar	16	9-Mar	29-Mar	21	12-Mar	18-Apr	38	9-Mar	6-Apr	29	5-Mar	16-Mar	12
Charlevoix	6-Mar	17-Apr	42	24-Feb	18-Apr	54	10-Mar	18-Apr	40	9-Mar	15-Apr	38	3-Mar	26-Mar	24
Cheboygan	8-Mar	13-Apr	37	12-Mar	16-Apr	36	17-Mar	22-Apr	37	13-Mar	24-Apr	43	8-Mar	1-Apr	25
Clare	10-Mar	7-Apr	29	13-Mar	10-Apr	30	10-Mar	18-Apr	40	25-Feb	15-Apr	51	3-Mar	31-Mar	29
Clinton	6-Mar	31-Mar	26	26-Feb	6-Apr	40	10-Mar	11-Apr	33	3-Mar	13-Apr	42	1-Mar	1-Apr	32
Crawford	6-Mar	9-Apr	35	22-Mar	20-Apr	40	12-Mar	18-Apr	38	6-Mar	15-Apr	41	8-Mar	26-Mar	19
Eaton	1-Mar	3-Apr	34	1-Mar	6-Apr	37	3-Mar	11-Apr	40	25-Feb	13-Apr	49	2-Mar	1-Apr	31
Emmet	1-Mar	4-Apr	34	1-Mar	29-Mar	29	10-Mar	18-Apr	40	9-Mar	15-Apr	38	2-Mar	26-Mar	25
Genesee	6-Feb	9-Apr	63	9-Mar	16-Apr	39	12-Mar	11-Apr	31	25-Feb	9-Apr	45	8-Mar	1-Apr	25
Gladwin	6-Mar	13-Apr	39	9-Mar	20-Apr	43	12-Mar	23-Apr	43	26-Feb	22-Apr	57	5-Mar	31-Mar	27
Grand Traverse	6-Mar	28-Mar	23	5-Mar	30-Mar	26	14-Mar	11-Apr	29	9-Mar	15-Apr	38	8-Mar	19-Mar	12
Gratiot	6-Mar	4-Apr	30	26-Feb	4-Apr	38	10-Mar	11-Apr	33	25-Feb	9-Apr	45	3-Mar	1-Apr	30
Huron	31-Jan	13-Apr	75	22-Mar	16-Apr	36	11-Mar	15-Apr	36				4-Mar	31-Mar	28
Ingham	9-Mar	13-Mar	5	5-Mar	3-Apr	30	10-Mar	11-Apr	33	25-Feb	9-Apr	45	1-Mar	1-Apr	32
Ionia	6-Mar	30-Mar	25	26-Feb	4-Apr	38	4-Mar	11-Apr	39	25-Feb	8-Apr	44	1-Mar	25-Mar	25
Iosco	10-Mar	7-Apr	29	12-Mar	20-Apr	40	17-Mar	23-Apr	38	9-Mar	20-Apr	43	8-Mar	1-Apr	25
Isabella	6-Mar	7-Apr	33	28-Feb	10-Apr	42	7-Mar	16-Apr	41	25-Feb	14-Apr	50	3-Mar	30-Mar	28
Kalkaska	6-Mar	12-Apr	38	12-Mar	23-Apr	43	17-Mar	22-Apr	37	6-Mar	15-Apr	41	8-Mar	25-Mar	18
Kent	6-Mar	28-Mar	23	26-Feb	30-Mar	33	3-Mar	18-Apr	47	25-Feb	1-Apr	37	26-Feb	25-Mar	28
Lake	8-Mar	30-Mar	23	5-Mar	30-Mar	26	10-Mar	8-Apr	30	25-Feb	7-Apr	43	3-Mar	26-Mar	24
Lapeer	6-Mar	3-Apr	29	9-Mar	16-Apr	39	12-Mar	21-Apr	41				19-Mar	1-Apr	14
Leelanau	8-Mar	28-Mar	21	9-Mar	19-Apr	42	12-Mar	22-Apr	42	6-Mar	3-Apr	29	8-Mar	16-Mar	9
Livingston	1-Mar	23-Mar	23	24-Feb	5-Apr	41	10-Mar	11-Apr	33	25-Feb	6-Apr	42	1-Mar	31-Mar	31
Manistee	10-Mar	30-Mar	21	5-Mar	30-Mar	26	10-Mar	11-Apr	33	26-Feb	14-Apr	49	2-Mar	19-Mar	18
Mason	6-Mar	28-Mar	23	5-Mar	9-Apr	36	10-Mar	18-Apr	40	25-Feb	13-Apr	49	4-Mar	19-Mar	16
Mecosta	8-Mar	31-Mar	24	9-Mar	6-Apr	29	10-Mar	11-Apr	33	25-Feb	27-Mar	32	4-Mar	19-Mar	16
Midland	6-Mar	7-Apr	33	28-Feb	16-Apr	48	10-Mar	15-Apr	37	25-Feb	15-Apr	51	1-Mar	5-Apr	36
Missaukee	6-Mar	4-Apr	30	12-Mar	2-Apr	22	12-Mar	18-Apr	38	6-Mar	9-Apr	35	5-Mar	19-Mar	15
Montcalm	6-Mar	30-Mar	25	26-Feb	30-Mar	33	3-Mar	18-Apr	47	25-Feb	1-Apr	37	26-Feb	25-Mar	28
Montmorency	1-Mar	7-Apr	38	1-Mar	30-Mar	30	17-Mar	18-Apr	33	6-Mar	28-Apr	54	26-Feb	26-Mar	29
Muskegon	6-Mar	30-Mar	25	26-Feb	30-Mar	33	3-Mar	15-Apr	44	25-Feb	1-Apr	37	26-Feb	29-Mar	32
Newaygo	9-Mar	30-Mar	22	1-Mar	6-Apr	37	10-Mar	17-Apr	39	25-Feb	1-Apr	37	2-Mar	19-Mar	18
Oceana	9-Mar	3-Apr	26	9-Mar	6-Apr	29	3-Mar	11-Apr	40	26-Feb	15-Apr	50	1-Mar	24-Mar	24
Ogemaw	8-Mar	7-Apr	31	9-Mar	13-Apr	36	17-Mar	23-Apr	38	6-Mar	22-Apr	48	8-Mar	1-Apr	25
Osceola	8-Mar	30-Mar	23	5-Mar	9-Apr	36	10-Mar	17-Apr	39	9-Mar	9-Apr	32	3-Mar	25-Mar	23
Oscoda	13-Mar	13-Apr	32	13-Mar	23-Apr	43	17-Mar	25-Apr	40	11-Mar	24-Apr	45	8-Mar	7-Apr	31
Otsego	9-Mar	9-Apr	32	9-Mar	2-Apr	25	12-Mar	18-Apr	38	9-Mar	15-Apr	38	8-Mar	26-Mar	19
Ottawa	6-Mar	13-Mar	39	26-Feb	29-Mar	32	10-Mar	11-Apr	33	25-Feb	1-Apr	37	3-Mar	25-Mar	23
Presque Isle	7-Mar	13-Apr	38	9-Mar	18-Apr	41	17-Mar	23-Apr	38	9-Mar	27-Apr	50	5-Mar	1-Apr	28
Roscommon	8-Mar	7-Apr	31	9-Mar	16-Apr	39	17-Mar	17-Apr	32	9-Mar	15-Apr	38	5-Mar	26-Mar	22
Saginaw	6-Mar	7-Apr	33	9-Mar	16-Apr	39	10-Mar	15-Apr	37	27-Feb	15-Apr	49	1-Mar	1-Apr	32
Sanilac	3-Mar	7-Apr	36	12-Mar	16-Apr	36	12-Mar	16-Apr	36				4-Mar	31-Mar	28
Shiawassee	1-Mar	30-Mar	30	26-Feb	16-Apr	50	10-Mar	17-Apr	39	25-Feb	9-Apr	45	2-Mar	31-Mar	30
Tuscola	6-Mar	7-Apr	33	12-Mar	16-Apr	36	13-Mar	18-Apr	37	3-Mar	15-Apr	44	8-Mar	31-Mar	24
Wexford	13-Mar	3-Apr	22	13-Mar	6-Apr	26	13-Mar	17-Apr	36	9-Mar	15-Apr	38	5-Mar	29-Mar	25

Source: Michigan Department of Transportation (MDOT)

Methodology

The start and end dates are colored in the maps we got from MDOT. The start was identified as the day one county is colored. The end date were identified as the last day the weight restriction is in effect (through 2006-2010). The duration of spring breakup were calculated by plus one to the difference between start and end dates.

Appendix B4-F Federal Forest Biomass Data

County code and name	LP/UP	N/S or E/W	Total	Softwoods	Hardwoods	soft_avail	hard_avail	soft_vol_ava	hard_vol_avail	soft_GT_avail	hard_GT_avail
26001 MI Alcona	LP	N	3,610,146	1,182,724	2,427,422	0.93288219	0.90959717	1,103,342	2,207,976	28,386	83,301
26007 MI Alpena	LP	N	0	0	0	0.93288219	0.90959717	0	0	0	0
26009 MI Antrim	LP	N	0	0	0	0.93288219	0.90959717	0	0	0	0
26011 MI Arenac	LP	N	0	0	0	0.93288219	0.90959717	0	0	0	0
26015 MI Barry	LP	S	0	0	0	0.93288219	0.90959717	0	0	0	0
26017 MI Bay	LP	N	0	0	0	0.93288219	0.90959717	0	0	0	0
26019 MI Benzie	LP	N	0	0	0	0.93288219	0.90959717	0	0	0	0
26029 MI Charlevoix	LP	N	0	0	0	0.93288219	0.90959717	0	0	0	0
26031 MI Cheboygan	LP	N	0	0	0	0.93288219	0.90959717	0	0	0	0
26035 MI Clare	LP	N	0	0	0	0.93288219	0.90959717	0	0	0	0
26037 MI Clinton	LP	S	0	0	0	0.93288219	0.90959717	0	0	0	0
26039 MI Crawford	LP	N	1,529,259	590,142	939,117	0.93288219	0.90959717	550,533	854,218	14,164	32,227
26045 MI Eaton	LP	N	0	0	0	0.93288219	0.90959717	0	0	0	0
26047 MI Emmet	LP	N	0	0	0	0.93288219	0.90959717	0	0	0	0
26049 MI Genesee	LP	S	0	0	0	0.93288219	0.90959717	0	0	0	0
26051 MI Gladwin	LP	N	0	0	0	0.93288219	0.90959717	0	0	0	0
26055 MI Grand Traverse	LP	N	0	0	0	0.93288219	0.90959717	0	0	0	0
26057 MI Gratiot	LP	S	0	0	0	0.93288219	0.90959717	0	0	0	0
26063 MI Huron	LP	S	0	0	0	0.93288219	0.90959717	0	0	0	0
26065 MI Ingham	LP	S	0	0	0	0.93288219	0.90959717	0	0	0	0
26067 MI Ionia	LP	S	0	0	0	0.93288219	0.90959717	0	0	0	0
26069 MI Iosco	LP	N	3,546,112	2,803,665	742,447	0.93288219	0.90959717	2,615,489	675,328	67,289	25,478
26073 MI Isabella	LP	N	0	0	0	0.93288219	0.90959717	0	0	0	0
26079 MI Kalkaska	LP	N	17,379	17,379	0	0.93288219	0.90959717	16,213	0	417	0
26081 MI Kent	LP	S	0	0	0	0.93288219	0.90959717	0	0	0	0
26085 MI Lake	LP	N	3,800,713	1,723,244	2,077,470	0.93288219	0.90959717	1,607,584	1,889,661	41,359	71,292
26087 MI Lapeer	LP	S	0	0	0	0.93288219	0.90959717	0	0	0	0
26089 MI Leelanau	LP	N	0	0	0	0.93288219	0.90959717	0	0	0	0
26093 MI Livingston	LP	S	0	0	0	0.93288219	0.90959717	0	0	0	0
26101 MI Manistee	LP	N	3,342,112	929,228	2,412,884	0.93288219	0.90959717	866,860	2,194,752	22,302	82,802
26105 MI Mason	LP	N	2,798,640	1,570,618	1,228,021	0.93288219	0.90959717	1,465,202	1,117,004	37,696	42,142
26107 MI Mecosta	LP	N	0	0	0	0.93288219	0.90959717	0	0	0	0
26111 MI Midland	LP	N	0	0	0	0.93288219	0.90959717	0	0	0	0
26113 MI Missaukee	LP	N	0	0	0	0.93288219	0.90959717	0	0	0	0
26117 MI Montcalm	LP	S	0	0	0	0.93288219	0.90959717	0	0	0	0
26119 MI Montmorency	LP	N	0	0	0	0.93288219	0.90959717	0	0	0	0
26121 MI Muskegon	LP	S	369,587	176,465	193,122	0.93288219	0.90959717	164,621	175,663	4,235	6,627
26123 MI Newaygo	LP	N	3,221,786	1,439,903	1,781,883	0.93288219	0.90959717	1,343,260	1,620,796	34,558	61,148
26127 MI Oceana	LP	N	2,233,111	975,326	1,257,785	0.93288219	0.90959717	909,864	1,144,078	23,408	43,163
26129 MI Ogemaw	LP	N	823,775	356,258	467,516	0.93288219	0.90959717	332,347	425,251	8,550	16,044
26133 MI Osceola	LP	N	0	0	0	0.93288219	0.90959717	0	0	0	0
26135 MI Oscoda	LP	N	6,278,618	3,352,508	2,926,110	0.93288219	0.90959717	3,127,495	2,661,581	80,462	100,414
26137 MI Otsego	LP	S	0	0	0	0.93288219	0.90959717	0	0	0	0
26139 MI Ottawa	LP	N	0	0	0	0.93288219	0.90959717	0	0	0	0
26141 MI Presque Isle	LP	N	0	0	0	0.93288219	0.90959717	0	0	0	0
26143 MI Roscommon	LP	S	0	0	0	0.93288219	0.90959717	0	0	0	0
26145 MI Saginaw	LP	S	683,156	0	683,156	0.93288219	0.90959717	0	621,397	0	23,444
26151 MI Sanilac	LP	S	0	0	0	0.93288219	0.90959717	0	0	0	0
26155 MI Shiawassee	LP	S	0	0	0	0.93288219	0.90959717	0	0	0	0
26157 MI Tuscola	LP	S	0	0	0	0.93288219	0.90959717	0	0	0	0
26165 MI Wexford	LP	N	4,680,902	2,101,463	2,579,439	0.93288219	0.90959717	1,960,417	2,346,250	50,436	88,518

Appendix B4-G State Forest Biomass Data

County code and name	LP/UP	N/S or E/W	Total	Softwoods	Hardwoods	soft_avail	hard_avail	soft_vol_ava	hard_vol_ava	soft_GT_avail	hard_GT_avail
26001 MI Alcona	LP	N	839,538	130,601	708,937	0.54210441	0.48138431	70,799	341,271	1821	12875
26007 MI Alpena	LP	N	1,567,513	1,023,803	543,710	0.54210441	0.48138431	555,008	261,733	14279	9874
26009 MI Antrim	LP	N	3,145,318	1,076,762	2,068,556	0.54210441	0.48138431	583,717	995,770	15017	37568
26011 MI Arenac	LP	N	625,930	88,609	537,321	0.54210441	0.48138431	48,035	258,658	1236	9758
26015 MI Barry	LP	S	876,142	260,052	616,090	0.89363253	0.88568285	232,391	545,660	5979	20586
26017 MI Bay	LP	N	234,995	0	234,995	0.54210441	0.48138431	0	113,123	0	4268
26019 MI Benzie	LP	N	3,182,835	949,901	2,232,934	0.54210441	0.48138431	514,946	1,074,899	13248	40553
26029 MI Charlevoix	LP	N	500,281	338,935	161,346	0.54210441	0.48138431	183,738	77,669	4727	2930
26031 MI Cheboygan	LP	N	4,751,606	1,511,757	3,239,849	0.54210441	0.48138431	819,530	1,559,612	21084	58840
26035 MI Clare	LP	N	1,494,315	638,650	855,665	0.54210441	0.48138431	346,215	411,904	8907	15540
26037 MI Clinton	LP	S	356,296	10,372	366,668	0.89363253	0.88568285	9,269	324,752	238	12252
26039 MI Crawford	LP	N	4,277,009	2,106,357	2,170,652	0.54210441	0.48138431	1,141,865	1,044,918	29377	39422
26045 MI Eaton	LP	N	209,943	0	209,943	0.54210441	0.48138431	0	101,063	0	3813
26047 MI Emmet	LP	N	2,665,256	1,130,362	1,534,894	0.54210441	0.48138431	612,774	738,874	15765	27876
26049 MI Genesee	LP	S	1,646,423	0	1,646,423	0.89363253	0.88568285	0	1,458,209	0	55014
26051 MI Gladwin	LP	N	2,497,107	368,529	2,128,577	0.54210441	0.48138431	199,781	1,024,664	5140	38658
26055 MI Grand Traverse	LP	N	1,728,621	771,223	957,399	0.54210441	0.48138431	418,083	460,877	10756	17388
26057 MI Gratiot	LP	S	219,986	0	219,986	0.89363253	0.88568285	0	194,838	0	7351
26063 MI Huron	LP	S	516,384	0	516,384	0.89363253	0.88568285	0	457,352	0	17255
26065 MI Ingham	LP	S	2,395,246	467,774	1,927,471	0.89363253	0.88568285	418,018	1,707,128	10754	64405
26067 MI Ionia	LP	S	2,090,294	0	2,090,294	0.89363253	0.88568285	0	1,851,338	0	69846
26069 MI Iosco	LP	N	370,824	201,494	169,330	0.54210441	0.48138431	109,231	81,513	2810	3075
26073 MI Isabella	LP	N	301,435	0	301,435	0.54210441	0.48138431	0	145,106	0	5474
26079 MI Kalkaska	LP	N	6,457,381	3,173,387	3,283,994	0.54210441	0.48138431	1,720,307	1,580,863	44259	59642
26081 MI Kent	LP	S	1,057,177	26,396	1,030,781	0.89363253	0.88568285	23,588	912,945	607	34443
26085 MI Lake	LP	N	2,018,012	970,798	1,047,214	0.54210441	0.48138431	526,274	504,112	13540	19019
26087 MI Lapeer	LP	S	287,692	14,375	273,317	0.89363253	0.88568285	12,846	242,072	330	9133
26089 MI Leelanau	LP	N	51,984	119,727	171,711	0.54210441	0.48138431	64,905	82,659	1670	3118
26093 MI Livingston	LP	S	592,829	7,604	585,225	0.89363253	0.88568285	6,795	518,324	175	19555
26101 MI Manistee	LP	N	1,008,053	349,266	658,788	0.54210441	0.48138431	189,339	317,130	4871	11964
26105 MI Mason	LP	N	420,665	230,698	189,967	0.54210441	0.48138431	125,062	91,447	3218	3450
26107 MI Mecosta	LP	N	431,641	0	431,641	0.54210441	0.48138431	0	207,785	0	7839
26111 MI Midland	LP	N	436,750	117,186	319,564	0.54210441	0.48138431	63,527	153,833	1634	5804
26113 MI Missaukee	LP	N	5,282,587	3,289,677	1,992,910	0.54210441	0.48138431	1,783,348	959,356	45881	36194
26117 MI Montcalm	LP	S	845,695	97,409	748,286	0.89363253	0.88568285	87,048	662,744	2240	25004
26119 MI Montmorency	LP	N	5,011,178	1,613,008	3,398,170	0.54210441	0.48138431	874,419	1,635,826	22496	61715
26121 MI Muskegon	LP	S	1,008,942	153,137	855,805	0.89363253	0.88568285	136,848	757,972	3521	28596
26123 MI Newaygo	LP	N	187,483	42,811	230,294	0.54210441	0.48138431	23,208	110,860	597	4182
26127 MI Oceana	LP	N	577,691	125,261	452,430	0.54210441	0.48138431	67,905	217,793	1747	8217
26129 MI Ogemaw	LP	N	2,713,088	1,023,469	1,689,619	0.54210441	0.48138431	554,827	813,356	14274	30686
26133 MI Osceola	LP	N	1,058,297	205,884	852,413	0.54210441	0.48138431	111,611	410,338	2871	15481
26135 MI Oscoda	LP	N	1,550,748	786,867	763,881	0.54210441	0.48138431	426,564	367,720	10974	13873
26137 MI Otsego	LP	S	4,105,273	2,249,565	1,855,708	0.89363253	0.88568285	2,010,284	1,643,569	51719	62007
26139 MI Ottawa	LP	N	261,688	43,461	218,227	0.54210441	0.48138431	23,560	105,051	606	3963
26141 MI Presque Isle	LP	N	2,211,446	1,398,746	812,700	0.54210441	0.48138431	758,266	391,221	19508	14760
26143 MI Roscommon	LP	S	4,260,801	2,039,244	2,221,557	0.89363253	0.88568285	1,822,335	1,967,595	46884	74232
26145 MI Saginaw	LP	S	131,429	44,773	86,656	0.89363253	0.88568285	40,011	76,750	1029	2896
26151 MI Sanilac	LP	S	594,126	0	594,126	0.89363253	0.88568285	0	526,207	0	19852
26155 MI Shiawassee	LP	S	276,188	34,481	241,708	0.89363253	0.88568285	30,813	214,077	793	8077
26157 MI Tuscola	LP	S	968,921	51,102	917,820	0.89363253	0.88568285	45,666	812,897	1175	30668
26165 MI Wexford	LP	N	2,575,447	1,421,017	1,154,430	0.54210441	0.48138431	770,340	555,724	19819	20966

Appendix B4-H Private Ownership Forest Biomass Data

County code and name	LP/UP	N/S or E/W	Total	Softwoods	Hardwoods	soft_availl	hard_availl	soft_vol_ava	hard_vol_avz	soft_GT_availl	hard_GT_availl
26001 MI Alcona	LP	N	6,570,977	2,055,367	4,515,610	0.68544762	0.56189444	1,408,846	2,537,296	36246	95725
26007 MI Alpena	LP	N	6,334,734	2,550,725	3,784,009	0.68544762	0.56189444	1,748,388	2,126,214	44981	80216
26009 MI Antrim	LP	N	5,299,749	340,356	4,959,393	0.68544762	0.56189444	233,296	2,786,655	6002	105133
26011 MI Arenac	LP	N	5,481,396	1,144,137	4,337,260	0.68544762	0.56189444	784,246	2,437,082	20177	91944
26015 MI Barry	LP	S	6,208,383	324,330	5,884,052	0.95282162	0.75485393	309,029	4,441,600	7950	167569
26017 MI Bay	LP	N	1,221,787	98,372	1,123,415	0.68544762	0.56189444	67,429	631,241	1735	23815
26019 MI Benzie	LP	N	3,386,431	635,114	2,751,316	0.68544762	0.56189444	435,337	1,545,949	11200	58324
26029 MI Charlevoix	LP	N	5,220,430	284,295	4,936,135	0.68544762	0.56189444	194,869	2,773,587	5013	104640
26031 MI Cheboygan	LP	N	9,709,089	3,054,729	6,654,360	0.68544762	0.56189444	2,093,857	3,739,048	53869	141064
26035 MI Clare	LP	N	6,664,000	1,337,892	5,326,108	0.68544762	0.56189444	917,055	2,992,710	23593	112907
26037 MI Clinton	LP	S	1,644,130	156,282	1,487,848	0.95282162	0.75485393	148,909	1,123,108	3831	42372
26039 MI Crawford	LP	N	1,652,232	660,802	991,430	0.68544762	0.56189444	452,945	557,079	11653	21017
26045 MI Eaton	LP	N	4,978,306	11,812	4,966,494	0.68544762	0.56189444	8,097	2,790,645	208	105283
26047 MI Emmet	LP	N	6,089,221	999,283	5,089,938	0.68544762	0.56189444	684,956	2,860,008	17622	107900
26049 MI Genesee	LP	S	3,645,186	87,016	3,558,170	0.95282162	0.75485393	82,911	2,685,899	2133	101332
26051 MI Gladwin	LP	N	3,931,523	734,654	3,196,869	0.68544762	0.56189444	503,567	1,796,303	12955	67770
26055 MI Grand Traverse	LP	N	5,995,581	2,976,889	3,018,692	0.68544762	0.56189444	2,040,501	1,696,186	52497	63992
26057 MI Gratiot	LP	S	2,047,095	0	2,047,095	0.95282162	0.75485393	0	1,545,258	0	58298
26063 MI Huron	LP	S	3,563,020	235,105	3,327,915	0.95282162	0.75485393	224,013	2,512,090	5763	94774
26065 MI Ingham	LP	S	1,939,039	62,954	1,876,085	0.95282162	0.75485393	59,984	1,416,170	1543	53428
26067 MI Ionia	LP	S	4,617,704	251,086	4,366,618	0.95282162	0.75485393	239,240	3,296,159	6155	124355
26069 MI Iosco	LP	N	4,807,607	1,353,276	3,454,331	0.68544762	0.56189444	927,600	1,940,969	23865	73227
26073 MI Isabella	LP	N	6,635,358	50,351	6,685,709	0.68544762	0.56189444	34,513	3,756,663	888	141729
26079 MI Kalkaska	LP	N	5,342,214	2,016,093	3,326,121	0.68544762	0.56189444	1,381,926	1,868,929	35553	70510
26081 MI Kent	LP	S	6,047,706	1,383,804	4,663,902	0.95282162	0.75485393	1,318,518	3,520,565	33922	132821
26085 MI Lake	LP	N	6,380,319	3,155,819	3,224,500	0.68544762	0.56189444	2,163,149	1,811,829	55652	68355
26087 MI Lapeer	LP	S	3,047,789	217,481	2,830,307	0.95282162	0.75485393	207,221	2,136,468	5331	80603
26089 MI Leelanau	LP	N	2,597,974	157,135	2,440,839	0.68544762	0.56189444	107,708	1,371,494	2771	51743
26093 MI Livingston	LP	S	2,321,003	316,326	2,004,677	0.95282162	0.75485393	301,402	1,513,238	7754	57090
26101 MI Manistee	LP	N	6,533,656	2,472,914	4,060,742	0.68544762	0.56189444	1,695,053	2,281,708	43609	86083
26105 MI Mason	LP	N	6,567,168	1,043,683	5,523,485	0.68544762	0.56189444	715,390	3,103,616	18405	117091
26107 MI Mecosta	LP	N	8,199,916	2,782,436	5,417,480	0.68544762	0.56189444	1,907,214	3,044,052	49067	114844
26111 MI Midland	LP	N	4,695,521	205,595	4,489,926	0.68544762	0.56189444	140,925	2,522,864	3626	95181
26113 MI Missaukee	LP	N	7,664,063	2,217,001	5,447,062	0.68544762	0.56189444	1,519,638	3,060,674	39096	115471
26117 MI Montcalm	LP	S	5,769,736	800,226	4,969,511	0.95282162	0.75485393	762,473	3,751,255	19616	141525
26119 MI Montmorency	LP	N	8,014,460	2,773,795	5,240,665	0.68544762	0.56189444	1,901,291	2,944,701	48915	111096
26121 MI Muskegon	LP	S	6,772,527	910,922	5,861,604	0.95282162	0.75485393	867,946	4,424,655	22330	166930
26123 MI Newaygo	LP	N	11,120,084	5,000,686	6,119,398	0.68544762	0.56189444	3,427,708	3,438,456	88186	129724
26127 MI Oceana	LP	N	7,816,973	2,017,992	5,823,777	0.68544762	0.56189444	1,383,228	3,272,348	35587	123457
26129 MI Ogemaw	LP	N	3,995,161	1,301,409	2,693,752	0.68544762	0.56189444	892,048	1,513,604	22950	57104
26133 MI Osceola	LP	N	6,292,884	1,571,219	4,721,665	0.68544762	0.56189444	1,076,988	2,653,077	27708	100093
26135 MI Oscoda	LP	N	4,173,132	1,193,189	2,979,943	0.68544762	0.56189444	817,869	1,674,413	21042	63171
26137 MI Otsego	LP	S	8,048,753	1,850,996	6,197,756	0.95282162	0.75485393	1,763,669	4,678,400	45374	176503
26139 MI Ottawa	LP	N	3,077,321	398,748	3,476,069	0.68544762	0.56189444	273,321	1,953,184	7032	73688
26141 MI Presque Isle	LP	N	7,380,021	2,514,124	4,865,897	0.68544762	0.56189444	1,723,300	2,734,120	44336	103151
26143 MI Roscommon	LP	S	2,155,717	191,913	1,963,804	0.95282162	0.75485393	182,859	1,482,385	4704	55926
26145 MI Saginaw	LP	S	4,749,511	227,164	4,522,347	0.95282162	0.75485393	216,447	3,413,711	5569	128790
26151 MI Sanilac	LP	S	3,111,512	335,663	2,775,849	0.95282162	0.75485393	319,827	2,095,361	8228	79052
26155 MI Shiawassee	LP	S	918,447	0	918,447	0.95282162	0.75485393	0	693,293	0	26156
26157 MI Tuscola	LP	S	3,913,234	420,931	3,492,303	0.95282162	0.75485393	401,072	2,636,179	10318	99456
26165 MI Wexford	LP	N	6,092,443	2,338,198	3,754,245	0.68544762	0.56189444	1,602,712	2,109,489	41233	79585

Appendix B4-I Distance Data

County (supplier)	Rectilinear Distance (miles)								
	Manton	Roscommon	Kingsley	Kalkaska	Gaylord	Clare	West Branch	Traverse City	Boyne City
Alcona	109.381	63.45	104.17	79.97	75.95	117.35	60.19	101.94	105.33
Alpena	131.073	85.14	125.86	98.35	53.18	0.00	81.88	117.54	78.89
Antrim	53.136	62.16	47.92	20.41	24.75	100.29	94.71	39.60	20.92
Arenac	97.71	63.79	116.33	109.42	105.40	60.43	31.24	131.39	134.78
Barry	0.00	0.00	0.00	0.00	0.00	111.73	0.00	0.00	0.00
Bay	118.37	84.45	136.99	130.08	126.06	46.32	51.90	0.00	0.00
Benzie	46.02	79.94	27.39	47.56	92.72	118.07	112.49	28.37	88.89
Charlevoix	74.514	82.36	69.30	41.79	40.75	0.00	114.92	60.98	11.37
Cheboygan	115.246	69.31	110.03	82.52	37.36	0.00	95.24	101.71	41.19
Clare	56.68	47.11	75.30	68.39	79.06	15.37	50.37	90.36	93.75
Clinton	0.00	0.00	0.00	0.00	0.00	69.99	108.73	0.00	0.00
Crawford	58.04	14.42	52.83	31.22	27.20	66.01	46.97	53.18	56.57
Eaton	0.00	0.00	0.00	0.00	0.00	87.40	0.00	0.00	0.00
Emmet	101.01	86.58	95.80	68.28	44.97	0.00	119.14	87.48	26.95
Genesee	0	0	0	0	0	108.79	114.37	0	0
Gladwin	78.99	45.08	97.62	90.71	86.69	30.27	26.89	112.68	116.07
Grand Traverse	25.73	59.65	7.10	23.03	68.19	97.78	92.20	7.96	64.36
Gratiot	117.37	83.46	0.00	0.00	0.00	45.32	85.23	0.00	0.00
Huron	0.00	122.61	0.00	0.00	0.00	89.91	90.05	0.00	0.00
Ingham	0.00	0.00	0.00	0.00	0.00	105.71	0.00	0.00	0.00
Ionia	0.00	0.00	0.00	0.00	0.00	75.79	0.00	0.00	0.00
Iosco	89.64	55.72	108.26	101.36	97.33	93.12	35.96	0.00	126.71
Isabella	81.03	70.68	99.66	92.75	102.64	16.78	73.94	114.72	0.00
Kalkaska	34.15	37.79	28.94	7.84	43.74	75.92	70.34	29.81	39.91
Kent	102.06	0.00	0.00	0.00	0.00	94.10	0.00	0.00	0.00
Lake	48.94	94.87	54.15	81.67	126.83	62.65	98.13	62.47	123.00
Lapeer	0.00	0.00	0.00	0.00	0.00	127.71	133.29	0.00	0.00
Leelanau	56.721	90.64	38.10	45.00	62.06	128.77	123.19	23.04	58.22
Livingston	0	0	0	0	0	128.32	0	0	0
Manistee	37.99	83.92	43.20	70.71	115.88	99.01	93.43	51.52	112.04
Mason	70.92	116.85	76.13	103.65	0.00	85.35	0.00	84.45	0.00
Mecosta	57.34	94.88	75.96	81.67	0.00	40.98	98.14	91.02	0.00
Midland	103.19	69.27	121.81	114.91	110.89	31.14	50.15	136.87	0.00
Missaukee	20.15	35.71	38.78	31.87	67.67	51.90	46.32	53.84	63.83
Montcalm	88.88	108.68	107.51	100.60	0.00	54.78	111.94	0.00	0.00
Montmorency	105.497	59.56	100.28	72.77	27.61	113.47	56.30	91.97	55.60
Muskegon	114.71	0.00	119.92	0.00	0.00	106.74	0.00	0.00	0.00
Newaygo	78.92	124.86	84.14	111.65	0.00	70.96	128.12	92.46	0.00
Oceana	96.32	0.00	101.54	129.05	0.00	88.36	0.00	109.86	0.00
Ogemaw	67.46	33.54	86.09	79.18	75.16	66.80	9.64	101.15	104.54
Osceola	33.02	71.03	51.65	57.82	102.98	39.03	74.29	66.71	99.15
Oscoda	82.053	36.12	76.84	54.54	50.52	90.02	32.86	76.50	79.89
Otsego	81.523	37.59	76.31	48.80	4.02	89.49	70.14	67.99	33.40
Ottawa	0	0	0	0	0	121.76	0	0	0
Presque Isle	137.05	91.12	131.84	104.32	59.16	0.00	87.86	123.52	62.99
Roscommon	43.86	11.56	62.49	55.58	51.56	42.34	22.61	77.55	80.94
Saginaw	0.00	107.70	0.00	0.00	0.00	69.57	75.15	0.00	0.00
Sanilac	0.00	0.00	0.00	0.00	0.00	0.00	129.01	0.00	0.00
Shiawassee	0.00	0.00	0.00	0.00	0.00	91.87	97.45	0.00	0.00
Tuscola	0.00	129.69	0.00	0.00	0.00	91.56	97.14	0.00	0.00
Wexford	13.86	59.80	19.08	46.59	91.75	75.74	70.16	30.00	87.92

Appendix B4-J Cost Data

County (supplier)	Cost Intensity (\$/ton)								
	Manton	Roscommon	Kingsley	Kalkaska	Gaylord	Clare	West Branch	Traverse City	Boyne City
Alcona	19.9084	13.1103	19.1369	15.5559	14.9607	21.0877	12.6278	18.8070	19.3088
Alpena	23.1188	16.3207	22.3473	18.2752	11.5911	999.0000	15.8382	21.1161	15.3963
Antrim	11.5841	12.9195	10.8126	6.7405	7.3836	18.5629	17.7372	9.5814	6.8163
Arenac	18.1805	13.1605	20.9370	19.9146	19.3195	12.6633	8.3428	23.1657	23.6676
Barry	999.0000	999.0000	999.0000	999.0000	999.0000	20.2563	999.0000	999.0000	999.0000
Bay	21.2382	16.2182	23.9947	22.9723	22.3772	10.5748	11.4005	999.0000	999.0000
Benzie	10.5307	15.5507	7.7742	10.7590	17.4432	21.1941	20.3684	7.9182	16.8759
Charlevoix	14.7481	15.9097	13.9765	9.9045	9.7507	999.0000	20.7274	12.7453	5.4026
Cheboygan	20.7764	13.9783	20.0049	15.9328	9.2487	999.0000	17.8148	18.7737	9.8160
Clare	12.1080	10.6915	14.8645	13.8422	15.4212	5.9954	11.1740	17.0933	17.5951
Clinton	999.0000	999.0000	999.0000	999.0000	999.0000	14.0778	19.8114	999.0000	999.0000
Crawford	12.3102	5.8540	11.5387	8.3401	7.7450	13.4895	10.6717	11.5912	12.0931
Eaton	999.0000	999.0000	999.0000	999.0000	999.0000	16.6545	999.0000	999.0000	999.0000
Emmet	18.6695	16.5343	17.8980	13.8259	10.3753	999.0000	21.3520	16.6667	7.7090
Genesee	999.0000	999.0000	999.0000	999.0000	999.0000	19.8211	20.6468	999.0000	999.0000
Gladwin	15.4111	10.3911	18.1676	17.1452	16.5501	8.1997	7.7002	20.3963	20.8982
Grand Traverse	7.5277	12.5478	4.7712	7.1280	13.8121	18.1911	17.3655	4.8975	13.2448
Gratiot	21.0914	16.0713	999.0000	999.0000	999.0000	10.4280	16.3333	999.0000	999.0000
Huron	999.0000	21.8657	999.0000	999.0000	999.0000	17.0265	17.0480	999.0000	999.0000
Ingham	999.0000	999.0000	999.0000	999.0000	999.0000	19.3646	999.0000	999.0000	999.0000
Ionia	999.0000	999.0000	999.0000	999.0000	999.0000	14.9365	999.0000	999.0000	999.0000
Iosco	16.9864	11.9664	19.7429	18.7205	18.1254	17.5021	9.0422	999.0000	22.4735
Isabella	15.7126	14.1806	18.4691	17.4467	18.9103	6.2033	14.6631	20.6978	999.0000
Kalkaska	8.7742	9.3131	8.0027	4.8811	10.1935	14.9565	14.1308	8.1322	9.6262
Kent	18.8255	999.0000	999.0000	999.0000	999.0000	17.6462	999.0000	999.0000	999.0000
Lake	10.9631	17.7612	11.7346	15.8067	22.4908	12.9928	18.2437	12.9659	21.9236
Lapeer	999.0000	999.0000	999.0000	999.0000	999.0000	22.6214	23.4471	999.0000	999.0000
Leelanau	12.1147	17.1347	9.3582	10.3806	12.9044	22.7781	21.9524	7.1295	12.3372
Livingston	999.0000	999.0000	999.0000	999.0000	999.0000	22.7106	999.0000	999.0000	999.0000
Manistee	9.3419	16.1400	10.1135	14.1855	20.8696	18.3738	17.5481	11.3447	20.3024
Mason	14.2160	21.0141	14.9875	19.0596	999.0000	16.3517	999.0000	16.2187	999.0000
Mecosta	12.2062	17.7622	14.9627	15.8078	999.0000	9.7849	18.2447	17.1914	999.0000
Midland	18.9920	13.9720	21.7485	20.7261	20.1310	8.3286	11.1416	23.9772	999.0000
Missaukee	6.7023	9.0051	9.4588	8.4365	13.7347	11.4011	10.5754	11.6876	13.1674
Montcalm	16.8748	19.8051	19.6313	18.6089	999.0000	11.8277	20.2876	999.0000	999.0000
Montmorency	19.3336	12.5355	18.5620	14.4900	7.8058	20.5128	12.0530	17.3308	11.9491
Muskegon	20.6968	999.0000	21.4683	999.0000	999.0000	19.5175	999.0000	999.0000	999.0000
Newaygo	15.4008	22.1988	16.1723	20.2443	999.0000	14.2215	22.6813	17.4035	999.0000
Oceana	17.9758	999.0000	18.7473	22.8194	999.0000	16.7965	999.0000	19.9785	999.0000
Ogemaw	13.7045	8.6845	16.4610	15.4386	14.8435	13.6068	5.1470	18.6898	19.1916
Osceola	8.6071	14.2318	11.3636	12.2774	18.9615	9.4963	14.7143	13.5923	18.3942
Oscoda	15.8638	9.0658	15.0923	11.7913	11.1962	17.0431	8.5833	15.0424	15.5443
Otsego	15.7854	9.2836	15.0139	10.9418	4.3154	16.9647	14.1013	13.7827	8.6635
Ottawa	999.0000	999.0000	999.0000	999.0000	999.0000	21.7406	999.0000	999.0000	999.0000
Presque Isle	24.0034	17.2053	23.2319	19.1598	12.4757	999.0000	16.7228	22.0007	13.0430
Roscommon	10.2119	5.4313	12.9684	11.9460	11.3509	9.9860	7.0658	15.1971	15.6990
Saginaw	999.0000	19.6599	999.0000	999.0000	999.0000	14.0165	14.8422	999.0000	999.0000
Sanilac	999.0000	999.0000	999.0000	999.0000	999.0000	999.0000	22.8130	999.0000	999.0000
Shiawassee	999.0000	999.0000	999.0000	999.0000	999.0000	17.3171	18.1427	999.0000	999.0000
Tuscola	999.0000	22.9147	999.0000	999.0000	999.0000	17.2713	18.0970	999.0000	999.0000
Wexford	5.7716	12.5697	6.5431	10.6152	17.2993	14.9289	14.1032	8.1597	16.7320

Note: where 999.00 is indicated that means the county is not available to supply feedstock to that specific location.

Appendix B4-K Energy Data

County (supplier)	Energy Intensity (1000 Btu/ton)								
	Manton	Roscommon	Kingsley	Kalkaska	Gaylord	Clare	West Branch	Traverse City	Boyne City
Alcona	485.790	339.502	469.187	392.128	379.322	511.166	329.120	462.088	472.888
Alpena	554.874	408.587	538.272	450.645	306.810	99999.000	398.204	511.778	388.695
Antrim	306.661	335.397	290.058	202.432	216.270	456.837	439.069	263.564	204.062
Arenac	448.607	340.582	507.924	485.923	473.117	329.884	236.910	555.884	566.684
Barry	99999.000	99999.000	99999.000	99999.000	99999.000	493.277	99999.000	99999.000	99999.000
Bay	514.405	406.380	573.722	551.721	538.915	284.940	302.708	99999.000	99999.000
Benzie	283.991	392.016	224.674	288.905	432.740	513.456	495.688	227.773	420.533
Charlevoix	374.745	399.743	358.143	270.516	267.207	99999.000	503.414	331.648	173.641
Cheboygan	504.468	358.181	487.866	400.240	256.404	99999.000	440.737	461.372	268.612
Clare	317.935	287.453	377.252	355.251	389.230	186.396	297.835	425.212	436.011
Clinton	99999.000	99999.000	99999.000	99999.000	99999.000	360.321	483.704	99999.000	99999.000
Crawford	322.285	183.355	305.683	236.853	224.047	347.662	287.026	306.813	317.613
Eaton	99999.000	99999.000	99999.000	99999.000	99999.000	415.769	99999.000	99999.000	99999.000
Emmet	459.130	413.183	442.527	354.901	280.647	99999.000	516.854	416.033	223.273
Genesee	99999.000	99999.000	99999.000	99999.000	99999.000	483.911	501.679	99999.000	99999.000
Gladwin	389.013	280.988	448.330	426.329	413.523	233.831	223.082	496.290	507.090
Grand Traverse	219.372	327.397	160.055	210.769	354.605	448.836	431.068	162.771	342.397
Gratiot	511.246	403.220	99999.000	99999.000	99999.000	281.781	408.858	99999.000	99999.000
Huron	99999.000	527.909	99999.000	99999.000	99999.000	423.775	424.237	99999.000	99999.000
Ingham	99999.000	99999.000	99999.000	99999.000	99999.000	474.089	99999.000	99999.000	99999.000
Ionia	99999.000	99999.000	99999.000	99999.000	99999.000	378.799	99999.000	99999.000	99999.000
Iosco	422.912	314.887	482.229	460.228	447.422	434.008	251.962	99999.000	540.989
Isabella	395.501	362.535	454.817	432.817	464.311	190.871	372.917	502.777	99999.000
Kalkaska	246.194	257.790	229.592	162.418	276.736	379.229	361.461	232.378	264.529
Kent	462.486	99999.000	99999.000	99999.000	99999.000	437.110	99999.000	99999.000	99999.000
Lake	293.297	439.585	309.899	397.526	541.361	336.973	449.967	336.394	529.154
Lapeer	99999.000	99999.000	99999.000	99999.000	99999.000	544.170	561.938	99999.000	99999.000
Leelanau	318.078	426.103	258.761	280.762	335.072	547.543	529.775	210.801	322.865
Livingston	99999.000	99999.000	99999.000	99999.000	99999.000	546.091	99999.000	99999.000	99999.000
Manistee	258.411	404.698	275.013	362.640	506.475	452.766	434.998	301.508	494.268
Mason	363.296	509.583	379.898	467.525	99999.000	409.252	99999.000	406.393	99999.000
Mecona	320.046	439.607	379.363	397.548	99999.000	267.943	449.989	427.323	99999.000
Midland	466.069	358.044	525.386	503.386	490.580	236.604	297.138	573.346	99999.000
Missaukee	201.610	251.162	260.927	238.926	352.939	302.721	284.953	308.887	340.732
Montcalm	420.511	483.567	479.828	457.827	99999.000	311.903	493.949	99999.000	99999.000
Montmorency	473.420	327.132	456.817	369.191	225.356	498.796	316.750	430.323	314.514
Muskegon	502.755	99999.000	519.357	99999.000	99999.000	477.379	99999.000	99999.000	99999.000
Newaygo	388.790	535.078	405.393	493.019	99999.000	363.414	545.460	431.887	99999.000
Oceana	444.202	99999.000	460.805	548.431	99999.000	418.826	99999.000	487.299	99999.000
Ogemaw	352.289	244.264	411.606	389.605	376.799	350.187	168.141	459.566	470.366
Osceola	242.598	363.637	301.915	321.578	465.413	261.733	374.019	349.875	453.206
Oscoda	398.755	252.468	382.153	311.119	298.313	424.132	242.086	381.080	391.879
Otsego	397.067	257.156	380.465	292.839	150.245	422.444	360.828	353.971	243.812
Ottawa	99999.000	99999.000	99999.000	99999.000	99999.000	525.217	99999.000	99999.000	99999.000
Presque Isle	573.910	427.622	557.307	469.681	325.846	99999.000	417.240	530.813	338.053
Roscommon	277.131	174.259	336.448	314.447	301.641	272.271	209.432	384.408	395.208
Saginaw	99999.000	480.442	99999.000	99999.000	99999.000	359.003	376.771	99999.000	99999.000
Sanilac	99999.000	99999.000	99999.000	99999.000	99999.000	99999.000	548.294	99999.000	99999.000
Shiawassee	99999.000	99999.000	99999.000	99999.000	99999.000	430.027	447.795	99999.000	99999.000
Tuscola	99999.000	550.482	99999.000	99999.000	99999.000	429.043	446.811	99999.000	99999.000
Wexford	181.581	327.868	198.183	285.810	429.645	378.637	360.869	232.971	417.437

Note: where 99999.00 is indicated that means the county is not available to supply feedstock to that specific location.

Appendix B4-L Emissions Data

County (supplier)	GHG Emissions Intensity (lb/ton)								
	Manton	Roscommon	Kingsley	Kalkaska	Gaylord	Clare	West Branch	Traverse City	Boyne City
Alcona	108.0733	73.4398	104.1427	85.8989	82.8671	114.0811	70.9818	102.4620	105.0188
Alpena	124.4290	89.7956	120.4984	99.7529	65.7000	999.0000	87.3375	114.2259	85.0861
Antrim	65.6645	72.4679	61.7339	40.9884	44.2645	101.2187	97.0121	55.4614	41.3744
Arenac	99.2703	73.6954	113.3136	108.1049	105.0731	71.1627	49.1512	124.6681	127.2249
Barry	999.0000	999.0000	999.0000	999.0000	999.0000	109.8459	999.0000	999.0000	999.0000
Bay	114.8480	89.2730	128.8912	123.6826	120.6507	60.5223	64.7288	999.0000	999.0000
Benzie	60.2976	85.8725	46.2543	61.4610	95.5139	114.6233	110.4167	46.9880	92.6238
Charlevoix	81.7836	87.7017	77.8530	57.1074	56.3240	999.0000	112.2459	71.5804	34.1722
Cheboygan	112.4955	77.8620	108.5649	87.8193	53.7664	999.0000	97.4072	102.2924	56.6565
Clare	68.3337	61.1172	82.3770	77.1683	85.2127	37.1920	63.5752	93.7314	96.2883
Clinton	999.0000	999.0000	999.0000	999.0000	999.0000	78.3687	107.5794	999.0000	999.0000
Crawford	69.3637	36.4719	65.4331	49.1376	46.1058	75.3715	61.0161	65.7007	68.2576
Eaton	999.0000	999.0000	999.0000	999.0000	999.0000	91.4958	999.0000	999.0000	999.0000
Emmet	101.7615	90.8836	97.8309	77.0854	59.5059	999.0000	115.4278	91.5584	45.9226
Genesee	999.0000	999.0000	999.0000	999.0000	999.0000	107.6284	111.8350	999.0000	999.0000
Gladwin	85.1615	59.5866	99.2047	93.9961	90.9643	48.4221	45.8773	110.5592	113.1160
Grand Traverse	44.9989	70.5738	30.9557	42.9624	77.0153	99.3246	95.1180	31.5988	74.1252
Gratiot	114.1000	88.5251	999.0000	999.0000	999.0000	59.7743	89.8597	999.0000	999.0000
Huron	999.0000	118.0449	999.0000	999.0000	999.0000	93.3914	93.5007	999.0000	999.0000
Ingham	999.0000	999.0000	999.0000	999.0000	999.0000	105.3031	999.0000	999.0000	999.0000
Ionia	999.0000	999.0000	999.0000	999.0000	999.0000	82.7434	999.0000	999.0000	999.0000
Iosco	93.1871	67.6121	107.2303	102.0217	98.9898	95.8140	52.7146	999.0000	121.1416
Isabella	86.6974	78.8927	100.7406	95.5320	102.9883	38.2514	81.3508	112.0951	999.0000
Kalkaska	51.3491	54.0944	47.4185	31.5151	58.5800	82.8452	78.6386	48.0782	55.6899
Kent	102.5563	999.0000	999.0000	999.0000	999.0000	96.5484	999.0000	999.0000	999.0000
Lake	62.5008	97.1342	66.4314	87.1769	121.2298	72.8411	99.5923	72.7039	118.3397
Lapeer	999.0000	999.0000	999.0000	999.0000	999.0000	121.8948	126.1014	999.0000	999.0000
Leelanau	68.3676	93.9426	54.3244	59.5330	72.3910	122.6933	118.4868	42.9699	69.5009
Livingston	999.0000	999.0000	999.0000	999.0000	999.0000	122.3495	999.0000	999.0000	999.0000
Manistee	54.2414	88.8749	58.1720	78.9176	112.9705	100.2550	96.0485	64.4446	110.0804
Mason	79.0729	113.7064	83.0035	103.7491	999.0000	89.9531	999.0000	89.2761	999.0000
Mecosta	68.8336	97.1395	82.8769	87.1822	999.0000	56.4982	99.5976	94.2313	999.0000
Midland	103.4045	77.8296	117.4478	112.2391	109.2073	49.0788	63.4101	128.8022	999.0000
Missaukee	40.7939	52.5253	54.8371	49.6285	76.6209	64.7318	60.5253	66.1916	73.7308
Montcalm	92.6185	107.5470	106.6618	101.4532	999.0000	66.9056	110.0050	999.0000	999.0000
Montmorency	105.1447	70.5113	101.2141	80.4686	46.4157	111.1526	68.0532	94.9416	67.5239
Muskegon	112.0898	999.0000	116.0204	999.0000	999.0000	106.0820	999.0000	999.0000	999.0000
Newaygo	85.1087	119.7422	89.0393	109.7849	999.0000	79.1008	122.2002	95.3118	999.0000
Oceana	98.2275	999.0000	102.1581	122.9037	999.0000	92.2197	999.0000	108.4307	999.0000
Ogemaw	76.4671	50.8922	90.5104	85.3017	82.2699	75.9695	32.8701	101.8648	104.4217
Osceola	50.4978	79.1536	64.5411	69.1963	103.2492	55.0279	81.6116	75.8956	100.3591
Oscoda	87.4680	52.8345	83.5374	66.7201	63.6883	93.4758	50.3764	83.2833	85.8401
Otsego	87.0683	53.9444	83.1377	62.3922	28.6333	93.0762	78.4886	76.8652	50.7851
Ottawa	999.0000	999.0000	999.0000	999.0000	999.0000	117.4078	999.0000	999.0000	999.0000
Presque Isle	128.9357	94.3022	125.0051	104.2595	70.2066	999.0000	91.8442	118.7326	73.0967
Roscommon	58.6735	34.3185	72.7167	67.5081	64.4762	57.5229	42.6457	84.0712	86.6280
Saginaw	999.0000	106.8073	999.0000	999.0000	999.0000	78.0565	82.2631	999.0000	999.0000
Sanilac	999.0000	999.0000	999.0000	999.0000	999.0000	999.0000	122.8713	999.0000	999.0000
Shiawassee	999.0000	999.0000	999.0000	999.0000	999.0000	94.8715	99.0781	999.0000	999.0000
Tuscola	999.0000	123.3893	999.0000	999.0000	999.0000	94.6385	98.8451	999.0000	999.0000
Wexford	36.0519	70.6854	39.9826	60.7281	94.7810	82.7049	78.4984	48.2185	91.8909

Note: where 999.00 is indicated that means the county is not available to supply feedstock to that specific location.

Appendix B4-M Data Requirements Summary Tables

Components of the Supply Chain Model	Inputs	Information Requests from Other Team Members (Tentative Data Needs)	Used in Simulation Model?	Used in Optimization Model?	Subtask Responsible	Notes
Harvesting/Processing	Harvest areas	Total feedstock availability by county, by type of ownership	X	X	Task A1~4	Ownership type refers to federal, state, private - company, private individual landowner; assumption is aggregate feedstock and from the centroid of the county.
	Seasonal factors	Length of spring breakup by county (historical trends)	X		Task B4	Using the lower peninsula counties and after statistically analyzing the data, it would appear that using the two month timeframe indicated at the MDOT website would be the most reliable.
	Energy consumption rates	Btu/ton-km	X	X	Task B5	Robert Handler provided
	Emissions rates	lbs GHG/ton-km	X	X	Task B5	Robert Handler provided
	Production (demand)	Average daily production requirement at biorefinery	X		Task B4	Assumed yearly annual production of 30, 40, and 50 million and a 50 weeks per year will allow for weekly and daily average production. It is assumed to be constant
Feedstock Inventory and Availability (Supply)	Competing purchasers of feedstock supply	Total feedstock consumed by other users such as biomass CHP and pulp mills	X	X	Task A3	We have a list of the biomass fired power plants existing and one that has been permitted. We do not have a list of the pulp mills. The total other consumption will reduce the total availability for the biorefinery(ies).
	Feedstock availability	Timing of harvesting and spring break-up considerations	X		Task B4	Assumed two month period starting March 1 and ending April 30.
	Target Supply	Target supply at biorefinery	X	X	Task B4	Demand at biorefinery

Transportation	Location and network connectivity	Location of harvesting areas	X		Task B4	Assumed to be centroid of each county
	Distances	Harvest area to biorefinery	X	X	Task B1	Preliminary is based on the rectilinear distance using latitude and longitude.
	Travel Time	Harvest area to biorefinery	X		Task B1	Based on the average road speed for truck
	Vehicle capacity	Batch size per truck	X		Task B1	Status report 1
	Vehicle capacity	Trucks/day	X		Task B4	Calculated
	Vehicles required	Maximum number of trucks	X		Task B4	Calculated
	Truck capacity	Tons of feedstock/truck	X		Task B1	Status report 1
	Transportation cost for truck	Truck transportation cost per ton by origin to destination	X	X	Task B1	Robert Handler provided
	Transportation cost	Transportation cost per mile by truck (per ton)	X	X	Task B1	Robert Handler provided
	Loading/unloading cost	Loading cost for truck	X	X	Task B1	Robert Handler provided
	Loading/unloading cost	Unloading cost for truck	X	X	Task B1	Robert Handler provided
	Energy consumption rates	Btu/ton-km	X	X	Task B5	Robert Handler provided
	Emissions rates	lbs/ton-km	X	X	Task B5	Robert Handler provided
	Feedstock availability	Federal forest management plans and state harvest plans	X	X	Task A1~4	
	Spring weight restrictions	Road restrictions associated with the spring thaw that limit use of truck transport	X		Task B4	Documented the policy
	Regulations and policies	Load restrictions by class of road/vehicle weight restrictions	X		Task B1	Same as above - MDOT
	Land restrictions	Identify counties with federal and state land restrictions for harvesting (i.e. dune areas etc.)	X	X	Task A1-A4	

Appendix B4-N Cost Optimization Results and Supply Locations for 50 MGY

MANTON COST OPTIMIZATION - 50MGY			
<i>County</i>	<i>Cost/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Benzie	\$10.53066	26,195	101,329
Grand Traverse	\$ 7.52774	117,902	117,902
Kalkaska	\$ 8.77420	171,816	171,816
Manistee	\$ 9.34193	206,185	206,185
Missaukee	\$ 6.70235	193,406	193,406
Osceola	\$ 8.60711	140,038	140,038
Roscommon	\$10.21187	148,910	148,910
Wexford	\$ 5.77158	245,548	245,548
Feedstock Demand		1,250,000	
Total Transportation Cost			\$ 10,036,544.95
Transportation Cost Per Ton			\$ 8.02924

ROSCOMMON COST OPTIMIZATION - 50MGY			
<i>County</i>	<i>Cost/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Crawford	\$183.35463	120,789	120,789
Kalkaska	\$257.78978	152,750	171,816
Missaukee	\$251.16221	193,406	193,406
Ogemaw	\$244.26393	122,488	122,488
Oscoda	\$252.46798	236,738	236,738
Otsego	\$257.15600	274,920	274,920
Roscommon	\$174.25884	148,910	148,910
Feedstock Demand		1,250,000	
Total Transportation Cost			\$ 10,442,290.00
Transportation Cost Per Ton			\$ 8.35383

KINGSLEY COST OPTIMIZATION - 50MGY			
<i>County</i>	<i>Cost/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Antrim	\$10.81260	134,827	134,827
Benzie	\$ 7.77416	101,329	101,329
Grand Traverse	\$ 4.77124	117,902	117,902
Kalkaska	\$ 8.00268	171,816	171,816
Leelanau	\$ 9.35821	48,922	48,922
Manistee	\$10.11345	206,185	206,185
Missaukee	\$ 9.45885	193,406	193,406
Osceola	\$11.36361	30,064	140,038
Wexford	\$ 6.54310	245,548	245,548
Feedstock Demand		1,250,000	
Total Transportation Cost			\$ 10,503,858
Transportation Cost Per Ton			\$ 8.40309

KALKASKA COST OPTIMIZATION - 50MGY			
<i>County</i>	<i>Cost/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Antrim	\$ 6.74053	134,827	134,827
Benzie	\$ 10.75903	101,329	101,329
Charlevoix	\$ 9.90448	96,751	96,751
Crawford	\$ 8.34012	120,789	120,789
Grand Traverse	\$ 7.12800	117,902	117,902
Kalkaska	\$ 4.88106	171,816	171,816
Leelanau	\$ 10.38059	48,922	48,922
Missaukee	\$ 8.43646	193,406	193,406
Otsego	\$ 10.94181	18,710	274,920
Wexford	\$ 10.61517	245,548	245,548
Feedstock Demand		1,250,000	
Total Transportation Cost			\$ 10,594,473
Transportation Cost Per Ton			\$ 8.47558

GAYLORD COST OPTIMIZATION - 50MGY			
<i>County</i>	<i>Cost/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Antrim	\$ 7.38359	134,827	134,827
Charlevoix	\$ 9.75070	96,751	96,751
Cheboygan	\$ 9.24869	225,280	225,280
Crawford	\$ 7.74501	120,789	120,789
Emmet	\$ 10.37526	25,576	138,994
Kalkaska	\$ 10.19352	171,816	171,816
Montmorency	\$ 7.80584	200,041	200,041
Otsego	\$ 4.31540	274,920	274,920
Feedstock Demand		1,250,000	
Total Transportation Cost			\$ 9,722,602.31
Transportation Cost Per Ton			\$ 7.77808

CLARE COST OPTIMIZATION - 50MGY			
<i>County</i>	<i>Cost/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Bay	\$ 10.57477	29,471	29,471
Clare	\$ 5.99535	154,447	154,447
Gladwin	\$ 8.19966	120,904	120,904
Gratiot	\$ 10.42795	65,649	65,649
Isabella	\$ 6.20329	147,913	147,913
Mecosta	\$ 9.78489	161,937	161,937
Midland	\$ 8.32857	105,192	105,192
Missaukee	\$ 11.40105	175,539	193,406
Osceola	\$ 9.49629	140,038	140,038
Roscommon	\$ 9.98602	148,910	148,910
Feedstock Demand		1,250,000	
Total Transportation Cost			\$ 11,109,941
Transportation Cost Per Ton			\$ 8.88795

WEST BRANCH COST OPTIMIZATION - 50MGY			
<i>County</i>	<i>Cost/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Arenac	\$ 8.34278	118,833	118,833
Crawford	\$ 10.67171	120,789	120,789
Gladwin	\$ 7.70016	120,904	120,904
Iosco	\$ 9.04223	159,343	159,343
Midland	\$ 11.14161	28,591	105,192
Missaukee	\$ 10.57536	193,406	193,406
Ogemaw	\$ 5.14702	122,488	122,488
Oscoda	\$ 8.58328	236,738	236,738
Roscommon	\$ 7.06584	148,910	148,910
Feedstock Demand		1,250,000	
Total Transportation Cost			\$ 10,730,698
Transportation Cost Per Ton			\$ 8.58456

TRAVERSE CITY COST OPTIMIZATION - 50MGY			
<i>County</i>	<i>Cost/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Antrim	\$ 9.58139	134,827	134,827
Benzie	\$ 7.91817	101,329	101,329
Crawford	\$ 11.59123	120,789	120,789
Grand Traverse	\$ 4.89749	117,902	117,902
Kalkaska	\$ 8.13218	171,816	171,816
Leelanau	\$ 7.12948	48,922	48,922
Manistee	\$ 11.34466	206,185	206,185
Missaukee	\$ 11.68758	102,682	193,406
Wexford	\$ 8.15970	245,548	245,548
Feedstock Demand		1,250,000	
Total Transportation Cost			\$ 11,360,514
Transportation Cost Per Ton			\$ 9.08841

BOYNE CITY COST OPTIMIZATION - 50MGY			
<i>County</i>	<i>Cost/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Antrim	\$ 6.81631	134,827	134,827
Charlevoix	\$ 5.40261	96,751	96,751
Cheboygan	\$ 9.81597	225,280	225,280
Crawford	\$ 12.09310	7,370	120,789
Emmet	\$ 7.70904	138,994	138,994
Kalkaska	\$ 9.62624	171,816	171,816
Montmorency	\$ 11.94910	200,041	200,041
Otsego	\$ 8.66350	274,920	274,920
Feedstock Demand		1,250,000	
Total Transportation Cost			\$ 11,239,737
Transportation Cost Per Ton			\$ 8.99179

Appendix B4-O Cost Optimization Results and Supply Locations for 40 MGY

MANTON COST OPTIMIZATION - 40MGY			
<i>County</i>	<i>Cost/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Grand Traverse	\$ 7.52774	117,902	117,902
Kalkaska	\$ 8.77420	171,816	171,816
Manistee	\$ 9.34193	131,290	206,185
Missaukee	\$ 6.70235	193,406	193,406
Osceola	\$ 8.60711	140,038	140,038
Wexford	\$ 5.77158	245,548	245,548
Feedstock Demand		1,000,000	
Total Transportation Cost			\$ 7,540,381.27
Transportation Cost Per Ton			\$ 7.54038

ROSCOMMON COST OPTIMIZATION - 40MGY			
<i>County</i>	<i>Cost/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Crawford	\$ 183.35463	120,789	120,789
Missaukee	\$ 251.16221	193,406	193,406
Ogemaw	\$ 244.26393	122,488	122,488
Oscoda	\$ 252.46798	236,738	236,738
Otsego	\$ 257.15600	177,670	274,920
Roscommon	\$ 174.25884	148,910	148,910
Feedstock Demand		1,000,000	
Total Transportation Cost			\$ 8,116,887.00
Transportation Cost Per Ton			\$ 8.11689

KINGSLEY COST OPTIMIZATION - 40MGY			
<i>County</i>	<i>Cost/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Benzie	\$ 7.77416	101,329	101,329
Grand Traverse	\$ 4.77124	117,902	117,902
Kalkaska	\$ 8.00268	171,816	171,816
Leelanau	\$ 9.35821	48,922	48,922
Manistee	\$ 10.11345	121,077	206,185
Missaukee	\$ 9.45885	193,406	193,406
Wexford	\$ 6.54310	245,548	245,548
Feedstock Demand		1,000,000	
Total Transportation Cost			\$ 7,843,646.00
Transportation Cost Per Ton			\$ 7.84365

KALKASKA COST OPTIMIZATION - 40MGY			
<i>County</i>	<i>Cost/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Antrim	\$ 6.74053	134,827	134,827
Charlevoix	\$ 9.90448	96,751	96,751
Crawford	\$ 8.34012	120,789	120,789
Grand Traverse	\$ 7.12800	117,902	117,902
Kalkaska	\$ 4.88106	171,816	171,816
Leelanau	\$ 10.38059	48,922	48,922
Missaukee	\$ 8.43646	193,406	193,406
Wexford	\$ 10.61517	115,586	245,548
Feedstock Demand		1,000,000	
Total Transportation Cost			\$ 7,919,992.00
Transportation Cost Per Ton			\$ 7.91999

GAYLORD COST OPTIMIZATION - 40MGY			
<i>County</i>	<i>Cost/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Antrim	\$ 7.38359	134,827	134,827
Charlevoix	\$ 9.75070	44,143	96,751
Cheboygan	\$ 9.24869	225,280	225,280
Crawford	\$ 7.74501	120,789	120,789
Montmorency	\$ 7.80584	200,041	200,041
Otsego	\$ 4.31540	274,920	274,920
Feedstock Demand		1,000,000	
Total Transportation Cost			\$ 7,192,869.81
Transportation Cost Per Ton			\$ 7.19287

CLARE COST OPTIMIZATION - 40MGY			
<i>County</i>	<i>Cost/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Clare	\$ 5.99535	154,447	154,447
Gladwin	\$ 8.19966	120,904	120,904
Gratiot	\$ 10.42795	20,659	65,649
Isabella	\$ 6.20329	147,913	147,913
Mecosta	\$ 9.78489	161,937	161,937
Midland	\$ 8.32857	105,192	105,192
Osceola	\$ 9.49629	140,038	140,038
Roscommon	\$ 9.98602	148,910	148,910
Feedstock Demand		1,000,000	
Total Transportation Cost			\$ 8,327,808.00
Transportation Cost Per Ton			\$ 8.32781

WEST BRANCH COST OPTIMIZATION - 40MGY			
<i>County</i>	<i>Cost/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Arenac	\$ 8.34278	118,833	118,833
Gladwin	\$ 7.70016	120,904	120,904
Iosco	\$ 9.04223	159,343	159,343
Missaukee	\$ 10.57536	92,785	193,406
Ogemaw	\$ 5.14702	122,488	122,488
Oscoda	\$ 8.58328	236,738	236,738
Roscommon	\$ 7.06584	148,910	148,910
Feedstock Demand		1,000,000	
Total Transportation Cost			\$ 8,059,031.00
Transportation Cost Per Ton			\$ 8.05903

TRAVERSE CITY COST OPTIMIZATION - 40MGY			
<i>County</i>	<i>Cost/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Antrim	\$ 9.58139	134,827	134,827
Benzie	\$ 7.91817	101,329	101,329
Grand Traverse	\$ 4.89749	117,902	117,902
Kalkaska	\$ 8.13218	171,816	171,816
Leelanau	\$ 7.12948	48,922	48,922
Manistee	\$ 11.34466	179,656	206,185
Wexford	\$ 8.15970	245,548	245,548
Feedstock Demand		1,000,000	
Total Transportation Cost			\$ 8,459,354.00
Transportation Cost Per Ton			\$ 8.45935

BOYNE CITY COST OPTIMIZATION - 40MGY			
<i>County</i>	<i>Cost/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Antrim	\$ 6.81631	134,827	134,827
Charlevoix	\$ 5.40261	96,751	96,751
Cheboygan	\$ 9.81597	182,691	225,280
Emmet	\$ 7.70904	138,994	138,994
Kalkaska	\$ 9.62624	171,816	171,816
Otsego	\$ 8.66350	274,920	274,920
Feedstock Demand		1,000,000	
Total Transportation Cost			\$ 8,342,249.00
Transportation Cost Per Ton			\$ 8.34225

Appendix B4-P Cost Optimization Results and Supply Locations for 30 MGY

MANTON COST OPTIMIZATION - 30MGY			
<i>County</i>	<i>Cost/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Grand Traverse	\$ 7.52774	117,902	117,902
Kalkaska	\$ 8.77420	53,106	171,816
Missaukee	\$ 6.70235	193,406	193,406
Osceola	\$ 8.60711	140,038	140,038
Wexford	\$ 5.77158	245,548	245,548
Feedstock Demand		750,000	
Total Transportation Cost			\$ 5,272,294.46
Transportation Cost Per Ton			\$ 7.02973

ROSCOMMON COST OPTIMIZATION - 30MGY			
<i>County</i>	<i>Cost/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Crawford	\$ 183.35463	120,789	120,789
Missaukee	\$ 251.16221	193,406	193,406
Ogemaw	\$ 244.26393	122,488	122,488
Oscoda	\$ 252.46798	164,407	236,738
Roscommon	\$ 174.25884	148,910	148,910
Feedstock Demand		750,000	
Total Transportation Cost			\$ 5,811,741.00
Transportation Cost Per Ton			\$ 7.74899

KINGSLEY COST OPTIMIZATION - 30MGY			
<i>County</i>	<i>Cost/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Benzie	\$ 7.77416	101,329	101,329
Grand Traverse	\$ 4.77124	117,902	117,902
Kalkaska	\$ 8.00268	171,816	171,816
Leelanau	\$ 9.35821	48,922	48,922
Missaukee	\$ 9.45885	64,483	193,406
Wexford	\$ 6.54310	245,548	245,548
Feedstock Demand		750,000	
Total Transportation Cost			\$ 5,399,676.00
Transportation Cost Per Ton			\$ 7.19957

KALKASKA COST OPTIMIZATION - 30MGY			
<i>County</i>	<i>Cost/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Antrim	\$ 6.74053	134,827	134,827
Charlevoix	\$ 9.90448	11,260	96,751
Crawford	\$ 8.34012	120,789	120,789
Grand Traverse	\$ 7.12800	117,902	117,902
Kalkaska	\$ 4.88106	171,816	171,816
Missaukee	\$ 8.43646	193,406	193,406
Feedstock Demand		750,000	
Total Transportation Cost			\$ 5,338,434.00
Transportation Cost Per Ton			\$ 7.11791

GAYLORD COST OPTIMIZATION - 30MGY			
<i>County</i>	<i>Cost/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Antrim	\$ 7.38359	134,827	134,827
Cheboygan	\$ 9.24869	19,424	225,280
Crawford	\$ 7.74501	120,789	120,789
Montmorency	\$ 7.80584	200,041	200,041
Otsego	\$ 4.31540	274,920	274,920
Feedstock Demand		750,000	
Total Transportation Cost			\$ 4,858,537.19
Transportation Cost Per Ton			\$ 6.47805

CLARE COST OPTIMIZATION - 30MGY			
<i>County</i>	<i>Cost/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Clare	\$ 5.99535	154,447	154,447
Gladwin	\$ 8.19966	120,904	120,904
Isabella	\$ 6.20329	147,913	147,913
Mecosta	\$ 9.78489	81,505	161,937
Midland	\$ 8.32857	105,192	105,192
Osceola	\$ 9.49629	140,038	140,038
Feedstock Demand		750,000	
Total Transportation Cost			\$ 5,838,350.00
Transportation Cost Per Ton			\$ 7.78447

WEST BRANCH COST OPTIMIZATION - 30MGY			
<i>County</i>	<i>Cost/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Arenac	\$ 8.34278	118,833	118,833
Gladwin	\$ 7.70016	120,904	120,904
Iosco	\$ 9.04223	2,128	159,343
Ogemaw	\$ 5.14702	122,488	122,488
Oscoda	\$ 8.58328	236,738	236,738
Roscommon	\$ 7.06584	148,910	148,910
Feedstock Demand		750,000	
Total Transportation Cost			\$ 5,656,221.00
Transportation Cost Per Ton			\$ 7.54163

TRAVERSE CITY COST OPTIMIZATION - 30MGY			
<i>County</i>	<i>Cost/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Antrim	\$ 9.58139	64,483	134,827
Benzie	\$ 7.91817	101,329	101,329
Grand Traverse	\$ 4.89749	117,902	117,902
Kalkaska	\$ 8.13218	171,816	171,816
Leelanau	\$ 7.12948	48,922	48,922
Wexford	\$ 8.15970	245,548	245,548
Feedstock Demand		750,000	
Total Transportation Cost			\$ 5,747,224.00
Transportation Cost Per Ton			\$ 7.66297

BOYNE CITY COST OPTIMIZATION - 30MGY			
<i>County</i>	<i>Cost/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Antrim	\$ 6.81631	134,827	134,827
Charlevoix	\$ 5.40261	96,751	96,751
Emmet	\$ 7.70904	138,994	138,994
Kalkaska	\$ 9.62624	104,508	171,816
Otsego	\$ 8.66350	274,920	274,920
Feedstock Demand		750,000	
Total Transportation Cost			\$ 5,901,027.00
Transportation Cost Per Ton			\$ 7.86804

Appendix B4-Q Energy Optimization Results and Supply Locations for 50 MGY

MANTON ENERGY OPTIMIZATION - 50MGY			
<i>County</i>	<i>1000 Btus/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Benzie	283.991	26195	101329
Grand Traverse	219.372	117902	117902
Kalkaska	246.194	171816	171816
Manistee	258.411	206185	206185
Missaukee	201.610	193406	193406
Osceola	242.598	140038	140038
Roscommon	277.131	148910	148910
Wexford	181.581	245548	245548
Feedstock Demand		1,250,000	
Total Energy in 1000 Btus			287,703,874
Total Energy Per Ton			230.163

ROSCOMMON ENERGY OPTIMIZATION - 50MGY			
<i>County</i>	<i>1000 Btus/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Crawford	183.355	120,789	120,789
Kalkaska	257.790	152,750	171,816
Missaukee	251.162	193,406	193,406
Ogemaw	244.264	122,488	122,488
Oscoda	252.468	236,738	236,738
Otsego	257.156	274,920	274,920
Roscommon	174.259	148,910	148,910
Feedstock Demand		1,250,000	
Total Energy in 1000 Btus			296,435,065
Total Energy Per Ton			237.148

KINGSLEY ENERGY OPTIMIZATION - 50MGY			
<i>County</i>	<i>1000 Btus/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Antrim	290.058	134,827	134,827
Benzie	224.674	101,329	101,329
Grand Traverse	160.055	117,902	117,902
Kalkaska	229.592	171,816	171,816
Leelanau	258.761	48,922	48,922
Manistee	275.013	206,185	206,185
Missaukee	260.927	193,406	193,406
Osceola	301.915	30,064	140,038
Wexford	198.183	245,548	245,548
Feedstock Demand		1,250,000	
Total Energy in 1000 Btus			297,759,956
Total Energy Per Ton			238.208

KALKASKA ENERGY OPTIMIZATION - 50MGY			
County	1000 Btus/Ton	Optimal Supply	Maximum Supply
Antrim	202.432	134,827	134,827
Benzie	288.905	101,329	101,329
Charlevoix	270.516	96,751	96,751
Crawford	236.853	120,789	120,789
Grand Traverse	210.769	117,902	117,902
Kalkaska	162.418	171,816	171,816
Leelanau	280.762	48,922	48,922
Missaukee	238.926	193,406	193,406
Otsego	292.839	18,710	274,920
Wexford	285.810	245,548	245,548
Feedstock Demand		1,250,000	
Total Energy in 1000 Btus			299,709,893
Total Energy Per Ton			239.768

GAYLORD ENERGY OPTIMIZATION - 50MGY			
County	1000 Btus/Ton	Optimal Supply	Maximum Supply
Antrim	216.270	134,827	134,827
Charlevoix	267.207	96,751	96,751
Cheboygan	256.404	225,280	225,280
Crawford	224.047	120,789	120,789
Emmet	280.647	25,576	138,994
Kalkaska	276.736	171,816	171,816
Montmorency	225.356	200,041	200,041
Otsego	150.245	274,920	274,920
Feedstock Demand		1,250,000	
Total Energy Green Ton Delivered (Btus)			280,948,168
Energy Per Green Ton Delivered (Btus)			224.759

CLARE ENERGY OPTIMIZATION - 50MGY			
County	1000 Btus/Ton	Optimal Supply	Maximum Supply
Bay	284.940	29,471	29,471
Clare	186.396	154,447	154,447
Gladwin	233.831	120,904	120,904
Gratiot	281.781	65,649	65,649
Isabella	190.871	147,913	147,913
Mecosta	267.943	161,937	161,937
Midland	236.604	105,192	105,192
Missaukee	302.721	175,539	193,406
Osceola	261.733	140,038	140,038
Roscommon	272.271	148,910	148,910
Feedstock Demand		1,250,000	
Total Energy in 1000 Btus			310,802,186
Total Energy Per Ton			248.642

WEST BRANCH ENERGY OPTIMIZATION - 50MGY			
<i>County</i>	<i>1000 Btus/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Arenac	236.910	118,833	118,833
Crawford	287.026	120,789	120,789
Gladwin	223.082	120,904	120,904
Iosco	251.962	159,343	159,343
Midland	297.138	28,591	105,192
Missaukee	284.953	193,406	193,406
Ogemaw	168.141	122,488	122,488
Oscoda	242.086	236,738	236,738
Roscommon	209.432	148,910	148,910
Feedstock Demand		1,250,000	
Total Energy in 1000 Btus			302,641,296
Total Energy Per Ton			242.113

TRAVERSE CITY ENERGY OPTIMIZATION - 50MGY			
<i>County</i>	<i>1000 Btus/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Antrim	263.56382	134,827	134,827
Benzie	227.77304	101,329	101,329
Crawford	306.81340	120,789	120,789
Grand Traverse	162.77127	117,902	117,902
Kalkaska	232.37826	171,816	171,816
Leelanau	210.80124	48,922	48,922
Manistee	301.50753	206,185	206,185
Missaukee	308.88671	102,682	193,406
Wexford	232.97063	245,548	245,548
Feedstock Demand		1,250,000	
Total Energy in 1000 Btus			316,194,255
Total Energy Per Ton			252.955

BOYNE CITY ENERGY OPTIMIZATION - 50MGY			
<i>County</i>	<i>1000 Btus/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Antrim	204.062	134,827	134,827
Charlevoix	173.641	96,751	96,751
Cheboygan	268.612	225,280	225,280
Crawford	317.613	7,370	120,789
Emmet	223.273	138,994	138,994
Kalkaska	264.529	171,816	171,816
Montmorency	314.514	200,041	200,041
Otsego	243.812	274,920	274,920
Feedstock Demand		1,250,000	
Total Energy in 1000 Btus			313,595,256
Total Energy Per Ton			250.876

Appendix B4-R Energy Optimization Results and Supply Locations for 40 MGY

MANTON ENERGY OPTIMIZATION - 40MGY			
County	1000 Btus/Ton	Optimal Supply	Maximum Supply
Grand Traverse	219.372	117,902	117,902
Kalkaska	246.194	171,816	171,816
Manistee	258.411	131,290	206,185
Missaukee	201.610	193,406	193,406
Osceola	242.598	140,038	140,038
Wexford	181.581	245,548	245,548
Feedstock Demand		1,000,000	
Total Energy in 1000 Btus			219,643,475
Total Energy Per Ton			219.643

ROSCOMMON ENERGY OPTIMIZATION - 40MGY			
County	1000 Btus/Ton	Optimal Supply	Maximum Supply
Crawford	183.355	120,789	120,789
Missaukee	251.162	193,406	193,406
Ogemaw	244.264	122,488	122,488
Oscoda	252.468	236,738	236,738
Otsego	257.156	177,670	274,920
Roscommon	174.259	148,910	148,910
Feedstock Demand		1,000,000	
Total Energy in 1000 Btus			262,049,255
Total Energy Per Ton			232.049

KINGSLEY ENERGY OPTIMIZATION - 40MGY			
County	1000 Btus/Ton	Optimal Supply	Maximum Supply
Benzie	224.674	101,329	101,329
Grand Traverse	160.055	117,902	117,902
Kalkaska	229.592	171,816	171,816
Leelanau	258.761	48,922	48,922
Manistee	275.013	121,077	206,185
Missaukee	260.927	193,406	193,406
Wexford	198.183	245,548	245,548
Feedstock Demand		1,000,000	
Total Energy in 1000 Btus			226,169,398
Total Energy Per Ton			226.169

KALKASKA ENERGY OPTIMIZATION - 40MGY			
<i>County</i>	<i>1000 Btus/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Antrim	202.432	134,827	134,827
Charlevoix	270.516	96,751	96,751
Crawford	236.853	120,789	120,789
Grand Traverse	210.769	117,902	117,902
Kalkaska	162.418	171,816	171,816
Leelanau	280.762	48,922	48,922
Missaukee	238.926	193,406	193,406
Wexford	285.810	115,586	245,548
Feedstock Demand		1,000,000	
Total Energy in 1000 Btus			227,812,297
Total Energy Per Ton			227.812

GAYLORD ENERGY OPTIMIZATION - 40MGY			
<i>County</i>	<i>1000 Btus/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Antrim	216.270	134,827	134,827
Charlevoix	267.207	44,143	96,751
Cheboygan	256.404	225,280	225,280
Crawford	224.047	120,789	120,789
Montmorency	225.356	200,041	200,041
Otsego	150.245	274,920	274,920
Feedstock Demand		1,000,000	
Total Energy in 1000 Btus			7,192,870
Total Energy Per Ton			7.193

CLARE ENERGY OPTIMIZATION - 40MGY			
<i>County</i>	<i>1000 Btus/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Clare	186.396	154,447	154,447
Gladwin	233.831	120,904	120,904
Gratiot	281.781	20,659	65,649
Isabella	190.871	147,913	147,913
Mecosta	267.943	161,937	161,937
Midland	236.604	105,192	105,192
Osceola	261.733	140,038	140,038
Roscommon	272.271	148,910	148,910
Feedstock Demand		1,000,000	
Total Energy in 1000 Btus			236,588,055
Total Energy Per Ton			236.558

WEST BRANCH ENERGY OPTIMIZATION - 40MGY			
<i>County</i>	<i>1000 Btus/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Arenac	236.910	118,833	118,833
Gladwin	223.082	120,904	120,904
Iosco	251.962	159,343	159,343
Missaukee	284.953	92,785	193,406
Ogemaw	168.141	122,488	122,488
Oscoda	242.086	236,738	236,738
Roscommon	209.432	148,910	148,910
Feedstock Demand		1,000,000	
Total Energy in 1000 Btus			230,804,250
Total Energy Per Ton			230.804

TRAVERSE CITY ENERGY OPTIMIZATION - 40MGY			
<i>County</i>	<i>1000 Btus/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Antrim	263.56382	134,827	134,827
Benzie	227.77304	101,329	101,329
Grand Traverse	162.77127	117,902	117,902
Kalkaska	232.37826	171,816	171,816
Leelanau	210.80124	48,922	48,922
Manistee	301.50753	179,656	206,185
Wexford	232.97063	245,548	245,548
Feedstock Demand		1,000,000	
Total Energy in 1000 Btus			239,418,777
Total Energy Per Ton			239.419

BOYNE CITY ENERGY OPTIMIZATION - 40MGY			
<i>County</i>	<i>1000 Btus/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Antrim	204.062	134,827	134,827
Charlevoix	173.641	96,751	96,751
Cheboygan	268.612	182,691	225,280
Emmet	223.273	138,994	138,994
Kalkaska	264.529	171,816	171,816
Otsego	243.812	274,920	274,920
Feedstock Demand		1,000,000	
Total Energy in 1000 Btus			236,898,802
Total Energy Per Ton			236.899

Appendix B4-S Energy Optimization Results and Supply Locations for 30 MGY

MANTON ENERGY OPTIMIZATION - 30MGY			
<i>County</i>	<i>1000 Btus/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Grand Traverse	219.372	117,902	117,902
Kalkaska	246.194	53,106	171,816
Missaukee	201.610	193,406	193,406
Osceola	242.598	140,038	140,038
Wexford	181.581	245,548	245,548
Feedstock Demand		750,000	
Total Energy in 1000 Btus			156,491,043
Total Energy Per Ton			208.655

ROSCOMMON ENERGY OPTIMIZATION - 30MGY			
<i>County</i>	<i>1000 Btus/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Crawford	183.355	120,789	120,789
Missaukee	251.162	193,406	193,406
Ogemaw	244.264	122,488	122,488
Oscoda	252.468	164,407	236,738
Roscommon	174.259	148,910	148,910
Feedstock Demand		750,000	
Total Energy in 1000 Btus			168,099,340
Total Energy Per Ton			224.132

KINGSLEY ENERGY OPTIMIZATION - 30MGY			
<i>County</i>	<i>1000 Btus/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Benzie	224.674	101,329	101,329
Grand Traverse	160.055	117,902	117,902
Kalkaska	229.592	171,816	171,816
Leelanau	258.761	48,922	48,922
Missaukee	260.927	64,483	193,406
Wexford	198.183	245,548	245,548
Feedstock Demand		750,000	
Total Energy in 1000 Btus			159,232,166
Total Energy Per Ton			212.310

KALKASKA ENERGY OPTIMIZATION - 30MGY			
<i>County</i>	<i>1000 Btus/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Antrim	202.432	134,827	134,827
Charlevoix	270.516	11,260	96,751
Crawford	236.853	120,789	120,789
Grand Traverse	210.769	117,902	117,902
Kalkaska	162.418	171,816	171,816
Missaukee	238.926	193,406	193,406
Feedstock Demand		750,000	
Total Energy in 1000 Btus			157,914,298
Total Energy Per Ton			210.552

GAYLORD ENERGY OPTIMIZATION - 30MGY			
<i>County</i>	<i>1000 Btus/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Antrim	216.270	134,827	134,827
Cheboygan	256.404	19,424	225,280
Crawford	224.047	120,789	120,789
Montmorency	225.356	200,041	200,041
Otsego	150.245	274,920	274,920
Feedstock Demand		750,000	
Total Energy in 1000 Btus			147,587,434
Total Energy Per Ton			196.783

CLARE ENERGY OPTIMIZATION - 30MGY			
<i>County</i>	<i>1000 Btus/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Clare	186.396	154,447	154,447
Gladwin	233.831	120,904	120,904
Isabella	190.871	147,913	147,913
Mecosta	267.943	81,505	161,937
Midland	236.604	105,192	105,192
Osceola	261.733	140,038	140,038
Feedstock Demand		750,000	
Total Energy in 1000 Btus			168,671,944
Total Energy Per Ton			224.869

WEST BRANCH ENERGY OPTIMIZATION - 30MGY			
<i>County</i>	<i>1000 Btus/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Arenac	236.910	118,833	118,833
Gladwin	223.082	120,904	120,904
Iosco	251.962	2,128	159,343
Ogemaw	168.141	122,488	122,488
Oscoda	242.086	236,738	236,738
Roscommon	209.432	148,910	148,910
Feedstock Demand		750,000	
Total Energy in 1000 Btus			164,752,737
Total Energy Per Ton			219.670

TRAVERSE CITY ENERGY OPTIMIZATION - 30MGY			
<i>County</i>	<i>1000 Btus/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Antrim	263.56382	64,483	134,827
Benzie	227.77304	101,329	101,329
Grand Traverse	162.77127	117,902	117,902
Kalkaska	232.37826	171,816	171,816
Leelanau	210.80124	48,922	48,922
Wexford	232.97063	245,548	245,548
Feedstock Demand		750,000	
Total Energy in 1000 Btus			166,711,018
Total Energy Per Ton			222.281

BOYNE CITY ENERGY OPTIMIZATION - 30MGY			
<i>County</i>	<i>1000 Btus/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Antrim	204.062	134,827	134,827
Charlevoix	173.641	96,751	96,751
Emmet	223.273	138,994	138,994
Kalkaska	264.529	104,508	171,816
Otsego	243.812	274,920	274,920
Feedstock Demand		750,000	
Total Energy in 1000 Btus			170,020,685
Total Energy Per Ton			226.694

Appendix B4-T Emission Optimization Results and Supply Locations for 50 MGY

MANTON EMISSIONS OPTIMIZATION - 50MGY			
<i>County</i>	<i>Lbs/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Benzie	60.29757	26195	101329
Grand Traverse	44.99891	117902	117902
Kalkaska	51.34910	171816	171816
Manistee	54.24144	206185	206185
Missaukee	40.79385	193406	193406
Osceola	50.49783	140038	140038
Roscommon	58.67346	148910	148910
Wexford	36.05195	245548	245548
Feedstock Demand		1,250,000	
Total Emissions (in lbs.)			59,442,263
Total Emissions Per Ton			47.55381

ROSCOMMON EMISSIONS OPTIMIZATION - 50MGY			
<i>County</i>	<i>Lbs/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Crawford	36.4719	120789	120789
Kalkaska	54.0944	152750	171816
Missaukee	52.5253	193406	193406
Ogemaw	50.8922	122488	122488
Oscoda	52.8345	236738	236738
Otsego	53.9444	274920	274920
Roscommon	34.3185	148910	148910
Feedstock Demand		1,250,000	
Total Emissions (in lbs.)			61,509,368
Total Emissions Per Ton			49.20749

KINGSLEY EMISSIONS OPTIMIZATION - 50MGY			
<i>County</i>	<i>Lbs/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Antrim	61.73394	134,827	134,827
Benzie	46.25432	101,329	101,329
Grand Traverse	30.95566	117,902	117,902
Kalkaska	47.41850	171,816	171,816
Leelanau	54.32438	48,922	48,922
Manistee	58.17205	206,185	206,185
Missaukee	54.83710	193,406	193,406
Osceola	64.54108	30,064	140,038
Wexford	39.98255	245,548	245,548
Feedstock Demand		1,250,000	
Total Emissions (in lbs.)			61,823,036
Total Emissions Per Ton			49.458

KALKASKA EMISSIONS OPTIMIZATION - 50MGY			
<i>County</i>	<i>Lbs/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Antrim	40.98839	134826.91	134826.908
Benzie	61.46099	101328.75	101328.746
Charlevoix	57.1074	96751.322	96751.3222
Crawford	49.13762	120788.72	120788.717
Grand Traverse	42.96236	117902.29	117902.286
Kalkaska	31.51513	171816.43	171816.431
Leelanau	59.53302	48922.09	48922.0901
Missaukee	49.62847	193405.96	193405.958
Otsego	62.39218	18709.712	274919.592
Wexford	60.72811	245547.83	245547.829
Feedstock Demand		1,250,000	
Total Emissions (in lbs.)			62,284,682
Total Emissions Per Ton			49.82775

GAYLORD EMISSIONS OPTIMIZATION - 50MGY			
<i>County</i>	<i>Lbs/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Antrim	44.26452	134,827	134,827
Charlevoix	56.32399	96,751	96,751
Cheboygan	53.76642	225,280	225,280
Crawford	46.10578	120,789	120,789
Emmet	59.50587	25,576	138,994
Kalkaska	58.57996	171,816	171,816
Montmorency	46.41568	200,041	200,041
Otsego	28.63334	274,920	274,920
Feedstock Demand		1,250,000	
Total Emissions Green Ton Delivered (lbs)			57,842,852
Emissions Per Green Ton Delivered (lbs)			46.27428

CLARE EMISSIONS OPTIMIZATION - 50MGY			
<i>County</i>	<i>Lbs/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Bay	60.52226	29,471	29,471
Clare	37.19200	154,447	154,447
Gladwin	48.42207	120,904	120,904
Gratiot	59.77430	65,649	65,649
Isabella	38.25137	147,913	147,913
Mecosta	56.49817	161,937	161,937
Midland	49.07881	105,192	105,192
Missaukee	64.73185	175,539	193,406
Osceola	55.02787	140,038	140,038
Roscommon	57.52285	148,910	148,910
Feedstock Demand		1,250,000	
Total Emissions (in lbs.)			64,910,778
Total Emissions Per Ton			51.92865

WEST BRANCH EMISSIONS OPTIMIZATION - 50MGY			
<i>County</i>	<i>Lbs/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Arenac	49.15119	118,833	118,833
Crawford	61.01613	120,789	120,789
Gladwin	45.87732	120,904	120,904
Iosco	52.71459	159,343	159,343
Midland	63.41008	28,591	105,192
Missaukee	60.52528	193,406	193,406
Ogemaw	32.87007	122,488	122,488
Oscoda	50.37644	236,738	236,738
Roscommon	42.64568	148,910	148,910
Feedstock Demand		1,250,000	
Total Emissions (in lbs.)			62,978,691
Total Emissions Per Ton			50.38295

TRAVERSE CITY EMISSIONS OPTIMIZATION - 50MGY			
<i>County</i>	<i>Lbs/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Antrim	55.46142	134,827	134,827
Benzie	46.98796	101,329	101,329
Crawford	65.70074	120,789	120,789
Grand Traverse	31.59882	117,902	117,902
Kalkaska	48.07825	171,816	171,816
Leelanau	42.96990	48,922	48,922
Manistee	64.44457	206,185	206,185
Missaukee	66.19159	102,682	193,406
Wexford	48.21849	245,548	245,548
Feedstock Demand		1,250,000	
Total Emissions (in lbs.)			66,187,348
Total Emissions Per Ton			52.94988

BOYNE CITY EMISSIONS OPTIMIZATION - 50MGY			
<i>County</i>	<i>Lbs/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Antrim	41.37443	134,827	134,827
Charlevoix	34.17223	96,751	96,751
Cheboygan	56.65651	225,280	225,280
Crawford	68.25755	7,370	120,789
Emmet	45.92256	138,994	138,994
Kalkaska	55.68988	171,816	171,816
Montmorency	67.52391	200,041	200,041
Otsego	50.78511	274,920	274,920
Feedstock Demand		1,250,000	
Total Emissions (in lbs.)			65,572,036
Total Emissions Per Ton			52.45763

Appendix B4-U Emission Optimization Results and Supply Locations for 40 MGY

MANTON EMISSIONS OPTIMIZATION - 40MGY			
<i>County</i>	<i>Lbs/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Grand Traverse	44.99891	117,902	117,902
Kalkaska	51.34910	171,816	171,816
Manistee	54.24144	131,290	206,185
Missaukee	40.79385	193,406	193,406
Osceola	50.49783	140,038	140,038
Wexford	36.05195	245,548	245,548
Feedstock Demand		1,000,000	
Total Emissions (in lbs.)			45,063,294
Total Emissions Per Ton			46.06329

ROSCOMMON EMISSIONS OPTIMIZATION - 40MGY			
<i>County</i>	<i>Lbs/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Crawford	36.4719	120,789	120,789
Missaukee	52.5253	193,406	193,406
Ogemaw	50.8922	122,488	122,488
Oscoda	52.8345	236,738	236,738
Otsego	53.9444	177,670	274,920
Roscommon	34.3185	148,910	148,910
Feedstock Demand		1,000,000	
Total Emissions (in lbs.)			48,000,357
Total Emissions Per Ton			48.00036

KINGSLEY EMISSIONS OPTIMIZATION - 40MGY			
<i>County</i>	<i>Lbs/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Benzie	46.25432	101,329	101,329
Grand Traverse	30.95566	117,902	117,902
Kalkaska	47.41850	171,816	171,816
Leelanau	54.32438	48,922	48,922
Manistee	58.17205	121,077	206,185
Missaukee	54.83710	193,406	193,406
Wexford	39.98255	245,548	245,548
Feedstock Demand		1,000,000	
Total Emissions (in lbs.)			46,608,303
Total Emissions Per Ton			46.60830

KALKASKA EMISSIONS OPTIMIZATION - 40MGY			
<i>County</i>	<i>Lbs/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Antrim	40.98839	134,827	134,827
Charlevoix	57.1074	96,751	96,751
Crawford	49.13762	120,789	120,789
Grand Traverse	42.96236	117,902	117,902
Kalkaska	31.51513	171,816	171,816
Leelanau	59.53302	48,922	48,922
Missaukee	49.62847	193,406	193,406
Wexford	60.72811	115,586	245,548
Feedstock Demand		1,000,000	
Total Emissions (in lbs.)			46,997,259
Total Emissions Per Ton			46.99726

GAYLORD EMISSIONS OPTIMIZATION - 40MGY			
<i>County</i>	<i>Lbs/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Antrim	44.26452	134,827	134,827
Charlevoix	56.32399	44,143	96,751
Cheboygan	53.76642	225,280	225,280
Crawford	46.10578	120,789	120,789
Montmorency	46.41568	200,041	200,041
Otsego	28.63334	274,920	274,920
Feedstock Demand		1,000,000	
Total Emissions (in lbs.)			212,165,404
Total Emissions Per Ton			212.165

CLARE EMISSIONS OPTIMIZATION - 40MGY			
<i>County</i>	<i>Lbs/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Clare	37.19200	154,447	154,447
Gladwin	48.42207	120,904	120,904
Gratiot	59.77430	20,659	65,649
Isabella	38.25137	147,913	147,913
Mecosta	56.49817	161,937	161,937
Midland	49.07881	105,192	105,192
Osceola	55.02787	140,038	140,038
Roscommon	57.52285	148,910	148,910
Feedstock Demand		1,000,000	
Total Emissions (in lbs.)			49,074,916
Total Emissions Per Ton			49.07492

WEST BRANCH EMISSIONS OPTIMIZATION - 40MGY			
<i>County</i>	<i>Lbs/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Arenac	49.15119	118,833	118,833
Gladwin	45.87732	120,904	120,904
Iosco	52.71459	159,343	159,343
Missaukee	60.52528	92,785	193,406
Ogemaw	32.87007	122,488	122,488
Oscoda	50.37644	236,738	236,738
Roscommon	42.64568	148,910	148,910
Feedstock Demand		1,000,000	
Total Emissions (in lbs.)			47,705,603
Total Emissions Per Ton			47.70560

TRAVERSE CITY EMISSIONS OPTIMIZATION - 40MGY			
<i>County</i>	<i>Lbs/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Antrim	55.46142	134,827	134,827
Benzie	46.98796	101,329	101,329
Grand Traverse	31.59882	117,902	117,902
Kalkaska	48.07825	171,816	171,816
Leelanau	42.96990	48,922	48,922
Manistee	64.44457	179,656	206,185
Wexford	48.21849	245,548	245,548
Feedstock Demand		1,000,000	
Total Emissions (in lbs.)			49,745,088
Total Emissions Per Ton			49.74509

BOYNE CITY EMISSIONS OPTIMIZATION - 40MGY			
<i>County</i>	<i>Lbs/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Antrim	41.37443	134,827	134,827
Charlevoix	34.17223	96,751	96,751
Cheboygan	56.65651	182,691	225,280
Emmet	45.92256	138,994	138,994
Kalkaska	55.68988	171,816	171,816
Otsego	50.78511	274,920	274,920
Feedstock Demand		1,000,000	
Total Emissions (in lbs.)			49,148,485
Total Emissions Per Ton			49.14848

Appendix B4-V Emission Optimization Results and Supply Locations for 30 MGY

MANTON EMISSIONS OPTIMIZATION - 30MGY			
<i>County</i>	<i>Lbs/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Grand Traverse	44.99891	117,902	117,902
Kalkaska	51.34910	53,106	171,816
Missaukee	40.79385	193,406	193,406
Osceola	50.49783	140,038	140,038
Wexford	36.05195	245,548	245,548
Feedstock Demand		750,000	
Total Emissions (in lbs.)			31,846,284
Total Emissions Per Ton			42.46171

ROSCOMMON EMISSIONS OPTIMIZATION - 30MGY			
<i>County</i>	<i>Lbs/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Crawford	36.4719	120,789	120,789
Missaukee	52.5253	193,406	193,406
Ogemaw	50.8922	122,488	122,488
Oscoda	52.8345	164,407	236,738
Roscommon	34.3185	148,910	148,910
Feedstock Demand		750,000	
Total Emissions (in lbs.)			34,594,543
Total Emissions Per Ton			46.12606

KINGSLEY EMISSIONS OPTIMIZATION - 30MGY			
<i>County</i>	<i>Lbs/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Benzie	46.25432	101,329	101,329
Grand Traverse	30.95566	117,902	117,902
Kalkaska	47.41850	171,816	171,816
Leelanau	54.32438	48,922	48,922
Missaukee	54.83710	64,483	193,406
Wexford	39.98255	245,548	245,548
Feedstock Demand		750,000	
Total Emissions (in lbs.)			32,495,244
Total Emissions Per Ton			43.32699

KALKASKA EMISSIONS OPTIMIZATION - 30MGY			
<i>County</i>	<i>Lbs/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Antrim	40.98839	134,827	134,827
Charlevoix	57.1074	11,260	96,751
Crawford	49.13762	120,789	120,789
Grand Traverse	42.96236	117,902	117,902
Kalkaska	31.51513	171,816	171,816
Missaukee	49.62847	193,406	193,406
Feedstock Demand		750,000	
Total Emissions (in lbs.)			32,183,239
Total Emissions Per Ton			42.91099

GAYLORD EMISSIONS OPTIMIZATION - 30MGY			
<i>County</i>	<i>Lbs/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Antrim	44.26452	134,827	134,827
Cheboygan	53.76642	19,424	225,280
Crawford	46.10578	120,789	120,789
Montmorency	46.41568	200,041	200,041
Otsego	28.63334	274,920	274,920
Feedstock Demand		750,000	
Total Emissions (in lbs.)			29,738,358
Total Emissions Per Ton			39.65114

CLARE EMISSIONS OPTIMIZATION - 30MGY			
<i>County</i>	<i>Lbs/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Clare	37.19200	154,447	154,447
Gladwin	48.42207	120,904	120,904
Isabella	38.25137	147,913	147,913
Mecosta	56.49817	81,505	161,937
Midland	49.07881	105,192	105,192
Osceola	55.02787	140,038	140,038
Feedstock Demand		750,000	
Total Emissions (in lbs.)			34,730,107
Total Emissions Per Ton			46.30681

WEST BRANCH EMISSIONS OPTIMIZATION - 30MGY			
<i>County</i>	<i>Lbs/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Arenac	49.15119	118,833	118,833
Gladwin	45.87732	120,904	120,904
Iosco	52.71459	2,128	159,343
Ogemaw	32.87007	122,488	122,488
Oscoda	50.37644	236,738	236,738
Roscommon	42.64568	148,910	148,910
Feedstock Demand		750,000	
Total Emissions (in lbs.)			33,802,236
Total Emissions Per Ton			45.06965

TRAVERSE CITY EMISSIONS OPTIMIZATION - 30MGY			
<i>County</i>	<i>Lbs/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Antrim	55.46142	64,483	134,827
Benzie	46.98796	101,329	101,329
Grand Traverse	31.59882	117,902	117,902
Kalkaska	48.07825	171,816	171,816
Leelanau	42.96990	48,922	48,922
Wexford	48.21849	245,548	245,548
Feedstock Demand		750,000	
Total Emissions (in lbs.)			34,265,859
Total Emissions Per Ton			45.68781

BOYNE CITY EMISSIONS OPTIMIZATION - 30MGY			
<i>County</i>	<i>Lbs/Ton</i>	<i>Optimal Supply</i>	<i>Maximum Supply</i>
Antrim	41.37443	134,827	134,827
Charlevoix	34.17223	96,751	96,751
Emmet	45.92256	138,994	138,994
Kalkaska	55.68988	104,508	171,816
Otsego	50.78511	274,920	274,920
Feedstock Demand		750,000	
Total Emissions (in lbs.)			35,049,421
Total Emissions Per Ton			46.73256

Appendix B4-W Visual Depiction of Counties to Supply Each Candidate Location for a 50 MGY Per Year Production

City of Boyne City

City of Clare

City of Gaylord

Village of Kalkaska

Village of Kingsley

City of Manton

Data Source: MI Geographic Data Library and FIA Forest Service
Fengli Zhang
Aug 24, 2010

Village of Roscommon

City of Traverse City

City of West Branch

Sub-Task B5: Understand Life Cycle Environmental Impacts of System Alternatives from Forest to Factory Gate

Reported by:

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The use of “ton” in this document means green short ton, where 1 short ton = 2000 lb, unless otherwise indicated.

Abstract:

The goal of Project B5 was to develop measures of the environmental footprint for primary forest products supply chain activities (harvesting and hauling wood) within the state of Michigan. We detailed a life-cycle assessment procedure, relying on a combination of peer-reviewed literature, national databases, and primary data collected from loggers and truckers within the study area. Several different equipment configurations and operating scenarios for roundwood harvesting are considered. Greenhouse gas emissions and fossil energy demand per unit of wood are calculated with the assistance of SimaPro 7.2 LCA software and literature values. Results indicated that a full processor / forwarder is the best choice of harvesting equipment configuration due to relatively low inputs and high reported productivity, although the burdens of harvesting depend strongly on the intensity of harvest being conducted. Multimodal truck + rail transport had roughly 2X lower environmental burdens than typical log truck transport, which was directly related to the increased fuel efficiency of rail transport.

1.0 Introduction

Emissions of greenhouse gases from transportation are a major contributor to human-caused climate forcing on a global scale. Recent studies have predicted serious consequences from a “business as usual” approach to energy production and use, including increasing global temperatures, sea level rise, displacements of human populations from submerged lands, changing weather patterns, and increase in incidence of certain diseases (IPCC, 2007a,b). Biofuels made from renewable feedstocks are among the largest expected contributors to the transportation industry’s planned emission reductions over the foreseeable future. Additionally, in recent years the U.S. has imported slightly more than half of its oil needs from foreign sources (Goerold, 2008). Such a high dependence increases U.S. strategic vulnerability, and a domestic biofuels industry is increasingly seen as a way to combat this trend while increasing employment in rural areas of the country.

Many industry sectors are addressing sustainability issues by reducing the emission of greenhouse gases across the entire production chain. For example, recently the dairy industry has been the subject of a comprehensive dairy milk carbon footprint study (Thoma et al. 2010), the goal of which is to identify opportunities for improvement at various steps along the life cycle. A commercial biofuel operation will rely on inputs of feedstock grown over a large area, with potentially variable supply over the course of a year. Assessing supply chain options and anticipating supply chain issues for this type of emerging industry will be critical for continued success.

This supply chain sustainability assessment project focused on forest-based biomass grown within the state of Michigan. We were tasked with developing environmental metrics for greenhouse gas emissions and fossil energy demand for forest-based biomass harvesting and transport within Michigan. To this end, we have developed a limited-scope life-cycle assessment (LCA) procedure for a few general scenarios, using a well-detailed process assumptions and inventory data. Results and methods from this study may be later used at different levels of data aggregation when considering specific bioenergy projects within the state of Michigan, or may possibly be applicable to forest-based biomass use within the broader Great Lakes region.

2.0 Methods

2.1 Goal and scope

The goal of our LCA is to determine greenhouse gas (GHG) emissions and fossil energy demand associated with harvesting and transport of forest-based biomass within the state of Michigan. For our purposes, harvesting includes cutting and moving wood to a forest landing, and transport refers to movements of wood from the forest landing to a processing facility. Our scope will be limited in the sense that our focus is only on major stages in the forest-based biomass supply chain that occur prior to biomass conversion at a processing facility into biofuels, bioproducts, or bioenergy. Material inputs used directly during these feedstock supply chain activities, i.e. wood harvesting and transport, will be considered. Of these inputs, fuel is the most important, but other inputs are also included, including major equipment used to harvest and transport wood (harvesters, forwarders, log trucks, etc.).

2.2 Functional unit

The functional unit for this study will be one green ton of forest biomass. Harvesting activity will be normalized to this unit, while transportation activity will be normalized on the basis of a ton-mile, due to the dependence of transport burdens on the particular distance moved. We have no specific origin-destination pairs of feedstock location and processing facilities, so this unit can be utilized by parties interested in specific case studies by multiplying environmental burdens per ton-mile by the mileage of the specific transport step, as we have done in a few examples presented here.

2.3 Life cycle inventory data

The data and assumptions required to develop our environmental burdens for harvesting and transport of wood within the state of Michigan came from a variety of sources. Environmental impacts of the production of material and energetic inputs, in addition to their direct use in this supply chain, were included as part of this assessment through use of the Ecoinvent 2.1 database (Frischknecht 2005), peer-reviewed literature, expert opinion, or other sources. An important component of our life cycle inventory was the use of primary data from loggers within the state of Michigan. In two separate survey campaigns led by Michigan State University researchers, loggers were identified and mailed a survey to gain information on their current equipment and operations for handling forest products in harvesting and transportation stages. The survey campaigns each covered different areas of the state and asked about forestry operations in different years (2009 and 2010), but in combination the results of over 220 unique survey respondents represent the most current and accurate picture of forest products operations over the entire state of Michigan. Please refer to FBSCC reports from Michigan State University Project B2 for a detailed summary of survey methods and results beyond the results utilized here for our LCA work. In the following sections, we detail how life cycle inventory data was developed for harvesting and transport of forest biomass.

Estimates of harvesting and forwarding activity were taken primarily from the state of Michigan logger survey, with supplementary information from other sources (Table 1). Three main harvesting/forwarding equipment configurations were used to characterize the logging industry in Michigan:

- a) full cut-to-length processor / forwarder

- b) feller-buncher / skidder / slasher
- c) chainsaw / skidder

From the logger survey results, we were able to obtain the average fuel use of various key pieces of forestry equipment, in gallons/hour. From Table 1, the amount of variability in fuel use estimates is large, and would be worthy of future sensitivity analysis investigations to determine the impacts of fuel use on overall forest biomass supply chain burdens. Estimates of lubricants and grease came from industry experts. In an effort to convert data to a consistent format and make valid comparisons, it was essential to make several key assumptions regarding the treatment of this data. Major assumptions are listed below in Table 2.

Table 1: Summary of inputs for harvesting configurations

Configuration A: Full Processor / Forwarder			
<u>Item</u>	<u>Units</u>	<u>Total</u>	<u>Data Source / Comments</u>
Fuel use	gal/hr	8.10 ± 2.98	Logger survey data, full processor = 4.9 ± 2.3 (n ^a =142), forwarder = 3.2 ± 1.9 (n=159)
Lubricants	gal / d	6.68	J.M. Longyear, no variability given
Grease	lb / d	2.00	J.M. Longyear, no variability given
Equipment	units	2	Major pieces of equipment
Configuration B: Feller-buncher / Grapple Skidder / Slasher			
<u>Item</u>	<u>Units</u>	<u>Total</u>	<u>Data Source / Comments</u>
Fuel use	gal/hr	14.63 ± 3.73	Logger survey data, feller buncher = 6.3 ± 2.6 (n=37), slasher = 3.9 ± 1.8 (n=18), weighted average of grapple (5.1 ± 2.3, n=33) and cable skidders (2.4 ± 1.0, n=11)
Lubricants	gal / d	2.48	J.M. Longyear, no variability given
Grease	lb / d	1.00	J.M. Longyear, no variability given
Saw gas	gal / d	1.00	J.M. Longyear, no variability given
Equipment	units	3	Major pieces of equipment
Configuration C: Chainsaw / Cable Skidder			
<u>Item</u>	<u>Units</u>	<u>Total</u>	<u>Data Source / Comments</u>
Fuel use	gal/hr	7.18 ± 2.07	Logger survey data, chainsaws = 1.1 ± 0.6 (n=35), 2.5 average chainsaws used per logging crew, weighted average of grapple (5.1 ± 2.3, n=33) and cable skidders (2.4 ± 1.0, n=11)
Lubricants	gal / d	0.40	Jason Keranen, no variability given
Equipment	units	1	Major piece of equipment

a- the n-values listed in Comments refer to the number of survey responses included in the reported average

Table 2- Key assumptions for developing harvesting / forwarding LCA estimates

<u>Item</u>	<u>Assumption</u>	<u>Additional Comment</u>
Duration of workday	8-hour productive workday, machines are in use continuously	Used to average hourly consumption of lubricants
Harvest Productivity	Harvest levels are sustained throughout an 8-hour productive workday	Used to normalize harvest inputs
Lifetime productivity of major piece of harvesting equipment	160,000 green tons (10 years, 40 weeks/year, 8 loads / week, 50 tons/ load)	Can change if better estimates are found, but overall LCA burdens for equipment fabrication and repair are likely to be small, as shown in results.

In order to transform life cycle inventory data for harvesting and forwarding, reported on the basis of hourly usage rates, into inputs normalized on the basis of one green ton of forest biomass, it is necessary to know the productivity of each equipment configuration in tons of wood per hour. In the state of Michigan logger surveys, respondents were asked to list their average harvest productivity (in tons or cords of green timber per hr) for three theoretical harvest types – clearcutting, a 70% (shelterwood) cut, and a 30% (selective cut) treatment. In each case, respondents were also asked to list which of the harvest equipment configurations, listed in a previous survey section, they would likely use in each treatment. For each of these treatment scenarios, there were also separate entry sections for entering productivity estimates for each of four potential forest types – natural hardwood stands, natural softwood stands, mixed hardwood/softwood stands, and softwood plantations.

Estimates of harvest productivity were wide-ranging, and this analysis required some standardization to ensure that accurate comparisons were being made. In previous survey sections, respondents were asked which equipment configurations (processor/ forwarder, feller-buncher/skidder, etc.) they used in their operations, along with the number of pieces of equipment owned. For the full processor and feller-buncher configurations, only respondents indicating that one or two pieces of harvesting equipment (one or two processors, one or two feller-bunchers) were included in the productivity analysis. In situations where respondents indicated three or more processors or feller bunchers, it was more likely that these pieces of equipment were working on different sites, or not all working at the same time, and therefore would not yield productivity data was reflective of the capability of each machine. This distinction was not made for the equipment configurations involving chainsaws as the main harvesting equipment, however an average of 2.5 chainsaws was indicated in the survey responses for loggers who used chainsaws as a tool to cut more than 50% of their total production in 2009-2010.

Weighted averages for each category were calculated as follows:

Average Productivity (cords / hr) = $(N1*P1 + N2*P2)/(N1 + N2*2)$

Where N1 and N2 are the number of 1-harvester and 2-harvester respondents, respectively, and P1 and P2 represent average productivity values for 1-harvester and 2-harvester respondents (in cords / hr).

Below in Table 3 is a summary of productivity estimates (average cords green timber / hr) for survey respondents that indicated a particular equipment configuration would be used in each cutting prescription and forest type. To convert these values into green tons / hour, an average conversion factor of 2.35 tons per cord has been applied. This value can vary between regions and tree species, and more specific data may be substituted if values are known for target species in a certain area.

As expected, average productivity for chainsaws is lower than the more mechanized systems, roughly 2 cords / hour across most harvest types and forest types. (Table 3). In both fully-mechanized systems (A and B), productivity increased as harvest treatment intensity rose from 30% to 70% to 100%, with feller-bunchers slightly more productive than full processors in 70% and clearcutting operations.

Table 3 : Combined state of MI productivity estimates for different logging equipment configurations

A: Full Processor / Forwarder		Productivity per harvester (cords/ hr)		
Treatment	Forest Type	N ^a	Average	Std. Dev
30% Cut (Selective)	Natural Hardwoods	54	3.34	1.38
	Mixed Hardwood / Softwood	48	3.83	1.48
	Natural Softwoods	47	3.95	2.16
	Softwood Plantations	37	4.57	2.11
70% Cut (Shelterwood)	Natural Hardwoods	43	4.09	1.80
	Mixed Hardwood / Softwood	41	4.51	1.81
	Natural Softwoods	38	4.66	2.15
	Softwood Plantations	29	4.97	2.13
Clearcutting	Natural Hardwoods	43	5.51	2.74
	Mixed Hardwood / Softwood	47	5.67	2.50
	Natural Softwoods	40	6.07	2.79
	Softwood Plantations	35	6.97	4.02

B: Feller-buncher / Skidder / Slasher				
Treatment	Forest Type	N	Productivity per harvester (cords/ hr)	
			Average	Std. Dev
30% Cut (Selective)	Natural Hardwoods	15	3.72	1.52
	Mixed Hardwood / Softwood	15	3.66	1.31
	Natural Softwoods	13	3.37	1.32
	Softwood Plantations	8	4.01	0.93
70% Cut (Shelterwood)	Natural Hardwoods	14	4.74	1.43
	Mixed Hardwood / Softwood	15	4.63	1.42
	Natural Softwoods	16	5.02	1.60
	Softwood Plantations	9	5.39	1.73
Clearcutting	Natural Hardwoods	13	6.82	2.68
	Mixed Hardwood / Softwood	13	6.59	2.98
	Natural Softwoods	11	6.42	2.83
	Softwood Plantations	9	7.10	4.19
C: Chainsaws / Skidder				
Treatment	Forest Type	N	Productivity (cords/ hr)	
			Average	Std. Dev
30% Cut (Selective)	Natural Hardwoods	32	2.02	1.33
	Mixed Hardwood / Softwood	19	1.95	1.46
	Natural Softwoods	17	1.84	1.56
	Softwood Plantations	13	1.76	0.86
70% Cut (Shelterwood)	Natural Hardwoods	20	2.20	1.61
	Mixed Hardwood / Softwood	18	1.94	1.40
	Natural Softwoods	14	1.88	1.48
	Softwood Plantations	12	1.74	1.06
Clearcutting	Natural Hardwoods	12	2.00	1.12
	Mixed Hardwood / Softwood	14	1.91	0.92
	Natural Softwoods	13	1.42	0.60
	Softwood Plantations	9	1.78	1.10

a- the n-values listed in Comments refer to the number of survey responses included in the reported average

In order to simplify the analysis for this report, the following data aggregation steps have been made. Productivities for all natural stands were averaged for each harvest configuration in each harvest type, resulting in 9 total productivity estimates. Plantations were left out of the analysis for now because they are still relatively uncommon in the state of Michigan, but this may change in the future. In order to arrive at an estimate of productivity for each harvest scenario, the data for different equipment configurations was combined with FBSCC Steering Committee input to yield a weighted average for each harvest scenario in the following manner (Table 4). In this way, we now have one estimate of productivity for each of the three harvest scenarios. If one single metric to encompass all potential harvest activity is desired, the data could be further

aggregated by taking a weighted average of the three harvest scenarios to represent their relative importance in terms of the overall harvest of forest biomass within the state of Michigan. An example of these weighted averages was discussed with the FBSCC steering committee and is presented in Table 4, but these estimations can be altered based on the planned operations for a specific facility and its supply area.

Table 4: Proportion of harvesting done in each scenario by each equipment configuration (%)

<u>Harvest scenario</u>	<u>Percentage of harvest using each equipment configuration</u>			<u>Total</u>	<u>Percentage of total harvest</u>
	<u>A: Full Processor</u>	<u>B: Feller-buncher</u>	<u>C: Chainsaws</u>		
30% Selective Cut	45	45	10	100	60
70 % Shelterwood	45	50	5	100	20
Clearcut	90	10	0	100	20
					100

For forest biomass transportation from a forest landing to a conversion facility, the two modes of transportation considered here are road and rail. Over-the-road transport can occur in log trucks (roundwood logs) or chip vans (processed biomass). In Michigan, log trucks are allowed to attain a gross vehicle weight of 164,000 lbs, which is considerably larger than other northern states such as MN or WI (80,000 lbs). These large trucks are the primary method of roundwood transport in the state. We will develop LCA profiles of transport based on an average log truck reported within the state of Michigan, but include estimates of fuel use for larger MI-only trucks (10 or 11 axles) and chip vans if LCA burdens for these modes of transport are desired in future work. Rail transport of forest biomass is typically performed by 80-ton log cars with roundwood logs. Rail is commonly perceived as being more fuel efficient than truck transport by a factor of 4-5X. Our estimates of fuel use for rail cars operating in MI come from national averages of a major rail company operating in the Upper Peninsula, and are in line with general estimates of rail fuel use (Table 5). We also consider the fuel use required to power hydraulic loaders present on most MI log trucks, incorporating one loading and unloading cycle into the estimates of fuel use (Table 5).

Table 5: Key input data and assumptions regarding transport of forest biomass in Michigan.

<u>Item</u>	<u>Data</u>	<u>Comment</u>
<u>Loading/Unloading</u>		
Fuel use required per ton of green timber	4.5 gallons / hour 1 hour to load or unload 40 green ton average load 0.225 gal / ton	Average of one full-day trial conducted with 2007 MI log truck equipped with self-loader
<u>Truck transportation</u>		

Log truck fuel use per ton-mile	4.48 ± 1.8 miles / gallon 40 green ton loaded average 50% loaded miles 0.0112 gal / ton-mile	Logger survey Fuel use for average of all forest biomass hauling trucks reported in survey (large 10-11 axle trucks = 3.66 ± 0.87 miles/ gallon, chip vans = 4.19 ± 0.99 miles/ gallon)
Lifetime ton-miles of log truck	15 yr productive life 55,000 miles / yr 40 ton loads, 50% loaded miles	Logger survey data, estimates from industry experts
<hr/> <u>Rail transportation</u>		
Rail fuel use per ton-mile	0.00253 gal / ton-mile	CN Railroad (2010), no variability given
Lifetime ton-miles of rail equipment	20,000,000 lifetime miles 2,000 tons loaded	Assumed values

2.4 Environmental impacts

We combined the life cycle inventory data detailed above with estimates of greenhouse gas emissions and fossil energy demand resulting from production and use of each of the inputs listed in the inventory. Environmental impact factors and their sources are detailed in Table 6. A majority of the factors are derived from national or regional databases and peer-reviewed literature sources. Emissions of different greenhouse gases (CO₂, N₂O, CH₄, etc.) are normalized on the basis of global warming potential (CO₂ – equivalents, CO₂eq) using either the IPCC GWP 100-year average (Ecoinvent data) or other means (see Table 6) and aggregated to estimate the overall impact of a product or process.

Table 6: Environmental impact factors and major assumptions

Item	Data	Comment
GHG emissions factor for fuels	27.37 lb CO ₂ eq / gal diesel, 24.75 lb CO ₂ eq / gal gasoline	(Skone 2008), combining data on emissions per MJ of fuel, energy content of fuels, density of fuels
Energy demand of fuels	153.5 MJ/gal , used for diesel and for gasoline	(Klvac 2003), cited in previous COEE reports, roughly 10% due to production of fuels
GHG Emissions factor for oils, lubricants	4.22 kg CO ₂ eq / kg material	1.05 kg GHG emissions from production (Ecoinvent) (Frischknecht 2005) + estimate for mineralization to CO ₂
Energy demand of oils, lubricants	219 MJ/gal	(Klvac 2003) values for synthetic oil
Emissions factor of grease	0	Assumed to be fairly recalcitrant, not combusted
Energy demand of Grease	35 MJ/lb	Ecoinvent factor for lubricating oil production
Emissions factors of harvesting / forwarding machine fabrication and repair	0.86 lb CO ₂ eq / Green ton, for each large machine involved	(Athanadiassis 2002) calculations based on Swedish forwarder, 41,873 kg CO ₂ eq per original machine, plus 50% extra for lifetime of repairs and maintenance, normalized to lifetime production
Energy demand for machine fabrication and repair	9.3 MJ/ Green ton, for full processor / feller/bunchers 7.4 MJ / Green ton for forwarders/skidders	(Athanadiassis 2002) calculations based on Swedish forwarder 66 MJ/kg for original machine, assumed 15,000 kg for harvesters and 12,000 kg for forwarders/skidders, plus 50% extra for lifetime of repairs and maintenance, normalized to assumed lifetime production
Emissions for log truck production, maintenance	55,400 kg CO ₂ eq	Ecoinvent for 40-t lorry production, maintenance
Energy demand for log truck production, maintenance	1,308,350 MJ	Ecoinvent for 40-t lorry production, maintenance
Emissions for rail equipment production, maintenance	2,537,000 kg CO ₂ eq	Ecoinvent for long-distance train production, maintenance
Energy demand for rail equipment production, maintenance	54,368,890 MJ	Ecoinvent for long-distance train production, maintenance

3.0 Results and Discussion

Combining the life cycle inventory with the environmental impacts listed above and normalizing the data to the basis of one green ton, we arrive at greenhouse gas emissions and fossil energy demand per green ton of forest biomass for harvesting and transportation stages within the state of Michigan. Due to the different units commonly employed in the areas of life-cycle assessment and forest products (English vs. metric units, green freshly cut wood vs. dry biomass), we shall present the main results using a variety of unit configurations. For conversions between green recently harvested timber and dry biomass, a moisture content of 50% was assumed in all cases. Due to the conversions between lb vs. kg and US short tons vs. metric tonnes, it appears that our unit conversions scale the data up or down by factors of 2 for the GHG emissions results.

Harvesting activity is the most complication part of this analysis (Table 7) due to the many possible levels of data aggregation. Chainsaw harvesting does not rate as the option with the lowest environmental footprint despite the low relative material requirements, due to the low efficiency of production compared to other harvesting scenarios. Within the full processor and feller-buncher harvesting scenarios, overall environmental impacts fall drastically as harvest intensity is increased from 30% to clearcutting, due to the increase in productivity in cords per hour. We only have one estimate of fuel use for each piece of harvest equipment, which we are then using as input data for several different harvesting scenarios with different productivities, which might not capture the variation in fuel use between the different harvest scenarios. This was a potential drawback of our survey method, but in any analysis there are tradeoffs between complexity and broad utility. Environmental impacts from fabrication and maintenance of equipment represents between 2-10% of overall greenhouse gas emissions and 3-15% of fossil energy demand, a small but non-trivial component of the environmental burdens for this life cycle stage.

Table 7: Environmental impacts of harvesting / forwarding at different levels of data aggregation

	Greenhouse gas emissions			Fossil Energy Demand		
	<u>lb CO₂ eq</u> green ton ^a	<u>kg CO₂ eq</u> green tonne ^b	<u>kg CO₂ eq</u> dry tonne	<u>MJ</u> green ton	<u>MJ</u> green tonne	<u>MJ</u> dry tonne
A: Full Processor / Forwarder						
30% Cut (Selective)	29.4	14.7	29.4	178.9	197.2	394.4
70% Cut (shelterwood)	24.6	12.3	24.6	150.5	165.9	331.7
Clearcutting	19.8	9.9	19.8	122.7	135.2	270.4
B: Feller-buncher / Skidder / Slasher						
30% Cut (Selective)	52.6	26.3	52.6	305.7	337.0	674.0
70% Cut (shelterwood)	38.3	19.1	38.3	225.1	248.1	496.3
Clearcutting	27.2	13.6	27.2	162.4	179.0	358.0
C: Chainsaws / Skidder						
30% Cut (Selective)	48.6	24.3	48.6	276.0	304.2	608.5
70% Cut (shelterwood)	46.6	23.3	46.6	264.8	291.9	583.7
Clearcutting	44.0	22.0	44.0	250.0	275.5	551.1
All 30% selective cut harvesting	41.8	20.9	41.8	245.7	270.8	541.6
All 70% shelterwood cut harvesting	32.5	16.3	32.5	193.5	213.3	426.6
All Clearcut harvesting	20.6	10.3	20.6	126.6	139.6	279.2
All harvesting activity	35.7	17.8	35.7	211.4	233.1	466.1

a – ‘ton’ refers to U.S. short ton

b – ‘tonne’ refers to metric tonne

Transportation of bioenergy feedstocks is potentially the largest source of environmental impacts in the entire supply chain (e.g. Sonne 2006), and this stage of the supply chain deserves as much scrutiny in regards to potential optimization as other life cycle stages. The small environmental metrics displayed here (Table 8) are normalized on the basis of a ton-mile as opposed to a ton, so multiplication of these values by an actual transport distance will yield an environmental burden with the same functional unit as the harvesting life cycle stage. For instance, if biomass is to be transported by truck 100 miles, the greenhouse gas emissions for one-way transport become $0.313 \text{ lb CO}_2 \text{ eq /ton-mile} \times 100 \text{ miles} = 31.3 \text{ lb CO}_2 \text{ eq /ton feedstock}$, which is comparable to estimates of the harvesting stage. If no backhauls are possible from the end-use facility, which is often the case in roundwood truck transport, then the impacts of the truck return trip must also be allocated to the feedstock, doubling the impact of the transport stage. A range of possible environmental burdens for sample truck trips is presented below in Table 9, indicating that transportation can easily be the most significant stage of the biomass supply chain if backhaul opportunities are limited and transport distance is increased. Multimodal transportation, combining a short truck movement combined with a longer rail transport step, has the ability to move forest products with an environmental burden similar to truck movements on a much smaller supply radius, as the example in Table 9 shows. As expected, environmental burdens from the equipment fabrication and maintenance considered in both truck and rail cases

represents a small component of the overall environmental footprint. Other transportation infrastructure could be considered, such as roads or rail lines, but normalization of this specific use among the lifetime of potential use experienced by that transportation infrastructure would inevitably make the impacts small enough to be disregarded in this type of analysis. Not shown in Tables 8 or 9 below is the environmental impact of the loading/unloading steps in the forest feedstock supply chain, which amount to 3.1 kg CO₂ eq /green tonne and 17.3 MJ / green tonne for greenhouse gas emissions and fossil energy demand, respectively.

Table 8: Environmental impacts of forest biomass transport

Item	Greenhouse gas emissions			Fossil Energy Demand		
	<u>lb CO₂ eq</u> ton - mile	<u>kg CO₂ eq</u> tonne - km	<u>kg CO₂ eq</u> dry tonne - km	<u>MJ</u> ton - mile	<u>MJ</u> tonne-km	<u>MJ</u> dry tonne-km
Log truck operations and equipment	0.313	0.097	0.194	1.79	1.23	2.46
Percentage due to equipment		2.3%			4.4%	
Rail operations and equipment	0.069	0.022	0.043	0.39	0.27	0.53
Percentage due to equipment		0.2%			0.3%	

Table 9: Potential environmental burdens associated with different trucking distances

One-way trip distance ^a	50 km 31 miles	100 km^b 62 miles (baseline)	150 km 93 miles	200 km 124 miles	20 km truck + 150 km rail (multimodal)
GHG emissions (kg CO ₂ eq / green tonne)	9.7	19.4	29.2	38.9	10.4
Fossil energy demand (MJ / green tonne)	122.8	245.7	368.5	491.3	129.2

a – environmental burdens calculated on the basis of round-trip impacts, assuming no backhauls

b – 100 km is assumed baseline scenario for additional comparisons

Environmental burdens for supplying forest-based biomass within the state of Michigan calculated in this work can be compared to similar estimates made in the literature, although the comparisons are not often perfect due to different assumptions and scenario boundaries among studies. Below in Table 10 is a comparison of our work with a few published results collected early in the project, before our results were tabulated with data from Michigan loggers. Our results for the state of Michigan are in reasonable agreement with the three studies considering harvesting and transport of forest-based biomass grown in natural stands, from Europe and different regions in the United States. It was unclear from Sonne 2006 what transport distance was used to calculate emissions for this stage of the supply chain, but their GHG emissions value is roughly twice as large as our baseline assumption considering a 200 km roundtrip distance. Johnson et al. (2005) consider a transport distance in line with our own assumption, but harvesting systems for the US Southeast and Pacific Northwest appear to be more energy

intensive than our Michigan logger survey data and default assumptions indicate – although if we were to assume a combination of feller-buncher and chainsaw harvesting, our harvesting impacts could be much higher.

Table 10: Comparison of MI environmental burdens to forest biomass supply in other studies

Source	GHG Emissions kg CO ₂ eq / tonne ^a	Fossil Energy Demand MJ / tonne	Comments
Sonne 2006	17.4 Harvesting 38.2 Transport 55.6 Total	--	Pacific NW, 2.9 Mg CO ₂ eq / 300 m ³ timber and 5.5 Mg CO ₂ eq / 300 m ³ timber for mechanized harvest and transport, respectively, Douglass fir density 0.48 g/cm ³ (Seely)
Johnson 2005	~ 50–58 Total	~ 615–715 Total	used for all density assumptions needed in subsequent comparisons Table 4b, harvesting and hauling fuel use, lubricant data for US Southeast and Pacific NW, 90-120 km one-way transport, CORRIM group
Klvac 2003	--	214 – 250 Harvesting Only	Estimates from Sweden and Ireland
Keoleian 2005	5.9 Harvesting Only	157.1 Harvesting Only	Willow Plantation, high intensity growth with periodic coppice harvest every 3 years, very different system
This Study	17.8 Harvest 3.1 Loading 19.4 Transport 40.3 Total	233 Harvest 17.3 Loading 246 Transport 495.3 Total	Assuming aggregated harvest data and baseline transport scenario as discussed above

a – all values in table listed on the basis of green tonnes

4.0 Conclusions

Using a combination of data from the local forest products industry, expert opinion, literature and database sources, we were able to construct a limited-scope life-cycle assessment of the forest biomass supply chain in Michigan. Greenhouse gas emissions and fossil energy demand for wood harvesting were highly dependent on the equipment configuration used and the intensity of the harvest scenario. Transport of forest biomass by truck carries a higher environmental burden per ton-mile than an equivalent distance of rail transport, usually by a factor of 4-5X. Calculated environmental burdens for a default harvest and transport supply chain in MI were within the range of values reported for similar operations in the literature. Loading and unloading of wood accounted for roughly 8% of overall GHG emissions and 3.5% of fossil energy demand, while remaining environmental burdens were divided relatively equally between harvest and transport steps. We hope that a detailed summary of our approach to arriving at these values will allow policy makers, business developers, and other stakeholders in the forest biomass industry to utilize these values with some degree of confidence when considering the environmental burdens of the forest biomass supply chain for planned biofuels and bioenergy facilities, or highlight areas where more location-specific data would improve the accuracy of a particular assessment.

5.0 Acknowledgements

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Sub-Task C1: Genetic Improvement of Planting Stock

Reported by: Daniel Keathley

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Final Report

(March 2009 through June, 2011)

Task Summary

Successful wood energy crop production systems will rely on planting stock that is genetically superior with respect to adaptability and growth. The only way to identify superior planting stock is to establish numerous genotypes on a range of sites and observe their performance over time. Five clonal trials of new hybrid poplar (*Populus* spp.) varieties (produced for the Lake States Region at the University of Minnesota's Natural Resources Research Institute) were established and two half-sib progeny tests of Silver maple (*Acer saccharinum*) were established under this task (Figure C1.1). This task ends with the establishment of these tests but future measurement and analysis of these plantings will help to identify improved stock for future plantings of these two taxa.

Funding for the work described here was shared among several funding sources including: (1) US Department of Energy award DE-EE-0000280, (2) the Frontier Renewable Resources Center of Energy Excellence award from the State of Michigan, (3) the US Department of Energy Regional Biomass Feedstock Partnership programs for both willow and poplar, and (4) Michigan State University AgBioResearch.

Hybrid Poplar Clonal Trials:

Three poplar clonal trial plantations were established in 2009 using materials newly developed by the University of Minnesota's Natural Resources Research Institute (NRRI) breeding program (Table C1.1). Plantations were composed of 70 clones of hybrid poplars arranged in one-tree plots with 6 blocks per site. The test in Escanaba was established on 6/3/2009, in Skandia on 6/19/2009, and in Brimley on 6/24/2009. Note that Table C1.1 contains a summary of clones included in a companion planting made in 2008 at the Escanaba site. This planting predates this task but will provide additional information about NRRI clonal performance in Michigan.

All three of the above plantations were maintained in a relatively weed-free condition during the 2009 growing season. Heights and survival were measured, recorded, and summarized at the end of the second growing season in these three plantings. Weed control was difficult due to the climate in summer 2010, which was highly conducive to weed growth. A mid-summer drought also impacted growth of the plantations, especially poplar at Brimley. An abrupt killing frost in the fall of 2009 also adversely effected the plantations there. Because of these factors, it is not clear that any meaningful growth data will be available until after the 2011 growing season.

Two additional 70-clone poplar clonal trial plantations were established as described above in the spring of 2010 to expand the network to a total of five locations (Table C2.1). The test in Lake City was established on 5/23/2010 and near Onaway on 5/22/2010. Maintenance of the plantations continues. Height and survival were measured at the end of the first growing season in these two trials.

Hybrid poplar trials at Escanaba, Skandia, Brimley, Onaway, and Lake City were measured by personnel from the Michigan Forest Biomass Innovation Center for height and survival and monitored for

melapsoara rust, Marssonia leaf spot, septoria leaf spot, and septoria canker. Data files were compiled and distributed to team members for review and analysis. Paul Bloese met with personnel from MFBIC to discuss the data and methods to be used for the analysis and compiled the following summary of results from all five sites. This data is highly preliminary and may only have value as subsequent years' data is collected and compared. All data collected here has been uploaded for inclusion in USDOE's Knowledge Discovery Framework.

Year-2 Results 2009 Plantings

In 2009 a trial of 70 hybrid poplar clones provided by the University of Minnesota was established at three sites in Michigan's Upper Peninsula: Escanaba, Skandia, and Brimley. In fall 2010 height and survival were measured in all three plantings. Measurements collected this early in the rotation have little or no immediate practical application, but may prove useful when re-analyzed with measurements collected throughout the rotation.

Site means for height and survival are given in Table C1.2. Site effects were significant ($\alpha \leq .01$) for both survival (Kruskal-Wallis test) and height (ANOVA).

Table C1.2. Site means for survival and height in a poplar clone trial after 2 years of growth at three Michigan sites.

Site	Year-2	
	Survival (%)	Height (cm)
Escanaba	0.97	282
Skandia	0.90	119
Brimley	0.85	45

The percent of the total variation in height accounted for by each of the modeled effects is given in Table C1.3. After 2 years of field growth site effects dwarfed all other effects in the model for height. Clone effects for height were significant, however clone performance varied widely from site to site. Clone x site effects were more than twice the magnitude of clone effects, and no clones were in the top 10% of the test population at all three sites. After two years of growth clone performance tends to be site specific.

Table C1.3. Percent of total variation in 2-year height attributable to modeled effects in a hybrid poplar clone trial (all effects significant at $\alpha \leq .01$).

Effect	DF	% of Total Variation
Site	2	87.4
Rep(site)	15	0.7
Clone	68	0.8
Clone * Site	136	1.8
Error	905	9.2

Year 1 Results 2010 Plantings

In spring 2010, a trial of 69 hybrid poplar clones provided by NRRI was established at two northern Michigan sites: Onaway and Lake City. Of these 69 clones, 30 are common to both the 2009 and 2010 plantations. Survival was tallied in both plantations in fall 2010. First year survival was 67% at Onaway and 60% at Lake City. Height was measured in fall 2010 and will be incorporated in future analyses.

Silver Maple Half-sib Progeny Testing

Acer saccharinum seed was collected in the spring of 2010 from twenty-two seed sources throughout the northeastern US and Ontario. These seeds were sown and grown in the tree nursery at Michigan State University's Tree Research Center located on Jolly Road in East Lansing, Michigan. Germination and growth were excellent, with successful establishment of planting stock from trees from Michigan, New York, Pennsylvania, Vermont, New Hampshire, Massachusetts, Connecticut, and Ontario. (Figure C1.2) Seedling growth in the nursery was outstanding. Two planting sites were prepared during the fall of 2010. One at the MSU's Dunbar Forest (approximately 10 miles east of the "Brimley" site) and the other on MSU's main campus in East Lansing. Seedlings were lifted from the nursery, prepared, and placed in cold storage in March of 2011. Seedlings were field planted at both sites in May of 2011 using randomized block designs with 5 blocks and 4-tree row plots of 32 seedlots. They are presently growing well (Figure C1.3).

Figure C1.1. Network of genetic testing sites in Michigan

Figure C1.2. Silver Maple seedlings growing in nursery beds.

Figure C1.3. Silver maple seedlings at Dunbar Forest in Michigan's Upper Peninsula, 2 months after planting.

Table C1.1. Poplar clones from NRRI included in Michigan trials.

CloneID	Latin Name	Escanaba08	Escanaba09	Skandia09	Brimley09	Onaway10	Lake City10
22090013	(Populus trichocarpa x deltoides) x deltoids					X	X
22090032	(Populus trichocarpa x deltoides) x deltoids	X					
22091021	(Populus trichocarpa x deltoides) x deltoids	X					
22091022	(Populus trichocarpa x deltoides) x deltoids	X				X	X
23054 30001	NRRI2009		X	X	X		
N944-4	NRRI2009		X	X	X		
21400	NRRI2010					X	X
6300	Populus X euramericana	X					
21700	Populus X euramericana	X	X	X	X	X	X
22700	Populus X euramericana	X	X	X	X		
23300	Populus X euramericana	X	X	X	X	X	X
24400	Populus X euramericana	X					
31500	Populus X euramericana	X					
34400	Populus X euramericana		X	X	X		
41700	Populus X euramericana	X				X	X
22021008	Populus X euramericana	X				X	X
22021009	Populus X euramericana	X				X	X
22021018	Populus X euramericana	X				X	X
22021021	Populus X euramericana					X	X
22021048	Populus X euramericana	X				X	X
22021051	Populus X euramericana	X				X	X
22033013	Populus X euramericana					X	X
22033018	Populus X euramericana		X	X	X	X	X
22057002	Populus X euramericana	X				X	X
22057006	Populus X euramericana	X				X	X
22057011	Populus X euramericana					X	X
22057030	Populus X euramericana	X					
22057032	Populus X euramericana	X					
22057033	Populus X euramericana		X	X	X		
22057059	Populus X euramericana					X	X
22069011	Populus X euramericana	X					
99001111	Populus X euramericana	X	X	X	X	X	X
99007071	Populus X euramericana	X				X	X
99007087	Populus X euramericana		X	X	X		
99007108	Populus X euramericana	X	X	X	X	X	X
99007115	Populus X euramericana	X	X	X	X	X	X
99007116	Populus X euramericana	X				X	X
99008002	Populus X euramericana	X				X	X
99008070	Populus X euramericana	X	X	X	X	X	X
99008080	Populus X euramericana	X	X	X	X		
99008081	Populus X euramericana					X	X
99008098	Populus X euramericana					X	X
99022069	Populus X euramericana		X	X	X		
99037017	Populus X euramericana		X	X	X	X	X
99037039	Populus X euramericana	X					

99037044	Populus X euramericana	X					
99037046	Populus X euramericana		X	X	X	X	X
99037049	Populus X euramericana	X	X	X	X	X	X
99037051	Populus X euramericana		X	X	X	X	X
99037053	Populus X euramericana	X					
99038002	Populus X euramericana		X	X	X	X	X
99038003	Populus X euramericana	X				X	X
99038005	Populus X euramericana	X					
99038007	Populus X euramericana					X	X
99038012	Populus X euramericana	X					
99038013	Populus X euramericana	X	X	X	X	X	X
99038022	Populus X euramericana	X	X	X	X	X	X
99038036	Populus X euramericana	X	X	X	X	X	X
99059016	Populus X euramericana	X	X	X	X	X	X
99059019	Populus X euramericana	X				X	X
99059043	Populus X euramericana	X	X	X	X	X	X
99059066	Populus X euramericana		X	X	X		
99098008	Populus X euramericana	X					
99105008	Populus X euramericana	X				X	X
99105088	Populus X euramericana	X				X	X
23057 32006	Populus X euramericana		X	X	X	X	X
23059 32018	Populus X euramericana		X	X	X	X	X
23071 33040	Populus X euramericana		X	X	X		
23071 33042	Populus X euramericana		X	X	X	X	X
23071 33057	Populus X euramericana		X	X	X		
23074 01609	Populus X euramericana		X	X	X		
23074 16002	Populus X euramericana		X	X	X		
23074 16008	Populus X euramericana		X	X	X		
23074 16037	Populus X euramericana		X	X	X		
23074 37038	Populus X euramericana		X	X	X		
23079 17041	Populus X euramericana		X	X	X	X	X
23079 17047	Populus X euramericana		X	X	X	X	X
23079 17069	Populus X euramericana		X	X	X	X	X
9732-07	Populus X euramericana					X	X
9732-11	Populus X euramericana	X				X	X
9732-18	Populus X euramericana					X	X
9732-19	Populus X euramericana	X				X	X
9732-24	Populus X euramericana	X				X	X
9732-31	Populus X euramericana	X				X	X
9732-32	Populus X euramericana					X	X
9732-36	Populus X euramericana					X	X
9732-40	Populus X euramericana					X	X
9732-48	Populus X euramericana					X	X
DN164	Populus X euramericana	X					
DN2	Populus X euramericana	X					
DN5	Populus X euramericana					X	X
252-4	Populus deltoids					X	X
D113	Populus deltoids					X	X

D124	Populus deltoides					X	X
22066086	Populus deltoides x (Populus trichocarpa x deltoides)	X					
22066094	Populus deltoides x (Populus trichocarpa x deltoides)	X					
23060 26041	Populus deltoides x (Populus trichocarpa x deltoides)		X	X	X		
23060 26063	Populus deltoides x (Populus trichocarpa x deltoides)		X	X	X		
23070 02099	Populus deltoides x (Populus trichocarpa x deltoides)		X	X	X	X	X
23070 27001	Populus deltoides x (Populus trichocarpa x deltoides)		X	X	X	X	X
23070 27023	Populus deltoides x (Populus trichocarpa x deltoides)		X	X	X		
23070 27061	Populus deltoides x (Populus trichocarpa x deltoides)		X	X	X		
23070 33014	Populus deltoides x (Populus trichocarpa x deltoides)		X	X	X	X	X
23070 33024	Populus deltoides x (Populus trichocarpa x deltoides)		X	X	X		
23076 01391	Populus deltoides x (Populus trichocarpa x deltoides)		X	X	X		
23076 01395	Populus deltoides x (Populus trichocarpa x deltoides)		X	X	X		
23076 18011	Populus deltoides x (Populus trichocarpa x deltoides)		X	X	X		
23076 18019	Populus deltoides x (Populus trichocarpa x deltoides)		X	X	X		
23076 20012	Populus deltoides x (Populus trichocarpa x deltoides)		X	X	X		
23076 20056	Populus deltoides x (Populus trichocarpa x deltoides)		X	X	X		
23076 21006	Populus deltoides x (Populus trichocarpa x deltoides)		X	X	X	X	X
5912917	Populus deltoides x deltoids					X	X
502.37	Populus deltoides X maximowiczii	X					
22007002	Populus deltoides X maximowiczii		X	X	X		
99002003	Populus deltoides X maximowiczii		X	X	X		
99002017	Populus deltoides X maximowiczii		X	X	X		
99002026	Populus deltoides X maximowiczii		X	X	X		
99002030	Populus deltoides X maximowiczii		X	X	X		
152x11861	Populus deltoides X maximowiczii	X					
NC14106	Populus deltoides X maximowiczii	X					
NM6	Populus nigra X maximowiczii	X					
22090013	Populus trichocarpa x deltoids		X	X	X		
52124074	Populus trichocarpa x deltoids		X	X	X		
52124105	Populus trichocarpa x deltoids		X	X	X		
52124144	Populus trichocarpa x deltoids		X	X	X		
52124230	Populus trichocarpa x deltoids		X	X	X		
23001 03057	Populus trichocarpa x deltoids		X	X	X	X	X
23001 03071	Populus trichocarpa x deltoids		X	X	X	X	X
23001 04014	Populus trichocarpa x deltoids		X	X	X		
23010 11022	Populus trichocarpa x deltoids		X	X	X		
23010 11024	Populus trichocarpa x deltoids		X	X	X		
23014 11066	Populus trichocarpa x deltoids		X	X	X		
TOTAL NUMBER OF CLONES per SITE		56	70	70	70	69	69

Sub-Task C2: Determine Yield of Poplar and Willow Clones

Reported by: David MacFarlane

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Final Report

(March 2009 through June, 2011)

Summary

Energy plantation yield relies heavily on the management system used and on the interaction between planting stock and planting site. Management system effects were investigated under task C3 while this task concentrated on defining yield variation among willow and poplar clones and among sites within Michigan. Taxa performance varies widely from place to place and so testing numerous clones of both poplar and willow over a range of site conditions is required to accurately predict yield. This task was divided into three sub-sections: (1) A yield trial of four poplar clones, established in 1998 in Escanaba, MI was harvested in 2009 to obtain yield information for these clones in this location; (2) A yield trial of 12 willow clones and 2 poplar clones, established in 2002 in Escanaba, MI was harvested in 2010 to obtain yield information for these clones at this location; and (3) A network of new poplar and willow yield trials was established at five sites in Michigan to eventually produce yield information for newer clones over a wider geographic region. Each sub-section is summarized below.

Funding for the work described here was shared among several funding sources including: (1) US Department of Energy award DE-EE-0000280, (2) the Frontier Renewable Resources Center of Energy Excellence award from the State of Michigan, (3) the US Department of Energy Regional Biomass Feedstock Partnership programs for both willow and poplar, and (4) Michigan State University AgBioResearch.

Poplar Yield in Escanaba, MI

In the first quarter, yield data from 1998 hybrid poplar test plantations in Escanaba were analyzed and yield curves were constructed, based on data obtained when the plots were destructively sampled. Plantations were harvested after the eleventh growing season (2009). Single-tree and whole-plot allometric biomass yield equations were developed for poplar taxa. These yield curves were adjusted for differences in planting density and the best growing clones were identified. The top performing clones were essentially the same as those identified in a Canadian study by Labrecque and Teodorescu (2005); NM6 was the top performer. A preliminary technical report was written to allow these results to be utilized by other researchers in this study (and ecologist, David Rothstein and an economist, Runsheng Yin, and a climate scientist, David Young). These results were presented at an international conference in Italy and a manuscript is currently under preparation based on these results.

Willow Yield in Escanaba, MI

Yield data from the first six years of a 2002 hybrid willow test plantation in Escanaba were analyzed. Under these trials, growing stock was coppiced in 2003 and harvested in 2004 and 2007. There were also poplar 'check' trials which were included to see how coppiced poplar compared to willow yield. As with poplar (above), taxa had a significant effect on growth and yield of hybrid willow, also confirming some of the results of Labrecque and Teodorescu (2005) in their trials for willow. The top five performing willow clone was SX61. The two poplar clones (NM5 and NM6) were the top biomass producers and were at least 30% percent more productive than willows.

In the fall of 2010, data from three additional years of growth were collected and analyzed. This was the third harvest cycle since initial planting and coppicing, so the cumulative effect of harvesting and re-growth from established root stools could be examined. Coppiced hybrid poplar clones continued to be among the best yielding taxa. However, the high yield rates of poplar remained relatively constant over three harvests, whereas most willow yield rates increased between the second and third harvests, except for lower-yielding clones, which already appear to be leveling off in growth rate. Adjusting for other effects, the recent increase in yield may come from an increase in the size and vigor of the willow root stools following the first two harvests. Since willow yields were initially lower but increasing, and poplar yields initially higher but relatively constant, willow yields rose toward highly productive poplar clone yields over multiple harvests. Combining results from both the poplar and willow trials, coppicing helped poplars to gain a stable and high biomass production early after planting, while most willow clones showed a generally constant increase in yield after successive coppicing indicating that stools are getting more vigorous after successive harvests. The study was not long enough to determine at what point that higher yielding willow clones would level off in mean annual yield growth rate.

Weather station data and mortality data from the willow yield trials were used to enhance analyses of the coppiced willow and coppiced poplar yield trial data to compare growth in Escanaba to growth of the same clones at two other locations in MI, the Tree Research Center and the Muck Farm. Yield analyses were adjusted for differences in initial planting density, climatic conditions, feedstock moisture content and mortality. The relative ranking of the biomass yield of various clones did not change much after adjustment, but differences in yield between some clones were either amplified or muted by climatic differences (principally represented by growing degree days). Results suggest that it is necessary to adjust for climatic differences to correctly assess between-clone differences in yield. Coppiced high-yield poplar check clones (NM5 and NM6) outperformed willow clones under most conditions, except at the MSU Tree Research Center site, where initially higher planting densities and intensive management (continued irrigation, fertilization and weeding) were employed. Hence, management practices acted as a leveling factor to offset genetic and climatic differences in biomass yield. A manuscript is currently under preparation based on these results.

Conclusions

Willow and poplar taxa selected as superior in previous biomass yield trials in Quebec and New York appear to perform similarly in Michigan. Poplar clones NM6 and NM 5 were the best-performing clones in all of the trials and coppicing appeared to allow for higher poplar yields to be achieved sooner, relative to non-coppiced poplar clones of the same type at the same location. The best performing willow clones were SX61, SX67 and PUR12; SX64 performed about as well as PUR12, but PUR12 was not tested at the Escanaba site. Willow yield rates increased over multiple harvests, apparently due to increased vigor of stools after establishment, adjusting for other factors, with the best performing willow clones approaching yields of the initially higher-yielding poplar clones. Growing stock taxa, initial planting density, and management appear to be the most important factors in willow and poplar biomass yield, but climatic and survival rate differences were also apparent. While differences in climate and mortality were directly related to the differences in willow and poplar yield, the main effect of climate appeared to be either enhancing or muting differences in growth and yield between taxa, except where intensive management was employed to compensate for natural limitations on growth and survival rates.

Poplar and Willow Yield Trial Network in Michigan

A network of yield trials for both hybrid poplar and willow was established under this task (Figure C2.1). The network now includes six sites in Michigan (Escanaba, Skandia, Brimley, Onaway, Lake City, and Albion). These sites span the range of site conditions on which energy plantation may be established in

the state. Yield trials were established over several years in order to distribute the work load of planting, maintenance, and data collection. Table C2.1 provides a summary of the schedule set for each trial.

Clones included in the trials were anticipated to be among the best available at the time, with respect to growth and pest resistance. Poplar clones were selected based on previous testing done in the Lake States Region and collected from a range of sources. Since most of these clones were not commercially available, cutting production nursery beds were established in East Lansing, MI at Michigan State University's Tree Research Center in order to produce the quantity of cuttings needed for the trials. Willow clones were obtained from the established breeding program at the State University of New York, College of Environmental Science and Forestry at Syracuse.

The poplar yield trials at each site contain at least 10 clones of poplar (Table C2.2) and are planted 64-tree plots arranged in a randomized block design with five blocks. Each plot has 8 rows separated by 8' with 8 trees in each row separated by 7' (Figure C2.2). The inner 16 trees of each plot are measured, leaving a two-row border around the measurement plot. The willow yield trials at each site contain at least 20 clones (Table C2.3) and are planted in 72-tree plots arranged in a randomized block design with four blocks. Plots employ the European double-row design depicted in Figure C2.3. The inner 18 trees of each plot are measured, leaving a two-row border around the measurement plot.

The main benefit of this unique piece of research infrastructure will accrue over the next few years as real yield data from scheduled harvests and clonal adaptability continues to be collected and analyzed.

Table C1.1. Timeline for willow and poplar yield trials in Michigan									
	SITE	2008	2009	2010	2011	2012	2013	2014	2015
Willow Yield Trials	Escanaba	plant			harvest			harvest	
	Skandia		plant			harvest			harvest
	Brimley		plant			harvest			harvest
	Onaway			plant			harvest		
	Lake City			plant			harvest		
	Albion				plant			harvest	
Poplar Yield Trials	Escanaba		plant					harvest	plant
	Skandia		plant					harvest	plant
	Brimley		plant					harvest	plant
	Onaway			plant					harvest
	Lake City			plant					harvest
	Albion				plant				

Publications & Presentations:

Miller, R.O., D.W. MacFarlane, D.E. Rothstein, and Z. Wang. 2010. Energy crop plantation system development for Salix and Populus in Michigan, USA. IN: Poplars and willows: from research models to multipurpose trees for a bio-based society. Proceedings of the Fifth International Poplar Symposium, Orvieto, Italy, September 20-25, 2010. [Appendix C2(a) - Poster]

Wang, Z. and D. MacFarlane (In Review). Evaluating the biomass production of coppiced willow and poplar clones in Michigan, USA, over multiple rotations and different growing conditions. Submitted to Biomass and Bioenergy, 2011.

Table C2.2. Poplar clones included in Michigan yield trials.							
CloneID	Latin Name	Escanaba	Skandia	Brimley	Onaway	Lake City	Albion
DN154	Populus X euramericana	X			X	X	X
DN164	Populus X euramericana	X			X	X	X
DN17	Populus X euramericana	X	X	X			X
DN170	Populus X euramericana				X	X	X
DN177	Populus X euramericana				X	X	X
DN182	Populus X euramericana	X	X	X	X		X
DN2	Populus X euramericana	X	X	X	X		X
DN34	Populus X euramericana	X	X	X	X	X	X
DN5	Populus X euramericana	X	X	X	X	X	X
DN70	Populus X euramericana	X	X	X	X	X	X
I4551	Populus X euramericana	X	X	X	X		X
NE222	Populus X euramericana	X	X	X	X	X	X
83XAA04	Populus alba						X
DM114	Populus deltoides X maximowiczii	X			X		X
NM2	Populus nigra X maximowiczii	X	X		X		X
NM5	Populus nigra X maximowiczii	X	X	X	X	X	
NM6	Populus nigra X maximowiczii	X	X	X	X	X	X
TOTAL NUMBER OF CLONES per SITE		14	11	10	15	10	16

Table C2.3. Willow clones included in Michigan yield trials.							
CloneID	Latin Name	Escanaba	Skandia	Brimley	Onaway	Lake City	Albion
SV1	Salix dasyclados	X	X	X	X	X	X
00X-032-094	Salix eriocephala	X					
9837-77	Salix eriocephala						X
S25	Salix eriocephala x eriocephala	X	X	X	X	X	
SX64	Salix miyabeana	X	X	X	X	X	X
SX67	Salix miyabeana	X					
94001	Salix purpurea					X	
01X-265-020	Salix purpurea						X
94001	Salix purpurea	X	X	X	X		
9882-34	Salix purpurea	X	X	X	X	X	X
9882-41	Salix purpurea	X					X
99113-012	Salix purpurea	X	X	X	X	X	
99239-015	Salix purpurea	X	X	X	X	X	X
9879	Salix purpurea x miyabeana		X	X	X	X	
99217-015	Salix purpurea x miyabeana	X	X	X	X	X	X
99217-023	Salix purpurea x miyabeana	X					
9980-005	Salix purpurea x miyabeana	X	X	X	X	X	X
SX61	Salix sachalinensis	X	X	X	X	X	X
9870-1	Salix sachalinensis x miyabeana	X					X
9870-23	Salix sachalinensis x miyabeana	X	X	X	X	X	X
9871-31	Salix sachalinensis x miyabeana	X	X	X	X	X	X
9970-036	Salix sachalinensis x miyabeana	X	X	X	X	X	X
01X-268-016	Salix viminalis x (S. sachalinensis x S. miyabeana)						X
01X-266-016	Salix viminalis x (S. viminalis x S. miyabeana)						X
99201-002	Salix viminalis x miyabeana	X	X	X	X	X	
99201-007	Salix viminalis x miyabeana	X	X	X	X	X	X
99202-004	Salix viminalis x miyabeana	X	X	X	X	X	X
99202-011	Salix viminalis x miyabeana	X	X	X	X	X	
99202-043	Salix viminalis x miyabeana	X					
99207-018	Salix viminalis x miyabeana	X	X	X	X	X	X
99207-020	Salix viminalis x miyabeana	X	X	X	X	X	X
99208-038	Salix viminalis x miyabeana	X					
TOTAL NUMBER OF CLONES per SITE		26	20	20	20	20	20

Figure 3.
Poplar yield trial plot layout

•	•	•	•	•	•	•	•
•	•	•	•	•	•	•	•
•	•	1	8	9	16	•	•
•	•	2	7	10	15	•	•
•	•	3	6	11	14	•	•
•	•	4	5	12	13	•	•
•	•	•	•	•	•	•	•
•	•	•	•	•	•	•	•

8' between rows
7' between trees within

Figure C2.2 Poplar yield trial
plot layout.

Willow yield trial plot layout

•	•		•	•		•	•
•	•		•	•		•	•
•	•						
•	•		1	18		•	•
•	•		2	17		•	•
•	•		3	16		•	•
•	•		4	15		•	•
•	•		5	14		•	•
•	•		6	13		•	•
•	•		7	12		•	•
•	•		8	11		•	•
•	•		9	10		•	•
•	•		•	•		•	•
•	•		•	•		•	•

2.5' between narrow rows
5' between wide rows
2' between trees within rows
Only interior 18 stools are measured
Tree number scheme is shown on above

Figure C2.3. Willow yield trial plot
layout.

Figure C2.4. Escanaba Yield Trial Tests in the fall of 2010.

Appendix

C2(a) – Abstract & Poster

Miller, R.O., D.W. MacFarlane, D.E. Rothstein, and Z. Wang. 2010. Energy crop plantation system development for *Salix* and *Populus* in Michigan, USA. IN: *Poplars and willows: from research models to multipurpose trees for a bio-based society*. Proceedings of the Fifth International Poplar Symposium, Orvieto, Italy, September 20-25, 2010.

Abstract

Woody biomass is potentially the key renewable feedstock for power, heat, and fuel production in the Northeast and Lake States region of the United States. Abundant natural forests and retired agricultural fields offer great potential for the production of these feedstocks which will, in turn, reduce the region's dependence on imported fossil fuels and support rural community development. Demand for biomass from industry in the region continues to grow and landowners increasingly seek advice about sustainable production systems. Michigan State University has built governmental, industrial, and university partnerships throughout the area and across the world and has taken the lead in improving woody biomass production systems and streamlining the feedstock supply chain for Michigan. Woody crop plantations are not yet used extensively in Michigan but offer the greatest potential for socially, environmentally, and economically sustainable production of biomass for energy. Current research centers on plantation management and sustainability improvements within these systems. A network of five sites throughout the state has been established on which clonal and yield trials, spacing trials, herbicide trials, and measurements of greenhouse gas fluxes are proceeding on taxa from the genera *Salix* and *Populus*. While still in the early stages, preliminary results are presented here that suggest that commercially viable biomass plantations of carefully selected taxa in Northern Michigan will be up to eight times as productive as native forests. The best performing clone (NM-6) averaged 8 dry Mg·ha⁻¹·yr⁻¹ after eleven growing seasons in our tests. Future work is examining yield variability across sites and new clones. In other initial studies we found that conversion of wet, high soil organic matter pasture to bioenergy plantations using conventional tillage regimes resulted in up to a 25-fold increase in soil N₂O flux. Soil CO₂ efflux measurements indicate substantial soil C loss as well, although estimates are complicated by difficulties accounting for autotrophic respiration. These results indicate that, under certain site conditions, pastureland conversion to poplar or willow can incur a significant greenhouse gas debt. Future work is focused on using site selection and novel methods of plantation establishment to reduce these impacts.

Keywords: populus, salix, biomass plantations, sustainability, yield

Energy Crop Plantation System Development for *Salix* and *Populus* in Michigan, USA

R.O. Miller; D.W. MacFarlane; D.E. Rothstein; Z. Wang; Department of Forestry, Michigan State University, USA

General Summary

Woody crop energy plantations are not yet used extensively in Michigan but offer great potential for socially, environmentally, and economically sustainable production of biomass. Interest in establishing commercial-scale energy plantations of these taxa is increasing. Michigan State University, together with collaborators from Minnesota, Wisconsin, and New York, has been testing and perfecting production systems for these crops for the last 40 years. Current research is concentrating on improving plantation silviculture and sustainability within these systems. A network of six sites has recently been established throughout the state to test *Salix* and *Populus* relative clonal performance, clonal yield, spacing effects, herbicide effectiveness and safety, and of greenhouse gas (CHG) fluxes during plantation preparation and between rotations. The breadth of testing is presented here along with results of an early poplar yield trial and of preliminary CHG flux investigations.

Hybrid Poplar Plantation Yield

Methods

5 poplar taxa were planted in 64-tree plots at Michigan State University's Forest Biomass Innovation Center in Escanaba, Michigan in 1998. Regression equations were developed relating individual-tree biomass in year 2008 to tree basal diameter (D_0) and height (H). These individual-tree biomass equations were used to estimate total plot dry & green biomass, accounting for 89% and 94% of the variance in the measured 2008 dry and green plot biomass, respectively. These equations were then used to estimate plot biomass yield using tree measurements from earlier years, producing yield curves.

Yield Trial Results

Yield curves for the 5 poplar taxa revealed that NM-6 was the most productive over the first 10 years, reaching maximum MAI most quickly. NE-222 has the potential to replace NM-6 as the most productive over a rotation of 14 or more years. Wood density variation was examined using ANOVA and no difference among taxa was found. This suggests that poplar biomass yield is primarily a function of volume yield.

Tree Biomass Equation Results

Analyses demonstrated that equations using proxy volume ($D_0^2 \times H$) explained a higher proportion of variance in biomass and had less bias than equations using diameter at breast height (DBH) and Height or DBH only. This suggests stem form is better modeled by including D_0 than by DBH.

Site Name	Established	Taxa	Trial	Owner or Funding Source
Skandia	1998/1999	P. alba, Populus	Populus Trial	USDA/MSU
	1997	Populus	Short Rotation Trial	USDA/MSU/MSU/MSU
	1999	P. alba, Populus	Populus Trial	USDA/MSU
	2001	Populus	Open Plot	USDA/MSU
	2002	Populus	Open Plot	USDA/MSU
	2003	Populus	Open Plot	USDA/MSU
	2004	P. alba, Populus	Populus Trial	USDA/MSU
	2005	Populus	Open Plot	USDA/MSU
	2006	Populus	Open Plot	USDA/MSU
	2007	Populus	Open Plot	USDA/MSU
Brimley	1998/1999	P. alba, Populus	Populus Trial	USDA/MSU
	1997	Populus	Open Plot	USDA/MSU
	1999	P. alba, Populus	Populus Trial	USDA/MSU
	2001	Populus	Open Plot	USDA/MSU
	2002	Populus	Open Plot	USDA/MSU
	2003	Populus	Open Plot	USDA/MSU
	2004	P. alba, Populus	Populus Trial	USDA/MSU
	2005	Populus	Open Plot	USDA/MSU
	2006	Populus	Open Plot	USDA/MSU
	2007	Populus	Open Plot	USDA/MSU
Escanaba	1998/1999	P. alba, Populus	Populus Trial	USDA/MSU
	1997	Populus	Open Plot	USDA/MSU
	1999	P. alba, Populus	Populus Trial	USDA/MSU
	2001	Populus	Open Plot	USDA/MSU
	2002	Populus	Open Plot	USDA/MSU
	2003	Populus	Open Plot	USDA/MSU
	2004	P. alba, Populus	Populus Trial	USDA/MSU
	2005	Populus	Open Plot	USDA/MSU
	2006	Populus	Open Plot	USDA/MSU
	2007	Populus	Open Plot	USDA/MSU
Onaway	1998/1999	P. alba, Populus	Populus Trial	USDA/MSU
	1997	Populus	Open Plot	USDA/MSU
	1999	P. alba, Populus	Populus Trial	USDA/MSU
	2001	Populus	Open Plot	USDA/MSU
	2002	Populus	Open Plot	USDA/MSU
	2003	Populus	Open Plot	USDA/MSU
	2004	P. alba, Populus	Populus Trial	USDA/MSU
	2005	Populus	Open Plot	USDA/MSU
	2006	Populus	Open Plot	USDA/MSU
	2007	Populus	Open Plot	USDA/MSU
Lake City	1998/1999	P. alba, Populus	Populus Trial	USDA/MSU
	1997	Populus	Open Plot	USDA/MSU
	1999	P. alba, Populus	Populus Trial	USDA/MSU
	2001	Populus	Open Plot	USDA/MSU
	2002	Populus	Open Plot	USDA/MSU
	2003	Populus	Open Plot	USDA/MSU
	2004	P. alba, Populus	Populus Trial	USDA/MSU
	2005	Populus	Open Plot	USDA/MSU
	2006	Populus	Open Plot	USDA/MSU
	2007	Populus	Open Plot	USDA/MSU
East Lansing	1998/1999	P. alba, Populus	Populus Trial	USDA/MSU
	1997	Populus	Open Plot	USDA/MSU
	1999	P. alba, Populus	Populus Trial	USDA/MSU
	2001	Populus	Open Plot	USDA/MSU
	2002	Populus	Open Plot	USDA/MSU
	2003	Populus	Open Plot	USDA/MSU
	2004	P. alba, Populus	Populus Trial	USDA/MSU
	2005	Populus	Open Plot	USDA/MSU
	2006	Populus	Open Plot	USDA/MSU
	2007	Populus	Open Plot	USDA/MSU

MICHIGAN STATE UNIVERSITY

Energy Plantation GHG Fluxes

Research Questions

- Do emissions of CHG associated with land conversion undermine the CHG benefits of biofuels production?
- How do site conditions and prior land use affect the CHG balance of SWRC plantations?

Study Sites

Site	Prior Land Use	Drainage	Soil Texture	Soil C (%)	Soil N (%)
Skandia	Pasture	Moderate	Loam	3.25	0.25
Brimley	Pasture	Poor	Silt loam	3.48	0.26
Escanaba	Poplar	Well	Sandy loam	1.80	0.15

Global Warming Potential (N₂O Fluxes Only)

Site	CO ₂ eq. Mg ha ⁻¹ year ⁻¹	
	Untilled	Tilled
Skandia	0.5 ± 0.19	12.3 ± 1.45
Brimley	0.2 ± 0.06	19.6 ± 5.57
Escanaba	0.3 ± 0.08	0.3 ± 0.10

Conclusions

- N₂O production due to disturbance of high-organic matter pasture soils is cause for concern.
- Conversion resulted in a greenhouse gas "debt" equivalent to 10-20 Mg-CO₂ ha⁻¹ from N₂O emissions in the first growing season alone (Table above).
- This compares to reported rates of aboveground C sequestration in Upper Michigan plantations of 15 and 10 Mg-CO₂ ha⁻¹ for poplar and willow, respectively.
- Comparison of pasture conversions to the former poplar plantation suggests that high N₂O emissions arise from the combination of high initial SOM and poor drainage.
- No-till methods of plantation establishment could decrease the CHG debt associated with establishment.

Figure 1. Soil N₂O fluxes over the 2009 snow-free season.

C2(b) – Abstract

Wang, Z. and D. MacFarlane (In Review). Evaluating the biomass production of coppiced willow and poplar clones in Michigan, USA, over multiple rotations and different growing conditions. Submitted to Biomass and Bioenergy, 2011.

Abstract

Willow and poplar are both important crops for Short Rotation Intensive Culture (SRIC). Here, we report the results of biomass yield trials at three locations in Michigan, where the average annual yield of twelve willow and two poplar clones were compared over three- or four-year growth periods after coppicing. On average, fast-growing hybrid poplars (NM5 and NM6) were more productive than any of the willow clones tested by about 30%. Poplar and willow revealed different growth patterns after successive harvests; poplars grew quickly and consistently while willow growth was initially slower but increased over time. Willows at the intensively managed site in southern Michigan were usually 2-5 times more productive than at the two less intensively managed sites in southern Michigan and northern Michigan, but poplars at both southern sites were similarly more productive than at the northern site. The annual yield of clones were further “standardized” to account for differences in growing degree days (GDD) between sites in southern and lower Michigan, which caused differences in the relative ranking of some willow clones to change. The results suggest that GDD-standardized yield rates are useful for comparisons of clonal performance over larger regions. Decomposition of clonal yield rates into individual stool yield and survival rates revealed a strong positive correlation ($r^2 = 0.94$) between them, indicating that faster-growing clones also had higher survival rates. The best performing clones for biomass production were also identified.

Under Review at Biomass and BioEnergy.

Sub-Task C3: Improve Energy Plantation Cultural Systems

Reported by: Raymond Miller

Michigan State University

Final Report
(March 2009 through June, 2011)

Task Summary

Sustainability of energy plantation systems will rely on balancing energy and cost inputs with yields. Choosing optimal planting densities, weed control methods, and fertilizer regimes will contribute to the success or failure of these systems. This task built on work previously begun in Escanaba, MI, by establishing and analyzing a poplar spacing trial, establishing and analyzing existing and new willow herbicide trials, and establishing blocks of willow and poplar in Escanaba for future fertilizer and harvesting trials. Results of this work are presented below.

Funding for the work described here was shared among several funding sources including: (1) US Department of Energy award DE-EE-0000280, (2) the Frontier Renewable Resources Center of Energy Excellence award from the State of Michigan, (3) the US Department of Energy Regional Biomass Feedstock Partnership programs for both willow and poplar, and (4) Michigan State University AgBioResearch.

Willow Herbicide Trials

Weed control during the establishment phase of woody energy crop plantations is critical to optimizing future biomass yield. Unfortunately, few herbicides have been tested for shrub willow establishment and none are registered for this use. Preliminary testing of various herbicides in Michigan willow plantations began at Michigan State University in 2007 and 2008 and continued through in this task in 2009 and 2010. The 2009 testing was done at both the Escanaba and Skandia locations while all other testing was done at the Escanaba location only (Table C3.1).

Table C3.1. Herbicide trial locations

<i>Site Name</i>	<i>Latitude/Longitude</i>	<i>Soil Series</i>
Escanaba, MI	45°45'50"N / 87°11'30W	Onaway fine sandy loam
Skandia, MI	46°21'43"N / 87°14'48"W	Munising fine sandy loam

Eight clones of willow were included in the testing over the years (Table C3.2) and thirteen pre-emergence and six post-emergence herbicide treatments (Table C3.3) were tested.

Table C3.2. Willow taxa tested in herbicide trials.

<i>Taxa</i>	<i>Code</i>	<i>Year Tested</i>
<i>Salix dasyclados</i>	SV1	2007, 2010
<i>S. sachalinensis</i>	SX61	2007, 2010
<i>S. miyabeana</i>	SX67	2007
<i>S. viminalis</i> x <i>S. miyabeana</i>	Tully Champion	2008, 2009, 2010
<i>S. sachalinensis</i> x <i>S. miyabeana</i>	Sherburne	2008, 2009, 2010
<i>S. purpurea</i>	Fish Creek	2009, 2010
<i>S. miyabeana</i>	SX64	2010
<i>S. purpurea</i> x <i>S. miyabeana</i>	Millbrook	2010

Table C3.3. Herbicides tested on newly planted willow cuttings.			
<i>Common Name</i>	<i>Trade Name</i>	<i>Manufacturer</i>	<i>Year Tested</i>
Pre-emergence products			
Oxyfluorfen	Goal 2XL	Dow AgriSciences	2010
Oxyfluorfen	Galigan 2E	Makhteshim-Agan	2010
Simazine	Princep 4L	Syngenta	2010
simazine + oxyfluorfen	Princep 4L & Goal 2XL	Syngenta & Dow AgriSciences	2007, 2008
Pendimethalin	Prowl H ₂ O	BASF	2010
imazaquin + pendimethalin	Scepter 70DG & Pendulum Aquacap	BASF	2007
pendimethalin + oxyfluorfen	Prowl H ₂ O + Goal 2XL	BASF & Dow AgroSciences	2010
s-metolachlor	Dual Magnum	Syngenta	2010
pendimethalin + s-metolachlor	Prowl H ₂ O + Dual Magnum	BASF & Syngenta	2010
Norflurazon	Solicam DF	Syngenta	2008, 2009, 2010
Flumioxazin	SureGuard	Valent	2009
Flumioxazin	Chateau	Valent	2010
Diuron	Karmex	DuPont	2010
Post-emergence products			
Clopyralid	Stinger	Dow AgroSciences	2010
fluazifop-p-butyl	Fusilade DX	Syngenta	2010
fluazifop-P	Fusilade DX	Syngenta	2010
Sethoxydim	Poast	BASF	2010
quizalofop-P	Assure II	DuPont	2010
halosulfuron-methyl	Sandea	Gowan	2010

Table C3.4. 2007 Trial Design

4 blocks
3 taxa (see Table C3.2)
Untreated control
Mechanically weeded control
Scepter _{0.25} + Pendulum _{2.0}
Scepter _{0.25} + Pendulum _{4.0}
Scepter _{0.50} + Pendulum _{2.0}
Scepter _{0.50} + Pendulum _{4.0}
Goal _{1.0} + Princep _{2.6}
Goal _{1.0} + Princep _{5.2}
Goal _{2.0} + Princep _{2.6}
Goal _{2.0} + Princep _{5.2}

(subscripts are lbs a.i./acre)

Table C3.5. 2008 Trial Design

4 blocks
2 taxa (see Table C3.2)
Untreated control
Mechanically weeded control
Goal _{1.0} + Princep _{2.0}
Goal _{1.0} + Princep _{4.0}
Goal _{2.0} + Princep _{2.0}
Goal _{2.0} + Princep _{4.0}
Solicam _{0.6}
Solicam _{1.2}
Solicam _{2.4}
Solicam _{3.6}

(subscripts are lbs a.i./acre)

Table C3.6. 2009 Trial Design

11 incomplete blocks
3 taxa (see Table C3.2)
Untreated control
Mechanically weeded control
SureGuard _{0.125}
SureGuard _{0.25}
SureGuard _{0.375}
SureGuard _{0.50}
SureGuard _{0.75}
SureGuard _{1.0}
Solicam _{2.0}
Solicam _{4.0}
Solicam _{6.0}
Solicam _{8.0}
Solicam _{12.0}
Solicam _{16.0}

(subscripts are lbs a.i./acre)

Table C3.7. 2010 Trial Design

4 blocks	
7 taxa (see Table C3.2)	
Untreated control	
Mechanically weeded control	
<i>Pre-emergence treatments</i>	
Goal _{1,0}	Goal _{2,0}
Galigan _{1,0}	Galigan _{2,0}
Princep _{2,0}	Princep _{4,0}
Prowl _{1,9}	Prowl _{3,8}
Dual _{1,9}	Dual _{3,8}
Solicam _{2,0}	Solicam _{4,0}
Chateau _{0,188}	Chateau _{0,375}
Karmex _{2,0}	Karmex _{4,0}
Goal _{1,0} + Prowl _{1,9}	
Dual _{1,9} + Prowl _{1,9}	
<i>Post-emergence treatments</i>	
Stinger _{0,125}	Stinger _{0,25}
Fusilade _{0,188}	Fusilade _{0,375}
Poast _{0,188}	Poast _{0,375}
Assure _{0,069}	Assure _{0,138}
Sandea _{0,047}	Sandea _{0,094}
<i>(subscripts are lbs a.i./acre)</i>	

(subscripts are lbs a.i./acre)

Figure C3.1. Willow Herbicide Trial Plots in Escanaba

All trials were planted using a split-plot randomized block design with herbicide treatment composing the “main plots” and willow clone composing the “sub-plots.” There were ten cuttings of each willow clone in each sub-plot. The specifics of the experimental design each year are detailed in Tables C3.4 through C3.7 below.

Data from all trials were compiled and compared across sites and years to identify patterns (Table C3.8). Results were presented at the Short Rotation Woody Crops International Conference in Syracuse, NY, October 17-19, 2010. Several generalizations were made:

1. Mixtures containing Princep can cause excessive mortality in the first year, particularly on lighter soils. Princep should only be used after a grower gains experience on their particular sites.
2. Substitution of Pendulum or Prowl for Princep with either Goal or Dual seems to improve survival and growth. This may be a safer alternative for a wider range of sites.
3. Both Solicam and SureGuard look favorable, particularly at the lower rates used here. Further testing is strongly encouraged for these chemicals.
4. Resprouting and growth in the second year (the year following coppicing) benefits greatly from good weed control in the planting year. Growth improves by as much as 40% and number of stems increases by as much as 3 times that of unweeded controls. This surprising result further reinforces the desirability of good weed control in the establishment year.
5. None of the post-emergence herbicide treatments were effective at controlling the weed populations present on the test sites.

Results of the 2010 Michigan trial are being combined with two replicate trials that were conducted by our partners at Cornell University in New York and being prepared by them for publication.

Poplar Spacing Trial

A poplar spacing trial was established in Escanaba, MI in the spring of 2008 (prior to the commencement of this contract). Tenth-acre, nearly square plots of seven hybrid poplar clones were planted at three densities in a randomized block design with four blocks. Rows were eight feet apart and trees within rows were seven, six, and five feet apart (778, 907, and 1089 trees per acre respectively). The inner 24, 28, or 32 trees in each spacing plot (depending on the plot density) were measured at the end of the third growing season (fall of 2010) as part of this task.

Heights (Ht), diameters at breast height (DBH), and pest incidence were measured and summarized. Although this is early in the life of this test, differences were beginning to emerge among the clones:

1. I4551 survived less well than all the other clones (Table C3.9). This may be due to improper handling of the cuttings prior to planting but may also represent a real problem with adaptability of this clone. Although we have not seen this pattern in other plantings, further testing of this clone is warranted to ascertain which is true.
2. Using a biomass index ($DBH^2 \times Ht$) *Populus nigra* X *P. maximowiczii* clones (NM2 and NM6) significantly outperformed the other clones (Table C3.9). These “NM” clones had biomass indices in excess of 120 while the others averaged only one third as much.
3. Stem cankering in the NM2 clone was greater than in other clones. This is a problem for the long-term sustainability of these trees if the pattern continues into the future. This bears continued monitoring.
4. Basal area (the sum of stem cross sectional area at 4.5' above the ground) per acre might be expected to increase with increasing stem density but this trend was only apparent in NM2, DN5, and DN34 (Figure 3.2). Further observation over time may show that higher basal areas (and consequently biomass accumulation) might be produced in plots with lower densities; thereby providing a path to reducing establishment costs without sacrificing yield.

Table C3.8. Generalized Performance of Pre-Emergence Herbicides on Various Willow Clones. Tested in 2007 - 2010 in Escanaba, Michigan

Treatment		\$/acre	Height	Survival	Weeds
Goal & Princep Group	Goal-1.0 (2010)	\$ 44	1.469	1.009	0.875
	Goal-2.0 (2010)	\$ 88	1.568	1.000	0.500
	Princep-2.0 (2010)	\$ 13	0.802	0.706	1.000
	Princep-4.0 (2010)	\$ 25	0.867	0.477	1.000
	Goal-1.0+Princep-2.0 (2008)	\$ 56	1.099	0.818	0.263
	Goal-2.0+Princep-2.0 (2008)	\$ 100	1.127	0.831	0.158
	Goal-1.0+Princep-2.6 (2007)	\$ 60	0.782	0.767	
	Goal-2.0+Princep-2.6 (2007)	\$ 104	0.790	0.478	
	Goal-1.0+Princep-4.0 (2008)	\$ 69	1.036	0.740	0.118
	Goal-2.0+Princep-4.0 (2008)	\$ 113	1.299	0.714	0.092
	Goal-1.0+Princep-5.2 (2007)	\$ 76	0.781	0.389	
	Goal-2.0+Princep-5.2 (2007)	\$ 120	0.721	0.322	
Pendulum Group	Goal-1+Prowl-1.9 (2010)	\$ 66	1.590	1.018	0.750
	Prowl-1.9 (2010)	\$ 23	1.558	1.028	1.000
	Prowl-3.8 (2010)	\$ 45	1.403	0.991	0.938
	Scepter-0.25+Pendulum-2.0 (2007)	\$ 64	0.360	0.578	
	Scepter-0.25+Pendulum-4.0 (2007)	\$ 103	0.370	0.489	
	Scepter-0.50+Pendulum-2.0 (2007)	\$ 88	0.252	0.356	
	Scepter-0.50+Pendulum-4.0 (2007)	\$ 127	0.260	0.244	
Solicam Group	Solicam-0.6 (2008)	\$ 20	1.220	1.013	0.842
	Solicam-1.2 (2008)	\$ 40	1.180	1.039	0.855
	Solicam-2.0 (2009)	\$ 66	0.961	0.981	0.481
	Solicam-2.0 (2010)	\$ 66	1.337	0.945	1.000
	Solicam-2.4 (2008)	\$ 80	1.204	1.039	0.750
	Solicam-3.6 (2008)	\$ 119	1.271	0.948	0.566
	Solicam-4.0 (2010)	\$ 133	1.279	0.670	0.625
	Solicam-4.0 (2009)	\$ 133	0.922	0.985	0.284
	Solicam-6.0 (2009)	\$ 199	0.940	0.957	0.143
	Solicam-8.0 (2009)	\$ 265	0.929	0.918	0.215
	Solicam-12.0 (2009)	\$ 398	0.914	0.881	0.260
	Solicam-16.0 (2009)	\$ 530	0.890	0.797	0.301
SureGuard Group	Sureguard-0.125 (2009)	\$ 31	0.976	1.000	0.022
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	Sureguard-0.25 (2009)	\$ 61	0.980	0.994	0.136
	Chateau-0.375 (2010)	\$ 83	1.289	0.651	0.813
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	Sureguard-0.75 (2009)	\$ 184	0.904	0.941	0.055
	Sureguard-1.0 (2009)	\$ 245	0.880	0.966	0.041
Other Chemicals	Dual-1.9 (2010)	\$ 29	1.337	1.028	1.000
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	Galigan-1 (2010)	\$ 41	1.429	1.000	1.000
	Galigan-2 (2010)	\$ 83	1.415	1.028	1.000
	Karmex-2 (2010)	\$ 16	1.453	0.752	0.813
	Karmex-4 (2010)	\$ 33	1.407	0.330	0.250

Herbicide names are followed by pounds of active ingredient applied per acre and (year tested). Performance is reported as a proportion of the response of the unweeded control plots (1=same as control, <1=less than control, >1=greater than control). Red shaded cells are significantly worse than control and green shaded cells are significantly better than control.

Miller, R.O.* and B.A. Bender. 2010. Four years herbicide trials for shrub willow biomass production systems in the Upper Peninsula of Michigan. In: Short Rotation Woody Crops in a Renewable Energy Future: Challenges and Opportunities. Syracuse, NY, October 17-19, 2010. *rmiller@msu.edu

Table C3.9. Growth and survival of 7 poplar clones after 3 growing seasons in a spacing trial located in Escanaba, Michigan.

Clone	Spacing							
	8' x 5'		8' x 6'		8' x 7'		Average	
	Biomass Index	Survival	Biomass Index	Survival	Biomass Index	Survival	Biomass Index	Survival
NM6	95	100%	135	100%	143	100%	124	100%
NM2	116	88%	140	84%	104	83%	120	85%
DN5	47	93%	50	86%	34	86%	44	88%
NE222	22	91%	22	92%	35	92%	27	91%
D105	20	92%	27	94%	25	95%	24	94%
DN34	17	95%	13	96%	14	97%	15	96%
I4551	14	47%	12	48%	13	61%	13	52%

Note: Three planting spacings were tested. Data include survival of the inner trees in 1/10th-acre plots, and biomass index (computed as $\sum D^2H$ of the inner trees of each plot)

Figure C3.2.
7 Poplar Hybrids' Growth After 3 Years At 3 Spacings in Escanaba, MI
(Total Basal Area per Acre)

Hybrid Poplar Clones at 3 planting spacings (8' x 5', 8' x 6', and 8' x 7')

Harvesting and Fertilizer Trial Blocks

A prerequisite to testing harvesting equipment or conducting herbicide trials is the establishment of plantings that will eventually attain the size required for these tests to be done. Several blocks of willow and poplar were established and are being maintained in Escanaba, MI as part of this task for these future tests (Table C3.10). The first of these plantings will be used in the fall of 2011 for trials of a new willow harvester obtained from Denmark for use in subsequent yield trial data collection activities. Fertilizer trials are being proposed that will use some of the other test blocks established here (Figure C3.3).

Table C3.10. Energy plantation harvesting and fertilizer trial test blocks established in Escanaba, MI

<i>Taxa</i>	<i>Description</i>	<i>Size</i>	<i>Established</i>
Poplar & Willow	3 poplar hybrids and 20 willow hybrids planted at high ¹ density. Taxa are in contiguous row plots.	0.7 acres	2009
Poplar & Willow	16 poplar and 7 willow clones planted at high ¹ density.	1.6 acres	2010
Poplar	A mixture of 6 poplar clones were planted at low ³ density in one intermixed block	0.8 acres	2010
Willow	One clone ("Tully Champion") of willow planted at high ¹ density	3.0 acres	2010
Willow	One clone ("Fabius") of willow planted at high ¹ density	3.0 acres	2011
Poplar	One clone (NM6) of poplar planted at medium ² density	3.0 acres	2011
Poplar	One clone (NM6) of poplar planted at high ¹ density	0.3 acres	2011

High¹ density = Double rows with 2 ½' between rows and 2' between plants separated by 5' gaps (7,920 trees per acre).
Medium² density = 8' between rows and 4' between trees within rows (1,361 trees per acre).
Low³ density = 8' between rows and 7' between trees within rows (778 trees per acre).

Figure C3.3. Willow test blocks in Escanaba, MI. Early in 1st year post coppice on left and 3rd year post coppice on left.

Publications & Presentations:

Miller, R.O. and B.A. Bender. 2010. Four years of herbicide trials for shrub willow biomass production systems in the Upper Peninsula of Michigan. IN: Short Rotation Woody Crops in a Renewable Energy Future: Challenges and Opportunities, Proceedings of the 8th Biennial SRWC Operations Working Group, Syracuse, NY, October 17-19, 2010. [Appendix C3(a) - Handout]

Miller, R.O. and B.A. Bender. 2011. Spacing Effects on Stand Development and Tree Growth of Seven Hybrid Poplar Clones After Four Years in a Replicated Trial in Escanaba, Michigan. IN: Poplars & Willows on the Prairies, Joint Conference of the Poplar Council of Canada, the International Poplar Commission, and the Poplar Council of the United States. Edmonton, Alberta, Canada. September 18, 2011.

Appendix

C3(a) – Abstract and Handout

Miller, R.O. and B.A. Bender. 2010. Four years of herbicide trials for shrub willow biomass production systems in the Upper Peninsula of Michigan. IN: Short Rotation Woody Crops in a Renewable Energy Future: Challenges and Opportunities, Proceedings of the 8th Biennial SRWC Operations Working Group, Syracuse, NY, October 17-19, 2010.

ABSTRACT

Renewable, woody biomass is becoming a promising alternative to fossil fuels for the production of energy products around the world. Specialized energy crops and cropping systems are slowly developing to meet the increased demand for energy wood. One promising system for the Northeast and Lake States regions of the United States relies on shrub willows (*Salix* sp.) grown at high densities and harvested on short rotations. This type of production system has the potential to produce exceptional yields but is expensive to establish. Yields and establishment costs are both strongly affected by the methods and effectiveness of weed control during the plantation's first two years. Weed control in young, dense willow energy plantations is challenging because the crop is sensitive to most commercial herbicides and crop use labels are exceptionally rare. Herbicide screening research has been underway at the Forest Biomass Innovation Center for the past four years to find promising chemicals and application rates to facilitate the labeling of appropriate treatment methods for commercial willow energy plantations. This presentation will provide a summary of five herbicide trials conducted in the Upper Peninsula of Michigan between 2007 and 2009. Six herbicides were tested on several taxa of willow with mixed results. This, together with data from other researchers, has led to a more comprehensive test of thirteen herbicides on three sites in both Michigan and New York during 2010. Preliminary results from the Michigan location of this comprehensive test will also be presented.

Keywords: weed control, herbicide, willow, energy crop, plantation

The handout distributed at the meeting follows:

Generalized Performance of Preemergence Herbicides on Various Willow Clones Tested in 2007 - 2010 in Escanaba, Michigan					
Treatment		\$/acre	Height	Survival	Weeds
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	Sureguard-0.75 (2009)	\$ 184	0.904	0.941	0.055
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Herbicide names are followed by pounds of active ingredient applied per acre and (year tested). Performance is reported as a proportion of the response of the unweeded control plots (1=same as control, <1=less than control, >1=greater than control). Red shaded cells are significantly worse than control and green shaded cells are significantly better than control.					

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Syracuse, NY, October 17-19, 2010. *rmiller@msu.edu

Sub-Task C4: Commercial Plantations of Tree Energy Crops

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30 September 2011

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Executive Summary

Little experience is available in the establishment and management of tree energy plantations in Michigan, despite conceptual appeal. A particular need is for the availability of established, commercial-scale (i.e., greater than 10 acre) trials that would facilitate research on operational-scale management. In this project, two commercial scale tree energy plantations were established in the western Upper Peninsula of Michigan. These plantations complement small-scale test plot networks and a commercial scale plantation established in the northern Lower Peninsula. In the spring and summer of 2010, the two retired agriculture fields were cultivated and hand-planted with hybrid poplar (mostly *Populus nigra x maximowiczii*) cuttings. Early results were positive, with high survival and acceptable growth. Some browse from native white-tailed deer was observed, and limited through the building of temporary fencing.

Introduction

Commercial-scale energy crop production is ideal on marginal or retired farmlands far from agricultural markets but close to biofuel facilities in rural forest/agriculture land matrixes. By locating plantations close to facilities transportation costs may be minimized. In parallel, by using marginal or retired farmlands competition with existing uses, especially for food production, is

minimized, and new productive purposes are created that may enhance economic opportunities in remote regions. The Upper Peninsula of Michigan (UP) is a remote, rural, and almost entirely forested region about 10.6 million acres in size (Froese et al. 2007). Forests, at over 8.4 million acres, dominate the UP landscape; however, a substantial area totaling 890,000 acres is presently in agriculture. If just one-third of these lands could be converted to tree energy plantations, with an average annual yield of 4 green tons per acre per year, more than 1 million green tons per year of raw biomass could be produced. At a rate of about 10,000 green tons per MW, this amount would be sufficient to feed a 100% biomass electric generation plant of about 100 MW in size. Alternatively, at a conversion rate of 40 gallons of ethanol per green ton the biomass produced on these lands could produce 40 million gallons of transportation fuel each year. The feasibility of such forecasts depends critically on assumptions about plantation productivity. Presently, there are little empirical data available in Michigan on expected growth, yield, productivity and sustainability for hybrid poplar plantations. In part, this need has been addressed by a network of research plantations established through sponsored research at Michigan Technological University and Michigan State University (e.g., Froese and Miller 2009; Miller and Bender. These plantations typically involve small test plots, perhaps 1,000 square feet in size,

the interior of which are large enough to simulate “whole field” conditions and provide reasonable

data on growth and yield. As these trials mature a reasonable set of empirical data may be available to improve landscape-scale plans and forecasts for a biomass industry.

Test plots are too small, however, for multiple research objectives or for research on operational-scale management of tree energy plantations, like time-and-motion studies of harvest equipment, at realistic scales. As of 2010 apparently only one commercial-scale plantation (i.e., greater than 10 acres) has been established in Michigan. That plantation is 25 acres in size, planted in spring 2010 on site near the town of Onaway, in the Northern Lower Peninsula, funded by Wolverine Power Cooperative. Thus, establishing additional commercial scale plantations, especially in the UP, is a critical need. Until plantations have been established and allowed to develop research on stand management practices, harvest technology and operational efficiency, and many other questions demanding plantations of that scale will not be possible.

Objectives

The overall goal of this project was to establish plantings that will in the future serve as foundations for research and education that rely on established test beds. Possible applications are: (1) applied ecosystem science research involving water, nutrient and matter cycles in relation to management regimes and regional climate trends; (2) augmenting species screening and stand management investigations using a narrow set of near-commercial species or genotypes; (3) engineering and equipment studies including time-in-motion, LCA input development, machine testing and optimization under operational conditions; and (4) stakeholder engagement and education opportunities for emerging undergraduate and graduate programs in sustainability, biomass feedstock production and biomass supply chain systems.

This goal was divided into several objectives:

5. Identify and secure a license for use on one or more sites in the western Upper Peninsula that would be suitable for establishment of commercial-scale hybrid poplar plantations;
6. Develop a conversion, planting and maintenance strategy;
7. Complete site conversion, planting and site maintenance through the end of the first growing season; and,
8. Monitor growth and construct deer exclusion fencing, as needed.

Methods

Site Selection

Candidate sites were identified through informal communication with local agriculture extension agents, economic development agencies, farmers, and professional contacts within the PI's network of collaborators. Key criteria for acceptable sites included:

1. A minimum size of 10 acres of plantable area
2. Soil textures that were either:
 - a. Common in the western upper peninsula, or
 - b. Of better than average moisture holding capacity (7 inches or more)
3. Free of woody vegetation or encroaching tree regeneration
4. Accessible via established road
5. Landowner willingness to enter into a license arrangement with terms established by Michigan Technological University
6. Within a one-way travel time of 2.5 hours from the MTU campus

The terms of license agreements, including license fees, were set by Michigan Technological University. License costs were not included in the scope of this sponsored project and were borne by Michigan Tech. Total target area for planting was a minimum of 30 acres in total across one or more sites.

Site Preparation and Planting

Best management practices for establishment of hybrid poplar plantations were used in this project (e.g., Isebrands 2007). The clone selected was *Populus nigra x maximowiczii* "NM-6", which has been extensively planted in Minnesota, shown to be of high productivity in block plantings in Michigan (Froese and Miller 2009, Miller and Bender 2008) and has been less prone to deer browse in mixed plantings elsewhere in the State (Froese, unpublished data). The bulk of the planting stock were obtained as 8" cuttings from the Verso Paper Company in Alexandria, MN, augmented by some additional material from a commercial nursery in Michigan.

The selected plantation design was row planting of poplar cuttings at a default 6-foot square spacing; i.e., rows six feet apart and trees planted each six feet along the row, requiring about 1,200 trees per acre. This spacing is thought to be a compromise between high densities (e.g., 3,000 trees per acre), which favor bioenergy production, and low densities (e.g., 300 trees per acre) that favor roundwood production. Because the planting stock and labor required increase exponentially as inter-tree spacing declines, a compromise was required that allowed multiple project objectives to be met. To facilitate possible future research and demonstration objectives that require lower densities, approximately 30% of each site was planted at lower densities of 8-foot and 10-foot square spacing (about 680 and 435 trees per acre, respectively). Also, an area of approximately 1 acre in size was reserved at each site for the establishment of small block plantings using alternative planting stock (bare root stock, whips, and an alternative clone). Site preparation was completed in May 2011 using broadcast application of glyphosate herbicide, followed by plowing and cultivation as soil conditions permitted. Cuttings were hand planted by planting crews during early June 2011. Bareroot stock was planted by hand in holes dug by tractor-mounted auger, and whips in 2-foot deep holes drilled with an extended masonry bit.

Weed and Deer Browse Control

Post-planting weed control was undertaken using a combination of mechanical methods, depending on soil conditions. Where the rock and stone content of the soil was low enough a tractor-mounted rototiller was used to cultivate the top layer of soil and mix in growing weeds. In areas of fields where rock content was high cultivation was completed using a tractor-mounted disc harrow.

Some deer browse was expected on all plantations, as white tailed deer are present throughout the western UP of Michigan. Anticipated browse levels were low because the western UP is generally thought to have high winter snow depths that limit deer densities to below those found in other regions.

Where deer browse proved to be high enough to warrant actions to limit tree damage, temporary electric fencing was constructed. The chosen design was a “3D” layout, which uses two rows of wire around the area to be protected (Hall et al. 1999). Fences were constructed using commercially available polypropylene/metal strand “polyrope”, temporary insulated posts, and energized using a solar-powered fence chargers.

Climate Data Collection

Baseline climate data were collected at each site in the first year by installing climate stations. These included solar-powered data loggers, collecting information on precipitation, temperature, relative humidity and solar insolation.

Results

Selected Sites

A number of candidate sites were identified in Keweenaw, Houghton, Ontonagon, Baraga and Dickinson counties, which initially met the selection criteria involving soil suitability, size, access and distance from the MTU campus. Site visits were conducted in 2010 and candidate sites were ranked in order of preference, where parcel size and soil suitability were given priority. Unfortunately, a use license could not be negotiated for the highest-priority property (near Iron Mountain, MI).

Ultimately two sites were identified and placed under a use license with MTU that met the selection criteria (Figure 28). The first site is a 20-acre property near the community of Redridge, in Stanton Township, Houghton County MI. This site is about 11 miles by road from the MTU campus. Past use was for pasture or hay production but the parcel had been retired from active management for several years.

Figure 28. Locations of the sites selected for this project.

The second site is a 10-acre property near the community of Mass City, in Greenland Township, Ontonagon County MI. This site is about 41 miles by road from the MTU campus. Past use for this property was similar to the Redridge site, but having been retired for much longer, perhaps more than 15 years. Both sites have reliable access across the owner's property and the property owners were excited about participating in the project.

Establishment

Unfortunately, because a license was ultimately not obtained for the highest-ranked property identified in 2010 the final site selection was not complete until early in 2011. Therefore, site preparation was not started in the fall as initially planned. This complicated site preparation for several reasons. Machine access is dependent on acceptable soil conditions (i.e., soils sufficiently dry to be trafficable) and soils were very wet in May and June of 2011. Also, herbicide application depends on sufficient plant development, so for increased effect a delay in site preparation until herbicides could be applied in mid-May was necessary.

Application of broadcast herbicides (glyphosate) was completed in late May and site preparation was completed by early June, undertaken by local contractors. Sites were prepared first by deep cultivation with a moldboard plough, followed by leveling using a disc harrow or field cultivator. Equipment selections were made by local contractors to maximize efficiency. Because of excess moisture and equipment limitations approximately half of the Redridge site did not receive deep ploughing and was instead repeatedly worked using a field cultivator.

Figure 29. Hand planting of unrooted hybrid poplar cuttings (photo taken June 2011).

Planting stock was transported by truck to Michigan Technological University and kept refrigerated at approximately 38 F until the day of planting. Stock was transported to the site and stored under reflective cover until needed. Unrooted cuttings were hand planted by temporary laborers in mid June under near ideal weather conditions (Figure 29).

Figure 30. Early growth of cuttings at the Redridge site (photo taken in July 2011).

Weed control through initial site preparation was very effective (Figure 30). Establishment and early survival of the poplar cuttings was very high, exceeding 95% of the stock planted. The weed community developed slowly in July and August, but was sufficiently developed by mid August to warrant treatment. Rototilling, where soils were suitable, was used for weed control; this was possible on the entire Mass City site and portions of the Redridge site, where rock content was low. Weed control was undertaken elsewhere using a combination of disc harrow and field cultivator. Precipitation was atypically low in August and September, which also had a negative effect on growth.

Fencing

Monitoring of plantation establishment through the end of July 2011 revealed little browse damage from white-tailed deer, with the exception of the field margins where adjacent land was in tree cover. By late August browse was observed throughout both the Redridge and Mass City locations, though the intensity was higher at the Redridge site likely because the site is secluded and surrounded on three sides by established forest.

Temporary electric fencing was installed at both sites in late Summer 2011 to reduce subsequent browse impact. Fences were monitored every second day for the first week after installation to detect any damage and to ensure they were operating correctly. Afterwards, fences were monitored weekly. No further browse was observed within fenced areas.

Discussion

This project was completed successfully, meeting all initial goals and despite some difficult challenges. Two sites were identified, use licenses were negotiated, and best management practices for hybrid poplar plantation establishment were followed. Weather and suboptimal timing delayed planting, but planting was finished after appropriate site preparation was completed in late spring within the recommended window.

Early survival was excellent, and trees achieved good growth with minimal weed competition until late in the growing season. Late season weed control and increasing deer browse through August depressed height growth somewhat on portions of the plantations. Overall those impacts were for the most part relatively small (apparently less than 20% of potential), especially after cultivation to control weeds and the construction of temporary fencing on portions of the plantations experiencing the greatest browse.

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Sub-Task C5: Evaluate Carbon and Nutrient Cycling

Reported by: David Rothstein

Michigan State University

Final Report

(March 2009 through June 2011)

Task Summary

The potential environmental benefits and long-term sustainability of biofuels production remains controversial, with uncertainty over what net reductions in greenhouse gas emissions are actually achievable, as well as concerns about the environmental consequences of planting large areas with biofuel crops. The purpose of this project was to develop a better understanding of the environmental impacts associated with conversion of retired agricultural lands to woody biofuels production, including: 1) emissions of greenhouse gases (GHG), 2) nutrient leaching and eutrophication potential, and 3) soil C loss/gain. To address the GHG and eutrophication issues we collected monthly measurements of soil GHG fluxes at four of the poplar and willow test sites (Figure C5.1) and measurements of NO_3^- leaching at two of the sites. Results from this study clearly show that disruption of the soil N cycle is a consistent feature of converting herbaceous open lands to woody bioenergy plantations – plantation establishment increased soil nitrous oxide (N_2O) emissions and hydrologic fluxes of NO_3^- . However, the magnitude of N_2O emissions was strongly dependent on site N capital and hydrology. To address the soil C issue we collected baseline soil C measurements in 2009 and 2010 at three of the sites prior to conversion to poplar or willow. Data from this sampling was instrumental in securing a recently awarded grant from the US Department of Agriculture (USDA-NIFA) that will fund resampling to detect soil C pool change in 2013 and 2014. Results from this study, along with continuing work that builds upon this foundation, will aid in selecting sites where short-rotation woody biomass crops (SRWC) can be established and grown with minimum environmental impacts.

Soil GHG Fluxes

Field sampling for this project took place in four of the poplar and willow test sites described in the Task C1 report (Figure C5.1). At each site we sampled soil GHG fluxes in four willow plots (*Salix sachalinensis* [SX61]), 5 poplar plots (*Populus nigra* x *P. maximowiczii* [NM6]) and in 4 control plots located in surrounding areas maintained in the previous land use. We measured soil GHG fluxes for 2 years at Skandia and Brimley, and for 1 year at Lake City and Onaway. We used static chambers with bases seated 10-cm deep in the soil to sample GHG fluxes. Chambers were enclosed and four samples of headspace gas collected at 0, 10, 20 and 30 minutes, which were analyzed for GHG concentrations using a Shimadzu GC-2014 Gas Chromatograph equipped with a methanizer and flame ionization detector for CO_2 and CH_4 and a ^{63}Ni electron-capture detector for N_2O . Sites were sampled monthly throughout the growing season, with the exception of Skandia which was sampled every 2-3 weeks in 2009 and then monthly in 2010. We used linear interpolation to estimate cumulative GHG fluxes.

Conversion of herbaceous open lands to SRWC had no clear effects on soil CO_2 efflux – although fluxes trended higher in the control plots relative to cultivated plots in most sites (Figure C5.2). It is likely that any increases in heterotrophic respiration in cultivated plots were matched by greater root respiration in the controls. Future sampling for soil C pools will help to resolve this question. Land conversion resulted in increased soil CH_4 efflux for the first growing season at Skandia only. There was no discernable conversion effect on CH_4 flux at any other site (Figure C5.3). Soil N_2O fluxes increased following

cultivation at all six sites; however, there was a nearly 40-fold range in N₂O fluxes across the sites (Figure C5.4). Preliminary estimates of cumulative fluxes suggest that land conversion resulted in GHG “debts” ranging from 0.3 (Lake City and Onaway) to 10.3 (Brimley) Mg-CO₂ equivalents ha⁻¹ from N₂O emissions in the first growing season alone. These data clearly show that N₂O is the GHG that is most responsive to land conversion, and that flux rates are strongly controlled by underlying site characteristics. Future work will focus on using these data to parameterize ecosystem process models to better understand the GHG impacts of SRWC plantation across the landscape.

Nutrient Leaching and Eutrophication

Conversion of herbaceous openlands to willow and poplar bioenergy plantations resulted in major disruptions to the soil N cycle at all four sites. In all cases, conversion resulted in 20 to 30-fold increases in soil NO₃⁻ levels (Figure C5.5). This likely arose due to the combination of reduced plant N demand and accelerated mineralization, which in turn stimulated the activity of nitrifying bacteria. Large increases in soil NO₃⁻ at the Skandia site resulted in marked increases in NO₃⁻ concentrations of soil leachate during the first growing season, which gradually subsided in 2010 (Figure C5.6). Lysimeters were installed in June 2010 at the drier Lake City site. However, the combination of drier weather in 2010 and a drier site, meant that the few of the lysimeters yielded solution. Based on the limited data it is clear that cultivation resulted in elevated leachate NO₃⁻ concentrations at this site as well. Our new USDA-NIFA grant will provide funding to continue sampling at these two sites as well as instrumenting the remaining sites with lysimeters.

Baseline Soil C Sampling

Baseline soil C measurements were collected at Skandia, Lake City and Onaway. Cultivation at the Brimley site had already taken place prior to the initiation of this project precluding baseline samples from that site. We collected five cores per plot in the poplar plots and four cores per plot in the willow and control plots. At Lake City we collected cores to a depth of 90 cm and separated these into 0-15, 15-30, 30-60 and 60-90 cm increments. At Skandia, a fragipan at approximately 60 cm depth stopped our coring so we collected soils in 0-15, 15-30 and 30-60 cm increments. At Onaway, shallow bedrock impeded core collection past a depth of 25 cm so there we collected soil to a depth of 25 cm in a single increment. In the lab, soils were dried, sieved and weighed to determine bulk density, picked free of roots, a subsample analyzed for C concentration, and another subsample archived for future analysis. Preliminary estimates of initial C stocks at all four sites are presented in (Figure C5.7). All core sampling points were georeferenced. As part of our recently funded USDA-NIFA grant, we will return to these same locations in 2013 (Skandia and Brimley) and 2014 (Onaway and Lake City) to resample in order to estimate changes in soil C due to plantation establishment. While the soil C data collected as part of this project cannot be used to draw conclusions on their own, they represent an unprecedented resource for understanding potential long term changes in soil C associated with SRWC plantations.

Outputs

Publications & Presentations

Rothstein, D., M. Palmer, J. Forrester, D. Mladenoff, and P. Nikiema (2010). Greenhouse-gas emissions associated with establishment of woody biomass plantations. Sustainability Retreat, Great Lakes Bioenergy Research Center, Kellogg Biological Station, Hickory Corners, MI, February 2010 [Appendix C5(f) - Poster]

Nikiema, P. and D. Rothstein (2010). Initial effects of pastureland conversion to hybrid poplar and willow bioenergy systems on N leaching and greenhouse gas emissions from soil. AT: Sustainability Retreat, Great Lakes Bioenergy Research Center, Kellogg Biological Station, Hickory Corners, MI, February 2010. [Appendix C5(g) – Poster]

Rothstein, D., P. Nikiema, and R. Miller (2010). Greenhouse-gas emissions associated with conversion of open lands to short-rotation woody biomass plantations. Climate Change Symposium, Michigan State University, Environmental Science and Policy Program, April 2010. [Appendix C5(h) - Poster]

Rothstein, D. M. Palmer, J. Forrester, and D. Mladenoff (2011). Nitrogen cycle impacts of short-rotation woody biofuels crop establishment across the Northern Lake States, USA. International Conference on Response of Forests and Adaptation Management to Climate Change. Yichun, China; August, 2011.

Palmer, M., D. Rothstein, J. Forrester, and D. Mladenoff (2011). Nitrogen cycle impacts of short-rotation woody crop establishment across the Northern Lake States. Ecological Society of America Annual Meeting, Austin, TX, August, 2011.

Nikiema, P., D. Rothstein, and R. Miller (In Review). Initial greenhouse gas emissions and nitrogen leaching losses associated with converting pastureland to short-rotation woody bioenergy crops in northern Michigan, USA. Submitted to Biomass and Bioenergy.

Grant Proposals

Rothstein, D. E., Mladenoff, D., D'Amato, A., "Carbon sequestration and greenhouse gas emissions associated with short-rotation woody biomass production in the Upper Great Lakes Region", USDA-NIFA. June 14, 2010; Amount requested: \$998,630; **Status: Funded.**

Miller, R., Rothstein, D. E., Leefers, L. A., MacFarlane, D. W., Dale, B., Miller, D., Saffron, C. M., Srivastava, A., Pan, F., "Research and Development of Advanced Woody Feedstocks and Biofuels Production Systems in the Upper Great Lakes States Region", USDA-NIFA. Type: Grant; Focus: Research/Creative Activity; Submitted: November 17, 2010; Amount requested: \$6,179,442; **Status: Not Funded.**

Future Directions

Our recently funded USDA-NIFA grant will support five years of continued measurement of these four sites along with three additional sites located in Upper Michigan, northern Wisconsin and Minnesota. This study will expand on the current work by including simulation modeling of ecosystem processes, life-cycle analysis of production systems, and scaling of model output to assess the landscape and regional scale impacts of expanding biofuels production. The infrastructure and preliminary data developed with funding from the MEDC/DOE Forest Biofuel Statewide Collaboration Center was instrumental in securing this grant.

Figure C5.1. Map of Michigan State University's network of poplar and willow test sites. Baseline soil C and GHG fluxes were sampled at Skandia, Brimley, Onaway and Lake City. NO_3^- fluxes were measured at Skandia and Lake City.

Figure C5.2. Soil CO_2 efflux over the 2009 and 2010 growing seasons. Vertical dashed lines indicate the date of initial cultivation. Black circles represent reference plots, red triangles represent poplar plots and blue squares represent willow plots.

Figure C5.3. Soil CH_4 efflux over the 2009 and 2010 growing seasons. Vertical dashed lines indicate the date of initial cultivation. Black circles represent reference plots, red triangles represent poplar plots, and blue squares represent willow plots.

Figure C5.4. Soil N_2O efflux over the 2009 and 2010 growing seasons. Vertical dashed lines indicate the date of initial cultivation. Black circles represent reference plots, red triangles represent poplar plots and blue squares represent willow plots. Insets for Lake City and Onaway show the same data with an expanded y-axis scale.

Figure C5.5. Soil extractable NO_3^- concentrations (top 10 cm) over the 2009 and 2010 growing seasons. Vertical dashed lines indicate the date of initial cultivation. Black circles represent reference plots, red triangles represent poplar plots and blue squares represent willow plots.

Figure C5.6 $\text{NO}_3^- \text{N}$ concentrations of soil leachate beneath control, willow and poplar plots at the Skandia site for 2009 and 2010 and at Lake City for 2010. Black circles represent reference plots, red triangles represent poplar plots and blue squares represent willow plots.

Figure C5.7. Baseline soil C storage for Skandia, Lake City and Onaway. Data are from samples collected in poplar and willow plots prior to any plantation establishment activities. Red triangles represent poplar plots and blue squares represent willow plots.

C5(a) – Map: Task C5 Study Sites

Fig. 1. Map of study site locations. Sampling at Skandia (SK) and Whiskey River (WR) began in 2009 and 2010; sampling at Onaway (ON) and Lake City (LC) began in 2010. All four sites are sampled for GHG fluxes; only SK and LC are sampled for NO_3^- leaching.

C5(b) – Report: 2009 and 2010 Greenhouse Gas Flux

Conversion of herbaceous open lands to SRWC had no clear effects on soil CO₂ efflux – although fluxes trended higher in the control plots relative to cultivated plots in most sites (**Fig. 2**). It is likely that any increases in heterotrophic respiration in cultivated plots were matched by greater root respiration in the pasture controls. Land conversion resulted in increased soil CH₄ efflux for the first growing season at Site 1 only. There was no discernable conversion effect on CH₄ flux at any other site (**Fig. 3**). Soil N₂O fluxes increased following cultivation at all six sites; however, there was a nearly 40-fold range in N₂O fluxes across the sites (**Fig. 4**). Preliminary estimates of cumulative fluxes suggest that land conversion resulted in GHG “debts” ranging from 0.3 (LC and ON) to 7.7 (WR) Mg-CO₂ equivalents ha⁻¹ from N₂O emissions in the first growing season alone.

Figure 2. Soil CO₂ efflux over the 2009 and 2010 growing seasons. Vertical dashed lines indicate the date of initial cultivation. Black circles represent reference plots, red triangles represent poplar plots and blue squares represent willow plots.

Figure 3. Soil CH₄ efflux over the 2009 and 2010 growing seasons. Vertical dashed lines indicate date of initial cultivation. Black circles represent reference plots, red triangles represent poplar plots and blue squares represent willow plots.

Figure 4. Soil N₂O fluxes over the 2009 and 2010 growing seasons. Vertical dashed lines indicate date of initial cultivation. Insets for LC and ON show the same data with an expanded y-axis scale. Black circles represent reference plots, red triangles represent poplar plots and blue squares represent willow plots.

Conversion of herbaceous openlands to willow and poplar bioenergy plantations resulted in major disruptions to the soil N cycle at all four sites. In all cases, conversion resulted in 20 to 30-fold increases in soil NO_3^- levels. This likely arose due to the combination of reduced plant N demand and accelerated mineralization, which in turn stimulated the activity of nitrifying bacteria. Loss of this NO_3^- , either through hydrologic leaching or N_2O production, was highly dependent on spatial and temporal variation in hydrology.

Figure 5. Potassium-chloride-extractable NO_3^- pools in the top 10 cm soil across all four sites during the 2009 and 2010 growing seasons. Vertical dashed lines indicate date of initial cultivation. Black circles represent reference plots, red triangles represent poplar plots and blue squares represent willow plots.

Cultivation of pastureland at the Skandia site resulted in marked increases in NO_3^- concentrations of soil leachate during the first growing season, which gradually subsided in 2010 (Fig. 6). Lysimeters were installed in June 2010 at the drier Lake City site. However, the combination of drier weather in 2010 and a drier site, meant that the soil of the lysimeters yielded solution. Based on the limited data it is clear that cultivation resulted in elevated leachate NO_3^- concentrations at this site as well. We have acquired funding to continue sampling on a different grant and expect to see a large flush of NO_3^- from this site in Spring 2011.

Figure 6. NO_3^- - N concentrations of soil leachate beneath control, willow and poplar plots at the Skandia site for 2009 and 2010 and at Lake City for 2010.

C5(e) – Report: Baseline Soil C Stocks

Preliminary estimates of soil C pools as a function of soil depth are presented in Figure 7 below. Baseline soil C samples were not collected at the Whiskey River site, because initial cultivation of the site took place prior to the initiation of this project. At the Skandia site a fragipan layer at ~ 60 cm limited our sampling depth, whereas at the Onaway site bedrock restricted sampling to the top 25 cm. As expected, these grassland soils store large pools of C in the surface horizons. Loss of this C due to land conversion has the potential to undermine the net C balance of bioenergy plantations. We have used the data collected with this award as leverage to secure a new five-year grant from USDA that will allow us to resample soils at these sites in 2013 and 2014 in order to assess changes in soil C storage due to land conversion.

Figure 7. Cumulative soil C storage as a function of soil depth at the Skandia, Lake City and Onaway study sites. Samples were collected prior to any conversion activities but are separated into plots that would be planted to poplar (red triangles) and those that would be planted to willow (blue squares).

Rothstein, D., M. Palmer, J. Forrester, D. Mladenoff, and P. Nikiema (2010). Greenhouse-gas emissions associated with establishment of woody biomass plantations. Sustainability Retreat, Great Lakes Bioenergy Research Center, Kellogg Biological Station, Hickory Corners, MI, February 2010.

Abstract

Multiple woody-biomass-based energy projects are in planning or underway in northern Michigan and Wisconsin, and old hay fields, pastures and abandoned agricultural land have been identified as targets for conversion to short-rotation woody biomass crops (SWRC) to supply feedstock. These open lands make up a significant portion of the landscape matrix of this region, including more than 260,000 ha in Michigan's Upper Peninsula alone. Widespread conversion of open lands to SRWC is likely to have significant environmental impacts, including: greenhouse gas (GHG) emissions, changes to soil C stocks, and changes to hydrologic fluxes of NO_3^- . We are studying the impacts of open-land conversion across a wide range of site conditions in northern Michigan and Wisconsin. Six sites were established in 2009 and 2010, all of which have plots planted to willow (*Salix*), plots planted to hybrid poplar (*Populus*) and control plots maintained in prior herbaceous vegetation. At all six sites, we measured soil GHG fluxes using static chamber methods. We have found that nitrous oxide production N_2O production due to disturbances of high-organic matter pasture soils is cause for concern. Preliminary estimates of cumulative fluxes suggest that land conversion resulted in GHG "debts" ranging from 0.2 (Site 6) to 7.7 (Site 2) Mg-CO_2 equivalents ha^{-1} from N_2O emissions in the first growing season alone. This range compares to reported rates of aboveground C sequestration in Upper Michigan plantations of 15 and 10 Mg-CO_2 $\text{ha}^{-1} \text{y}^{-1}$ for poplar and willow, respectively. Soil C loss may make an even greater contribution to GHG emissions; however we will need to use sequential coring over time to quantify this. Development of no-till methods of plantation establishment could decrease the GHG debt associated with establishment.

Greenhouse-gas emissions associated with establishment of woody biomass plantations

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Introduction and Rationale

- Multiple woody-biomass-based energy projects are in planning or underway in northern Michigan and Wisconsin.
- Old hay fields, pastures and abandoned agricultural land have been identified as targets for conversion to short-rotation woody biomass crops (SRWC) to supply feedstock.
- These open lands make up a significant portion of the landscape matrix of this region, including more than 260,000 ha in Michigan's Upper Peninsula alone (Fig. 1).

Figure 1. Northern Lake States landscape matrix showing locations of six existing study sites (Table 1). Land cover data show only non-forest classes (NLCD 2001).

- Widespread conversion of open lands to SRWC is likely to have significant environmental impacts, including: greenhouse gas (GHG) emissions, changes to soil C stocks, and changes to hydrologic fluxes of NO_3^- .

Figure 2. Establishment of experimental plantations. Initial site conditions (a), planting unrooted cuttings in freshly tilled soil (b), one-month old poplar (c) and willow (d) plantings.

Study Sites

•We are studying the impacts of open-land conversion across a wide range of site conditions in northern Michigan and Wisconsin.

•Four sites were established in 2009 and 2010 by the Michigan Agricultural Experiment Station as clonal yield trials to assess the performance of different varieties of willow (*Salix*) and poplar (*Populus*) (Sites 1-4; Fig. 1; Table 1.).

•Two sites were established in 2010 as part of GLBRC's Woody Biomass Initiative (Sites 5 and 6)

•All sites have plots planted to willow (*Salix*), plots planted to hybrid poplar (*Populus*) and control plots maintained in prior herbaceous vegetation.

Table 1. 2009 Study site characteristics. Locations of all sites are shown in Fig. 1. Initial soil organic C and N concentrations are given in units of g kg^{-1} for the surface 10 cm.

Site	Established	Texture	Drainage Class	Prior Land Use	Initial Soil C	Initial Soil N
1	2009	Fine sandy loam	Moderately well	Pasture/Hay	33	2.4
2	2009	Silt loam	Somewhat poorly	Pasture	35	2.7
3	2010	Sandy loam	Well	Pasture	19	1.4
4	2010	Loam	Somewhat poorly	Grass-alfalfa hay	28	1.9
5	2010	Fine sandy loam	Well	Grass-alfalfa hay	26	1.9
6	2010	Loamy sand	Well	Grass hay	18	1.4

•Plantations were established by applying glyphosate to existing vegetation, followed by tillage, application of preemergent herbicide and planting of unrooted willow and poplar cuttings (Fig. 2).

Results

•Conversion of herbaceous open lands to SRWC had no clear effects on soil CO_2 efflux – although fluxes trended higher in the control plots relative to cultivated plots in sites 1-3 (Fig. 3)

Figure 3. Soil CO_2 efflux over the over the 2009 and 2010 growing seasons. Vertical dashed lines indicate date of initial cultivation.

•Soil N_2O fluxes increased following cultivation at all six sites; however, there was a nearly 40-fold range in N_2O fluxes across the sites (Fig. 4).

Figure 4. Soil N_2O fluxes over the 2009 and 2010 growing seasons. Vertical dashed lines indicate date of initial cultivation. Insets for sites 3-6 show the same data with an expanded y-axis scale.

•Land conversion resulted in increased soil CH_4 efflux for the first growing season at Site 1 only. There was no discernable conversion effect on CH_4 flux at any other site (Fig. 5).

Figure 5. Soil CH_4 efflux over the 2009 and 2010 growing seasons. Vertical dashed lines indicate date of initial cultivation.

•Response of N_2O fluxes to cultivation appeared most strongly related to initial soil N concentrations (Fig. 6).

Figure 6. Cumulative soil N_2O fluxes for the first year following cultivation as a function of initial soil N concentration (0-10 cm depth). Cumulative fluxes were calculated by linear interpolation of rates presented in Figure 4. Data points are averages (SE) of willow and poplar plots.

Conclusions To Date

- N_2O production due to disturbances of high-organic matter pasture soils is cause for concern.
- Preliminary estimates of cumulative fluxes suggest that land conversion resulted in GHG "debts" ranging from 0.2 (Site 6) to 7.7 (Site 2) $\text{Mg-CO}_2\text{ equivalents ha}^{-1}$ from N_2O emissions in the first growing season alone
- This range compares to reported rates of aboveground C sequestration in Upper Michigan plantations of 15 and 10 $\text{Mg-CO}_2\text{ ha}^{-1}\text{y}^{-1}$ for poplar and willow, respectively.
- Soil C loss may make an even greater contribution to GHG emissions; however we will need to use sequential coring over time to quantify this.
- Development of no-till methods of plantation establishment could decrease the GHG debt associated with establishment.

Future Directions

We have recently received funding from USDAs Agriculture and Food Research Initiative Competitive Grants Program. This grant will fund continued data collection on the clonal yield trial sites through 2015, establishment of a new experimental site in northern Minnesota, as well as work on the following broader objectives:

- Determine field-scale relationships between site conditions, prior land use and the net C and GHG balance of SRWC plantations.
- Compare the total C and GHG footprints of conventional, tillage-based establishment methods with reduced-tillage and no-till methods.
- Develop a GIS-based assessment of the relative suitability of open lands across the region for conversion to SRWC plantations.
- Scale field-based findings to quantify consequences for regional C storage and GHG fluxes of different levels and landscape allocation patterns of SRWC production.

Acknowledgements

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C5(g) Abstract and Poster

Nikiema, P. and D. Rothstein (2010). Initial effects of pastureland conversion to hybrid poplar and willow bioenergy systems on N leaching and greenhouse gas emissions from soil. AT: Sustainability Retreat, Great Lakes Bioenergy Research Center, Kellogg Biological Station, Hickory Corners, MI, February 2010.

Abstract

We investigated the effects of converting pastureland into woody bioenergy plantations on soil greenhouse gas fluxes and nitrate leaching. Soil CO₂ emissions did not differ among treatments, suggesting that any increases in heterotrophic respiration in cultivated plots were matched by greater root respiration in the pasture controls. Methane emissions increased 2-fold in the poplar and willow plots; however, flux rates were very low overall. In contrast, pasture conversion resulted in 25.9- and 20.7-fold increases in N₂O flux in the poplar and willow plots, with rates as high as 250 ng N₂O-N cm⁻² h⁻¹. Similarly, cultivation resulted in marked increases in NO₃⁻ concentrations of soil leachate which were negligible under the controls (0.1 ppm), but regularly exceeded 5 ppm in the plantations. Stimulation of nitrification following cultivation appears to be the driving factor behind increased N₂O and NO₃⁻ fluxes. An initial estimate of cumulative emissions suggests that pastureland conversion resulted in a greenhouse gas “debt” equivalent to 7.1±0.7 and 5.3±1.3 Mg-CO₂ ha⁻¹ for poplar and willow plots, respectively, from N₂O emissions in the first growing season alone. This compares to reported rates of aboveground C sequestration in Upper Michigan plantations of 15 and 10 Mg-CO₂ha⁻¹y⁻¹ for poplar and willow, respectively.

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Abstract

We investigated the effects of converting pastureland into woody bioenergy plantations on soil greenhouse gas fluxes and nitrate leaching. Soil CO_2 emissions did not differ among treatments, suggesting that any increases in heterotrophic respiration in cultivated plots were matched by greater root respiration in the pasture controls. Methane emissions increased 2-fold in the poplar and willow plots; however, flux rates were very low overall. In contrast, pasture conversion resulted in 25.9- and 20.7-fold increases in N_2O flux in the poplar and willow plots, with rates as high as $250 \text{ ng N}_2\text{O-N cm}^{-2} \text{ h}^{-1}$. Similarly, cultivation resulted in marked increases in NO_3^- concentrations of soil leachate which were negligible under the controls (0.1 ppm), but regularly exceeded 5 ppm in the plantations. Stimulation of nitrification following cultivation appears to be the driving factor behind increased N_2O and NO_3^- fluxes. An initial estimate of cumulative emissions suggests that pastureland conversion resulted in a greenhouse gas "debt" equivalent to 7.1 ± 0.7 and $5.3 \pm 1.3 \text{ Mg-CO}_2\text{ha}^{-1}$ for poplar and willow plots, respectively, from N_2O emissions in the first growing season alone. This compares to reported rates of aboveground C sequestration in Upper Michigan plantations of 15 and $10 \text{ Mg-CO}_2\text{ha}^{-1}\text{y}^{-1}$ for poplar and willow, respectively.

Introduction

Recent legislation and interest in bio-based energy has resulted in a rapid development of biomass energy projects across the predominantly forested landscapes of northern Michigan. While a tremendous amount of standing biomass exists on federal, state and private forest lands in this region, it is unclear to what degree harvesting of current forest land represents a sustainable source of feedstocks for these new bioenergy projects – particularly given the economic competition from higher-value uses such as paper or lumber. Instead, the deployment of short-rotation woody-biomass crop plantations such as willow and poplar, on non-forested lands is gaining increased interest. Because of their high sensitivity to competition and to ensure optimum tree growth, establishment of genetically-improved willow and poplar clones typically involves herbicide application, extensive soil tillage, and provision of essential plant nutrients. These open lands, however, have been in grazing or hay production for decades and they likely have accumulated large stores of soil organic matter that would be susceptible to mineralization once they are disturbed. Thus, it is likely that the initial conversion from pastureland to bioenergy plantation will incur some level of GHG "debt" due to enhanced emissions of CO_2 , N_2O and CH_4 . The goal of this study, therefore, was to quantify the environmental impacts associated with converting long-term pastureland to woody bioenergy crops at a site in the central Upper Peninsula of Michigan.

Materials and methods

Site and field experiment : A field experiment was established in the summer of 2009 at Skandia in the Upper Peninsula of Michigan in a former pastureland, on a moderately well-drained Munising fine sandy loam. The experiment consisted of three treatments: 1) a yield trial of 11 clones of hybrid poplar; 2) a yield trial of 20 clones of willow and; 3) control plots retained in pasture. The poplar yield trial (2.2 ha) was planted at a spacing of 2.4 m between rows and 2.1 m between trees within rows; while the willow (0.4 ha) was planted in double spacing with 0.8 m between narrow rows, 1.5 m between wide rows and 0.6 m between trees within rows. Weed control consisted of applying glyphosate to both poplar and willow plots on May 23; pendulum aqua cap and sceptor to willow plots on June 17; simazine and goal to poplar plots on June 18, 2009. The field was plowed and disked on May 31 and the trees planted on June 16-18, 2009. The whole experiment was protected with an electric fence to limit the impact of deer browsing on July 13, 2009. Trees were coppiced on October 20, 2009.

Newly planted trees after the field has been tilled

Research site prior to yield trial establishment

Greenhouse gas sampling

GHG and N leaching monitoring: Four and five plots were randomly selected from the willow and poplar trials, respectively and 4 plots of undisturbed pasture were located around the periphery of the yield trials. We used 1 static chamber per plot to measure GHG fluxes and 2 tension lysimeters (1 between tree rows and 1 within tree row) to collect leachate water from a depth of 50 cm. For GHG fluxes we pulled headspace gas samples at 0, 20, 40 and 60 minutes following chamber closure at 2-3 week intervals from May 22 to November 11, 2009. Aboveground vegetation was clipped immediately prior to sampling in order to avoid respiratory fluxes of CO_2 from aboveground plant parts. Chambers were relocated periodically to avoid artifacts of repeatedly clipping the same spot. Leachate collection began on July 14 and continued through October 27, 2009. At each sampling date we collected a single, 10-cm deep soil core near the static chamber for determination of extractable N and soil moisture. Nitrification potentials were measured twice during the sampling period (pre- and post-cultivation).

Data analysis: GHG fluxes were calculated using a corrected quadratic model that takes into account chamber-based flux underestimation. Data were analyzed using a repeated measures analysis of variance. An initial attempt to estimate cumulative GHG fluxes using simple interpolation was also performed.

Figure 1: Fluxes of (a) CO_2 , (b) N_2O and (c) CH_4 . Black solid, dashed dot-dot and long dashed arrows indicate dates for herbicide application, tillage and plantation, respectively.

Figure 4: Soil (a) KCL-extractable NO_3^- (0-10cm), (b) temperature (5cm) and (c) gravimetric moisture (0-10cm) and rainfall. Black solid, dashed dot-dot and long dashed arrows indicate dates for herbicide application, tillage and plantation, respectively.

Table 1: selected soil properties (0-10 cm)

System	Total C ¹	Total N ¹	C/N ¹	Bulk density ²	Root biomass ²	Porosity ²	pH ²
	-----%		ratio	g m ⁻³		-----%	
Pasture	3.25	0.25	13.0	1.13	496	57	5.59
Poplar	3.42	0.22	15.5	0.89	133	66	5.38
Willow	3.00	0.20	15.0	1.10	53	59	4.96
	¹ Pre-cultivation	¹ Post-cultivation					

Conclusion

These preliminary results suggest that the combination of enhanced nitrification potential and decreased vegetative sinks resulted in elevated NO_3^- levels throughout the first growing season following pastureland conversion. These in turn led to sustained emissions of N_2O and leaching losses of NO_3^- . Our preliminary estimate indicates that plantation establishment has resulted in a GHG debt of 5-7 Mg-CO_2 equivalent from N_2O emission alone. This figure does not include any GHG debt associated with soil C loss or fossil fuel inputs for cultivation.

Acknowledgement

This study was funded by the Michigan Agricultural Experiment Station with a grant from the State of Michigan and by the Department of Energy under award number DE-EE-0000280. A special thanks goes to Ray Miller, Brad Bender, Phu Nguyen, Kevin Haynes, Ben Daly and Andy Mueller, for their valuable assistance with field and lab work, and to Cathy McMinn and Kevin Kahmark assistance with GHG analysis.

Results

- CO_2 flux spiked in the cultivated plots following field cultivation; but differences between the bioenergy plots and the controls disappeared within a month of tillage (Fig.1a). Greater root biomass in the control plots (Table 1) than in the treated plots suggests that higher autotrophic respiration in the pastureland is masking any increase in soil C mineralization in the bioenergy plots;
- Conversion of the pastureland to bioenergy plantations resulted in a large and sustained N_2O flux throughout the growing season (Fig 1b);

Table 2 : cumulative CO_2 , N_2O and CH_4 emissions from May throughout November 2009

Systems	CO_2	N_2O	CH_4
	----- $\text{CO}_2 \text{ eq. Mg ha}^{-1}$ -----		
Pasture	44.0	0.3	0.02
Poplar	42.9	7.4	0.04
Willow	45.5	5.9	0.04

Figure 2: NO_3^- concentration in leachate (50cm)

Figure 3: Nitrification potential (0-10cm)

- CH_4 flux was 2-fold higher in the bioenergy plots; however flux rates were low overall (Fig. 1c);
- Higher concentrations of NO_3^- were recorded in leachate water from the poplar and willow plantations throughout the sampling period, relative to the control plots (Fig. 2);
- Cultivation of the plantation plots stimulated soil organic matter decomposition and nitrification (Fig 3 and Fig 4a), thus resulting in a subsequent increase of N_2O and NO_3^- fluxes; Soil temperature (Fig 4b) and moisture (Fig 4c) were similar between the pasture and bioenergy plots;
- The cultivation of this pastureland resulted in a GHG debt of $7.1 \text{ Mg-CO}_2\text{ha}^{-1}$ for poplar and $5.3 \text{ Mg-CO}_2\text{ha}^{-1}$ for willow (Table 2) during the first growing season for N_2O alone.

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Rothstein, D., P. Nikiema, and R. Miller (2010). Greenhouse-gas emissions associated with conversion of open lands to short-rotation woody biomass plantations. Climate Change Symposium, Michigan State University, Environmental Science and Policy Program, April 2010.

Abstract

The conversion of open lands to short-rotation woody-biomass crop (SRWC) plantations is gaining increased interest as a way to supply feedstock to several new bioenergy plants in development across the northern Michigan and Wisconsin. Open lands most likely to be converted include abandoned agricultural lands and economically-marginal pastures and hay fields. Soil C loss, emissions of N₂O and fossil fuel combustion associated with SWRC establishment and production all have the potential to undermine the net greenhouse gas (GHG) reductions associated with substituting biomass fuels for fossil fuels. This is of particular concern for old pasture lands and hayfields in the northern Lake States where soil organic matter (SOM) levels can be extremely high, suggesting that conversion to SWRC may incur a significant GHG debt due to oxidation of soil C and emissions of N₂O resulting from increased rates of nitrification and denitrification. We have begun to study GHG emissions associated with conversion to SWRC across a range of sites in northern Michigan and Wisconsin. Initial results from two pasturelands with high levels of SOM and restricted drainage show very large releases of N₂O associated with conversion. Specifically, we have found that impacts of conversion on direct N₂O emissions alone have resulted in a GHG debt equivalent to 10-20 Mg CO₂ ha⁻¹ during the first year of establishment. These data suggest that selection of suitable sites and development of no-till methods of plantation establishment will be critical to the development of a sustainable SWRC industry in this region. We are expanding our work to include four new sites in 2010 that encompass a wider variety of initial site conditions, and will use long term monitoring to assess impacts of conversion on soil C stocks.

Greenhouse-gas emissions associated with establishment of short-rotation woody biomass plantations

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Introduction and Rationale

- Multiple woody-biomass-based energy projects are in planning or underway in northern Michigan and Wisconsin, including:
 - 1) a wood-based ethanol plant,
 - 2) a biofuel "cube" plant,
 - 3) a biomass-gasification plant,
 - 4) conversion of multiple coal-fired power plants to woody biomass feedstock.
- Old hay fields, pastures and abandoned agricultural land have been identified as targets for conversion to short-rotation woody biomass crops (SWRC) to supply feedstock.
- These open lands make up a significant portion of the landscape matrix of this region, including more than 260,000 ha in Michigan's Upper Peninsula alone (Fig. 1).
- Widespread conversion of open lands to SWRC is likely to have significant environmental impacts, including: greenhouse gas (GHG) emissions, changes to soil C stocks, and changes to hydrologic fluxes of NO_3^- .
- We need a better understanding of potential feedstock production, GHG emissions and NO_3^- leaching resulting from maintaining open lands in herbaceous cover vs. converting them to SWRC.

Figure 1. Northern Michigan and northern Wisconsin study region context

Research Questions

- To what degree do soil C loss and emissions of GHG associated with land conversion undermine the GHG benefits of biofuels production?
- How do site conditions and prior land use affect the net C and GHG balance of SWRC plantations?

Study Sites

- We are studying the impacts of open-land conversion across a range of site conditions in northern Michigan and Wisconsin.
- Three sites were established in 2009 (Table 1, Fig. 2)
- Four sites are being established in 2010 (Fig. 2).
- At all but one site we have replicated willow and hybrid-poplar plantings along with reference plots maintained in the prior land use.
- The FBIC site is an old poplar plantation that was harvested in 2008, and is being replanted with a new genotype (Table 1).

Figure 2. Locations of study sites. Skandia, Whiskey River and FBIC were established in 2009.

Table 1. 2009 Study site characteristics

Site	Prior Land Use	Drainage	Soil Texture	Soil C (%)	Soil N (%)
Skandia	Pasture	Moderate	Loam	3.25	0.25
Whiskey River	Pasture	Poor	Silt loam	3.48	0.26
FBIC	Poplar	Well	Sandy loam	1.80	0.15

Year 1 Results

- Conversion of pastures to SWRC resulted in no discernable change to soil CO_2 efflux (Fig. 3).
- Differences in autotrophic respiration are likely masking an increase in oxidation of soil C due to land conversion. Re-sampling of sites for soil C stocks will be used to assess this.
- Overall CO_2 efflux was lower at the FBIC site which started with lower levels of soil C (Table 1).

Figure 3. Soil CO_2 efflux over the 2009 snow-free season.

- Conversion of pastures resulted in large, and sustained, increases in soil NO_3^- production in the two former pastures (Fig. 4).
- NO_3^- levels were low overall and unaffected by tillage at the former poplar plantation.

Figure 4. Soil extractable NO_3^- levels over the 2009 snow-free season.

- The combination of high soil NO_3^- levels and poor drainage resulted in extremely high fluxes of N_2O from the two converted pastures (Fig. 5).
- N_2O fluxes were very low and unaffected by tillage in the former poplar plantation.

Figure 5. Soil N_2O fluxes over the 2009 snow-free season.

Conclusions To Date

- N_2O production due to disturbances of high-organic matter pasture soils is cause for concern.
- N_2O has 300 times the heat trapping capacity of CO_2 .
- Conversion resulted in a greenhouse gas "debt" equivalent to 10-20 $\text{Mg-CO}_2\text{ha}^{-1}$ from N_2O emissions in the first growing season alone (Table 2).
- This compares to reported rates of aboveground C sequestration in Upper Michigan plantations of 15 and 10 $\text{Mg-CO}_2\text{ha}^{-1}\text{y}^{-1}$ for poplar and willow, respectively.
- Comparison of pasture conversions to the former poplar plantation suggests that high N_2O emissions arise from the combination of high initial SOM and poor drainage.
- Soil C loss may make an even greater contribution to GHG emissions; however we will need to use sequential coring over time to quantify this.
- Development of no-till methods of plantation establishment could decrease the GHG debt associated with establishment.

Table 2. Global warming potentials of N_2O emissions expressed as CO_2 equivalents.

Site	Untilled	Tilled
	CO_2 eq. Mg ha^{-1}	CO_2 eq. Mg ha^{-1}
Skandia	0.5 ± 0.19	12.3 ± 1.45
Whiskey River	0.2 ± 0.06	19.6 ± 5.57
FBIC	0.3 ± 0.08	0.3 ± 0.10

Acknowledgements

This study was funded by the Michigan Agricultural Experiment Station with a grant from the State of Michigan and by the Department of Energy under award number DE-EE-0000280. A special thanks goes to R. Miller, B. Bender, P. Nguyen, K. Haynes, B. Daly and A. Mueller, for their valuable assistance with field and lab work. We are also thankful to C. McMinn and K. Kahmark from KBS for providing GHG sampling protocols and analyzing the first sets of our GHG samples.

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Sub-Task C6: Characterize Wood Properties of Poplar and Willow Clones

Reported by: Pascal Kamdem

Michigan State University

Final Report

Four poplar clones and twelve taxa of Willow grown in a short rotation plantation in Upper Michigan along with one aspen were harvested and materials collected for the chemical and thermal characterization in summer 2009. Bark was manually removed from the stem and the xylem stored in a room conditioned at 70% relative humidity and 22 °C before the chemical characterization. Chemical composition including holocellulose, lignin, extractives and ash content in percentage mass/mass were evaluated using well established ASTM and TAPPI standards methods and protocols available in the literature.

Three trees per clone were selected for straightness of bole and absence of decay symptoms. Cookies were taken at breast height (1.2m) from each clone. The bark was removed; wood samples were taken and ground to pass through 40 mesh sieve. Wood powder was used in chemical analysis and x-ray measurement. Samples were air dried before the crystallinity measurements; the samples were stored in normal room conditions for 3 months. Chemical composition was evaluated using the following procedures: ASTM D1105-96 for extractive content; ASTM D 1102-84 for ash content; ASTM D 1106-96 for Klason lignin content. Six replicates were used for wood extractives content, Klason lignin and holocellulose, and only three replicates for wood ash content.

Data generated on poplar clones and aspen were used to prepare a manuscript that was published in the Journal of Cellulose Chemical Technology 43(7-8): 229-232 in 2009. The data summary is in Table 1.

Table 1: chemical composition and calorific values of Poplar clones

Poplar						
names	Lignin, %	Holocellulose, %	Extractives, %	Ash,%	crystallinity, %	Calorific values, MJ/kg
NM-6	20.39	80.05	4.16	1.00	36-38	19.54
DN-34	21.60	79.58	3.98	0.97	37-42	18.50
NE-222	22.55	80.18	4.00	0.69	37-43	18.72
DN-5	21.70	79.71	4.62	0.89	38-45	19.15
Aspen	21.48	77.23	6.28	0.82	49-52	19.04

In summary, no significant difference was observed in the calorific value of the 16-year-old, four hybrid poplar clones. A high calorific value of 4.67Kcal was obtained for NM-6 clone followed by DN-5 with calorific value of 4.58 kcal/gm (19.15MJ/kg) then DN-34 with 4.42 kcal/gm (18.50MJ/kg). High calorific value of NM-6, DN-5 and DN-34 was attributed to the density, extractive, lignin and holocellulose content in the respective clones. One of the most important parameters of this study was the effect of density. A strong positive correlation was found between the cellulose, hemicellulose, lignin and calorific values and the specific gravity. The specific gravity is the ratio between the density of materials using oven dry weight and the density of water.

The difference between the cellulose, hemicellulose and extractives content of willow clones was not significant for three year old materials to justify a robust statistical analysis to determine the clone with high potential for high lignin and cellulose content as listed in Table 2. . Significant difference was found on poplar clones, the faster the growth, the lower the density, and the lower the cellulose and hemicellulose content due to the thin cell wall and high lumen volume of fibers and vessels. Cellulose content of willow clones varied from 38 to 46%, the extractives content (4-6%) was lower than the 8-10% generally reported for willow; this may be due to their young age (3 years old) in comparison to mature tree.

Table 2: Chemical Composition and calorific values of Willow clones

Names	Percent of dry wood without bark, %						
	Cellulose	Hemicellulose	Lignin	Ash	Extractives	Calorific values	SG*
SV 1	42	21.8	29.8	2.34	4.9	19.6	0.44
S 365	46.2	23.4	29.2	2.55	3.2	19.2	0.38
S 287	43.1	22.8	28.6	2.19	5.8	19.4	0.40
S 25	42.9	23.5	27.9	1.75	6.1	19.26	0.40
S 185	45.2	22.8	27.4	1.70	5.0	18.8	0.42
S 546	44.9	24.3	28.9	1.48	3.5	19.13	0.39
S 301	43.8	23.9	26.7	2.38	5.0	18.98	0.39
SX 64	42	25.1	29.1	2.40	5.4	19.3	0.41
SX 67	43	23.3	28.7	2.28	5.5	18.45	0.34
PUR 12	41.9	18.9	27.9	1.79	5.3	19.35	0.43
94001 (FC185)	44.6	23.2	26.9	1.20	6.8	19.08	0.41
94003 (FC187)	45.2	21.6	25.8	1.32	4.9	19.54	0.42
94012 (B196)	43.2	22.9	29.0	1.70	5.7	19.4	0.40
SX 61	38	25.1	30.2	2.25	5.8	18.63	0.36

SG: specific gravity

The calorific values of three year old willow increased with the specific gravity from 18.5 MJ/kg for low density willow SX-67 and SX-61 clones (0.34) to 19.6 MJ/kg for high SG clones. Due to the young age of willow used in this study, it is strongly suggest that older materials be used for the calorific values in the future.

Publications:

Paper in preparation will be submitted to Wood and Fiber Science on the chemical composition of willow clones

Jim, X., and Kamdem, D.P. (2009). Chemical composition, crystallinity and crystallite cellulose size in *Populus* hybrids and aspen. *Cellulose and Chem. Technol.*, 43(7-8): 229-232 (2009).

Abstract

The chemical composition (holocellulose, lignin, extractives and ash) of four *Populus* hybrid clones and an aspen sample was investigated. Statistical analyses indicated that no significant differences existed among the four *Populus* hybrid clones, although a notable discrepancy regarding the holocellulose content was found between aspen and the other four *Populus* hybrid clones. X-ray was used to study the crystallinity and the average thickness of cellulose crystallites in the four *Populus* hybrids and in aspen; the crystallinity index (Ic) ranged between 6.1 and 51.5%, and a negative correlation was found between the diameter breast height (DBH) and Ic (-0.85); thickness of the crystallite cellulose ranged from 5.67 to 7.09 nm, with no significant difference in the tree samples. No definite tendency was noticed, which is an obvious effect of wood ash application on DBH and Ic, and also on the thickness of crystallite cellulose.

Keywords: *Populus* hybrid, aspen, cellulose, crystallinity

Sub-Task C7: Spatial Forest-Based Biomass Availability

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30 September 2011

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Preface:

In this report, unless otherwise specified, values for mass of biomass are reported in SI units (tonnes) on an oven-dry basis.

Executive Summary

Forest residue products are those typically left after timber harvest and include tree tops, branches, standing dead wood, downed dead wood, and non-merchantable trees. Removing residues from forests represents a substantial source of biomass feedstock for biofuel applications. This scale of removal calls for research to understand the sustainability of residue removal from forests. The scope of the research objective is to address the efflux of carbon (C) and nutrients released from forest residue products, which would otherwise be left on site, and to address recovery of forests' productivity following harvest operations when residue removal is increased. Recovery of soil productivity after harvesting is directly affected by forest management and there is a need to identify the level of organic matter that can be sustainably harvested. Results from previous studies indicate that C and nutrient pools and fluxes are extremely sensitive to site specific conditions and require site specific models to be built. Quantifying the pools and fluctuation of C and nutrients in organic material within the Northern Hardwood Forest Ecosystems is crucial to understanding the sustainability of residue harvesting in Michigan and the neighboring states. An assessment of Biomass Harvesting Guidelines and literature review is used as a baseline to discuss potential impacts of residue removal.

Introduction

Biomass broadly defined is living material produced directly or indirectly by the fixation of carbon dioxide (CO₂) through photosynthesis (Barnes, 1998). The term has become more refined in the forestry discipline to describe the by-products, or residues, of management, restoration, and fuel load reductions, which includes limbs, tops, needles, leaves and woody debris (Becker, 2009). This refined definition is of particular interest in production of alternative energy. On a mass basis wood is about 50% Carbon (C) and is a substantial source of heat energy when combusted to produce energy (Becker et al. 2009, Van Miegroet and Johnson 2009, Jenkins et al. 2004, Powers et al. 2005). Many states of the Great Lakes Region are accelerating biomass utilization to meet renewable portfolio standards. Michigan has specifically targeted 10% of all energy utilities by 2015 to be produced from renewable resources. Forest products have the potential to be a key component of meeting renewable energy standards and many companies have already invested in utilizing biomass for combined heat and power production, and even the production of liquid-fuels in the form of cellulosic ethanol.

Residue removal from forest harvesting represents a substantial source of biomass feedstock for biofuel applications. These logging residues are being increasingly removed and utilized as part of operations to augment management, fuels loads reduction, and to generate additional revenue from harvesting. This scale of removal calls for research to understand the sustainability of forest productivity following harvesting and residue removal. Comprehensive life-cycle analyses are needed to address recovery of forests from intensified harvest operations and to build an accurate regional C budget. Contributing environmental impact assessments to these life cycle analyses is imperative in establishing sustainable management in biomass and residue harvesting. Research has identified critical environmental components in life-cycle analyses as soil organic matter and nutrient pools and fluxes. The long-term productivity of soils is dependent upon adequate organic matter and nutrient to sustain forest productivity. There are many uncertainties in the effects of residue harvest on forests under different silvicultural treatments. This uncertainty highlights the need to estimate the scale of current and future removals and assess how that will effect future management of our forests. These uncertainties and discrepancies in soil biogeochemistry will need to be addressed with site-specific research (Van Miegroet and Johnson 2009).

For the purposes of this review and study the focus has been limited to Northern Hardwood Ecosystems. This ecosystem was chosen in part because of a lack of consensus as to the effects of residue removal under different silvicultural practices. This ecosystem also represents a huge source of feedstock for biomass power plants and cellulosic ethanol production. Current growth to removal estimates from FIA data are represented in

Table 12. Growth and Removal estimates in cubic meters from FIA, and % of growth removed, by ownership class

Ownership		Growth total (m ³)	Removal total (m ³)	% Growth removed
All ownerships	Total	19,654,029	9,166,680	46.64
	Softwoods	6,087,113	2,189,501	35.78
	Hardwoods	13,566,916	6,977,179	54.03
National Forest	Total	2,375,346	412,527	18.07
	Softwoods	1,226,786	256,867	20.94
	Hardwoods	1,148,560	155,660	14.94
Other federal	Total	250,470	0	0
	Softwoods	119,690	0	0
	Hardwoods	130,779	0	0
State and local	Total	3,651,148	1,666,746	48.26
	Softwoods	1,483,590	581,622	38.90
	Hardwoods	2,167,558	1,085,124	54.79
Private	Total	13,323,391	6,276,633	47.71
	Softwoods	3,239,652	1,147,694	35.02
	Hardwoods	10,083,739	5,128,938	51.65
Other	Total	53,674	810,775	1468.07
	Softwoods	17,394	203,318	1149.52
	Hardwoods	36,280	607,457	1587.89

Site productivity is strongly governed by physical, chemical, and biological processes affected directly by management and there is a need to identify and quantify the level of organic matter (OM) being removed (Jenkins et al. 2004, Powers et al. 2005). The OM being described as residue products have a high nutrient content, as well as play a pivotal role in trophic cycles within and between ecosystems. Nutrients critical to Net Ecosystem Productivity (NEP) include nitrogen (N), magnesium (Mg), calcium (Ca), phosphorus (P), potassium (K), and sulfur (S). Increased harvest intensity will invariably represent an increase in the removal of OM and thereby removal of nutrients from forest stands. The level of this removal necessitates research to further understand the short and long-term impacts. Long-term study sites need to be established to record baseline data from target forest types to follow nutrient and forest recovery from intensified harvesting.

Biomass Harvesting Guidelines

Biomass Harvesting Guidelines generally make management recommendations for the following criteria. These criteria are reflective of best management practices (BMP's), but specifically written to address how biomass harvesting and residue removal can potentially impact these ecosystem processes and services (Evans and Perschel 2009, Janowiak and Webster 2010, Shepard 2006).

1. *Dead woody material*
2. *Wildlife and Biodiversity*
3. *Water Quality and Riparian*
4. *Soil Productivity*
5. *Silviculture*
6. *Disturbance Considerations*

Dead woody material – Harvesting guidelines generally recommend a percent retention of coarse/fine woody material and standing snags. These retention guidelines represent an area of great uncertainty.

While most of these accomplish a pre-emptive goal in sustainable management, they fail in truly representing a quantitative impact assessment of residue removal under different retention guidelines as well as under different harvest intensities. For instance, retaining 1 in 3 tree tops from a minimal harvest will have a very different impact compared to retaining 1 in 3 tree tops from a clear cut or maximum selection cut. For the purpose of the research represented here this is the area that needs the most research, monitoring, and assessment. This will be discussed in greater detail to follow.

Wildlife and Biodiversity – In some instances residue harvesting could have negative impacts on wildlife and overall biodiversity in forest stands. These guidelines recommend environmental impact-type assessment of species composition of harvest area and connectivity to sensitive species/ecosystems.

Water Quality and Riparian Zones – Best Management Practice (BMP's) were drafted in part as a response to the clean water act, and the connection to biomass harvesting guidelines recommend and highlight very similar concerns. Operational and residue removal recommend environmental impact-type assessment of riparian zones, wetlands, and hydrology that have connectivity to the harvest area.

Soil Productivity – Soil productivity is central to all ecosystem processes and services. Assessing the short-term and long-term impacts of residue removal is pivoted on how soil conditions are impacted. These guidelines highlight the need to make site-specific assessments of soil conditions to understand impacts and recovery time. The soil conditions that have short-term, and potentially long-term impacts, center on nutrient cycles, soil compaction, and biological material.

Silviculture Treatment – Management objectives are highly variable, from site to site, and even within the same cover types. Recommendations generally center around implementing treatment objectives for a harvest area, with particular respect to planning, selection harvesting, regeneration timeline, operations, road/trail layout, re-entry, aesthetics, and post-operation treatment. The incorporation of residue removal into silvicultural prescriptions and objectives is imperative to sustainable use of residues.

Disturbance Considerations – Management objectives and silvicultural prescriptions must assess the size and type of disturbance from harvesting having a direct impact on species composition, disease/pest susceptibility, and fire/fuels management.

There is currently little consensus on how northern hardwood forests will recover from residue removal. Meta-analysis has shown that site conditions and harvest intensities have highly variable impacts to recovery of forest stands to variable levels of disturbance (Janowiak and Webster 2010, Mroz et al 1985). This variability highlights the need for additional research and for the active practice of adaptive management. Dynamic relationships exist between the quality and quantity of tree removal and the recovery of forests from harvests.

To enumerate these relationships on an ecosystem level is vital to understanding the sustainability of increased removal of residues. These relationships include the cycles of C and nutrients, the temperature and moisture regimes of the ecosystem, as well as how silvicultural treatment affects the interaction of each of these components.

Summary of Regional Biomass Harvesting Retention Guidelines.

The criteria mentioned above are represented to some degree or another in all state biomass harvesting guidelines (Table 13). The greatest differences between BMP's, or Forest management guidelines (FMG's), pertain to retention of wood material and operational changes associated with residue removal. Where additional or specialized management consideration have not been identified (e.g.-sensitive species and habitats) retention recommendations are, or should be, based upon organic matter and nutrient budgets.

Table 13. Summary of biomass harvesting guidelines by state, recommended retention of tree tops/fine woody debris.

State	Retention of tree tops
Michigan	1/6 to 1/3 of harvested trees
Minnesota	1/5 to 1/3 of harvested trees
Wisconsin	1/10+ of harvested trees
Maine	Variable, site specific
Pennsylvania	1/10 to 1/3, variable

Wisconsin's Forestland Woody Biomass Harvesting Guidelines (WIDNR 2008), and the supplementary document Rationale for Guidelines, demonstrate particularly well the rationale and considerations when implementing residue removal. Conversely, the "Considerations and Recommendation for Retaining Woody Biomass on Timber harvest Sites in Maine" demonstrates the need for land managers to make site specific assessments, and goes on to discuss ecological indicators which are imperative to monitoring short-term and long-term impacts to the ecological processes and services. Ecological indicators will be discussed in greater detail to follow.

Biogeochemical Processes

Physical, chemical, and biological processes are driving forces behind site productivity. A conceptual model of how an ecosystem cycles organic matter and nutrients is illustrated in Figure 31. CO₂ is fixed through photosynthesis to form carbohydrates in the form of biomass. Biomass is accumulated until plant senescence and is afterwards decomposed, which leads to formation of CO₂, or becomes incorporated into other forms of biomass, soil organic carbon, and, to a smaller degree, recalcitrant organic compounds. The fixation of carbon through photosynthesis is strongly correlated with the availability of nutrients necessary for biological compounds, which mediate and facilitate photosynthesis. Nutrients enter the system by atmospheric deposition, mineralization, or through biological fixation (i.e., N₂→NH₄⁺) and leave the system through leaching or gaseous loss. Carbon and nutrients within a system are tightly cycled through litter production, decomposition, and subsequent assimilation into biomass of the ecosystem.

Figure 31. Carbon balance and rate of biomass accumulation following stand-level disturbance (reproduced from Barnes 1998).

The formation and decay of organic matter is an integral process regulating atmospheric, hydrospheric, and biospheric processes at a global scale. The composition and interaction of these biogeochemical processes within forest stands and across landscapes makes comprehensive life-cycle analyses difficult. Similarly, site specificity lends a great deal of uncertainty to drawing large-scale conclusions. Managing forest resources and assessing the environmental impact of management are ingrained in making sustainable use of these resources and making accurate life-cycle analyses.

Carbon Cycling

Carbon pools, fluxes, and the sequestration potential of forests have become a defining focus due to the action of CO₂ as a greenhouse gas. Forest systems within the U.S. have been estimated to contain 35 percent of C in live vegetation, 52 percent in soils, and 14 percent in dead organic material (e.g., DDW; Woodall 2010). While biomass is theoretically a “carbon neutral” fuel source, because of its ability to “close the C loop” through sequestration by subsequent re-growth of forests, this model may not be pragmatic in addressing the effects on soil C pools and efflux of CO₂ through edaphic processes (Luiro 2010).

The relationships between Gross Primary Production (GPP), Net Primary Production (NPP), Net Ecosystem Production (NEP), Autotrophic respiration (R_A), and Heterotrophic Respiration (R_H) are illustrated in Figure 31. NEP is a good measure of the total C-sequestering capacity of an ecosystem as a whole because $NEP = GPP - R_A - R_H$. After a major stand-level disturbance event, a net emission of CO₂ can be observed due to heterotrophic respiration from decomposition of organic matter outpacing Net Primary Production (NPP). As GPP from new growth begins to rise NEP will become positive because

of the fixation of CO₂ into live woody biomass. It should be noted however that in Northern Hardwoods R_H will actually steadily increase with the accumulation and decomposition of DDW. This explains the steady decline of NEP at longer time-scales. The decomposition of DDW actually offsets much of the CO₂ sequestered through photosynthesis.

While NEP is a good indication of annual sequestration of CO₂, it does not fully reflect the accumulation or efflux of C compounds within soil. Decomposition of woody organic matter, typified by high C content, can be measured in terms of each constituent's rate of decay. Constituent C groups include glucose, proteins and simple sugars, cellulose, hemicellulose, and lignin. Decomposition is defined by the relationship $A_t = A_0 e^{-kt}$, where A_t is the substrate remaining, A_0 is initial concentration, k is the rate constant for a given compound (in days⁻¹, months⁻¹, or years⁻¹). Values for k for different organic compounds are shown in Table 14. These decompositions were performed under laboratory conditions by measuring the decline in a substrate during decomposition (Barnes 1998). A higher k value indicates a faster rate of decomposition. From these indices a direct relationship can be drawn between decomposition and use for microbial biosynthesis.

Table 14. Rate constants for the decomposition of organic compounds contained in plant litter. $A_t = A_0 e^{-kt}$.

Compound	Rate Constant for k (day ⁻¹)
Glucose	0.500 to 1.000
Proteins and Simple Sugars	0.200
Cellulose	0.036 to 0.080
Hemicellulose	0.030 to 0.080
Lignin	0.003 to 0.010

After Barnes et al., from (Veen 1984, Alexander 1997, Paul and Clark 1996)

Lignin is a complex and highly recalcitrant material and produces precursors, along with microbial activity, for the accrue ment of humic compounds in soils (Paul and Clark 1996). This represents a significant C pool within Northern Hardwood Forests.

Decomposition is also strongly governed by C:N ratios. The availability of N will regulate the rate of decomposition by the ability of microbes to synthesize essential cellular material. Residue products with the highest C:N ratio are leaves and needles, followed by branches, then bole-wood, and this ratio progressively goes down as dead wood becomes more decomposed (Luiro 2010, Andrew and Dean 2006). The removal of N rich biomass then has the potential to affect the soil productivity on a longer time-line than typical with stem-only harvests (Andrew and Dean 2006, Johnson et al. 1982, Weatherall et al. 2006a, Weatherall et al. 2006b). Johnson et al. (1982) note however that "soil reserves and atmospheric inputs may be adequate to sustain total N, P, and K supplies with whole-tree harvesting, but soil amendments may be necessary to sustain Ca supplies."

Davidson and Janssens (2006) note that empirical models can relate the efflux of CO₂ from soils to an optimal temperature curve, and to some scalar of soil water content or precipitation, and that this much is not controversial. However, there are myriad reactions and feedback mechanisms that ultimately govern soil C cycles relating to disturbance events. Many studies have been conducted to compare whole tree harvest (WTH) to bole-only (or stem-only) harvest (Jenkins et al. 2004). Covington (1981) produced a study in 1981 that became definitive for forest floor decomposition, and was widely cited. Covington reported that during the first 15 year after clearcutting the forest floor decreased by 30.7 Mg/ha, which is a decline of over 50%. It became generally accepted that this loss of forest floor biomass was due to increased surface temperatures and availability of moisture, leading to increase microbial decomposition. This assumption has been accepted to the point of becoming a paradigm and has even come to point of no longer being cited in literature (Evans and Pershal 2009, Janowiak 2010). Yanai et al. (2003) present an in depth discussion about the merits of this work and present research that challenges the "Covington

curve” and explanation for measured changes in forest floor mass. In summary, there have been many decomposition studies which have presented widely varying results (e.g., Yanai et al. 2003, Harmon 2010, Moore 2006, Moore 2005). The variability of physical, chemical, and biological conditions from site to site makes it inherently difficult to generate data that can be applied over landscapes. Researching and predicting carbon and nutrient cycles is an inherently difficult area of research because of site-specific conditions and the long-term nature of carbon and nutrient cycling itself. This also highlights the importance of adaptive management being incorporated into silvicultural management.

Nitrogen Cycling

Figure 32. Nitrogen cycle of a northern hardwood ecosystem (reproduced from Barnes 1998).

C and N cycles are tightly coupled within an ecosystem by way of the essentiality of N to accumulate C via the composition of living biomass. Nitrogen is most commonly the limiting nutrient in forest ecosystems (when moisture and temperature are not limiting), and can govern the productivity of a forest. Bioavailable N typically comes in the form of ammonium (NH_4^+) and nitrate (NO_3^-). N as an essential nutrient is used in chlorophyll, amino acids (and hence proteins which catalyze biochemical reactions), nucleic acids (DNA, RNA), and secondary metabolites. For this reason N cycling in forests is relatively closed, that is to say that N loss is relatively low in mature forest stands (Barnes 1998). Intensive harvesting can cause increased nitrification ($\text{NH}_4^+ \rightarrow \text{NO}_3^-$) through microbial processes. NO_3^- is water-soluble and is subject to leaching through hydrologic export.

Recovery of N, and other nutrients, on the Eastern portion of the contiguous 48 states is ameliorated, in part, due to atmospheric deposition (Figure 33), as well as microbial N fixation.

Figure 33. Atmospheric nitrogen deposition in the U.S. (reproduced from Barnes 1998).

Mg, Ca, K, P, S Cycling

While N is commonly the limiting nutrient to growth in an ecosystem with adequate moisture and favorable temperature, there are two other nutrients considered essential macronutrients for plant growth, which are K and P. K is required for osmotic regulation and carbohydrate translocation, and P is required for energy (ATP, ADP), in nucleic acids, and phospholipids. Mg, Ca, and S are considered secondary macronutrients, but can impose moderate to severe limitation on plant growth and overall stand-growth. Mg is an integral metallic factor in chlorophyll and thereby photosynthesis. S is a constituent of several amino acids and plays a direct role in N use efficiency. Ca is an integral part of cell wall formation in plant tissues and can adverse impacts on stand-level productivity. Atmospheric deposition of Ca is low (**Error! Reference source not found.**), especially relative to N deposition and potential Ca losses with biomass harvest.

Figure 34. Atmospheric Calcium Deposition in the U.S. (reproduced from Barnes 1998).

Figure 5 shows Ca pools in kg ha^{-1} , and fluxes in $\text{kg ha}^{-1} \text{ yr}^{-1}$, of a Northern Hardwood Forest Ecosystem. Conceptually this model can be fit to other secondary nutrients although the specific amount held within pools and levels of flux will vary.

Figure 35. Calcium Cycle of a Northern Hardwood Forest Ecosystem (Barnes 1998)

Calcium has been found to be the slowest nutrient to recover after harvest losses in Northern Hardwood Systems (Jenkins 2004, Silkworth and Grigal 1982). This is explained, in part, by how labile Ca is within soils and the associated potential for loss through leaching. A complete model of nutrient balance after whole-tree harvest of trembling aspen ecosystems in Minnesota is given by Silkworth and Grigal (1982;

Table 15). While this forest type is fairly divergent from the Northern Hardwood Forest Ecosystem, it does have bearing on nutrient balance after stand-level disturbance events. Loss of productivity due to Ca (and Mg) deficiency could be ameliorated through ash fertilization and eventually through atmospheric deposition.

Operational Considerations

Maine's biomass harvesting guidelines summarize very well the importance of adaptive and 'on-the-ground' management when integrating residue removals into roundwood harvest. Precedence should be given in implementing Best Management Practices (BMP's) to minimize impact to water quality, sensitive habitats, and so forth. Implementing residue removal as a standard portion of silvicultural prescription is the most responsible way to reduce the potential impacts to stand level ecosystem services. In many cases the precedence of BMP's will dictate how and to what degree biomass is available for removal. In this way, biomass harvesting guidelines also echo what has already been outlined in BMP's.

Table 15. Nutrient Balance for Whole-Tree Harvested *Populus tremuloides* Ecosystems in Minnesota (Silworth and Grigal 1982).

	N kg ha ⁻¹	P	K	Ca	Mg
Annual Input					
Precipitation	6.9	2.6	9.5	5.0	1.7
Mineral weathering	0.0	0.4	8.7	20.8	10.4
N ₂ fixation	3.0*	-	-	-	-
Annual output					
Normal annual leaching	0.4	0.6	3.6	28.8	11.3
Net annual gain (input-output)	9.5	2.4	14.6	-3.0	0.8
Harvest losses					
Leaching due to harvest	0.0	0.0	0.0	62.3	0.0
Removal in biomass	452	43.1	354.6	1034	94.5
Years to replenish harvest losses	48	18	24	No	118
Ecosystem storage	4834	148	643	9081	1866

*Nitrogen input from fixation in the Northern Hardwood Forest Ecosystem can be up to 14.2 kg ha⁻¹ year⁻¹.

Augmenting harvesting operations with residue removal has the potential to offset other costs of harvesting, including the silvicultural prescription, and treating forest health issues such as overstocking, and salvage operations which utilize timber and residues from disease and insect caused mortality (Benjamin, 2009). But these products are still viewed as low value products and present problems in economic viability to utilize (Becker 2009, Benjamin, 2009, Andersson, 2009).

Residue products are handled within the existing operation, and to be utilized are brought to a landing area and fed into a chipper or a grinder on site and loaded into a chip van. As stated by Benjamin (2009), existing operations are not designed to utilize this low quality and smaller material, which makes it a risk for loggers to invest time and resources into new endeavors. Specialized equipment is at a high cost which is risky for such a low value product and when there is uncertainty as to the demand for wood chips (Benjamin, 2009, Flynn, 2002, Becker, 2009).

Operationally, this turns residue removal into utilization of tree tops, which are non-merchantable branches < 4" in diameter and including the foliage depending on season of harvest, non-merchantable cut trees, and standing live trees below merchantable size. In this way the sustainability of residue removal must draw upon silvicultural treatment objectives and the sustainability of whole-tree harvesting.

Methods

A combined sampling plan was implemented to inventory forest stands harvested in the Upper and northern Lower Peninsulas of Michigan. A field inventory of all above ground biomass and downed dead wood, along with sample collection of soils and leaf litter, was used as a baseline survey to answer the research questions outlined in the introduction. Field inventory was an essential baseline survey to establish an estimate of forest stand conditions pre- and post-harvest. This inventory is also a keystone in establishing long term monitoring sites to track additional long term changes in various stand conditions. Measurement of above ground vegetation was done in a way to reconstruct pre-harvest condition and make predictive measurement of current stand conditions. Measurement focused on tree identification and measurement of diameter at breast height (dbh).

Field Inventory

In this field program an assessment was being made of production and harvest removals from northern hardwood forest types in Michigan, under State, Non-Industrial Private Forest, and Corporate ownerships. A common thread is the assessment of production and sustainability under current and alternative management scenarios. The basic sampling design involved two phases: stand selection and within-stand field measurement. Stands were selected by identifying a pseudorandom sample from planned or recently completed timber sales within three ownership types.

Site Selection

The stands in which measurements are being made are under three types of ownership. Stands are within State Forests managed by the Department of Natural Resources and Environment (DNRE), on property under non-industrial private ownership and management, as well as industrial or corporate ownership. Stands have been selected for inclusion on the basis of the following criteria.

1. Northern hardwoods cover type
2. 20 acres or larger in size
3. Harvested within the 6 years prior to field sampling in 2010.

State timber harvests were sampled proportionally, based on the number of northern hardwoods timber sales open in each Forest Management Unit (FMU) in 2009. DNR employees identified the stands meeting our criteria and a total of 42 stands on state land were sampled.

Non-industrial lands were located using two different methods. Initially, landowners were selected randomly from a previously compiled list of Michigan forest landowners. They were contacted and asked if their properties met our criteria, and then asked to include their lands in the study. The sample of stands generated from this approach was supplemented by contacting consulting foresters working throughout the Upper Peninsula and northern Lower Peninsula. A total of 30 non-industrial private forest stands were sampled. An additional 31 corporate stands were sampled through contact with three different corporate forest land owners.

Stand Locations across the State of Michigan

Figure 36. Locations of the stands sampled by owner-class.

Stand Level Sample Protocol

The basic sampling unit in each stand is a set of fixed-area plots. Plot centers are established through random points generated within ESRI ArcMap software. A total of 12 points were generated in an effort to sample at least 10 plots per stand and plot locations were adjusted or not sampled to accommodate for harvest boundaries, or areas within a stand that were not harvest and were not representative of the harvested population of interest. These fixed-area plots used a nested design to sample a range of attributes efficiently.

The basic unit was a 100 m² circular plot. On every plot, overstory and downed dead wood attributes were measured; a subset, of half the plots within a stand, includes an additional set of measurements and sampling of understory vegetation, leaf litter and soils. These are termed extensive and intensive sampling plots, respectively (Figure 37).

Figure 37: Field plot layout.

The detailed field protocol used during field sampling was as follows:

100 m² plot - Extensive

1. Record stand-level attributes including slope, aspect, elevation, GPS coordinates, microtopography.
2. Measure the diameter at stump height and height for every stump included in the plot that appears to have been cut in the last five years. Record the tree species as well.
3. Measure the diameter and species of every tree >10 cm DBH. Record whether the tree is acceptable growing stock or unacceptable growing stock. Estimate crown ratio.
4. For each species, measure DSH and height at DSH on at least the same amount of standing trees as the amount of stumps within a plot.
5. Measure the height of each standing tree which had DBH and height at DSH measured. Make sure this includes the height of the largest tree by DBH.

6. Measure the percent canopy cover at the center of the plot by taking four measurements in each cardinal direction using a spherical densiometer.
7. Use the plot center to measure coarse woody debris using Limiting Distance Sampling. Characterize each log by decay class, using the criteria attached to this document.
8. Take a photograph due north from plot center.

100 m² plot - Intensified

Within each intensified plot all of the extensive measurements are recorded. In addition, three nested subplots are established. One is a 4 m² circular plot offset from plot center within which woody species < 10 cm dbh are measured. The other two are 1 m² square subplots within which observations of understory vegetation and forest floor are made. Also, forest floor and soil samples are collected adjacent to both of the 1 m² subplots.

4 m² circular subplot

Establish a circular subplot, 2.82 m on center, due east of the center of the 100 m² plot. Within this subplot, measure the following:

1. Record the diameter of woody stems by species 0.5 m tall to 10 cm DBH. Measure diameters at 10 cm above ground for stems < 1 in DBH. For stems < 1 cm and less than 10 cm DBH measure diameters at breast height.
2. Measure the heights of all individuals for which diameters were measured.

1 m² square subplots

Establish two subplots, 2.82 m on center, due north and due south of the 100 m² plot center. Within each subplot, measure the following:

1. Record the percent coverage of herbaceous vegetation by species/group using the following cover classes: 0-1, 1-2, 2-5, 5-10, 10-25, 25-50, 50-75, 75-95, 95-100. Some individuals will only be identified to group (e.g., grasses, sedges, mosses, lichens).
2. Record the percent coverage of the forest floor in the following classes: leaf litter (duff), bare soil, CWD, fine woody debris (< 10 cm midpoint diameter, FWD), rocks, and other (e.g., water, stumps, fungi, etc).
3. Record the percent of the plot that shows evidence of logging-related physical disturbance to the forest floor (e.g., soil compaction, duff displacement).
4. Measure the forest floor depth at location of leaf litter sample collection.

Down Dead Wood Sampling

Downed dead wood was sampled using a limiting distance sampling protocol called "Line Intersect Distance Sampling" (Affleck 2008, 2010). Three 63 m transects are run out from plot center at 0°, 120°, and 240° bearings. DDW is measured along each transect with the smallest pieces being most likely to be counted close to plot center, as the transect distance increased the limiting distance for diameter of the DDW becomes greater. For those particles of DDW which fall within the limiting distance the decay class is recorded based on the characteristics in

Table 16. Characteristics of DDW decay stages adapted from Maser et al. (1979) and Pyle and Brown (1998). Table reproduced from Jenkins et al. (2004).

Decay Class Description
Stage 1
-bark firmly attached
-exposed wood not stained by weathering
-log is round
-small branches present
-log is resting on surface
-primary surface substrate: sound bark
Stage 2
-bark not firmly attached, patchy
-exposed wood may be bleached
-log is round
-small branches absent
-wood is mostly solid
-log is resting on surface
-primary surface: hard wood, decayed bark
Stage 3
-bark generally absent, but may be present in patches
-log structure is solid, not brittle, firm when kicked
-dry log surface flaky
-wet log surface spongy
-log partially sunk into ground
-primary surface substrate: soft wood
Stage 4
-log is no longer solid, although some fairly solid segments remain
-log breaks into pieces when kicked
-log oval or flattened, one third or more sunk into ground
-primary surface substrate: spongy or powdery wood
Stage 5
-log is flat, mostly sunken into the ground
-log is soft and powdery in texture
-log is often obscured by litter
-primary surface substrate: loosely aggregated blocks

Forest Floor and Soil Sampling

Immediately adjacent to the 1 m² subplots south of plot center locate a 25 cm x 25 cm subplot to collect litter layer for laboratory analysis.

1. Using a metal sampling frame and a knife/spatula, extract the forest floor down to the surface of the bare mineral soil and place this in a paper bag for transport back to the lab.
2. Use a 2" diameter, 45 cm length soil core sampler to extract a soil core from the center of the cleared forest floor.

Soil samples were kept in coolers until returned to the lab at which point they were put into a chest freezer at -17 C until processing. Leaf litter samples were kept as cool and dry as possible in the field. Upon return to the lab they were preferably oven dried at 70 C for 48 hours or put into cold storage at 4 C until they could be oven dried.

Sample Processing

Soil and leaf litter sample processing occurred concurrent with collection and was completed following summer field inventory. Soil and leaf litter was stored as aforementioned until ready for oven drying and subsequent procession. Procedures below outline processing.

Leaf Litter

Leaf litter was removed from the oven and weighed as soon as possible and within no longer than 2 hours from removal from the oven. Sticks larger than 1 cm in diameter were removed prior to weighing. Leaf litter was then sealed in ziplock bags and stored at room temperature until grinding.

Each sample was ground to ~1mm particle sizes in a milling machine. After course grinding, the samples were finely ground in a ball mill. The ball mill cylinder, cap and steel balls were washed, sanitized, and dried between leaf litter samples to minimize contamination. Leaf litter was afterwards returned back to a paper cup and mixed together. One vial sized leaf litter sample was removed from each cup, and sealed in a vial.

Afterwards, finely ground samples were prepared for elemental analysis. Using a microbalance a silver foil cap was filled with a subsample from each vial and weighed. Mass was recorded and the silver foil was sealed. Soils then proceeded to elemental analysis.

Soil Samples

Field samples were spread on freezer paper for air-drying (approx. 1 to 1.5 days.). Once air-dried the soil samples were gently crushed, using a mortar and pestle, to destroy clods. Samples were placed in a 2 mm sieve to separate material into three possible sub-samples:

1. < 2 mm material
2. > 2 mm rock fragments, and
3. > 2 mm roots and organic material.

Light pressure was placed on soil in the sieve, when necessary, to reduce clods such that they pass. Sub-samples were then bagged with proper identification noted on bag, and it was ensured that the sieve was free of all material.

The < 2mm soil samples and organic material samples that did not pass the 2 mm sieve were placed in foil pans with a paper identification label and oven dried at 70 degrees C for 48 hours. Oven-try weight was obtained and soils were kept in labeled plastic bag for future storage.

Rock fragments (> 10 mm) were cleaned and dried, and then weighed. Then, an approach using water displacement in a graduated cylinder was used to obtain the volume of fragments. If the sample was large and contained fragments > 10 mm, then instead of measuring volume for the entire sample up to three large fragments were selected, weighed, and volume of each was determined. Again, all samples were re-bagged for long-term storage.

Using a ball mill, soil samples were further ground. The ball mill was washed, sanitized and dried between soil samples. Afterwards, soil was returned to the paper cup and mixed together. One vial sized soil sample was removed from each cup, and sealed in a vial. Later, a subsample from each vial was taken and the specified amount placed into the silver cap. The mass was recorded, and the cap placed in a sample collection tray pending elemental analysis.

Elemental Analysis

Elemental Analysis of carbon and nitrogen content was completed using a Fissons NA 1500 Elemental Combustion System. Protocol for EA analysis, software interface, and data interpretation was developed from user's manual and personal communication with lab technicians at the MTU Forest Ecology Laboratory.

Data Analysis

Data analysis relied largely upon established allometric relationships between biomass and field inventory mensuration. Diameter at breast height (DBH) is the most common metric for allometric calculation of values of above ground biomass, below ground biomass, and component biomass. To establish pre-stand conditions tree stumps were measured for diameter and height from ground surface of measurement, these metrics were used to estimate DBH of trees prior to harvest.

The following work to generate diameter at breast height (DBH) from diameter at stump height (DSH) was done by Nan Pond, a fellow graduate student working in cooperation.

Generating accurate estimates of pre-harvest basal area of harvested trees requires a method of predicting the diameter at breast height (DBH) of each harvested tree. Species, stump diameter (DSH), and height at which diameter was measured were recorded for each stump and potentially useful predictor variables. Our data set includes 4,400 trees of 29 species for which DSH and DBH measurements were made, and 2011 stumps of 22 species for which predictions are necessary.

Prediction equations available in peer-reviewed literature and technical reports were reviewed for utility. The oldest equations described were simple linear regression equations based on a simple ratio of DBH:DSH (Horn and Keller 1957, Bones 1960). Other simple linear regressions using only DSH as a variable were published for Indiana (Johnson and Weigel 1990), the southeast (Bylin 1982) and northeast (Wharton 1984). More complex equations including stump height as an additional predictor also exist for southeastern and northern species (McClure 1968; Raile 1977).

After several decades of silence in the literature on this subject, a more complex set of equations for 18 species groups common to the northeast was published by Westfall (2010). Westfall's equations are of the form:

$$DBH = DSH * \left(\frac{4.5}{H}\right)^{B_0} + B_1 * (4.5 - H)$$

Where DBH and DSH are in inches and H is stump height in feet.

Notable to this equation form is the inclusion of stump height as both an absolute and relative predictor. Our data set includes stumps measured at a wide range of heights, and we chose to utilize Westfall's equations to include stump height as a variable. Westfall's coefficients were created using a dataset from 13 northeastern states, which did not include Michigan.

Species groups were assigned following Scott (1981). Westfall's published coefficients were used to generate predictions using a prediction data set composed of the 3,857 stems from 15 species groups. 542 stems were removed from the data set because they were from multi-stemmed trees, or determined from review of the original data sheets, residuals, and plots of DSH versus DBH to be extreme outliers. Predictions and residuals were plotted and visually examined. Equations were re-fit for all species groups representing 2% or greater of the fitting data set; i.e., those groups with more than 88 data points.

Equations were re-fit with a nonlinear generalized least squares approach, using the `gnls()` function in the `nlme()` package for the R Environment for Statistical Computing, using the coefficients provided by Westfall as a starting point. Increasing variance as DBH increased was observed in keeping with Westfall (2010)'s findings. Heteroscedasticity was accounted for by weighting DBH within the `gnls()` function;

for all species groups, the resulting coefficients were determined by ANOVA to be significantly different from those generated from a non-weighted gnls approach and from those provided by Westfall.

Most published equations are species- and region-specific. The development of substantially different prediction equations in different regions suggests that there are notable growth differences between states and regions. Our Michigan-specific coefficients generate more accurate predictions for our data set than any of the available equations and predictions, suggesting that this straightforward exercise was worthwhile.

Coefficients generated were subsequently used to predict the DBH from the DSH of all measured stumps. Then, the predicted DBH could be used with allometric equations to estimate above-ground biomass components.

Allometry and Calculations for Above Ground Biomass

In accordance to Jenkins (2003) above ground biomass (AGB) is calculated from generalized DBH to biomass conversion equations of the form:

$$\text{Total BM} = \text{Exp}(\beta_0 + \beta_1 \ln \text{dbh})$$

Where: **BM** = total aboveground biomass (kg dry weight) for trees 2.5 cm dbh and larger, **Exp** = exponential function, **dbh** = diameter at breast height (cm), **ln** = log base e (2.718282), parameters β_0 and β_1 are unique to species groups. See Jenkins (2003; 2004) for detailed information on the use, accuracy, and additional discussion about the application of these allometric equations.

Allometry and Calculations for Component Biomass

Biomass for tree components is derived from total biomass using component ratio multipliers from Jenkins (2003). Components are broken down into the following categories:

1. Foliage
2. Branches
3. Course roots
4. Stem bark
5. Stem wood

Biomass for each component is calculated from input parameters input into the equation of the form:

$$\text{Ratio multiplier} = \text{Exp}(\beta_0 + \beta_1/\text{dbh})$$

Where: **Exp** = exponential function, **dbh** = diameter at breast height (cm), parameters β_0 and β_1 are unique to component for hardwood and softwood species. The ratio multiplier is then multiplied against the Total BM equation aforementioned. Figure 38, reproduced from Jenkins (2003), show graphically how component biomass varies as a function of DBH.

Figure 38. Proportion of aboveground biomass for hardwood and softwood species groups (left and right, respectively). Reproduced from Jenkins (2003).

See Jenkins (2003), and Jenkins (2004) for detailed information on the use, accuracy, and additional discussion about the application of these allometric equations.

Allometry and Calculations for Downed Dead Wood

The DDW sampling protocol followed Affleck (2008) and is a direct calculation based on particle tally. The total volume is calculated as follows:

$$\text{Volume (m}^3\text{/ha)} = (\text{PI}) * (10000) / (2 * 900) * (\text{Transect tally})$$

Volume was calculated for each transect by decay class, then averaged to plot level and stand level. Then a total mass was calculated by assigning density to each decay class, following Harmon et al. (2008):

$$\text{Mass}_{\text{DC-Sp-S}} (\text{Mg/ha}) = \text{Volume (m}^3\text{/ha)} * \text{Density (Mg/m}^3\text{)}$$

$$\text{Uncertainty Mass}_{\text{DC-Sp-S}} (\text{Mg/ha}) = \text{Volume (m}^3\text{/ha)} * \text{Uncertainty}_{\text{Density}} (\text{Mg/m}^3)$$

Since species distribution was not available for tallies of DDW we assumed that the DDW distribution matched the pre-harvest BA distribution. Thus, the density multiplier for each decay class was calculated by a weighted average of pre-harvest BA percentage by species for each stand:

$$\bar{x} = \frac{\sum_{i=1}^n w_i x_i}{\sum_{i=1}^n w_i},$$

Where w_i is the pre-harvest BA percent by species, and x_i is the density multiplier, of each decay class, for each species.

Allometry and Calculations for Soils

Soil carbon estimation in the case of measuring the < 2 mm fraction was done with an Elemental Analyzer machine, percent carbon of this fraction can then be multiplied back to density to obtain an estimation of total carbon by density. Organic matter fraction > 2 mm was weighed and can be multiplied by a factor of 0.5 to obtain carbon by density. Inorganic fractions > 2 mm were weighed and volume displaced for density and are assumed to contain no organic carbon.

Results

Above Ground Biomass

Table 17 summarizes averaged harvest intensity on a landscape level (all stands) in terms of basal area per hectare, and trees per hectare.

Table 17. Landscape level average of harvest intensities.

Pre-harvest Basal Area/Hectare	Post-harvest Basal Area/Hectare	Basal Area removed	Pre-harvest trees/hectare	Post-harvest trees/hectare	Trees/hectare removed
33.2783	22.0974	11.1809	736.0591	539.3114	196.7477

Standing Live Biomass

Results for standing biomass, both pre- and post-harvest, are presented in Table 18 through Table 22.

Table 18. Pre- and post-harvest above ground biomass in tonnes/hectare.

Pre-harvest Above Ground Biomass (tonnes/hectare)		Post-harvest Above Ground Biomass (tonnes/hectare)	
Mean	463.5976	Mean	284.1188
Standard Error	10.2942	Standard Error	8.3900
Standard Deviation	103.4554	Standard Deviation	84.3184
Sample Variance	10703.0219	Sample Variance	7109.5873
Range	479.6559	Range	429.9014
Minimum	292.7582	Minimum	100.0043
Maximum	772.4141	Maximum	529.9057

Table 19. Pre- and post-harvest live branch biomass in tonnes/hectare.

Pre-harvest Branch (tonnes/hectare)		Post-harvest Branch (tonnes/ha)	
Mean	66.2356	Mean	41.9846
Standard Error	1.3520	Standard Error	1.1542
Standard Deviation	13.5870	Standard Deviation	11.5998
Sample Variance	184.6068	Sample Variance	134.5549
Range	60.0681	Range	56.6780
Minimum	42.6290	Minimum	17.1963
Maximum	102.6971	Maximum	73.8742

Table 20. Pre- and post-harvest live foliage biomass in tonnes/hectare.

Pre-Harvest Foliage (tonnes/hectare)		Post-harvest Foliage (tonnes/hectare)	
Mean	10.6320	Mean	6.6266
Standard Error	0.6207	Standard Error	0.4114
Standard Deviation	6.2378	Standard Deviation	4.1348
Sample Variance	38.9107	Sample Variance	17.0962
Range	30.5785	Range	19.4996
Minimum	5.2292	Minimum	1.8462
Maximum	35.8078	Maximum	21.3458

Table 21. Pre- and post-harvest live stem wood in tonnes/hectare.

Pre-harvest Stem Wood (tonnes/hectare)		Post-harvest Stem Wood (tonnes/ha)	
Mean	326.2434	Mean	198.5383
Standard Error	7.4284	Standard Error	5.9855
Standard Deviation	74.6548	Standard Deviation	60.1532
Sample Variance	5573.3387	Sample Variance	3618.4100
Range	355.1336	Range	308.7689
Minimum	198.7997	Minimum	67.9316
Maximum	553.9333	Maximum	376.7004

Table 22. Pre- and post-harvest live stem bark in tonnes/hectare.

Pre-harvest Stem Bark (tonnes/hectare)		Post-harvest Stem Bark (tonnes/ha)	
Mean	60.4866	Mean	36.9692
Standard Error	1.3757	Standard Error	1.1107
Standard Deviation	13.8254	Standard Deviation	11.1627
Sample Variance	191.1423	Sample Variance	124.6053
Range	66.7468	Range	57.0037
Minimum	35.6193	Minimum	13.0302
Maximum	102.3661	Maximum	70.0339

Standing Live Biomass Removed

Results for live biomass removed in the most recent harvest are presented in Table 30 through Table 32.

Table 23. Above ground biomass removed in tonnes/hectare.

Removed Above Ground Biomass (tonnes/hectare)	
Mean	179.4788
Standard Error	8.2895
Standard Deviation	83.3082
Sample Variance	6940.2497
Range	405.7909
Minimum	31.4143
Maximum	437.2052

Table 24. Branch and foliage biomass removed*in tonnes/hectare. *Removed in case of these harvest areas does not mean site removal, as they were left on site.

Removed* Branches (tonnes/hectare)		Removed* Foliage (tonnes/hectare)	
Mean	24.2510	Mean	4.0053
Standard Error	1.0949	Standard Error	0.2720
Standard Deviation	11.0033	Standard Deviation	2.7331
Sample Variance	121.0721	Sample Variance	7.4700
Range	55.1420	Range	15.0029
Minimum	4.0294	Minimum	0.5418
Maximum	59.1715	Maximum	15.5447

Table 25. Stem wood and Stem bark removed in tonnes/hectare.

Removed Stem Wood (tonnes/hectare)		Removed Stem Bark (tonnes/hectare)	
Mean	127.7051	Mean	23.5174
Standard Error	5.9545	Standard Error	1.0991
Standard Deviation	59.8421	Standard Deviation	11.0457
Sample Variance	3581.0771	Sample Variance	122.0070
Range	289.8579	Range	53.7141
Minimum	22.6716	Minimum	4.1716
Maximum	312.5294	Maximum	57.8857

Downed Dead Wood

Results for estimates of DDW by decay class are presented in

Table 33 through
Table 37.

Table 26. DDW Biomass – Decay Class 1, and uncertainty* in allometric calculation. *Equivalent to one standard error of the mean.

<i>Biomass - Decay Class 1 kg/ha</i>		<i>Biomass uncertainty* - Decay Class 1 kg/ha</i>	
Mean	12.9975	Mean	0.8318
Standard Error	0.9768	Standard Error	0.0646
Standard Deviation	9.4204	Standard Deviation	0.6233
Sample Variance	88.7439	Sample Variance	0.3885
Range	46.5246	Range	2.9121
Minimum	0.0000	Minimum	0.0000
Maximum	46.5246	Maximum	2.9121

Table 27. DDW Biomass – Decay Class 2, and uncertainty* in allometric calculation. *Equivalent to one standard error of the mean.

Biomass - Decay Class 2 kg/ha		Biomass uncertainty* - Decay Class 2 kg/ha	
Mean	9.3561	Mean	1.6498
Standard Error	0.8045	Standard Error	0.1396
Standard Deviation	7.7582	Standard Deviation	1.3461
Sample Variance	60.1890	Sample Variance	1.8120
Range	38.1217	Range	7.7918
Minimum	0.2514	Minimum	0.0476
Maximum	38.3732	Maximum	7.8393

Table 28. DDW Biomass – Decay Class 3, and uncertainty* in allometric calculation. *Equivalent to one standard error of the mean.

Biomass - Decay Class 3 kg/ha		Biomass uncertainty* - Decay Class 3 kg/ha	
Mean	3.4187	Mean	0.5718
Standard Error	0.1730	Standard Error	0.0313
Standard Deviation	1.6683	Standard Deviation	0.3023
Sample Variance	2.7834	Sample Variance	0.0914
Range	6.9921	Range	1.4392
Minimum	0.5592	Minimum	0.0808
Maximum	7.5514	Maximum	1.5200

Table 29. DDW Biomass – Decay Class 4, and uncertainty* in allometric calculation. *Equivalent to one standard error of the mean.

Biomass - Decay Class 4 kg/ha		Biomass uncertainty* - Decay Class 4 kg/ha	
Mean	1.3871	Mean	0.2967
Standard Error	0.0936	Standard Error	0.0274
Standard Deviation	0.9030	Standard Deviation	0.2640
Sample Variance	0.8154	Sample Variance	0.0697
Range	4.3647	Range	1.3269
Minimum	0.0000	Minimum	0.0000
Maximum	4.3647	Maximum	1.3269

Table 30: DDW Biomass – Decay Class 5, and uncertainty* in allometric calculation. *Equivalent to one standard error of the mean.

Biomass - Decay Class 5 kg/ha		Biomass uncertainty* - Decay Class 5 kg/ha	
Mean	0.9704	Mean	0.1940
Standard Error	0.0708	Standard Error	0.0180
Standard Deviation	0.6824	Standard Deviation	0.1737
Sample Variance	0.4656	Sample Variance	0.0302
Range	3.1850	Range	1.1079
Minimum	0.0000	Minimum	0.0000
Maximum	3.1850	Maximum	1.1079

Leaf Litter

Most leaf litter samples were of relatively low density, below about 0.06 g/cm³ (Figure 39; Table 38). Total C content was about 45% and N content 1.3%, yielding a C:N ratio of about 32:1 (Table 39).

Table 31: Leaf litter densities in g/cm³

Density (g/cm³)	
Mean	0.0519
Standard Error	0.0017
Standard Deviation	0.0526
Sample Variance	0.0028
Range	0.4170
Minimum	0.0030
Maximum	0.4201
Confidence Level (95.0%)	0.0033

Figure 39: Frequency of leaf litter density by class and cumulative percentage represented in each density class.

Table 32. Percent nitrogen, percent carbon, and carbon:nitrogen ration for leaf litter.

% Nitrogen		% Carbon		C:N	
Mean	1.3480	Mean	43.5714	Mean	32.4975
Standard Error	0.0350	Standard Error	1.0984	Standard Error	1.0150
Standard Deviation	0.1212	Standard Deviation	3.8048	Standard Deviation	3.5160
Sample Variance	0.0147	Sample Variance	14.4766	Sample Variance	12.3626
Range	0.4210	Range	12.8120	Range	12.7589
Minimum	1.1330	Minimum	34.5350	Minimum	26.7299
Maximum	1.5540	Maximum	47.3470	Maximum	39.4887
Confidence Level (95.0%)	0.0770	Confidence Level (95.0%)	2.4175	Confidence Level (95.0%)	2.2340

Below Ground Biomass
Coarse Roots

Table 33. Pre- and post-harvest coarse roots for live trees in tonnes/hectare.

Pre-harvest Course Roots (tonnes/hectare)		Post-harvest Course Roots (tonnes/hectare)	
Mean	87.6849	Mean	53.8405
Standard Error	1.9524	Standard Error	1.5879
Standard Deviation	19.6218	Standard Deviation	15.9584
Sample Variance	385.0153	Sample Variance	254.6719
Range	88.5255	Range	79.5276
Minimum	54.4027	Minimum	18.6592
Maximum	142.9282	Maximum	98.1868

Table 34. Coarse roots associated with cut trees in tonnes/hectare.

Removed* Course Roots (tonnes/hectare)	
Mean	33.8444
Standard Error	1.5474
Standard Deviation	15.5516
Sample Variance	241.8528
Range	75.1308
Minimum	5.8072
Maximum	80.9380

Soils
Soil Carbon

Table 35. Density of soil fraction < 2 mm in grams/cm³

Density (g/cm3)	
Mean	1.0970
Standard Error	0.0128
Standard Deviation	0.2806
Sample Variance	0.0787
Range	1.6529
Minimum	0.0755
Maximum	1.7284

Table 36. Percent carbon for soils.

% Carbon	
Mean	2.8944
Standard Error	0.1620
Standard Deviation	3.6897
Sample Variance	13.6137
Range	47.2840
Minimum	0.3250
Maximum	47.6090

Table 37. Organic matter fraction > 2 mm weight in grams.

Organic matter > 2mm Weight (g)	
Mean	4.3126
Standard Error	0.1556
Standard Deviation	3.4620
Sample Variance	11.9857
Range	29.0300
Minimum	0.1300
Maximum	29.1600

Soil Nitrogen

Table 38. Percent carbon for soils.

% Nitrogen	
Mean	0.1681
Standard Error	0.0075
Standard Deviation	0.1699
Sample Variance	0.0289
Range	1.8590
Minimum	0.0230
Maximum	1.8820

Carbon Nitrogen ratio

Table 39. Carbon:nitrogen ratio for soils.

C:N	
Mean	16.7972
Standard Error	0.1980
Standard Deviation	4.5107
Sample Variance	20.3460
Range	36.2256
Minimum	11.0882
Maximum	47.3138

Predicting DDW Volume production

Predicting the amount of material produced from a conventional harvest has made it difficult to estimate what amount of residue material is functionally available. As mentioned in the operational considerations section, predicting DDW production as a function of harvest intensity can assist land managers in all facets of operations: economically, meeting management guidelines, and meeting management objective which improve forest health and productivity. The relationship shown in Figure 40 can be used to forecast residue production from pre-harvest cruise data.

Figure 40. Predicting volume of DDW production from harvest intensity (BA removed).

Discussion

An analysis of the sustainability of biomass harvest with requires application of the three pillar model of sustainability: social, economic, and environmental constraints and concerns. Biomass harvesting represents a significant feedstock for the generation of heat, power, and liquid fuels. However there are many constraints which limit its economic and social viability. Similarly, there are environmental concerns over its impacts on forest productivity and wildlife habitat. This scope of this research requires an analysis of models for sustainability and their specific application to biomass utilization.

The mode and quantity of utilizing energy resources is a keystone of sustainable development in our society. Biomass utilization for the production of liquid fuels, as well as electricity and heat, has become a focal point in satisfying renewable energy policy standards. The immediacy of renewable energy utilization has spurred a proliferation of research and development into biologically sourced energy (Kajikawa & Takenda, 2008). The appeal of a carbon-neutral energy sources from potentially closed-loop systems, in terms of biomass, has lead to the increased utilization of energy resources such as energy crops, forest residues, food wastes. Utilization of forest residue products for the production of heat, power, and liquid bio-fuels (i.e. – ethanol and biodiesel) is gaining popularity as a way to meet the renewable energy demands of our society (Perlack et al. 2005).

Forest residue products are typically left after timber harvest and include tree tops, branches, defective and non-merchantable trees. Removing these residues from forests represents a substantial source of

biomass feedstock for bioenergy applications; however this potential scale of removal calls for research to understand the sustainability of residue utilization.

While environmental impacts are at the core of understanding the sustainability of residue harvest, as well as the utilization of energy crops, etc., there is a largely undertreated dimension of sustainability science which deals with the normative nature of resource management (Hagan and Whitman, 2007, Hagan and Whitman, 2006, Vucetich and Nelson 2010, Kajikawa, 2008).

Society, Economics, and Sustainability

A superficial treatment of the social and economic nature of sustainability will be discussed in this paper, inasmuch as it is a grossly overlooked when discussing the science of sustainability. Kajikawa (2008) highlights this point succinctly noting that “Defining sustainability is ultimately a social choice about what to develop, what to sustain and for how long, and is thus a deeply normative process”. The treatment of models of sustainability in this paper will briefly cover the three pillar model which has been a commonly used model for sustainable enterprise. The aspects of the three pillar model are the social, economic and environmental dimensions. This model serves as a foundation for many scientific endeavors toward development in the direction of each pillar, as it were, in the effort to attain “sustainability”. While this model serves well as a conceptual foundation toward defining sustainability, in many ways it does not address the normative process directly, and moreover, does not further answer the question of whether human needs define the limits of sustainability, or if economic or environmental constraints should define the limits of human need and utilization (Vucetich & Nelson, 2010).

Defining human need is similarly a deeply normative process which involves making conscientious decisions in defining standard of living and quality of life. Ideally speaking, without resource scarcity, this would involve a quality of life which is defined by physical health, namely the availability to nutrition, clean water, and shelter. A standard of living is similarly defined in a socially normative way which reflects what a society has come to expect as an acceptable standard of consumption. It is not the intent for this discussion to address the standard of living as it is ethically debatable what should constitute defining standard of living. It should not go without saying however that this question in and of itself is what needs discussion and agreement when defining the sustainability of any resource use. The United Nations defined sustainability in such a way by saying “sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” (UN General Assembly, 2005).

Forest Health and productivity

At the core of this discussion are inherent difficulties in sampling methodology with an enormous potential to introduce bias. Contrasting, anomalous, and even conflicting data has been found from studies such as the North American Long-term Soil Productivity (LTSP) Experiment (Powers et al. 2005), as well as those mentioned above (Covington, Yanai et al. 2003, Moore 2005, Moore 2006). The LTSP study notes no general decline in soil C concentrations, after a decade, in treatments where all aboveground living vegetation was removed, with the exception of the forest floor being retained. In a second treatment all organic matter, including leaf litter, exposing mineral soil, was removed. Results for this treatment were anomalous in that soil C concentration increased for some sites over the decade. Possible explanations are posited ranging from sampling error to bias sampling due to mixing of organic matter into mineral soils during harvest operations, to overall bulk density increase from soil compaction at sample sites. Similarly, Covington’s sample design is questionable in that plots were selected based on non-random assumptions about the behavior of the forest floor. Overall, this illustrates the dynamic nature of edaphic processes. While conflicting data can result in lack of consensus about the effects of residue harvest, we can make some generalized assumptions that are supported in literature:

1. Complete removal, or at least large proportions, of nutrients in the form of biomass, leaf litter, and down dead wood will at some point have deleterious effects on soil productivity (Vance, 2000, Burger 2002, Fisher and Binkley, 2000, Van Miegroet, 2009).
2. Harvesting operations on short rotation will have a higher probability of having negative short- and long-term impacts on soil productivity.
3. Certain ecosystems are more susceptible to nutrient depletions. This is most dependent upon soil characteristics, such as shallow soil depths, texture (course sandy being most susceptible), pH (site dependent and nutrient capital dependent), and extremely poorly drained sites (Benjamin 2009). For example Wisconsin identifies “dysic Histosols” as sites for completely restricted for removing woody debris.
4. Harvest operations should follow BMP’s for reducing impact to soils either through compaction or tillage (Sheperd 2006).

Historically, human need has come to define the limits of a resource use, until it becomes scarce. Much to this effect, forests in past have been utilized in an environmentally un-sustainable way, which has typically led toward strongly governed use of a scarce resource. A recent example would be the practice of litter raking in Europe, which was widely socially acceptable through the mid-1900’s, until it became known that it was steadily diminishing forest productivity (Van Miegroet, 2009). This boom and bust cycle is repeated throughout history and to varying degrees, and today is becoming more of a reality with respect to a diminishing fossil fuel supply.

The more immediate problem has become an ever increasing energy demand, and the ultimate scarcity of resources to satisfy this increase. As a confounding problem, greenhouse gas emission of anthropogenic sources is changing our climate and consequently the ecological world which thrives upon it. For this reason alternative and renewable energy resources, such as forests, have had a resurgence of interest in their sustainable utilization (Kajikawa and Takenda, 2008). If forest products are used to offset fossil fuel consumption, there is a potential to realize a closed-loop system of utilization. A closed-loop system of carbon involves the sequestration of carbon emissions through photosynthesis of trees.

Answering the complex question of sustainability of residue harvesting from forests comes down to what we value in a forest. For the purpose of this discussion, site productivity is the focal point as a proxy of forest health to meet human needs. It could go without saying that valuation of site productivity alone does not satisfy the three pillar model of sustainability, due to added values of ecosystems, such as biodiversity, aesthetics, ecosystem services and trophic cascades, clean water, etc. For this reason, shifting values in how we utilize our forest resource represents a shift in the normative values that define how we view the sustainability of forest harvesting.

The three pillar model on its own is an acknowledgement of the multi-dimensional nature of sustainability science, where social, economic, and environmental considerations are all recognized as important factors to sustainable development. On its own it serves well in balancing management directives that have at their core the interest of satisfying all three dimensions. Figure 41 is a Venn diagrammatic representation of this idea, where the areas of overlap are those that satisfy more than one component, and similarly, the area in the middle where all three overlap is conceptually where we attain sustainable development that can satisfy all three dimensions. Alternatively, Figure 42 is a conceptually different model where we define goals of sustainability by the limits within the environmental dimension. The concept between these models is quite different and can be said to represent a very different set of normative values.

Many historical examples show a shift from the stand alone three-pillar model to the environmentally constrained model of sustainability. An immediately relevant example is the establishment of “Best

Management Practices (BMP's)". Similarly, the drafting and adoption of Biomass Harvesting Guidelines is a reflection of the acknowledgement that impacts to environmental health have a large effect on long-term economic and social sustainability. Each of these management directives represents a shift in a normative valuation resulting from a potentially "un-sustainable" use of forest resources.

Figure 41. Stand-alone 3-pillar model.

Figure 42. 3-pillar model defined by the limits of environmental sustainability.

By approaching resource management from a scientific approach with these dimensions of sustainability in mind we can make more informed and educated decision. Making more informed and conscious decisions in management highlights the importance of adaptive management. To highlight this difference, Kajikawa, 2008 states:

"Sustainability literally means the ability to sustain...The term has been used to express the state in which levels of harvest in agriculture, fisheries, and forestry are maintained within the capacity of the ecosystem, which is therefore recoverable. In that sense, sustainability means environmental

sustainability – in other words sustainability of the ecosystem’s function to provide us with food, fish, and other products and services. It is not the same as conservation, where the intention is to preserve the ecosystem regardless of human purpose.”

It is thereby important to designate that, while not mutually exclusive, sustainability and conservation represent two very different sets of normative values, again highlighting the importance of adaptive management. To this extent BMP’s represent a valuation for human providence from forest productivity. Similarly, Biomass Harvesting Guidelines reflect a value of forests beyond strictly short-term economic or social gain.

As mentioned previously Biomass Harvesting Guidelines generally recognize the following criteria as components of impacts in consideration (Evans and Perschel 2009):

- *Dead woody material* – includes percent retention recommendations of coarse/fine woody material and standing snags.
- *Wildlife and Biodiversity* – environmental impact on species composition in harvest area and with connectivity to sensitive species/ecosystems.
- *Water Quality and Riparian Zones* – environmental impact on riparian zones, wetlands, and hydrology that have connectivity to harvest area.
- *Soil Productivity* – recovery rates that affect sustainability of harvest with respect to nutrients, soil compaction, and biological material.
- *Silviculture Treatment* – implementing treatment objectives for harvest area with respect to planning, variable retention harvesting, regeneration timeline, operations, road/trail layout, re-entry, aesthetics, and post-operation treatment.
- *Disturbance Considerations* – size and type of disturbance from harvesting having a direct impact on species composition, disease/pest susceptibility, and fire/fuels management.

These guidelines represent at their core a valuation of these ecosystem services and characteristic for either their inherent value or their value to meet the needs at present, without compromising the social, economic, and environmental needs of future generations.

Site productivity is strongly governed by physical, chemical, and biological processes affected directly by management (Pritchett and Fisher, 1987). Figure 41 showed a conceptual model of how carbon and nutrients are cycled through and within an ecosystem, and represent the areas of interest in measurement as indicators of ecosystem health. Sustaining these processes for future utilization of these resources is integral in the long-term sustainability of biomass harvesting for bioenergy feedstock. An adaptive framework for application to different management objectives is necessary to attain long-term sustainability. This includes discourse and establishments of indicators to hallmark whether we are sustainably developing renewable energy sources from biomass.

The following frame outlined by Kajikawa, 2008, is a systematic approach which synthesizes the multi-faceted goals of BMP’s and Biomass Harvesting Guidelines. Application of such a framework pre-emptively to biomass harvesting can in itself help assess whether we are sustaining each dimension of sustainability. The framework is outlined in such a way:

Research Core and Framework of Sustainability Science (Kajikawa, 2008):

- I. Goal setting- normative goal setting.
- II. Indicator setting- Targets are quantitative values of indicators for attaining the goal at a specific time or within a certain timeframe.
- III. Indicator measurement- Indicators are quantitative measures selected to assess progress toward or away from a stated goal.
- IV. Causal chain analysis- Complexity, vulnerability, and resilience are the key concepts to understanding and modeling a coupled human-environment system.
- V. Forecasting- predictive modeling for goal setting from conception to completion
- VI. Backcasting- predictive modeling for goal from completion to conception.
- VII. Problem–solution chain analysis- predictive model of foreseeable problems and solutions.

This framework as applied to biomass harvesting encompasses the dimensions outlined in the three pillar models of sustainability. While the social dimension is in part reflected in our goals for biomass harvesting, it is important to also apply this framework to the social dimension of sustainability is a systematic way to assess our successes, or failures, toward social sustainability. Indicators can be applied to both economic and environmental dimensions as well, where these will serve the function of indicating whether it is economically feasible and will maximize an ecosystems ability to provide to human needs. Objectives IV-VII outline the need for adaptive management during the process of biomass harvesting.

“Goal setting is a normative process based on visions and social and political processes rather than on scientific activity per se, but it should have some rational basis” (Kajikawa, 2008). The rational basis for this is founded on the state of the science. From this information a systematic and adaptive approach needs to be taken when addressing the sustainability of biomass harvesting. This framework of management can be incorporated into BMP’s and Biomass Harvesting Guidelines, and to a large degree is reflected in those recommendations. Forest harvesting operations aimed at meeting these recommendations have to the best of their ability addressed the impacts of increased harvested intensity. However, these decisions need to be made on the ground and explicitly targeted at specific management objectives. This to a large extent has gone undone, and as well to a large extent is not based in concrete knowledge of the impacts that residue removal will have. Adaptive management, analogous to silvicultural management, needs to be implemented on a site by site and case by case basis. This requires more definitive research to be done in the area of harvesting in Northern Hardwood forests to calculate the impacts of residue harvesting. While this research is needed immediately, it does not have to halt the utilization of this resource. Implementing the research framework outlined above can serve as research in itself to answer the question of how sustainable is residue harvesting. Loggers, consultants, and forest resource managers should incorporate residue removal and retention in an adaptive and prescriptive manner.

Biomass harvesting for use as a resource for biofuel feedstock has a huge potential to satisfy each dimension of sustainability. Given the current economic, social, and environmental climates, this alternative energy source used in a sustainable way has the potential to meet renewable energy standards, improve forest health, improve the socio-environmental interaction, and the socio-economic interaction. A systematic framework of research, monitoring, and oversight of biomass harvesting needs to be established. With a systematic and adaptive framework this renewable energy resource can be used as piece of the puzzle in meeting the ever increasing demand for energy while mitigating the growing problem of anthropogenic sources of greenhouse gas emissions. In balancing each dimension of

sustainability in a rational way based on current science we can utilize this resource to its maximum potential. The realization of that potential can only be made through scientific research into each dimension and by satisfying all three dimensions.

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Sub-Task D1: Engage Supply Chain Partners in Producing Biofeedstocks.

Reported by Christopher Peterson and William Knudson

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Final Report
(March 2009 through September 2011)

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EXECUTIVE SUMMARY

The Supply Chain

This report outlines the tasks and findings that were achieved within Task D1 – Engage Landowners in Producing Biofeedstocks of the project. The purpose of this task was to design a landowner engagement process, including the optimal design of the contracting relationships with the landowners who are the ultimate sources of access to the woody biomass supply in the Upper Peninsula.

There are four major segments in the wood and biomass supply chain in Michigan. Landowners own and manage wood and forest residue production areas. Loggers either provide harvesting services to landowners or buy stumpage from them. Sequentially, whoever owns stumpage and residues trades with saw mills or directly with final processors such as pulp and paper companies, bioelectricity producers, or potential cellulosic ethanol firms.

Transactions between landowners and loggers take distinctive formats depending on the nature of the production field. For instance, wood and biomass from state and federal land are largely traded via auctions. For these public lands, the trading process unfolds as follows: 1) State and federal land administrators define the section of land to be exploited and write a formal contract specifying rights and obligations to the winning bidder; 2) Loggers interested in acquiring stumpage from the specific land section must register for the auction; 3) Registered loggers bid and as result of the auction, the highest bid wins the right to harvest wood and forest residues in the segment of land, and finally; 4) Contracts are signed between federal/state parks and loggers for a single harvest.

The trading process differs when small private landowners are the sellers. In this case, loggers contact landowners and instigate the buying proposes. Occasionally similar offers are made to neighbor landowners in order to dilute fixed harvesting costs and increase profit margins due to economies of scale. Agreements between small scale farmers and loggers are often informal unwritten agreements.

When corporations own production land, loggers are likely to provide services of harvest and transportation without trading wood or residues. In this case, corporations keep the ownership of the forest products and outsource harvesting and transportation services. Personal conversations with experts suggest that the outsourcing strategy decreases risks related to market uncertainty and decreases production costs associated with machinery ownership. Contracts between corporations and loggers usually last between one and three years.

Commercial landowners trade timber with saw mills and with pulp and paper companies directly using formal trading contracts. Secondary contracts may also be settled with furniture manufacturers, wood preservation firms, etc. for high-value wood products such as veneer logs. Forest residues from commercial lands are also delivered to electricity generators based on formal contracts. Because of the higher ex-ante bargaining power and lower ex-post monitoring costs, commercial landowners are able to settle longer written contracts with mills and processors compared to independent loggers. The potential opportunistic behavior and market power of mills and processors tends to be offset by the economies of scale achieved by commercial landholders.

Generally, processors of forest residues and loggers settle formal written trading contracts that last between one and three years. The price for residue is determined at the delivery time as a function of the load weight. Other specific attributes such as quality, quantity, delivery schedule, and payment timing are ex-ante defined through formal contracts between the parties. Personal conversations with industry agents suggest that the limited number of residue processors exploit their market power and frequently act opportunistically (i.e. hold-up contracts).

Findings

Our analysis reveals two primary types of private landowners. The first are large commercial landowners; many of these firms are or were paper companies. The second type of private landowners includes: trusts, hunt clubs, camps, and various sundry other types of landowners. These landowners may or may not see forestry and forest management as the primary reason for owning the land.

As part of our analysis of wood/biomass procurement strategies, two focus groups were conducted in the Escanaba region at the end of August. The first focus group examined the perceptions of landowners about the challenges of selling wood/biomass to downstream players and more specifically about their opinions of various coordination mechanisms including contracts and contract terms. Similar questions were also explored in a second focus group; however, this group was composed solely of loggers in the region.

The results of the focus group discussions presented above provide several insights on how to best govern supply chain relationships in the Michigan Upper Peninsula wood industry. Contracts are the primary mechanism used in the industry today. This finding is consistent with transaction cost theory.

The central conflict in the Michigan Upper Peninsula wood supply chain is the logger (or commercial landholder) and mill relationship; therefore, we focus our attention here. The results of the focus groups also indicate that uncertainty is a primary driver of the types of contract terms and conditions that these supply chains players are willing to accept. To address this issue, respondents suggested that an optimal contract would contain the following coordination features: a) flexibility in compensation and contract terms, b) terms that are binding and enforceable, c) short term length, d) cost of production adjustments, e) ability to procure a steady supply, and f) minimize transaction costs. Using these features, we analyzed four types of contracts: 1) handshake agreements, 2) fixed price contracts, 3) short-term performance contracts, and 4) long-term performance contracts. The results of this analysis can be found in Appendix D1(d).

Our analysis indicates that a short-term performance contract is likely to be best alternative to govern the relationship between loggers and mills. This type of contract offers loggers the ability to be flexible in the volume and timing of their deliveries by providing premiums or discounts for meeting contract specifications rather than “all or nothing” provisions. From the logger’s perspective this feature is likely to increase the perceived stability of the contract.

Contracts should also have a short-medium term, likely no more than 3 years. Loggers expressed significant concern about the uncertainty of market; they are sensitive to getting locked in to unfavorable contract terms as market conditions change. One way for a mill to extend the term of the contract may be to include a “renewal” mechanism in which contract may be automatically renewed, renegotiated, or extended if certain market/production conditions are recognized. As an example, a contract may be renewed if prices trade within a certain range for a specified period of time during the contract. Contracts should also include transparent and automatic cost of production adjustments.

Two issues of concern to loggers remain unaddressed by the alternative contract types that were explored: 1) the ability to maintain a steady supply of biomass, and 2) the potential of the saw mill to holdup the contract. Weather is a primary determinant of a small or independent logger’s ability to meet delivery schedules. However, this is not a variable that is under the control of the logger. At the same time, mills require a steady supply of biomass to operate their facilities at an efficient capacity. Two potential mechanisms may help to resolve this issue. The first would be to encourage coordination of supply among loggers. For example, poor logging conditions in one area could be offset by expanded production from other loggers without disruption to wood supply to the mill. Another option would be to store biomass for down production periods. Mechanisms to share the risks and costs of storing inventory between loggers and mills could increase the viability of this option.

Potential holdups are also an issue, and according to loggers, have been common in the industry. These holdups have eroded the trust of loggers and the reputation of mills. One way to resolve this issue would be to include hostages/bonds in the contract. Guarantees, upfront (non-refundable) payments, or investment in relationship specific assets are potential solutions. With respect to the latter, these investments do not necessarily need to be monetary. For example, mills could commit to support (e.g. share marketing and production information, etc.) and/or procure from a select group of loggers using exclusivity clauses.

FINAL TECHNICAL REPORT

This report outlines the tasks and findings that were achieved within Task D1 – Engage Landowners in Producing Biofeedstocks of the project. The purpose of this task was to design a landowner engagement process, including the optimal design of the contracting relationships with the landowners who are the ultimate sources of access to the woody biomass supply.

The Michigan/Upper Peninsula Wood Supply Chain

The purpose of this section is to document the wood supply chain for the Michigan forestry biofuels industry with a particular emphasis on the Upper Peninsula of Michigan. The schematic found in Appendix D1(a) serves to outline the competitive structure and dynamics present in this industry. This supply chain representation is the result of meetings with forestry experts, summary reports released by different sectors of the agri-food and forestry industries and an extensive search of the scientific literature. We also used the methodology of the North American Industry Classification System (NAICS) to better estimate the interactions among agents within the supply chain. Furthermore, we included two main flows of material; the first (dark solid line) represents the regular flow of primary wood products. The second (green dashed line) represents the flow of forest residues or biomass.

There are four major segments in the wood and biomass supply chain in Michigan. Landowners own and manage wood and forest residue production areas. Loggers either provide harvesting services to landowners or buy stumpage from them. Sequentially, whoever owns stumpage and residues trades with saw mills or directly with final processors such as pulp and paper companies, bioelectricity producers, or potential cellulosic ethanol firms.

In the Upper Peninsula (UP) of Michigan, state and federal land together represents 49% of the total forest land. Corporations, or large commercial landowners, own and manage almost 24% of the production area and the remainder is shared among multiple types of private landowners. Transactions between landowners and loggers take distinctive formats depending on the nature of the production field. For instance, wood and biomass from state and federal land are largely traded via auctions. For these public lands, the trading process unfolds as follows: 1) state and federal land administrators define the section of land to be exploited and write a formal contract specifying rights and obligations to the winning bidder; 2) loggers interested in acquiring stumpage from the specific land section must register for the auction; 3) registered loggers bid and as result of the auction, the highest bid wins the right to harvest wood and forest residues in the segment of land, and finally 4) contracts are signed between federal/state parks and loggers for a single harvest.

The trading process differs when small private landowners are the sellers. In this case, loggers contact landowners and instigate the buying proposes. Occasionally similar offers are made to neighbor landowners in order to dilute fixed harvesting costs and increase profit margins due to economies of scale. Agreements between small scale farmers and loggers are usually informal unwritten agreements. Moreover, it is not unusual to note consulting companies representing landowners in the negotiations with loggers. These consultants (also named foresters) seek better returns to landowners who quite often inherited land and are not familiar with the business opportunities available in their land.

When corporations own production land, loggers are likely to provide services of harvest and transportation without trading wood or residues. In this case, corporations keep the ownership of the forest products and outsource harvesting and transportation services. Personal conversations with experts suggest that the outsourcing strategy decreases risks related to market uncertainty and decreases production costs associated with machinery ownership. Contracts between corporations and loggers usually last between one and three years.

After harvesting forest products from public lands or from small scale private properties, loggers resell these materials to saw mills and to end use processors. In the UP of Michigan, saw mills and pulp & paper companies are the main destinations of the wood harvested. Transactions of wood between loggers and pulp & paper companies are sometimes arranged through informal agreements which are settled at the delivery time. Loggers also deliver forest products to veneer producers, wood pellet producers, wood pallet firms, furniture companies, and potentially to cellulosic ethanol producers.

Forest residues, on the other hand, are delivered to a limited amount of processors (most of them engaged in biomass-based electricity generation). As observed, the few electricity generators located in the UP of Michigan are likely to be integrated with pulp and paper companies. Forest residues and mill waste are utilized to generate electricity which is employed in the process of pulp and paper production. There are six biomass-based electricity generators in the State of Michigan but only one of those located in the UP trade electricity with utilities for distribution.

Generally, processors of forest residues and loggers settle formal written trading contracts that last between one and three years. The price for residue is determined at the delivery time as a function of the load weight. Other specific attributes such as quality, quantity, delivery schedule, and payment timing are ex-ante defined through formal contracts between the parties. Personal conversations with industry agents

suggest that the limited number of residue processors exploit their market power and frequently act opportunistically (i.e. hold-up contracts).

Commercial landowners trade timber with saw mills and with pulp and paper companies directly using formal trading contracts. Secondary contracts may also be settled with furniture manufacturers, wood preservation firms, etc. for high-value wood products such as veneer logs. Forest residues from commercial lands are also delivered to electricity generators based on formal contracts. Because of the higher ex-ante bargaining power and lower ex-post monitoring costs, commercial landowners are able to settle longer written contracts with mills and processors compared to independent loggers. The potential opportunistic behavior and market power of mills and processes tends to be offset by the economies of scale achieved by commercial landholders.

Saw mills are likely to be integrated with numerous other specialized firms due to the high level of asset specificity required for efficient production and the frequency with which transactions take place. Specifically, wood pallet production, wood preservation, re-sawing & planning, veneer production, window & door manufacturing, and wood pellet production all require specific assets and frequency delivery of wood for production. Therefore to minimize transaction costs it is often beneficial for mills to integrate with these types of firms. In the supply chain scheme (see Appendix D1(a)), the blue shaded area represents potential vertical integration among firms.

Besides the processing wood products, saw mills also produce different types of residues that are used for multiple purposes. Home heating, for instance, can be generated from burning saw dust, wood bark can be employed on electricity generation, and wood chips can be used for pellet manufacturing.

Wood and forest residues are used extensively as inputs into other sectors. The supply chain scheme (appendix D1(a)) highlights the most likely flows of wood products and forest residues among final processors. For instance, furniture companies may supply residues to electricity generators; paper and pulp companies may supply residues to cellulosic ethanol production; and so forth.

Among end processors of wood and residue, research has mainly focused on opportunities for electricity and cellulosic ethanol production. As mentioned before, there are cases of vertical integration between paper and pulp companies and electricity generators in the UP of Michigan. However, the biomass-based electricity has not been generally produced for sale purposes. In fact, in most cases, it has been used to replace other energy generating inputs such as coal in on-site production or energy purchased from local utilities.

The Optimal Contract Problem and Agency Issues

We reviewed the literature on procurement methods used in forestry, conducted an industry interview, and developed a base conceptual model to study potential contracting issues. Our findings indicate that only few studies have focused on wood procurement strategies in the last two decades. For instance, according to our review, a study conducted by Stier & Engelhard (1986) was the last study to review pulpwood procurement practices in Wisconsin and Upper Peninsula in Michigan. For a summary of the literature in this area see Appendix D1(b). This review is particularly important to help identify the strategies that may be used to ensure the consistent supply of wood and woody biomass for, either the generation of bioelectricity or for producing advanced biofuels (ex: cellulosic ethanol). The findings of the Stier & Engelhard (1986) study are summarized below.

Findings of Pulpwood Procurement Practices in Wisconsin and the Michigan Upper Peninsula (Stier & Engelhard 1986)

According to this study there are three factors that affect the wood procurement practices of a pulp and paper mill: (1) the operating policies of the mill, (2) the technological input requirements and (3) market demand (e.g. demand for pulp, etc.). Furthermore, pulp mills were found to use three alternative methods to procure pulpwood:

- a) **Direct purchase of timber:** Most mills who own forestland also purchase additional standing timber. Direct purchases account for 5 to 10% of the total pulpwood supply.
- b) **Contract directly with independent producers:** The most common procurement practice was to contract directly with independent producers (i.e. logging firms or landowners) to harvest and deliver pulpwood to mills. This method accounted for 75% of the total pulpwood supply (and industry professionals indicated the continued importance of contracts in pulpwood procurement). On average, pulp mills procured fiber from 100 different producers. Larger mills often dealt with more producers although they also have the option to deal with few very large producers. Some small producers are landowners who elect to harvest their own. The practice of directly dealing with landowners is limited to mills using softwood.
- c) **Pulpwood dealers or brokers:** Brokers are middlemen who serve the purpose of linking independent producers with the mill. Brokers take orders from mills and then contract with producers to fulfill the requirements of these orders. They also serve to pool the production of a large number of producers and schedule deliveries to the mill. By charging a brokerage fee for their service, wood sourced from brokers is relatively expensive. In 1986, pulp mills seldom relied on brokers with two exemptions: 1) being when the timber shed is located a significant distance from the mill, or 2) when the pulpmill required specific wood that could not be easily be supplied by independent producers. Under these two exemptions, brokers were used to mitigate asymmetric information concerns particularly given that local harvest conditions were not easily observed by the pulp mill.

Stier and Englehard (1986) also reviewed the terms and conditions of wood agreements that were available at the time. Their findings reveal the following characteristics of these agreements:

- a) *Shift from informal verbal agreements to formal written contracts.* However, written contracts were not viewed as legally enforceable and procurement managers strived to maintain strong relationships with the independent producers to mitigate conflicts.
- b) *Contract specifications* typically included a description of species, size requirements, price to be paid/received, unit of measurement (standard cord of 100 – in bolts vs. weight of wood), and volume to be supplied over a specified period of time.
- c) *Length of contract varied significantly* ranging in duration from annual (5 firms), biannual (1 firm), quarterly (6 firms), monthly (3 firms) to multi-year (2 firms) contracts.
- d) *Specified contingency arrangements.* For example, producers who failed to provide their delivery quota during a specified time period were either required to renegotiate the contract, or where shirking was evident, forced to except smaller or no contracts in the next period

Optimal Contract Design for Wood Procurement

A simple principal-agent model is informative to highlight the potential issues associated with procurement contracts for wood. Consider that, in general, a wood supply chain is composed of two self-interested actors: suppliers (i.e. logging firms) who harvest and deliver wood, and processors (i.e. ethanol producers, furniture manufacturers, pulp and paper mills, bioelectricity firms, etc.) who transform wood into other wood products. The contractual interaction between these two broadly understood classes of actors defines an agency relationship.

As an illustrative example of the types of contract design decisions that are necessary, consider a cellulosic ethanol producer (CE) who wishes to maximize profits from biofuel production using wood as the input. In order to do, the CE (i.e. principal) can enter into a contractual relationship with a logging firm (i.e. agent) to procure a supply of a specific type of wood (e.g. hardwood pulpwood). The cellulosic content contained in the wood is the major input for cellulosic ethanol production; the more cellulose that is contained in the wood, the more cellulosic ethanol the processor can produce. However, it is also known that the cellulosic content of wood diminishes over time after it has been harvested. One study estimates that an uprooted tree loses 40-60 per cent of the cellulosic content if the wood is left unprocessed for 10-15 days (Maser et. al., 1988). Therefore the CE desires that landing (i.e. the removal of logs from the forest) and delivery operations (i.e. transportation of wood to the processing site) be completed by the loggers soon after the tree has been cut.

From the agent's perspective, their goal is to harvest, land and deliver wood to the principal at the lowest possible cost to maximize their profits. In many cases, this means that it may be cost effective for logger's delay delivery until they have a full load or until weather conditions permit using lower cost logging practices. Since the loss of cellulosic content due to delayed landing has an adverse effect on ethanol production and on the principal's profitability, the principal's and the agent's incentives may be misaligned. This misalignment of incentives gives rise to a conflict of interest between the principal (CE producer) and the agent (logging firm) known as the *agency problem*. Further exacerbating this potential problem is that it is often difficult and/or costly for the principal to:

- 1) *ex ante* identify loggers who will delay delivery (i.e. *hidden information*), and
- 2) *ex post* monitor the logging practices of agents to determine the length of time between harvest and delivery (i.e. *hidden action*)
- 3) measure the cellulosic content of the wood before processing it

As a result, significant *agency costs* (e.g. monitoring, bonding and residual costs) may be incurred to address these incentive misalignment issues. In short, agency problems (i.e. moral hazard and adverse selection) are anticipated in the contractual relationship between the CE producer and the logging firm.

The Model

The contractual relationship described above can be captured in a simple principal-agent model. Consider that the prime objective of the principal (i.e. the ethanol processor) and the agent (i.e. the logger) is to maximize their respective utility functions. Their utility functions can be expressed as follows:

- (1) Principal's utility function: $B[R(c(t)) - w]$
- (2) Agent's utility function: $U(w, e) = u(w) - v(e)$, where
 $R(c(t))$: denotes that the revenue from the sale of ethanol is function of the cellulosic content in the wood which in turn is dependent on time taken (t) to land and deliver the wood after the tree has been cut.
 w : denotes the compensation received by the agent
 e : denotes the agent's effort exerted during logging and landing; high effort agents do not delay the delivery of wood
 $v(.)$: disutility from a particular level of effort

For the sake of simplicity, we assume a single-shot game and just two effort levels: high effort and low effort. Hence $e \in \{e^H, e^L\}$ where the disutility from higher effort is greater than the disutility from lower effort level, i.e. $v(e^H) > v(e^L)$.

The agent is interested in a wage, w , which is a cost to the principal, whereas the principal is interested in high levels of effort, e^H , since e^H implies the wood with higher cellulose content will be procured and therefore higher revenues. However, a high e^H translates into higher disutility for the agent. This explains the source of conflict in the relationship. This conflict results in costs associated with 1) measuring and monitoring the performance of agents, 2) creating incentives or bonds to align the interests of the agent with those of the principal, and 3) using suboptimal wood.

The design of effective incentive mechanism to minimize these costs is a central component of any optimal contract. Incentive mechanisms are used to either align the interests of the agent to those of the principal or to make it in the best interest of the agent to reveal the effort level they will exert. Examples of incentive mechanisms include adjusting compensation (i.e., wages) according to some sort of performance attribute (e.g. cellulosic content of the wood), profit sharing, and creating hostages (i.e. assets whose value will be decreased if the contract is broken). The goal of this project is to find out what incentive mechanisms will work best for the Michigan Upper Peninsula wood supply chain.

Landowners in the affected area

Using plat maps for the Upper Peninsula of Michigan researchers identified all landowners of 1,000 or more contiguous acres and categorized *these landowners* by type (i.e. federal, state, commercial, non-commercial, etc.) and by size (see Figure 1 below). A list of landowners with forest land over 1000 acres can be found in Appendix D1(c).

As suggested earlier, large landowners are more likely to be interested in and better able to service the needs of a large consumer of wood such as a power plant. Both the federal government and state government were found to be large landowners. State and federal parks, national shorelines, game areas, and similar types of land that are set aside for a specific purpose that precludes commercial forestry were excluded from the analysis.

Our analysis reveals two primary types of private landowners. The first are large commercial landowners; many of these firms are or were paper companies. The second type of private landowners include: trusts, hunt clubs, camps and various and sundry other types of landowners. These landowners may or may not see forestry and forest management as the primary reason for owning the land. Generally speaking, those landowners focused on forest management (i.e. large commercial landowners) enroll their land in the Commercial Forest Program. This program reduces property tax payments while the forest grows. In order to qualify for the program, the landowner must submit a forest management plan. While less common, noncommercial landowners also take advantage of the Commercial Forest Program.

Figure 1: Types of Landholders (>1000 acres) in the Michigan Upper Peninsula

Results of Landowner and Logger Focus Groups

As part of our analysis of wood/biomass procurement strategies two focus groups were conducted in the Escanaba region at the end of August. The first focus group examined the perceptions of landowners about the challenges of selling wood/biomass to downstream players (i.e. loggers and processing mills) and more specifically about their opinions of various coordination mechanisms including contracts and contract terms. Similar questions were also explored in a second focus group; however, this group was composed solely of loggers in the region. The qualitative analysis of this data collection is reported below.

Landowner Focus Group.

The landowner focus group was comprised of two individuals: one representing a large commercial landowner (LCL) and one who had a good working knowledge of small private landowners (SPL). In general, these two types of landowners have distinct motives for selling wood and marketing strategies. Notes from the focus groups are available from the author upon request.

LCLs own and manage forest land for wood production. They tend to formal written contracts with loggers, truckers and mills to harvest, deliver, and process wood/biomass, respectively. In general, they find it easy to attract loggers to harvest trees since there is both a large supply of logging firms in the Michigan Upper Peninsula and loggers are motivated to cut trees to repay debts incurred to enter/expand in the industry (i.e. logging is highly mechanized and requires large capital expenditures). The terms of a contract with a logger tend to be flexible to allow for the relationship to adapt to market/production conditions and may last as long as couple of years.

LCLs market their own wood/biomass via contracts to several mills. These contracts are volume-based and are negotiated frequently (i.e. quarterly). Though not common, large landowners may also store wood (typically only high value veneer logs) in order to maximize the value of the woodlot; however low quality or biomass is always delivered to the mill as soon as possible to minimize weight loss. For the LCLs, price is the most important factor in marketing wood production.

SPLs, on the other hand, tend to enter into agreements only when an opportunity presents itself, often as a result of contact with a logger. It is not uncommon for this type of landowner to be uninformed of the potential of their woodlot for wood/biomass production; SPLs are likely only to market their wood production once or twice in their lifetime. As such, SPLs frequently rely on foresters or independent loggers to value their parcel and find markets for their wood production. The greatest challenge that SPLs face is in determining which loggers to contract with to harvest/sell wood production (SPLs do not sell directly to mills). To solve this issue, many SPLs contract the services of foresters to value their tree stand and identify credible loggers (foresters also serve as an aggregator of forest land for loggers).

Most contracts with loggers are one-time formal written agreements although handshake agreements are not uncommon. Price is the most significant factor and terms may vary significantly (and are often renegotiated during the agreement period). SPLs also expressed concerns about Sustainable Forest Initiatives, emphasizing that certification is expensive and that loggers may find it difficult to obtain SFI certified wood in the future.

With respect to Federal and State-owned land, parcels are put up for bid to loggers. Successful loggers enter into formal written contracts that tend to be long and cumbersome. These contracts may last as long as three years. In recent years, Federal authorities have significantly decreased the amount of forest land they put up for auction. This has limited the amount of stumpage that is available and stumpage prices have increased dramatically.

In general, the results of the two focus groups indicate that price is the most important factor in determining the availability of biomass to the market. Furthermore, market stability is a significant concern. Expected markets have not materialized and there is a large amount of skepticism that they ever will.

Logger Focus Group.

The logger focus group was comprised of two independent loggers. Notes from the discussion with the loggers are also available from the research team. As indicated above, loggers play a central role in the wood/biomass supply chain. This group expressed several significant challenges they face with respect to wood availability and marketing wood to mills. In particular, existing market dynamics have squeezed margins significantly. On the supply side, forest availability is constrained as both federal and state landowners have taken significant acres of forest land out of production. This has increased rivalry within the industry as loggers compete for these limited supplies (stumpage prices have dramatically increased). Further increasing the amount of rivalry in the industry has been the failure of the BCAP program, a federal program designed to encourage the production and harvesting of bioenergy crops, and logger independence. While the BCAP was successful in creating interest among loggers and loggers have either entered or expanded their operations in this industry, new markets for biomass have not realized (there is little trust among loggers that there will eventually be a stable market for biomass). As a result, there is currently a significant oversupply of logging capacity in the industry.

In addition to new markets not being realized, mills have been able to exploit their market power on the demand side (note: the one mill that procured pulpwood biomass in the region recently went bankrupt). In fact, loggers expressed displeasure that mills often “hold-up” or break contracts with loggers, strictly adhere to contract terms (i.e. rigid delivery schedule, inflexible volume requirements, etc.), are very price sensitive, and have low switching costs to source from other loggers. Trust and reputation effects are very low between loggers and mills as loggers explained that long term relationships are often ignored for immediate gains and loyalty is non-existent. Furthermore, contract enforcement is a problem – given the market power of mills, mills are able to penalize loggers that decide to take legal action to enforce a

contract with them by locking them out of future business. Finally, efforts to increase the market power of loggers by coordinating production (e.g. cooperatives, joint production, etc.) have not been successful for two reasons: 1) in the past mills have aggressively suppressed collaboration by refusing to purchase from loggers that collaborate together, and 2) loggers are naturally independent.

Specific to the harvest of biomass, loggers also expressed concern. SFI has made it more difficult to harvest biomass since it requires that loggers to use the cut-to-length method and not whole tree removal. Furthermore, harvesting biomass requires specialized equipment (i.e. chipper), additional operating costs to enter the forest twice and to run the chipper, and transportation costs are greater for biomass as it is a less dense product. On the demand side, biomass is perceived to be a low cost (i.e. free) byproduct on harvesting trees. Loggers explained that the costs of production are actually greater for biomass.

Loggers use several procurement methods depending on the landowner type. In general however:

- formal written are used for all landowners;
- SPLs – prices are negotiated by species, contracts are flexible and allow for renegotiation later on, trees to be harvested are marked often with landowner's forester (relationship with forester has diminished over time)
- LCLs – annual contracts
- Federal/State – prices determined in a bidding process, no price negotiation.

In addition to price, other procurement considerations are: type of wood, quality of wood, and location of parcel relative to the mill.

With respect to the marketing of wood/biomass to mills, loggers often enter into formal written contracts as well. Price is the key attribute and generally loggers receive a “per unit” price by tree species; biomass (i.e. fuel chips) is priced based on weight only. Quality does not affect prices received but mills may reject loads based on quality. Volumes are specified in the contract and delivery schedules are explicit (source of most hold-up issues). Furthermore, contracts vary in length from monthly to two years. However, loggers expressed that longer duration contracts are not preferred due to: a) the uncertainty of their ability to supply wood on schedule (related to availability of wood to harvest and weather conditions), b) stumpage price fluctuations, and c) gas price volatility, etc.

Loggers were also asked about the most important factors that would affect their decision to enter into long-term relationships to supply biomass to mills/processors. There was strong agreement among the loggers that they would not enter into a contract longer than 2-3 years maximum; market uncertainty is seen as a significant barrier. Other factors that would be necessary would include: a formal written contract, committed volumes, a flexible delivery schedule, cost of production adjustments (i.e. fuel), and fixed prices. However, given these requirements, loggers still view mills with skepticism and there is little confidence that mills would hold to terms of a contract they entered into. Performance guarantees and relationship bonds may be attractive.

Finally, loggers were asked if they would be willing to supply biomass to a future bioenergy facility. They agreed that they would be willing if prices exceed their costs of production and if the location of the facility minimized their transportation costs. It was also expressed that it is not feasible to harvest only biomass and that markets for roundwood, etc. would also be needed. In conclusion, they agreed that new “credible” markets would also be needed to increase the supply of biomass.

Analysis of Potential Contracting Options

The results of the focus group discussions presented above provide several insights on how to best govern supply chain relationships in the Michigan Upper Peninsula wood industry. As discussed above, contracts are the primary mechanism used in the industry today. This finding is consistent with transaction cost theory.

As discussed earlier and reconfirmed by focus group respondents, the central conflict in the Michigan Upper Peninsula wood supply chain is the logger (or commercial landholder) and mill relationship; therefore, we focus our attention here. The results of the focus groups also indicate that uncertainty is a primary driver of the types of contract terms and conditions that these supply chains players are willing to accept. To address this issue, respondents suggested that an optimal contract would contain the following coordination features: a) flexibility in compensation and contract terms, b) terms that are binding and enforceable, c) short term length, d) cost of production adjustments, e) ability to procure a steady supply, and f) minimize transaction costs. Using these features, we analyzed four types of contracts: 1) handshake agreements, 2) fixed price contracts, 3) short-term performance contracts, and 4) long-term performance contracts. The results of this analysis can be found in Appendix D1(d).

Recommendations

Our analysis indicates that a short-term performance contract is likely to be the best alternative to govern the relationship between loggers and mills. This type of contract offers loggers the ability to be flexible in the volume and timing of their deliveries by providing premiums or discounts for meeting contract specifications rather than “all or nothing” provisions. From the logger’s perspective, this feature is likely to increase the perceived stability of the contract. Contracts should also have a short-medium term, likely no more than 3 years. Loggers expressed significant concern about the uncertainty of market; they are sensitive to getting locked-in to unfavorable contract terms as market conditions change. One way for a mill to extend the term of the contract may be to include a “renewal” mechanism in which contract may be automatically renewed, renegotiated or extended if certain market/production conditions are recognized. As an example, a contract may be renewed if prices trade within a certain range for a specified period of time during the contract. Contracts should also include transparent and automatic cost of production adjustments.

With respect to the analysis in Appendix D1(d), two issues of concern to loggers remain unaddressed by the alternative contract types that were explored: 1) the ability to maintain a steady supply of biomass, and 2) the potential of the saw mill to holdup the contract. Weather is a primary determinant of a small or independent logger’s ability to meet delivery schedules. However, this is not a variable that is under the control of the logger. At the same time, mills require a steady supply of biomass to operate their facilities at an efficient capacity. Two potential mechanisms may help to resolve this issue. The first would be to encourage coordination of supply among loggers. For example, poor logging conditions in one area could be offset by expanded production from other loggers without disruption to wood supply to the mill. Another option would be to store biomass for down production periods. Mechanisms to share the risks and costs of storing inventory between loggers and mills could increase the viability of this option.

Potential holdups are also an issue, and according to loggers, have been common in the industry. These holdups have eroded the trust of loggers and the reputation of mills. One way to resolve this issue would be to include hostages/bonds in the contract. Guarantees, upfront (non-refundable) payments, or investment in relationship specific assets are potential solutions. With respect to the latter, these investments do not necessarily need to be monetary. For example, mills could commit to support (e.g. share marketing and production information, etc.) and/or procure from a select group of loggers using exclusivity clauses.

This report also includes two documents that can be used to present the findings of this reach to interested stakeholders. This outreach material can be found in Appendices D1(e and f).

D1(a) – The Michigan Wood/Biomass Supply Chain.

D1(b) – Review of Wood Procurement Literature.

<u>Paper</u>	<u>Context</u>	<u>Why is it important?</u>	<u>Research Question</u>	<u>Theoretical Lens</u>	<u>Methods</u>	<u>Findings</u>
<p><u>Title:</u> The Effects of Contractual Restrictions on Industrial Organization: The Case of Swedish Pulpwood Transactions</p> <p><u>Author:</u> Per-Olof Bjuggren</p> <p><u>Journal:</u> International Review of Law and Economics, 1992</p>	<p>The Swedish forest products industry witnessed structural changes in the form of anti-land acquisition laws and restrictions on cutting rights. This has affected the ability of pulp & paper firms to source pulpwood.</p>	<p>Theory predicts vertical integration & long term contracts with considerable appropriable quasi-rents. However both the options are not available in Swedish forest industry. Given these contractual restrictions, the paper attempts to explain increased pulpwood imports even though domestic forests are left untouched.</p>	<p>TCE is used to explain the 2 puzzling phenomenon in Swedish forest sector- a) Recent rise in net imports of wood and decline in felling in relation to growth of standing timber b) Forward integration of forest owners' associations during 60's & 70's</p>	<p>Transaction Costs Economics</p>	<p>Case Study</p>	<p>The Swedish forest industry wields less monopsonistic power on the global market. Therefore it has become more profitable to import wood, and this has led to a decline in the demand for domestic wood, and in turn, a decline in felling.</p> <p>Forward integration can be seen as an alternative nonrestricted way to avoid bilateral exchange problems and price distortion due to market power.</p>
<p><u>Title:</u> Biomass Supply From Conventional Forestry</p> <p><u>Author:</u> C.P. Mitchell</p> <p><u>Journal:</u> Biomass & Bioenergy, 1992</p>	<p>The work conducted under the IEA Bioenergy Agreement Task VI Biomass Supply from Conventional Forestry in the period 1989 - 1991 is described.</p>	<p>Wood energy has become important over the years. However standard systems of maintaining woodland, harvesting and other related activities have not been yet developed on a commercial scale. Therefore very often the cost of recovering biomass exceeds its value.</p>	<p>Identify technologies & systems for the production, collection, harvesting, preparation, storage and drying of wood for energy from conventional forestry.</p>	<p>Summary report</p>	<p>Case Study</p>	<p>The work under the cooperation has recognized the importance of developing forest management and planning systems to enable a greater portion of forest biomass to be utilized than is currently the case.</p> <p>The main drawback to commercialization of the technology is economics, the harvesting operation must be profitable to encourage uptake.</p>
<p><u>Title:</u> The economics of biomass in industrialized countries: An Overview</p> <p><u>Author:</u> Marian Radetzki</p> <p><u>Journal:</u> Energy</p>	<p>The circumstances under which biomass is supplied and consumed, differ markedly between industrialized and developing countries, and warrant separate analytical treatments and approaches. The focus is also</p>	<p>Successful establishment of bio-economy is dependent on our ability to distinguish the main sources of biomass supply, identify the significant political & public interest in this energy source and suggest an approach for determining the socially warranted level of</p>	<p>The primary purpose of the paper is to paper lists and briefly explore the issues and factors that have aroused the strong interest in energy source, that explained its limited current</p>		<p>Supply side analysis, use of IEA database, establishing chronological series of event leading to resurgence of</p>	<p>The external costs of biomass are higher than the ones arising from the use of fossil fuels, with one very important exception. Fossil fuels add more to greenhouse warming, than biomass. The competitiveness of biomass vs. fossil fuels will improve or deteriorate when external effects</p>

Policy, 1997	prompted by a wish to verify the frequent assertions that biomass provides a socially superior alternative to fossil fuels, and that it could potentially play a much expanded role in the energy systems of the rich market economies	biomass consumption in developed economies.	(1990's) role in the energy systems of rich countries, and that will determine its future potential.		interest in biofuels	are taken into account, depending on the relative importance attached to greenhouse warming and other environmental damage.
<u>Title:</u> Wood Fuel procurement Strategies of district heating plant <u>Author:</u> A. Roos, F. Bohlin, B. Hektor, & B. Hillring) <u>Journal:</u> Energy, 2003	Wood fuel use in the Swedish district heating sector increased significantly from 1985 to 1999. Priorities and concerns in the industry involved an increased wood fuel share, ambitions to create an environmental image, cost minimization, awareness about the role of energy policies for fuel choice, improvement of wood fuel quality and the ambition to maintain a competitive wood fuel market with several suppliers	Strategies on a factor market are seldom discussed in literature, which normally focus on product markets. This research provides a comprehensive description of the strategies and considerations concerning wood fuel procurement among Swedish district heating plants	Analysis of strategies and considerations concerning wood fuel procurement in district heating plants in Sweden.	Procurement Strategy	Factor (Principal Component) analysis	This study yielded five dimensions in the wood fuel procurement strategies among the district heating companies: (1) increased wood fuel use; (2) import; (3) spot market wood fuel purchases; (4) focus on refined wood fuels; and (5) using price only when deciding whether to use wood fuels or other fuels
<u>Title:</u> Variation and trends in sawmill wood procurement in the Northeastern United States <u>Author:</u> Nate Anderson and René Germain, <u>Journal:</u> Forest Products Journal, 2007	Recent trends like divestment of industrial forest ownerships to institutional investors and parcelization of nonindustrial private forests have been central concern in the North East. The saw mill industry faces a potential threat to its supplies, which had otherwise, in general well defined wood sheds to	This study seeks to quantify the attributes of wood procurement operations for sawmill in 7 North East states in the context of regional trends in industry concentration, log exportation, forest parcelization, urbanization and exploitative harvesting practices.	What factors affect log supply and how an individual firm should adapt its procurement operations to a changing landscape in order to positively affect its competitiveness and profitability?		Survey instrument, ANOVA and MANOVA. Data was collected from survey of 211 sawmills in seven states	In general, respondent mills procured 90 percent of their total 2005 round wood supply from within 30 to 70 miles of the mill. Of the 1.2 BBF of log procurement reported in the survey, gate wood was the most dominant log source (54%), followed by roadside sources (23%) and stumpage (16%). A majority of mills reported declines in log quality and volume per log between 1994 and

	procure stumpage and logs.					2005.
<p><u>Title:</u> Assessing wood procurement management systems in the forest products industry</p> <p><u>Author:</u> S. Harris, et al.</p> <p><u>Journal:</u> Forest Products Journal, 2003</p>	<p>Nonindustrial private forestlands (NIPFs) are a key supplier of raw materials to the forest products industry in the US. In response to concerns about their sustainability of harvests on NIPFs, forest product firms are striving to improve their wood procurement operations.</p>	<p>There is little research addressing the adoption of an EMS for wood procurement by the forest products industry.</p>	<p>What is the impact of incorporating environment management systems (EMS) on wood procurement management systems?</p>		<p>Industry wide surveys and informal interviews was conducted to measure development of wood procurement management systems designed to improve forest management on NIPFs</p>	<p>The results indicated that operations with production capacities greater than 30 MMBF or with more than 500 employees, as well as those participating in the Sustainable Forestry Initiative standard, had moderately developed or well-developed wood procurement management systems. Sawmills producing less than 10 MMBF, especially those that did not adhere to any forest management standard, had poorly developed or undeveloped wood procurement management systems, which will make it difficult for these sawmills to improve their environmental performance and gain access to NIPFs and future markets.</p>
<p><u>Title:</u> Contracting for timber property rights in the southern United States: An historical analysis of industry location and structure, and the impact of contractual restrictions on bid prices</p> <p><u>Author:</u> Michael Dunn</p> <p><u>Journal:</u> Thesis, 1997</p>	<p>The purpose of this study was to examine and apply institutional theory regarding transaction costs to the forestry sector. This was accomplished through two unique essays that, when combined, form a partial description of the process of contracting for timber property rights in the southern United States</p>	<p>Existing research has studied bidder behavior. However none of the previous studies has attempted to analyze specific contractual restrictions and their impact on bid prices. The possible reason of absence of this research gap is the recentness with which many contractual restrictions have occurred in forestry.</p>	<p>What is the impact of contractual provisions on stumpage bid prices for Alabama state timber sales?</p>	<p>New Institutional Economics (contracts, property rights and transactions cost)</p>	<p>Data collected from 105 timber sales conducted by the Alabama State Lands Division of the Department of Conservation were utilized in a simple linear regression model</p>	<p>The results indicate that certain contractual provisions--such as landowner assistance and bonding requirements--negatively impact the high bid received for state timber sales. Other provisions, including one requiring that forestry Best Management Practices guidelines be followed, had a positive and significant impact upon the high bid received per acre.</p>
<p><u>Title:</u> Transactions Costs and the Efficient</p>	<p>Individuals and firms have incentives to develop institutions and adopt</p>	<p>Detailed analyses of particular production processes, like the analysis presented in this</p>	<p>A transaction costs framework is developed to explain</p>	<p>Transaction Costs Economics</p>	<p>Predictions about which contract type</p>	<p>Landowners will maximize their profits by restricting competition for their timber. The intuition for</p>

<p>Organization of Production: A Study of Timber-Harvesting Contracts</p> <p><u>Author:</u> Keith B. Leffler & Randal R. Rucker</p> <p><u>Journal:</u> Journal of Political Economy, 1991</p>	<p>contractual arrangements that minimize the dissipation resulting from transaction costs (TC). In any particular instance, the precise nature and relative magnitude of transaction costs will be determined by the physical properties of the goods being exchanged and the characteristics of the buyers and sellers involved.</p>	<p>paper, can therefore improve our understanding of the relationship between transaction costs and observed institutions and contracts. Such studies are few, presumably because of the difficulty in identifying and quantifying the relevant transaction costs of policing and enforcing input exchange agreements.</p>	<p>the choice between lump-sum and per unit payment provisions in private timber-harvesting contracts.</p>		<p>minimizes TC of presale measurement and contract enforcement and monitoring are derived and tested using private timber sales contracts from North Carolina.</p>	<p>this, is that for any given harvest level, the increase in enforcement costs associated with a higher per unit bid may more than offset the additional revenues associated with a higher bid. There are no similar enforcement cost-based incentives to restrict competition in the analysis of lump-sum sales. The paper predicts a greater reliance on negotiated sales for per unit than for lump-sum contracts.</p>
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DI(c) – List of Major Landowners in the Upper Peninsula

Researchers at Michigan State University analyzed Plat Books to develop the list of major landowners in the Upper Peninsula. Owners of land in excess of 1,000 acres were included, and were broken down by county. The table below shows the major landowners by county.

County	Owners
Alger	Escanaba Paper Company DNR U.S. Forest Service Heartwood Forestland Fund IV
Baraga	DNR Heartwood Forestland Fund IV U.S. Government Escanaba Timberland Holdings IV LLC All Wood Inc. BPB Manufacturing Inc GMO Threshold Timber Michigan LLC Bucky Heights LLC U.S. Forest Service WE Energies Michigan College of Mining and Technology Baraga Land and Timber Co. Scott Homan Trust Messenger Fishing & Hunting Camp, Greg Andrew and Jeff Messenger Heartwood Forestland Fund III King Lake Wilderness Recreational Properties LLC
Chippewa	DNR Crisp Point Properties Bernice Pauahi Bishop Trust Hiawatha Club Escanaba Paper Company University of Michigan U.S. Forest Service Maple Ridge Club BDN Group N and D Armstrong K. Keely Jorgensen Enterprises USX Corp John Kennedy R&K Poljan Cedarwood LLC Stone Mountain Properties Lee and Helen Draper Klamerus Family Trust

Delta	DNR Escanaba Paper Company Michigan State University U.S. Forest Service Whitefish Hunting Club
Dickinson	DNR International Paper Co. Escanaba Paper Co. Wisconsin Electric Power Company International Paper Forest Resources Jeff White
Gogebic	Gogebic County Keweenaw Land Association Ltd. Ironwood Charter Township U.S. Forest Service Heartwood Forestland Fund IV International Paper Champion International Corporation DNR Lake Land and Timber Steiger Lumber Company Connor Forest Industries Inc. Longyear Realty Corp University of Notre Dame Du Lac Institute in Basic Life
Houghton	U.S. Forest Service Steven E. and Dana V. Rensma U.P.. Power Company Keweenaw Land Association Ltd. DNR Vulcan Corp. Lake Superior Land Co. Nordine Lumber Co., Inc. Heartwood Forestland Fund IV GMO Threshold Timber Michigan, LLC Heartwood Forestland Group
Iron	U.S. Forest Service Heartwood Forestland Fund III DNR Escanaba Timberlands Holding I CBF Investment LLC Plum Creek Timberlands L.P.

	Plum Creek Land Co. Gary L. Seevers G.M.O. Threshold Timber Michigan, LLC Forest Park School District Escanaba Timberlands Holding IV Wisconsin Electric Energies Gary L. Ort Sustainable Forest Northern Trust Company
Keweenaw	GMO Threshold Timber Michigan, LLC Lake Superior Timberlands, LLC Longyear Realty Corp. Heartwood Forestland Fund II Blue Stream Properties, LLC DNR CECE Investments, LLC
Mackinaw	DNR Patrick & Timothy Abraham Escanaba Timberland Holding William S. and Sylinda Brost Robert J. Brotherton Timothy D. Putman Trust Frank Frisch et al Norton Oglebay Limestone Co. GDO Investments Ronald W. Clark Trust Hiawatha Sportsman's Club U.S. Forest Service
Luce	DNR William Zellar et al Trustee of Bernice Bishop Escanaba Paper Company Richard Devree Raymond Tokarz Harry Ade et al Kalamazoo Nature Center Devereaux Family Limited Davis Properties Mary McDuffie Syphon Inc Jerry Biehl Trust East Branch Sportsmen's Club The Nature Conservancy Robert Bonner Trust Crisp Point Properties

Marquette	Escanaba Paper Company Jeffrey DeBacker DNR Ronald Siems et al Heartwood Forestland Foundation IV Murphs Camp Inc. Michigan Northwoods Club St. John Real Estate Marquette County Champion Timberlands Marquette Iron Mining C. Empire Iron Mining Partners Tilden Mining Company Cleveland Cliffs Iron Company U.S. Government Champion International Corp. O'Dovero Properties Longyear Realty Corporation U.S. Forest Service Loma Farms Inc. Davenport ME Foundation AL Matthews LLC JM Longyear Heir Huron Mountain Club Carroll Paul Forest Keweenaw Land Association Cliff Lake Club
Menominee	Michigan Environs Inc. DNR John Webber et al Kenneth and Donna Linder Champion International St. John Real Estate Company International Paper Co. U.P. Northwoods Land Co. Hannahville Native American Comm. Tribal Land Escanaba Paper Company Earl St. John Jr. Earl Jr. and Rosemary St. John Roger Stebbins
Ontonagon	U.S. Forest Service Upper Peninsula Power Company UPPCO Keweenaw Land Association Ltd.

Champion International Corp.
Bernice Pauahi Bishop Estate
DNR
Copper Range Co.
George W. and Jeannie D. Knabb
Escanaba Paper Company
Lake Superior Land Company
Iron River Association LLC
Northern Land and Sales Inc.
Stone Mill Operating Corporation
Champion Timberlands
Vulcan Corporation

Schoolcraft

Escanaba Paper Company
DNR
Oglebay Norton Limestone Co.
U.S. Forest Service
Tooth and Nail Land Inc.
John Zellar
Bishop Estate
Richard Mancini
Bologna Properties

D1(d) – Analysis of Contracting Options

Coordination Type	Coordination Features					
	Flexibility	Binding (contract enforceability)	Time Length	Cost of production adjustment	Steady Supply	Associated Transactions Cost
Handshake	<p>->Quantities must be delivered as per delivery schedule.</p> <p>->Weather plays important role in meeting the terms of contract (TOC)</p>	<p>-> Low degree of enforceability due to:- a) no legal enforcement b) under developed biomass market, c) supply exceeds demand, d) absence of economies from reputation, e) very low mill switching cost</p>	<p>->Very short (3 months) to short time length (1 year) due to uncertainty in:</p> <p>a) wood supply, b) cost of production, c)price</p>	<p>-> Mill has little or no incentive to share fluctuations in production costs</p>	<p>-> Steady supply of biomass will depend on a) weather conditions, b) ability of logger to find wood/biomass, c) number of suppliers in the market at current price</p> <p>->Non enforceability & price fluctuations lead to unsteady supply</p>	<p>-> Recurring search cost</p> <p>-> Recurring negotiation costs</p> <p>-> Low supplier switching cost giving rise to hold up costs</p>
Fixed price contract	<p>-> Low incentives for mills to allow flexibility in delivery schedules</p>	<p>-> While legally enforceable but not binding under current market structure because if logger sued the buyers, it would be forced out of the market, that is, there is high enforcement cost</p>	<p>-> Maximum length of the contract is 1 - 3 years</p>	<p>->Possibility of having a clause for risk sharing due to frequent changes in production cost</p> <p>-> Sensitivity of production cost adjustments would largely</p>	<p>->TOC with respect to supply defaults will largely determine supply steadiness</p> <p>->Loggers have limited ability to control supplies under severe weather conditions</p>	<p>-> low to medium monitoring costs</p> <p>->contract design cost</p> <p>->contract enforcement cost (under</p>

				depend on negotiation power of the contracting parties		current market structure logger is expected to incur this cost)
Fixed price contract with performance incentives (incentives may be given to achieve: a) high btu value, b)delivery schedules, or c)delivery of contracted quantities)	-> Low incentives for mills to offer flexibility in delivery schedules ->Performance incentives likely to compensate for the absence of significant supply flexibility from loggers' perspective	>Not binding under current market structure, where there are very few buyers and large number of biomass sellers	-> Maximum length of the contract is 3 years	>Possibility of having a clause for risk sharing due to frequent changes in production cost -> Sensitivity of production cost adjustments would largely depend on negotiation power of the contracting parties	->Performance contracts are designed to ensure consistency in quantity (as well as quality) and frequency of delivery	->high monitoring cost to ensure performance ->cost of contract design ->contract enforcement cost (under current market structure logger is expected to incur this cost)
Long term contracts with performance incentives	->inbuilt in the structure of the contract ->both have incentives to have supply flexibility (loggers face supply, weather, production cost	->will depend on existence of economies from reputation, switching cost and number of buyers & sellers ->institutional changes in long	Contract length is more than 3 years	->Mills have incentive to share cost changes so as to ensure consistent supplies, and also that their suppliers remain in business	->designed to ensure steady supply from mills' perspective ->loggers will enter into such arrangements if biomass business generates significantly large	->high design cost ->monitoring cost ->enforcement cost (with the increase in number of buyers, it is likely to

	uncertainties & mill primarily faces uncertain demand	run			portions of their total revenue/profits	decrease)
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The Wood Supply Chain in the Upper Peninsula
By
Guilherme Signorini, Bill Knudson, Brent Ross and Vivek Pandey

This fact sheet provides a brief overview of the wood supply chain. The supply chain developed was the results of discussions with forestry experts in the supply chain with a focus on the Upper Peninsula. There are four primary actors in the wood and biomass supply chain in Michigan.

- Landowners who control wood and forest residue production areas.
- Loggers who either provide harvesting services to landowners or buy stumpage from them.
- Saw mills who do the initial processing of the wood
- Final users of the wood, including pulp and paper mills, bioelectricity producers, potential cellulosic ethanol firms, and other final users.

It should be noted that there is some vertical integration in this sector particularly in the case of final users of the wood that also do the initial processing at the facility that produces the final product. Wood harvested in the Upper Peninsula is used for a wide range of products, but these can be combined in the following general categories: pulp and paper, construction and prefabricated wood buildings, bioelectricity, furniture, power poles, firewood and potentially cellulosic ethanol. Pulp and paper remains the largest of these sectors.

The following schematic drawing outlines the supply chain for wood in the Upper Peninsula. The numbers in parentheses are the North American Industrial Classification System (NAICS) codes which help to categorize the type of industry. The dollar figures are in thousands of dollars. In some cases it is not possible to obtain the size of the industry because of disclosing individual operations or because that information is not gathered.

The solid lines represent the flow of primary wood products. The dashed lines represent the flow of forest residues or byproducts. This supply chain shows that wood is used for a wide range of products. Byproducts are used for firewood, pulp and paper, and bioelectricity. Byproducts from pulp and paper can also be used for cellulosic ethanol production.

Contracts in the Biomass Sector

By

Vivek Pandey, Bill Knudson, Brent Ross, and Guilherme Signorini

Overview of the Project

Researchers at Michigan State University have recently concluded a study of contracts in the woody biomass sector. This fact sheet outlines some of the challenges to contracting in the biomass sector and attributes of good contracts. One way to think of a contract is a way to reduce costs by outlining the responsibilities of each party of the contract. The following types of contracts were analyzed.

- Handshake contracts which are informal and are not legally binding
- Fixed price contracts where the volumes and prices are negotiated between the parties
- Fixed price contracts with performance incentives, this allows for degree of flexibility
- Long term contracts with performance incentives, which are similar to fixed price contracts with performance incentives but are more than three years in duration

Our researched discovered that the key actor in the sector is the logger who generally contracts with both the landowner and the user of the woody biomass. This brief paper outlines the challenges to contracts and the attributes of a good contract in the woody biomass sector.

Challenges

There are several challenges that were identified with respect to contracts. Generally speaking timber is a commodity and margins throughout the sector are small. This is particularly true for biomass used for energy production where the biomass competes with coal. Further compounding the problem is the fact that despite the increase in the forest resource stumpage prices are high. This appears to be due to the lack of interest on the part of landowners particularly the federal government in selling stumpage. Forest land is owned and held for a number of reasons, the sale of stumpage being only one.

Loggers believe that the process of entering into contracts to harvest wood on federal land is too complicated and too time consuming. Harvesting wood for biomass, including forest residue, is as expensive as harvesting round wood, prices need to reflect this fact in order to increase the supply of biomass. Given the economies of scale involved loggers also believe that 40 acres is the minimum lot size to justify the harvesting of biomass.

Another issue is the relationship between the mills and the loggers. Given the transportation costs involved, loggers generally work with only one or two buyers at a time. This makes it easy for the buyer to break a contract. A logger cannot press his or her claim without running the risk of offending a major or perhaps the only customer. Loggers lack market power compared to mills.

Smaller landowners sometimes lack knowledge about market conditions. This may make contracting with smaller landowners more difficult and time consuming. Often small landowners

will only have one or two timber sales in their lifetimes. This reduces the amount of flexibility for both the landowner and the logger. Larger landowners who often sell stumpage have a better feel for the market and can offer loggers some flexibility in choosing locations on which to cut trees and collect biomass.

These challenges point out the importance of developing good, enforceable contracts.

Attributes of a Good Contract

Conceptually, there appears to be relatively wide agreement as to what a good contract should look like. There is widespread agreement that performance criteria need to be included. This includes volume and delivery criteria as well as establishing prices. Despite this consensus, creating contracts that would allow sufficient flexibility to take changing economic conditions, fuel prices and weather into account is difficult. The need for taking changing fuel prices into consideration is particularly important. Contracts need to be enforceable; some loggers believe that this is currently not the case. Formal written contracts would help address this issue as would explicit penalties for breaking contracts. Performance bonds are another alternative to ensure that performance goals are met.

One issue that needs to be addressed is weight. Biomass users would prefer a dry product, but the price is often based on weight which means that wet wood is sold at a higher price than dry wood.

The length of the contract should be less than three years in duration. The level of uncertainty and risk with respect to the future makes longer contracts impractical.

Sub-Task D2: Engage Communities in Producing Bio-feedstocks

Reported by Wynne Wright

Michigan State University

Final Report

(March 2009 through June 2011)

Abstract:

The purpose of this sub-task has been to design a community process to facilitate a broader level of engagement in woody biomass decision-making and planning. This approach involved three interrelated phases: framing, training and community engagement. First, we developed an Issue Guide and video that presents an overview of the issues raised by the principals around the sourcing of woody biomass. The guide was prepared with input from biomass and general community stakeholders in Michigan's Upper Peninsula based on a one-day framing workshop held to access public opinion and reactions. Framing workshop attendees included a broad range of interested stakeholders in wood-based bioenergy development, such as community leaders, foresters, loggers as well as members of the environmental community. The Issue Guide and video provided the basis for the second phase, the development of a training module for Extension Educators to encourage public dialogue around biomass issues. A training workshop "Building Common Ground: Helping Communities Address Natural Resource Issues" was held to train Extension Educators on how to conduct forums to deliberate biomass issues at the community level. This was a one and one half day event held in Gaylord and attended by 10 people. The workshop concluded with encouragement from the trainers for the trainees to organize and hold a public forum in their community. The first community engagement workshop was held in Port Huron and was well received. On-going research into each stage of this work has illuminated the merits of this approach for advancing citizen engagement in biomass decision-making for various participants involved in the outreach initiative.

Introduction:

In forested places such as northern Michigan, rural communities are interested in using local resources, such as forests and fresh water, to supply both local energy and provide new sources of income to area residents. As with all proposed natural resource developments, community level decision-makers are assessing the related risks and potential benefits of bioenergy development. Risks and benefits, however, are not always clear, complicating the evaluative basis for development decisions. Despite some relatively accessible technological developments, bioenergy, an umbrella term for using biomass, such as trees and perennial woody-plants, as an energy feedstock, is faced with many economic and social hurdles. For instance, while many actors support bioenergy as a sustainable and available means to produce not only local and renewable energy, but also jobs and economic development, others are raising questions about its viability and validity in relation to other environmental, energy, and job creation scenarios (Wright and Reid, 2011). Our ongoing research complements the findings of other scholars (e.g. van der Horst et al. 2002) in reporting that the perception of exclusion from community level decision-making by various publics contributes to increased levels of social opposition as well as increased community polarization and political gridlock on renewable energy issues. Essentially, top-down, exclusionary decision-making can erode the bonds of social trust between actors necessary for communities to obtain their goals (Renn 2008, Wynne 1992). With these lessons in mind, the aim of this project is to create ways to broaden the range of stakeholders, such as area residents, who participate in discussions of local bioenergy, both formally and informally, in order to forestall polarization and political gridlock and engender more open and democratic exchanges of ideas and information. Specifically, our aim is to train Extension Educators in activities that

catalyze community level conversations and identify places of common ground from which residents can begin to implement resolutions to energy and economic challenges in a sustainable manner. This view was echoed to us by one member of an environmental group engaged in region-wide controversy over the local siting of a biomass electrical plant:

There's so much polarization in this country and in our state and in the community around this issue that the best thing that we can do right now in my view is to bring people together where we do agree and have common ground and start there. Then we can deal with our disagreements further on down the line, but you don't start with where you disagree. You start with where you already agree (Community participant E).

It is our belief that doing so induces mutual-learning, a process by which expert and lay, specialist and citizen knowledge on bioenergy is developed in tandem, resulting in a more democratic, ethical and ultimately sustainable process of renewable energy implementation.

Methods: Framing, Training, Engagement, and Research

The goal of this outreach/research initiative was to create the context for community engagement in bioenergy decision-making. To accomplish this we organized three events/activities designed to gather input for the development of educational materials, train Extension Educators to implement public dialogic encounters in their communities, and to host a community forum. In doing so, we concluded all objectives of our original proposal. These three events were:

1. Biomass Framing Workshop, Escanaba, MI, July 27, 2010.
2. Extension Educator Training Workshop, Gaylord, MI, February 7 and 8, 2011
3. Community Engagement Workshop, Port Huron, MI, April 21, 2011

Biomass Framing Workshop We organized and hosted a one-day, biomass framing workshop at Bay College in Escanaba on July 27th²⁹. Thirty-two individuals attended the workshop representing various sectors of the woody biomass supply chain. The workshop was designed to identify the salient opportunities and challenges that are at work in creating a woody biomass sector from the various perspectives of the participants involved. Workshop facilitators were Extension Educators Claire Layman, Michelle Walk, and Anne Chastain.

The data collected from this event was used to develop an Issue Guide that presented the various opportunities and challenges facing the development of a woody biomass sector in Michigan. The Issue Guide is composed of five sections, each designed to provide readers with an overview of the issues and possible trajectories for consideration. An Issue Guide is a tool to help citizens engage in informed and meaningful conversations about difficult issues that impact their communities. The Issue Guide provides an overarching framework of the problem and outlines different approaches or strategies for addressing the

²⁹ Wynne Wright and graduate assistant Weston Eaton traveled to Escanaba on 6/9/10 to conduct interviews with principals in the supply chain and Dr. Wright gave a public presentation to the Delta County Joint Governmental Group to explain this outreach/research initiative. Participants were pleased we had selected their community and were eager to offer assistance by giving us names of individuals to include in our work. We also used this opportunity to begin to make arrangements for the upcoming biomass framing workshop. Escanaba was selected because previous efforts to conduct this work in Kinross were thwarted and Escanaba officials were eager to have us engage with their community. Escanaba also met the criteria as having a biomass facility in transition with community dialogue taking place in the public sphere.

issue at hand – in our case, the appropriate role for biomass in Michigan communities. Each approach offers a distinct definition of the challenge that lies at the heart of the issue. Each problem definition advances different goals and values that lead to a different set of action steps. The intent is not for participants to pick one choice and reject the others. Most people find at least a little bit to like in several choices as they begin to see the world from the perspective of others. The goal is to help everyone in the dialogue reach a clearer, deeper understanding of the multiple viewpoints on an issue, including their own, and to identify some common ground for future action. Subsequently, the Issue Guide can help people see how socio-economic development decisions align with or threaten social values.

In addition to collecting data to inform the contents of the Issue Guide, we also took a film crew along with us to Escanaba and filmed 18 interviews with local leaders, biomass entrepreneurs, loggers, activists, Extension Educators, and city officials. These individuals were filmed to capture their perspectives on biomass in their area. The finished product is titled “Michigan Talks Biomass” and is a seven minute video that highlights what people are saying about biomass from diverse perspectives. It presents the issues in a way as to welcome dialogue rather than shutting down engagement through ‘expert’ testimony and scientific ‘facts’ as is often the case in such programming. Extension Educators can use the video documentary to jumpstart public conversations around biomass in their community.

The Issue Guide and the “Michigan Talks Biomass” video were both placed on a web site to be easily accessed by citizens across the state (see http://fooddemocracyproject.org/biomass_archive/index.php). The video was also placed on You-Tube to attract a broader non-Michigan audience.

Extension Educator Training Workshop. When the educational Issue Guide and video were completed, we used them, along with the Building Common Ground curriculum developed in previous trainings, to train Extension Educators on how to promote deliberative dialogue on biomass issues in local communities. This two day workshop, titled, “Building Common Ground: Helping Communities Address Natural Resource Issues” was held at the University Center in Gaylord on February 7-8. The purpose of the workshop was to nurture future facilitators – especially Extension Educators – to use deliberative practices to engage community dialogue around biomass issues. Six Extension Educators and six MSU graduate students took part in this workshop. By combining these populations, our goal was to facilitate sharing and co-teaching among the workshop participants. Extension Educators were taught to see the theoretical framework behind this work more clearly through their interactions with students. In doing so, the Extension Educators were able to crystalize real world challenges faced in their work to enhance social and economic development for students to better appreciate. The goal of deliberative dialogue is to help everyone engaged in the process reach a clearer, deeper understanding of the multiple viewpoints on an issue, including their own, and to identify some common ground for future action. Having a mixture of students and Extension Educators engage in the training helped us set the context for differing worldviews, similar to the context we might find in typical community settings. This mixture of students and Educators was one of the most beneficial aspects of the workshop according to evaluations from the participants and interview data.

In general, evaluations from the event ranked the training workshop very highly. For instance, eight out of the ten evaluations signified that they left the workshop with new ideas as well as gained insights and support from others. Forty percent of the respondents stated that they would definitely hold a public forum in their community after the training, and sixty percent indicated that they would probably do so. We find this degree of support overwhelmingly supportive and encouraging. We will continue to communicate with this group to encourage them to move forward with a community forum and we will offer our consultation and support to the degree they desire to assist in this effort. One Educator from Port Huron volunteered to host a community forum on biomass in his community immediately.

Community Engagement Workshop. (Port Huron, MI, April 21, 2011) On April 21st James Ribbron, an Extension Educator from Port Huron, hosted a community forum on biomass at the County Administration

Building. We offered our services to co-facilitate this event which was attended by five community members. The event helped participants vision the role that citizens can play in advancing positive community/industry relations, probe the role of industry in the community and deliberate the best way to express these needs and concerns to achieve sustainable relationships. The Issue Guide and the starter video were used as tools to facilitate deliberative dialogue in this community. These materials and trainings helped Extension Educators respond to the changes in their community in a proactive way and helped the community uncover the opportunities in bioenergy for Michigan.

The engagement workshop proved successful in engendering exchanges of perspectives and possibilities for bioenergy development between professionals who are not usually in communication with one another. Despite the modest turnout, participants in the workshop were from diverse sectors of society, representing planners, farmers, government agencies as well as the private sector. One outcome of the forum was the increased awareness by participants of the possibilities for bioenergy development locally. Key overall for participants was the way by which the forum format created a comfortable environment for thoughtfully considering the issues and range of possibilities. As one participant later reflected, “I felt like people listened to me and the comments that I made. I didn’t hear a lot of disagreement except from [another attendee]. But even that was a good exchange because he was coming at it as an expert in his area and I didn’t have expertise in his area...I felt that he listened to me too, and by the end of it, I felt we both had an understanding of what each other was trying to express” (Community participant A).

Although the materials focus specifically on woody-biomass, they proved versatile when the discussion was broadened to include agricultural crops. Participants and moderators alike found that the approaches set up in the Issue Guide and video easily transferred to discussion of other technologies as the underlying scenarios captured the essence of concerns for more than one technological possibility.

Following this event, we conducted evaluative research on all phases of this outreach initiative to assess its utility in helping citizens understand the complexity of biomass development issues in their community. A graduate student researcher was assigned to document and evaluate this process with the expectation that scholarship would emerge to inform other communities regarding strategies for meaningful engagement of diverse actors in biomass development. Interviews were used to gauge input from participants involved in each of the three events. This research component has allowed us to develop insights into the use of deliberative dialogue to address natural resource controversies and has also allowed us the chance to submit this scholarship to peer-reviewed journals (currently in process). To date, we have presented findings from this work at the Michigan Sociological Association as well as the International Symposium on Society and Resource Management Conference, which was held in Madison Wisconsin in June (Eaton 2010; Eaton 2011). We will also be submitting this work at the Rural Sociological Society annual meetings in Boise, ID in July, 2011 and the National Outreach and Scholarship Conference in East Lansing, MI in October, 2011 (see Appendix D2(c)).

In the following sections, we detail the major findings from the research component of this study.

Impacts: Inquiry and Discovery

This section discusses what we have discovered to be the usefulness and resonating impacts of a dialogic approach for addressing the, at times, contentious and dividing topic of forest-based bioenergy development in Michigan.

While we plan to hold additional community engagement forums in partnership with Extension Educators embedded in potential Michigan-based bioenergy communities in the near future, at this time we have gleaned insights into the impacts of this outreach/research initiative on bioenergy issues from two main sources: (1) our own observations as organizers and participants in the workshops as well as from (2) 14

follow-up, one-on-one interviews with several participants from each of the three workshops. Specifically, our findings consist of insights into the usefulness of this method for learning for two populations of participants, (1) ten MSU Extension Educators (seven of which participated in follow-up interviews) and (2) six graduate students (three of which were later interviewed) as well as perspectives emanating from the broader bioenergy community, including industry members, loggers, resource managers, foresters as well as community leaders and residents.

A) General insights that resonated for Extension Educators:

Extension Educators participated in each of the three workshops, acting as both arbiters of local and expert knowledge during the framing workshop, as trainees and practitioners during the training workshop, and finally as facilitators at the community engagement forum. Educators hold a range of knowledge from expert to familiarity with the technical issues at hand. Additionally, some educators came to the workshops as passionate advocates for bioenergy development, seeing the training as a means to “head off resistance at the pass” and “create an environment that would be conducive for people to say ‘this is a good idea.’” When asked how they now view woody biomass, a common response was “Michigan has a wealth of...woody-biomass so it would be in the state’s best interest if we were doing something with it. And I already come in with the idea that we need to utilize woody-biomass in a sustainable way for the benefit of the citizens of the state. That could take a lot of different forms. And that didn’t change” (Extension participant B). What did change for some, however, was the means by which they might communicate this position with broader publics in their future work.

While some were passionate about bioenergy being a potential solution to a host of environmental and economic problems, other educators developed a sense of neutrality on the issue, prioritizing not their own understanding, but the values within specific communities considering bioenergy development. The insights presented below represent extension participant’s understandings on citizen and community engagement after participation in the various workshops. We are not arguing that these insights represent all-together new notions for participants, rather, these ‘lessons learned’ grew salient and concrete throughout participation and engagement with others during the workshops.

Insight One: Using public deliberation as an alternative to expert-driven community engagement

The public deliberation format for catalyzing conversations about bioenergy may prove a useful alternative engagement tool to more traditional forms of often expert-driven community level public engagement, especially for communities with residents who express at least some skepticism as to the desirability of the local development of bioenergy facilities. While bioenergy is certainly not contentious in every community, Extension Educators feel populations in and around communities which host universities most often raise critical questions - and at times oppose bioenergy. In these circumstances, where people attribute competing meanings and values to local natural resources, Extension Educators are especially interested in the utility of the public deliberation format. As opposed to relying on traditional sources of expertise to convey specific scientific information about bioenergy to skeptical populations, where the goal is to convert skeptics by communicating specific scientific evidence, the deliberative dialogue format has local residents collectively review and discuss three different approaches to bioenergy as presented in the workshop’s materials as well as in the video. By doing so, participants play an active role in determining their own understanding of the issue, as opposed to being passive receivers of specific expertise. Such scenarios forces citizens to relinquish their citizenship responsibilities.

Speaking of the materials (Issue Guide and video) participants reviewed in the training and engagement workshops, one Extension Educator explained: “the stage that they set and the forum they present for

discussion on various topics were quite well done. [The materials] present information for those that are not as knowledgeable on the forest...to gain new insights” (Extension participant F). Extension Educators felt the insights gained in this process might contribute to new understandings about the potential for bioenergy in Michigan communities and in turn enable better decision-making on the issue.

Insight Two: Earning the public’s trust

Research on technology disputes and risk has shown that trust is earned and not granted. When people feel left out of decisions they feel will impact their lives, trust in the institutions perceived to be behind such decisions is eroded (Renn 2008). For some Extension Educators, the key insight taken from participation in the training and other workshops was that the inclusive character of public deliberation for community engagement may help overcome what is seen as a growing mistrust between traditional institutional authorities and community residents. The reflections of one Extension Educator illustrates this point: “Here’s what concerns me the most, is that we in this country, we don’t believe our scientists and I don’t know how we got there. Maybe we’ve just politicized the issue enough and there’s enough of the talking heads that bastardize science. [We] say it’s the curse of the Internet...cause you can start blogging anything and if you get enough people in a group they all tend to start believing it” (Extension participant E).

As opposed to contributing to further politicization, Extension Educators felt that public deliberation might be a means to rebuild trust not only between experts and residents, but within the community as a whole. The format is thought to do this in two ways. First, the Issue Guide, video, and discussions are built around what extension participants feel to be credible and accurate positions on bioenergy issues. The grounding of these materials in the region contributed to the sense of credibility within the extension community. For instance, one educator told us, “I especially liked that this was a real thing...here it is in practice, here’s people from a real community, here’s their thoughts, here’s their opinions. Because so many times I think, especially with extension, you go to trainings [and you’re told] okay now go out and use this. But this was really showing you here it is in practice” (Extension participant D).

Therefore, these materials delineated the bounds of credible and acceptable discussion while positions that strayed from these sources became subject to collective scrutiny. The format and materials therefore framed a discussion all participants felt to be reasonable and supported by empirical evidence as well as personal experience. As one Extension Educator explained, “I think everybody there was from an academic realm and I think valued scientific evidence” (Extension participant F). Secondly, while this provided a dialogic space most everyone was comfortable with, the range of perspectives offered in the materials and workshop activities allowed participants to maintain feelings of autonomy and control over their own judgments and evaluations. The result was a training and engagement workshop where people grew to value each other’s perspectives as relevant and important despite differences on the topic. Extension Educators felt this format may enable trust to be re-established between bioenergy and resource development and management experts and wider publics.

Insight Three: Recognizing the multiplicity of values which underlie biomass production for diverse population:

When asked what they found most beneficial about engaging with others at the training workshop, Extension Educators told us they grew to value the reality of the existence of a multiplicity of values, meanings, perceptions and understandings of bioenergy. For some participants the workshop made salient the notion that despite the confidence each of them hold in their own views on the topic, other conflicting perceptions not only exist, but deserve consideration. As one participant put it, “you’re not on an island” (Extension participant E), in reference to what this person felt to be the need to examine how the decisions and actions of one group may indeed impact other groups without their consent.

Moreover, when asked about how their participation in the workshops made an impact on their perceptions of bioenergy, some Extension Educators expressed that groups with differing values have the right to those perceptions. For example, one educator reflected, “That’s what I bring home from something like this. It’s looking at that other perspective. ...When [people] start talking about these environmentalists, ‘what do [environmentalists] know?’ Well, they breathe the same air, they like to canoe up the same rivers. Your industry, while you feel it’s very important, people don’t feel it’s as important as you do.” This person grew to value the diverse opinions that came about during the training workshop, seeing them as a means for keeping personal biases “in check”. Professionally, this educator works with farmers, a “typically conservative group,” the main lesson learned being not to “forget that there are other opinions” (Extension participant E).

More than one educator located the origin of this insight in not only the materials covered during the workshop, but through engagement with others during the training workshop as well as during informal conversations that took place during lunch and dinner breaks. A simplistic illustration of the demographic context of the training forum finds two groups that do not often interact: Extension Educators specializing in engaging with farmers and communities on bioenergy issues and graduate students interested in social and environmental justice issues. The ‘ah-ha’ moments for Extension Educators came when graduate students sought to make arguments on behalf of stakeholders not typically represented in bioenergy discussions, such as the rights of plants, animals and native cultures. One Extension Educator explains: “I don’t necessarily agree with [the view expressed by the student], but I appreciate it. I use that as a perspective to say okay, you don’t think it, but there are people that think this way and feel very strongly. They believe as strongly in their position as you believe in yours” (Extension participant E). This statement reveals the utility Extension Educators found for learning to value the multitude of perceptions of bioenergy: sharing their appreciation for the perceptions of others as a means to build trust and communication between contending factions of society. Overall, Extension Educators felt that simply being knowledgeable of the fact that bioenergy is being examined from multiple angles is more important than evaluating these disparate positions as either right or wrong. In the future, educators were excited to use this tool as a means to not only engage with clients such as farmers and loggers but to share their insights into its value for building trust and a sense of community.

Insight Four: Enhancing the participation of a wider group of stakeholders and residents in important decisions about the community’s energy future:

Extension agents interested in developing the state’s wood-based bioeconomy felt they were struggling with two key hurdles amongst the wider publics: complacency and skepticism. Participants often lamented that “change would not occur until things started to hurt”, meaning they felt the public would not seek out renewable energy alternatives until the cost of current technologies became use prohibitive. Another part of this complacency relates more closely with bioenergy technologies. As one educator explained, “We have a difficult time engaging people’s attention until it’s physically taking place; that to me is the challenge.” Where other technologies are more visible, this person went on to express that “a lot of [advanced bioenergy technology] is still in the laboratory and it’s not really sexy” unlike newly re-proposed coal plants in the state which “immediately engage the public” (Extension participant E). These comments capture the feelings of uncertainty, lack of familiarity as well as a perceived lack of attention by the public for vaguely understood technologies such as cellulosic ethanol. In this scenario, it seems possible that decisions about developing such technologies locally might be perceived as excluding the public. This may in fact be so if there is not significant interest by the public in how this technological system is to be developed and implemented. Therefore, some Extension Educators saw the public deliberation format as a means to begin a community level discussion on a topic many may not be familiar with in order to impart the sense of urgency they feel for tackling the problem of society’s reliance on non-renewable fuel sources.

Extension agents also understood the deliberative dialogue format to be a means to counteract controversy and polarization in communities through mutual learning. As one educator explained, “My purpose for participation is recognizing that I’m part of an issue that is controversial...and so if I could learn some skills or be able to preempt some of this controversy before it occurs than that’s what I wanted to do.” These skills are both personal, as in learning and practicing moderation techniques, as well as embedded in the workshop’s process, which aims for reaching ‘common ground’ rather than compromise. One Extension Educator summed the outcome of the training thusly: “rather than arriving at a goal, it was more of helping people do some self-discovery, listen to each other, create an environment where you can have some discussion [and] address an issue from [multiple] standpoints rather than ‘okay we need to make some decisions right now’” (Extension participant B).

B) Insights for graduate students

Graduate students in MSU’s CARRS Department also participated as trainees in the workshop. Unlike the Extension Educators who were drawn to the workshop because of their interest in bioenergy development within their region, the graduate student attendees were primarily interested in the public deliberation format as a means to engage with communities on potentially contentious energy and environmental issues. The insights they gained from participation in this project are therefore distinct from those expressed by the other groups as their motivation for involvement excluded specific institutional agendas to forward or at least explore bioenergy possibilities. For this group, bioenergy was merely the backdrop to learn more about ways to foster deliberative dialogue.

Insight One: Role for extension in communities across Michigan

For many of the students, Michigan State Extension was little understood or of little professional interest before the training workshop. In later interviews, some of the students told me that they were unaware of exactly what role extension played in communities and how Extension Educators interacted with residents, businesses, decision-makers and farmers. Participation in this training opened a window into the world of extension for these students who came to understand extension work as a process of ongoing and equal engagement with both institutional knowledge and lay expertise.

The specific expertise exhibited by Extension Educators on bioenergy development was foundational for the interest sparked for extension services by the students. Some of the students, for instance, expressed that the passion they saw exuded by the Educators for developing an alternative energy system inspired them to gain similar levels of expertise and capacity for meeting their own prominent environmental and professional goals. This remained salient despite differences in understandings, values and perceptions of bioenergy technology systems.

Insight Two: Public deliberation as a means to facilitate contentious and polarized issues and become skilled in community-level engagement.

As graduate students in MSU’s CARRS department, student attendees came to the training workshop with knowledge of a broad spectrum of environmental and resource conflicts. While the unique mechanics of bioenergy development were new to the students, competing claims for best use of natural resources was not new territory. Where the majority of Extension Educators envisioned the various workshops as tools that might help overcome resistance to bioenergy development, student attendees were more cognizant of the potential “wickedness” associated with resource conflicts (Batie, 2008). Students came to the workshops with a theoretical understanding of the role expert-driven public engagement might play in inciting or flaring up wicked problems, a position more difficult for persons knowledgeable on bioenergy and invested in the success of bioenergy development. In general, the student’s lack of preconceptions and

therefore initial neutrality on bioenergy issues meant each of the three approaches provided by the Issue Guide were carefully considered and weighed equally, while persons with bioenergy experience more quickly found the approach that most closely aligned with their own perceptions and values. While Extension participants found utility in assessing bioenergy from multiple perspectives, it can be said that the unfamiliarity the students had for the topic contributed to their eagerness to learn and practice a technique and process of moderation and engagement that bypassed traditional expert-driven forums.

Many students in fact plan to incorporate the deliberative dialogue format into either their upcoming Master's level research or professional careers. As one student exuberantly expressed to us, "there is a job market for these skills!"

Insight Three: The 'Empty Chair' philosophy

The 'Empty Chair' philosophy resonated with student participants as a key insight into enhancing often exclusive decision-making processes. The exercise calls for participants to consider not only the various stakeholders who have accessed 'seats at the decision-making table' but for those who are not in attendance. The students explained that this exercise transformed their concerns for bioenergy from an initially personal evaluative process into a community-based perspective. When asked to consider the empty chair, participants in the training were being asked to think about what others who are not with them physically during the workshop might wish to see or value over and beyond the one's own individual interests. Examples that resonated with students were poorer populations who struggle with high energy costs or future generations who will be left to manage whatever systems are put in place today. Students felt that such an exercise was especially useful in contexts where it is not practical or even useful to incorporate an intentionally broad range of stakeholders in a workshop setting, such as cases of especially complex technical challenges under the auspice of commonly agreed upon ends. While in certain contexts, bioenergy does not represent a commonly agreed upon or socially acceptable end, students felt that thinking about and encouraging others to think about the empty chair, or the perspective of 'others', was an especially useful way of expanding the considerations of decision-makers beyond what might simply be best for their interests, industry, or those privileged to have the opportunity to engage on the topic.

Insight Four: A role for bioenergy as a potential renewable energy source

Unlike the majority of Extension Educators, student participants were largely unfamiliar with bioenergy as a means to produce renewable energy. Again, the background of the student's research interests played a role in their perceptions of the topic. Bioenergy was first vaguely understood as a conflicted technology, one that would burn trees, which is not unproblematic, while producing renewable electricity, heat and potentially liquid fuel, which is good. While overall the positive picture extension painted for the technology largely swayed skeptics, the potential environmental and social detriments as covered in the workshop materials were not missed by the students. Students felt that their largest insight was gained when considering the 'Empty Chair' as described above in insight three. Using this technique, meditation on the various approaches as presented in the Issue Guide as well as the video was transformed from questions of individual and personal evaluation to those of community need. In doing so, the student participants largely grew to consider bioenergy through the lens of the communities and places that were considering such developments, such as the community of Escanaba as presented in the "Michigan Talks Biomass" video. In this way, students came to understand bioenergy largely as a feasible technology given that conditions such as proximity to feedstock and sustainability of forest resources as well as cultural characteristics were met and maintained in conjunction with this new technological development.

C) Researcher insights

Finally, we report our own overall preliminary insights as researchers interested in the utility, practicality and potential of deliberative dialogue as a means to catalyze and engage conversation in potential bioenergy communities.

Insight One: Conversations about bioenergy contribute to new understandings

Simply put, when people come together to talk about bioenergy issues they become more familiar with potentially new, vague, uncertain and little understood technology and the ways it may impact their daily lives. While this may sound overly simplistic, creating an environment where people from different aspects of society can come together and talk openly and with respect to one another about a potentially contentious topic is a challenge, yet core to exercising our citizenship responsibilities. The traditional format for such intentional discussions has been public hearings and forums. In these situations, experts and proponents are enlisted to defend and advocate for specific forms of development – to take partisan positions. While these events are often framed as opportunities for the public to provide input to decision-makers and authorities, it is often the case that public forums and hearings are only organized and attended after important decisions have already been made or are led by local leaders in a manner to achieve a prescribed end. When the topic is contentious, as bioenergy development has recently become in some Michigan communities, such engagement formats may contribute to controversy rather than encouraging productive discussion (Dietz and Stern 2008). In these instances, Extension Educators and other visible parties can then become lightning rods. In contrast, opportunities for deliberative dialogue provide a means for all interested residents to participate in meaningful conversation about the impacts of local and regional development of bioenergy and in doing so find common ground from which to build their visions for a sustainable future. These new understandings and visions can then catalyze future intention and interactions on community-level energy and resource decisions and beyond.

Insight Two: Connecting bioenergy to place

Participants of all types told us what made the deliberative dialogue sessions unique and salient to them was the tie between abstract thinking on renewable energy and concrete discussion on place. Beginning with the video which portrayed the multiple views on bioenergy development in Escanaba, participants were invited to discuss an issue that would impact not only their state and region, but potentially their own communities. By grounding this training in a case study of Escanaba and its real world challenges we were able to put a face on bioenergy. While this added credibility to the delineated bounds of appropriate discussion on the issue during the workshops, it also served to engage participants in a way that connected them not only professionally, but personally to the discussion and issue at hand. In doing so, a sense of both urgency and importance undergirded the framing, training as well as engagement workshops. Simply put, by embedding bioenergy development within the region and community, bioenergy and the challenges of renewable energy development were transformed from problems other people have to solve, such as specialists and government agents, into an issue that deserves consideration, input and action from all – or leadership for the public good.

Insight Three: Bridging expertise and lay knowledge

Beyond the framing workshop, where participants were invited based on their knowledge of various aspects of bioenergy issues, both the training as well as our initial community engagement workshops were attended by both conventional bioenergy experts and people with only a cursory knowledge of the specific mechanics of wood-based bioenergy technical systems.

While the conventional means of organizing these two types of participants would be for the experts to act as teachers and the non-experts to act as students, the deliberative dialogue format turns this approach on its head. In this alternative format, experts and lay publics are asked collectively to discuss bioenergy issues from a multitude of perspectives and make considerations for perspectives they might otherwise disregard as incorrect or lacking legitimacy. By struggling with the reality that seemingly contradicting perspectives exist simultaneously not just in society, but in local communities, both experts and non-experts were encouraged to engage and reengage with an issue previously felt to be thoroughly and completely understood. This is not to say that the workshops unseated the underlying values and intentions either group came with to the program. Rather, in recognizing, for example, the ‘expert perspective’ as being only one way to understand bioenergy development, those who hold alternative understandings of bioenergy were transformed in the minds of bioenergy advocates from ‘irrational opponents’ into fellow members of society who are also interested in resolving complex issues in a sustainable fashion. We feel this may have the potential to lay the ground work for more productive social interactions and cooperation for achieving community and regional goals in a way that takes into account a multiplicity of values and goals, and also revealing special interests and community power dynamics that threaten democratic decision-making. As a first step, catalyzing conversations within communities considering bioenergy development may be a means to exchange political gridlock with welcomed democratic innovation.

Publications & Presentations:

Eaton, W. and W. Wright (2010). Michigan’s energy future: Is there a role for woody-biomass? Michigan Sociological Association Annual Meeting, Bay City, MI. November 6, 2010. [Appendix D2(a)]

Eaton, W. (2011). Opposition to bioenergy: How trust and identity shape risk controversies. International Symposium on Society and Resource Management, Madison, WI. June 8, 2011. [Appendix D2(b)]

Eaton, W. and W. Wright. (2011). Community engagement for common ground: Catalyzing deliberative dialogue on contested natural resource issues. Rural Sociological Society Annual Meeting, Boise, ID. July 30, 2011. [Appendix D2(c)]

Eaton, W., W. Wright, J. Stone, S. Gasteyer, K. Whyte, and P. Gehrke (2011). Citizen Engagement and Outreach Strategies for Emerging Technologies. 12th Annual National Outreach Scholarship Conference, East Lansing, MI. October 4, 2011. [Appendix D2(d)]

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Appendix:

D2(a) – Abstract: Michigan’s energy future: Is there a role for woody-biomass?

Eaton, W. and W. Wright (2010). Michigan’s energy future: Is there a role for woody-biomass? Michigan Sociological Association Annual Meeting, Bay City, MI. November 6, 2010.

Abstract:

In response to demands for energy and economic security, a nexus of state, academic and private leaders in Michigan are working together to grow a bio-based economy in the effort to reduce dependence on non-renewable, costly and polluting fossil fuels such as coal while supplying economic development. To meet this goal, the state’s abundance of woody-biomass is being targeted as a potential supplier of renewable energy resources, mainly in the forms of wood-fired power plants and cellulosic ethanol facilities. Yet woody-biomass technology systems are laden with uncertainties as they provide both benefits as well as challenges, especially to the rural communities in which new operations are proposed. Rising levels of scientific and political controversies and contestations in targeted communities are opening new gaps between citizens, professionals and decision-makers who hold dissimilar values, beliefs and preferences for local bioenergy, raising questions about how bioenergy is being forwarded. Michigan State University, in partnership with the Michigan Agricultural Experiment Station, has developed discussion materials to be used by extension educators to catalyze community-level conversations around this contested issue, especially in communities anxious to consider bioenergy. Playing an alternate role than that of an expert advisor armed with scientific objectivity, this project aims to create a space for dialogue in prospective communities around three approaches identified by the research in order to better achieve a community’s goals.

Note: A copy of this PowerPoint presentation is included in the auxiliary appendix file: “*MSU_FBSCC_Auxiliary_Appendices.*”

D2(b) – Abstract: Opposition to bioenergy: How trust and identity shape risk controversies.

Eaton, W. (2011). Opposition to bioenergy: How trust and identity shape risk controversies. International Symposium on Society and Resource Management, Madison, WI. June 8, 2011.

Abstract:

Given concerns about climate change and the need for alternatives to fossil fuels, bioenergy from wood is promoted as a viable source of base load power. Attempts to site bioenergy facilities, however, have met local, regional, and environmental organization opposition. Bioenergy development is the tale of two diverging narratives about how to develop renewable energy and address climate change. On the one hand, coalitions of actors from government, business and scientific communities frame bioenergy as a sustainable solution to environmental and economic challenges. On the other, coalitions of local actors tied to state and national non-governmental organizations and networks question the science, economics, social policies and legitimacy of bioeconomy development. This ongoing clash halts development, polarizes communities and erodes the bonds of social trust.

In this paper, a case study of opposition to bioenergy development in the forested rural communities of northern Michigan is used to illustrate critical social processes involved in the opposition's development. My interest is in the formation of these contending narratives, particularly those developed by groups challenging the official networks of established law, regulation and decision-making power. I ask, what motivates concern and resistance despite regulatory and scientific approval? What are the shapes and contours of opposition movements? My findings show that opposition to bioenergy is not monolithic.

At least two species of oppositional behavior are identified, falling on either end of a radicalized-to-professionalized continuum. I unpack this development by gleaning insights from three areas of scholarship: (1) 'collective identity,' (2) the processes of public engagement and risk characterization, as well as (3) deriving contextual and historical foundations from literature on scientific and technological controversies. Contrary to oft heard characterizations, my findings also suggest that opposition to bioenergy is not 'irrational' - that skepticism of bioenergy development is not likely to be foiled by additional efforts at 'educating the public'. This paper clarifies the ways in which such characterizations and understandings may contribute to opposition, rather than dispel felt risks.

Note: A copy of this PowerPoint presentation is included in the auxiliary appendix file: "*MSU_FBSCC_Auxiliary_Appendices.*"

D2(c) – Abstract: Community engagement for common ground: Catalyzing deliberative dialogue on contested natural resource issues.

Eaton, W. and W. Wright. (2011). Community engagement for common ground: Catalyzing deliberative dialogue on contested natural resource issues. Rural Sociological Society Annual Meeting, Boise, ID. July 30, 2011.

Abstract:

In response to demands for energy and economic security, a nexus of state, academic and private leaders across the country are working together to grow a bio-based economy in the effort to reduce dependence on non-renewable, costly and polluting fossil fuels such as coal and oil while supplying economic development. To meet this goal, many states are looking to their abundant supplies of woody-biomass as a potential supplier of renewable energy resources, mainly in the forms of wood-fired power plants and cellulosic ethanol facilities. Yet woody-biomass technology systems are laden with uncertainties as they provide both economic and environmental benefits as well as challenges, especially to the rural communities in which new operations are proposed.

Nationally and locally, new bioenergy proposals are met with mixed reactions from stakeholders, and in some instances, fierce opposition. New gaps are opening between residents and decision-makers who hold dissimilar values, beliefs and preferences for local bioenergy. This raises important questions about how bioenergy is being forwarded: how are communities engaging in discussions on local bioenergy development?

Playing an alternative role to that of an expert adviser armed with scientific 'objectivity', we explore methods to catalyze community level conversations around this contested issue. This project aims to create a space for deliberative dialogue around different bioenergy approaches in order to better facilitate the obtainment of a community's goals.

Note: A copy of this PowerPoint presentation is included in the auxiliary appendix file: "*MSU_FBSCC_Auxiliary_Appendices.*"

D2(d) – Abstract: Citizen Engagement and Outreach Strategies for Emerging Technologies.

Eaton, W., W. Wright, J. Stone, S. Gasteyer, K. Whyte, and P. Gehrke (2011). Citizen Engagement and Outreach Strategies for Emerging Technologies. 12th Annual National Outreach Scholarship Conference, East Lansing, MI. October 4, 2011.

Abstract:

Emerging technologies, such as nanotechnology and synthetic biology, have potential applications in agrifood, water, and bio-energy/fuels. This symposium explores creative citizen engagement strategies in each of these areas, with an eye toward potential social and ethical dimensions. To promote active panel debate with audience members, five-minute project overviews will be (30 minute total), followed by 10 minute panel discussion to identify cross-cutting themes in their approaches, findings, and outcomes. In the ensuing 20 minutes, audience members and panelists will debate these themes in light of the broader conference emphasis on engaged scholarship and evidence-based practice. Individual presentations will address collaborative citizen engagement strategies in the following settings: (1) A USDA-funded project to build risk perception mapping capacities within Cooperative Extension on matters pertaining to agrifood nanotechnologies (Stone); (2) An NSF-funded project supporting stakeholder workshops to identify social and ethical dimensions of nano-biosensors in the beef sector (Whyte); (3) An NSF-funded project examining how people discuss new scientific discoveries and emerging technologies in social, civic, community, business, and educational groups (Gehrke); (4) A Michigan Economic Development Corporation (MEDC) project investigating socio-political mobilization against the siting of bio-energy facilities (Gasteyer/Eaton); and (5) an MEDC funded initiative to create a role for public engagement in contested biomass decision-making at the community level (Wright/Eaton). To the extent possible, one graduate student will participate per project and all will be encouraged to integrate symposium outcomes into a single article for submission to the Journal for Higher Education, Outreach and Engagement special 2011 conference issue.

Sub-Task D3: Communicate to Stakeholders Through Multiple Avenues

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Abstract

A key objective of the Forestry Biofuel Statewide Collaboration Center (FBSCC) is to increase understanding of forest biomass production systems for biofuels among a broad range of stakeholders. Sub-task D.3 of this project engaged stakeholders by developing a website to house information on the multiple components of the FBSCC, thus providing a forum for distributing publications, event announcements and research results to varied user groups. The website was developed with a range of stakeholder groups in mind, and structured with non-technical language at the higher levels leading to more in-depth and technical information with further exploration of the site. In addition, a seminar series was recorded and distributed online, giving project investigators the opportunity to present research outcomes to targeted stakeholder groups. This video seminar series is hosted through the project website, and provides opportunities for viewer interaction by allowing comments on presentations and the submission of questions for speakers. Throughout the duration of the project, potential website users have been informed of the resources available and new postings through electronic mail and existing mailing lists, linkages with cooperating websites, and outreach and extension personnel. The website is available at <http://www.michiganforestbiofuels.org/> and <http://www.michiganwoodbiofuels.org/>.

Introduction

The use of woody biomass to meet energy requirements has the potential to provide significant environmental and economic benefits, such as the reduction of fossil fuel emissions (Malmsheimer 2008) and economic growth for rural communities (Domac et al. 2005). According to recent estimates, U.S. forests could potentially provide the energy production necessary to offset approximately 190 teragrams of fossil fuel carbon emissions per year (Ryan et al. 2010), however the authors are careful to specify that this number is contingent on the public supporting this use of forests. Public support for forms of bioenergy such as cellulosic ethanol have been demonstrated for the upper midwestern United States (Johnson et al. 2011). However there are still concerns from various publics regarding issues such as the long-term supply and sustainability of forest feedstocks (Janowiak & Webster 2010) and the cost effectiveness of bioenergy compared to fossil fuel use. It is therefore important that research and information that directly addresses these questions is made readily available to the public, and especially to stakeholders that might be directly involved in the forest-to-gate supply chain for wood energy feedstocks. Given general attitudes regarding biomass supply for energy, Joshi and Mehmood call for “a full range of communication in the form of education and outreach programs” (2011). Sub-task D.3 addresses this by providing a forum for distributing information on FBSCC research to varied stakeholder groups. The website was also structured to house information on a related but separate biofuel project, the Feedstock Supply Chain Center of Energy Excellence, in order to strengthen the ability to reach a wide audience without duplicating outreach efforts.

Methods

Website Development

We began by developing a draft structure for the website with periodic feedback from the FBSCC Steering Committee (Figure 1). The website was designed to reach a broad audience while primarily being accessible to three main audiences identified by FBSCC and Feedstock Supply Chain Center of Energy Excellence collaborators through a logic mode process: various publics, loggers/truckers, and landowners.

Subsequently, we completed an Internal Survey of Communication Needs to help us further refine the website structure and form a procedure for gathering and developing website content. We met with FBSCC investigators from Michigan Technological University and Michigan State University to discuss the proposed structure and how the website could effectively integrate their research results and publications, and accommodate materials that were yet to be developed. Project leaders were asked about information that they wanted to share online, the timeline for making such information available, and a point of contact for each project component (sub-tasks or groupings of related sub-tasks).

Once the website structure was determined, we worked closely with a web design consultant to develop a preliminary graphical interface for the website. We also began to write and collect the content that we needed. For general webpages that described the FBSCC project and its significance, text was written by the subtask D.3 collaborators. The individual research summary pages for each project component were written in conjunction with contacts for each project (approximately 15 in total). We worked with each contact to complete draft text, edit text for readability and broad audience accessibility, and add visual components and summary information. After collecting the bulk of the necessary content, we worked with a web developer to set up a website on a test server, refine the site organization, and tag and sort webpages as appropriate. We also chose domain names for the website. The steering committee reviewed the entire site, providing commentary on overall organization, text, pictures, and future methods for reviewing new website content.

The final steps involved moving the website onto the Michigan Tech server and launching it for public use. At the time of site launch, we also drafted a press release that was reviewed by the steering committee and sent to multiple contacts, mailing lists, and extension personnel interested in bioenergy and woody biomass utilization. Shortly after the site launch, tools to track usage statistics were implemented. The site has been continually updated and refined since its launch, in consultation with the Steering Committee and other project collaborators. Periodic emails have been issued to FBSCC PI's with requests for updated information, publications, and presentations.

Video seminar series

Throughout the website design process, we made investigators aware of our planned seminar series in order to recruit investigators as presenters. The seminar series was scheduled for the last Quarter of the project in order to allow investigators time to collect and process research results. We worked with our web developer to create a space to house the recorded videos on the project website, and to include some interactive features such as question forms and space to comment on material.

Initially conceived as a series of live webinars, a small proposal on how to run the webinar series was drawn up for the Steering Committee that included information on possible presentation themes, speakers, and potential avenues for reaching interested audiences. At the suggestion of the Steering Committee, we altered the proposal slightly to do recordings of each presentation as opposed to live webinars to allow viewers more flexibility in viewing the material. We then contacted potential individual speakers to finalize commitments and schedule presentation recording times. We also issued an 'open call' for presentations among all FBSCC investigators to accommodate everyone interested in giving a presentation on their work. Each presenter was asked to make their presentation accessible to a non-technical audience.

In total, six presentations were scheduled and recorded, featuring speakers from the Michigan Economic Development Corporation, Michigan Technological University, and Michigan State University. Each of the presentations was recorded in a Michigan Tech ‘learning classroom’ facility set up with recording equipment. Live audiences were invited to each recorded presentation through a variety of local mailing lists and on-campus news distribution mechanisms. Final talks that have been through a Steering Committee review are posted on the project website’s ‘Videos and Presentations’ page, and are available in multiple viewing formats. Announcements about the series were sent to various individuals, extension personnel, and mailing lists pertaining to forestry and bioenergy. A video format that will be viewable by smartphone and tablet devices will be completed shortly.

Results

Website

The website can be found at <http://www.michiganforestbiofuels.org/> and <http://www.michiganwoodbiofuels.org/> (Figure 2).

To break down the FBSCC project in a way that was non-technical and user-friendly, we centered the website structure around three key themes:

1. How much woody biomass is available?
2. How can woody material for fuel be sustainably produced?
3. What are the most efficient ways to move and process woody material?

To accommodate audiences that may be looking for more technical information, there are also ways to access current project publications (<http://www.michiganforestbiofuels.org/publications>), a list of project webpages specific to the FBSCC (<http://michiganforestbiofuels.org/category/tags/fbscc>), and a list of project investigators (<http://www.michiganforestbiofuels.org/project-collaborators>).

The website provides brief descriptions of the overall FBSCC project and the related Feedstock Supply Chain Center of Energy Excellence project, and general information on each of the three themes to give the reader some context, before providing more detailed information on the individual research summary pages (featuring either project sub-tasks or groupings of related sub-tasks). The ‘progress and results’ section of each research summary page is the area where technical documents and publications are housed. Additional introductory information is provided on the ‘Wood bioenergy basics’ page (<http://www.michiganforestbiofuels.org/wood-bioenergy-basics>) and the ‘Supply chain basics’ page (<http://www.michiganforestbiofuels.org/supply-chain-basics>).

Since its launch in March of 2011, the website has received 1,444 visits, with the bulk of those visits coming from the state of Michigan.

Seminar Series

The seminar series “Wood Biofuel Energy in the State of Michigan” can be viewed at <http://michiganforestbiofuels.org/videos/> (Figure 3).

Six talks in total were recorded on the following subjects:

- Why Study the Forest – Dana Johnson, Michigan Economic Development Corporation, Recorded July 27th, 2011
- Michigan's Forest Inventory: Present and Future – Robert Froese, Michigan Technological University, Recorded July 15th, 2011
- Producing Wood Energy Crops in Michigan – Ray Miller, Michigan State University, Recorded July 27th, 2011
- What Can Life Cycle Analysis Tell Us About Sustainability? – David Shonnard, Michigan Technological University, Recorded July 27th, 2011
- Supply Chain Model: Optimization Models – Cost, Energy, Emissions – Dana Johnson, Michigan Technological University, Recorded August 25th, 2011
- Supply Chain Model: Simulation Model – Cost, Energy, Emissions – Fengli Zhang, Michigan Technological University, Recorded August 25th, 2011

Presenters included researchers and project collaborators from the Michigan Economic Development Corporation, Michigan Technological University, and Michigan State University. Each presentation was advertised locally and attended by between 18 and 25 live audience members. The seminar series currently features two different video formats: a flash format that is hosted directly on the project website, and a MediaSite option with a slightly different viewing template, hosted by Michigan Tech. A third format is being finalized that would allow viewing on smartphones and tablets. Usage statistics for the videos page are being tracked.

Discussion & Conclusions

The overall goal of the Forestry Biofuel Statewide Collaboration Center is to improve the forest feedstock supply infrastructure to sustainably provide woody biomass for biofuel production in Michigan over the long-term. To be successful in this goal, it is essential that stakeholders be well-informed about the information and knowledge produced by the FBSCC and the research process leading to project conclusions. These stakeholders may include landowners, who own a large portion of the woody biomass in Michigan, loggers and truckers, who may work directly in the industry, policy-makers, and environmental groups.

Since many people use online resources as a primary information source and/or an initial way to find desired information, web-based distribution of project information is a practical and efficient way of communicating with audiences. In addition, having a central website for posting project information makes it easier to share results with stakeholders who have collaborated in producing project information, for example survey participants and fellow investigators.

The creation of a project website and recorded seminar series fulfills the original goal of sub-task D.3 by providing means of communication through which to engage a wide variety of stakeholder groups. Milestones listed in the project description were all met, including the initial development of a project website, website updates, and establishment of a seminar series. The only change to

these listed products was the switch from the webinar seminar series that was planned initially, to the recorded presentation seminar format. This was done due to the varied schedules of the expected viewership, and the expected convenience of being able to watch a high-quality recorded presentation as opposed to attend a live webinar. Some of the expected dates for milestones were altered throughout the course of the project due to technological hurdles and delays in receiving content from different project components. The principle changes to the expected timeline were a delay in the website launch date due to difficulty transferring the site from the test server (Quarter 4 as opposed to Quarter 2) and delaying the recorded seminar series to the final Quarter of the project to await more advanced project results from investigators.

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Figures

MTU Biofuels Website Diagram
July 26, 2010

Figure 1: Draft website structure

Figure 2: A screenshot of the final website format and graphic design.

Michigan Forest Biofuels Research

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What can Life Cycle Analysis tell us about sustainability? - David Shonnard

00:23 54:21

Powerpoint Slides:
[Life Cycle Assessment FBSCC - Shonnard.pdf](#)

MediaSite Presentation URL:
<http://webcasts.mtu.edu/mediasite/SilverlightPlayer/Default.aspx?peid=81...>

Explore the process of life cycle analysis, and how it can be used for a project on wood based bioenergy to help determine the environmental impact of different fuels. Please visit the [project webpage](#) for more information on this subject.

[Add new comment](#)

How much forest-based biomass is available?

How can woody fuel material be sustainably produced?

How can we efficiently harvest, move and produce biofuel?

Events & Postings

Event : [Minnesota Extension's Fall 2011 Woody Biomass Webinar Series](#)

Event : [Northeast Wood Energy Webinars](#)

Announcement : [New videos and presentations available](#)

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Figure 3: A screenshot of the webpage for a presentation in the video seminar series