The Environmental Benefits of Cellulosic Energy Crops at a Landscape Scale

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I. Introduction

The objective of this paper is to present a broad overview of the potential environmental impacts of biomass energy from energy crops - particularly the cellulosic energy crops currently under development.

For this discussion, the term "energy crop" refers to a crop grown primarily to create feedstock for either making biofuels such as ethanol or burning in a heat or electricity generation facility. Corn, sugarcane, and short-rotation tree plantations of poplar (Populus sp.), sycamore (Platanus occidentalis) or eucalyptus are examples of energy crops currently in production. The term "cellulosic energy crops" is used to differentiate energy crops grown for their cellulose content from energy crops grown for their starch or sugars (e.g., corn or sugarcane). Cellulosic energy crops are designed to be used in cellulose-based ethanol conversion processes (as opposed to starch or sugar-based ethanol conversion processes). As more cellulose can be produced per hectare of land than can sugar or starch, the cellulose-based ethanol conversion process is a more efficient use of land for ethanol production. Cellulosic energy crops currently under development in the U.S. include switchgrass (Panicum virgatum) and short rotation woody crops - especially poplar and willow (Salix sp.). Switchgrass is a drought-tolerant prairie grass species with an extensive natural range in North America. It is the model herbaceous energy crop selected by the U.S. Department of Energy and is well-suited for cellulose-based ethanol conversion processes (Wright et al. 1993). Cellulosic energy crops are also appropriate for use in heat or electricity generation.

From the perspective of a farm enterprise, energy crop production is generally compatible with food crop production. Farmers will most likely use energy crops as one component in a mix of several crops. Introducing these crops into a larger farming scheme does however, require careful planning as cellulosic energy crops are generally perennial (e.g. trees and switchgrass) with rotations of five to twenty years.
Assessing the environmental impacts of biomass energy from energy crops is complex because the environmental impact of using biomass for energy must be considered in the context of alternative energy options while the environmental impact of producing biomass from energy crops must be considered in the context of alternative land-uses. Using biomass-derived energy can reduce greenhouse gas emissions or increase them; growing biomass energy crops can enhance soil fertility or degrade it. Without knowing the context of the biomass energy, one can say little about its specific environmental impacts. The primary focus of this paper is an evaluation of the environmental impacts of growing cellulosic energy crops especially at the landscape or regional scale. However, to set the stage for this discussion, we begin by comparing the environmental advantages and disadvantages of biomass-derived energy relative to other energy alternatives such as coal, hydropower, nuclear power, oil/gasoline, natural gas and photovoltaics.

II. Comparing Biomass energy with other energy sources

Assessing the environmental impacts of using biomass energy is complex because biomass energy can be used to produce heat, electricity or fuels (e.g. ethanol) and it can substitute for fossil energy, nuclear energy and other renewable energy technologies.

Coal. Biomass-derived energy is most advantageous when compared to coal. Using biomass to displace coal in power generation has the greatest greenhouse-gas reduction benefits and the greatest air pollution benefits. A recent U.S. analysis calculated that using the wood grown on a hectare of land in short-rotation woody energy crops instead of coal could annually displace 5.2 Mg of fossil C in CO₂ (Graham et al., 1992). Biomass burns cleanly and with much lower SO₂ and somewhat lower NOₓ emissions. Two additional environmental benefits are the reduction in the environmental damage associated with coal mining and the avoidance of coal ash disposal problems. Burning wood for power or heat not only produces much less ash than coal but wood ash can be returned to agricultural soil.

Oil/gasoline. The greenhouse gas benefit of using biomass-derived ethanol to displace gasoline is considerable but still less than that of displacing coal because of the much higher energy content of gasoline per unit of fossil carbon. The CO₂ benefit of using cellulosic energy crops for ethanol is estimated to be about half that for displacing coal (Graham et al., 1992). If a high fossil-input energy crop such as corn is used to produce ethanol as a replacement for gasoline, the greenhouse gas savings may be quite low; the current process of growing corn and converting it to ethanol produces 0.6 to 0.8 units of CO₂ for every 1.0 unit of gasoline-CO₂ displaced (Marland and Turhollow, 1991). The low ratio is due to the heavy use of nitrogen fertilizers and the use of fossil fuels (coal) in the conversion process.
Using ethanol rather than gasoline to power automobiles has air pollution benefits. Ethanol emissions are lower in carbon monoxide, sulfur dioxide, and hydrocarbons but slightly higher in NO emissions (Graboski, 1993). They are higher in aldehydes but the aldehydes are mostly acetaldehyde rather than the formaldehyde produced by the combustion of gasoline (Macedo, 1993). Acetaldehyde is both less reactive and less toxic than formaldehyde. In general, ethanol emissions are less toxic than gasoline emissions (La Rovere and Audinet, 1993). When compared to reformulated gasoline to which oxygenates have been added, biomass-derived ethanol has no real air pollution advantages or disadvantages other than the reduction in CO₂ (Tyson et al., 1993).

Natural gas. The environmental advantages of displacing natural gas with biomass-derived electricity are less than those for displacing coal or oil/gasoline. Not only does natural gas contain twice as much energy per unit of carbon than coal but natural gas power plants are more energy efficient than coal plants (Turhollow and Perlack, 1991). Consequently the CO₂ benefit of substituting biomass for natural gas, while still positive, is much less than that for coal.

Nuclear and renewable energy sources (hydro, wind, photovoltaics). The environmental advantages of biomass energy are fewer when compared to greenhouse-neutral energy types such as nuclear, wind, hydropower, and photovoltaics. Biomass energy creates some greenhouse gas emissions as fossil fuels are likely to be used in the production of energy crops (fuel for tractors, fertilizer etc.). While the greenhouse gas emissions per unit of biomass power produced are 1/10th to 1/20th of that from coal power, they are still not zero (Turhollow and Perlack, 1991). Also, biomass power has more air pollution and greenhouse gas concerns than any of these four alternative power sources. However, the safety and waste disposal problems associated with nuclear power are avoided with biomass. Biomass also does not have the land loss and fishery damages that are associated with dams and hydropower.

Land requirements. Biomass energy’s universal disadvantage is that it requires large acreages of land. An efficient biomass power plant (33%) will require 200 to 400 ha of land in energy crops per MW of baseload power depending on the biomass yield (Mg/ha/yr). Cellulose to ethanol technology is expected to require 150-300 ha per million liters of ethanol assuming moderate cellulosic energy crop yields (10 to 20 dry Mg biomass/ha); U.S. corn to ethanol production averages close to 300 ha per million liters (Hohman and Rendelman, 1993). Thus it is important to consider and quantify the environmental impacts that could be associated with major land-use shifts to growing energy crops. Shifting from conventional agricultural land uses to energy crops could change soil erosion patterns, water quality of regional streams, wildlife abundance and kind, and regional air quality. Characterizing and quantifying these potential impacts is challenging as they are dependent on multiple site- and crop-specific factors.
III. Factors Controlling Environmental Impacts from Energy Crop Production

In this section we review the multiple crop and site factors that will control the potential environmental impacts of growing energy crops. All of these factors must be addressed if the regional environmental impact of developing a biomass-based energy industry is to be understood. In the section IV, we describe an approach for quantifying environmental impacts to these resources which takes into account not only crop and site factors but the economic drivers which will control them.

Crop factors. The type of energy crop grown to produce biomass is a deciding variable in predicting environmental impacts from energy crop production; different crops have different effects on erosion, water availability and quality, wildlife habitat, and air quality. For example, growing corn is likely to create more soil erosion and use more fertilizers than growing a short rotation poplar crop. However, because tree crops will use more water than herbaceous crops, tree crops may reduce stream flow. Wildlife will differentiate between different crop types; for example, tree crops can provide habitat for forest bird species (Wright et al., 1993; Hoffman et al., 1995; Tolbert and Schiller, in press). Perennial grass species enhance soil carbon more than annual herbaceous species such as corn. Tree crops release more hydrocarbons into the air than do herbaceous crops (Perlack et al., 1992).

The management of the crop is also important (Cook et al., 1991). Interplanting a cover crop between trees in the early stages of a short-rotation wood crop production is likely to reduce erosion as compared to leaving the soil bare. The amount of fertilizer applied and the timing of the applications will affect water quality as will the choice of pesticides. Harvesting trees during the winter reduces the loss of nutrients from the site as the leaves are not removed. Burning crop residues in the field, as is done with sugarcane, can have negative impacts on local and regional air quality (La Rovere and Audinet, 1993).

Site factors. Physical characteristics of the land will strongly influence the potential productivity of energy crops and therefore the likelihood that the land will be used for energy crops (Liu et al., 1992 and 1993). Soil type, climate, and topography will affect probable erosion and runoff (OTA, 1993; Hoffman et al., 1995; Tolbert and Schiller, in press). Soil type will also influence the need for fertilizers and the rate at which pesticides and fertilizers leach through the soil to contaminate ground water. Highly organic soils will retain pesticides and nutrients better than soils with a low organic content. Warmer climates will enhance the breakdown of pesticides but will also increase their volatilization.

The former use of the land is an especially important consideration at the regional scale and when developing policies to promote or discourage energy crops. It is the comparison of the environmental effects of the former land use with the energy crop land use that determines the environmental value of energy crops. For example,
growing switchgrass rather than growing soybeans has many environmental
advantages. Compared to soybeans, switchgrass will increase soil carbon, reduce
erosion, improve water quality, and provide better animal habitat. Thus a policy
which encourages the production of switchgrass on land that was formerly in soybeans
would be for the environmental good. However, if that same policy promotes the
conversion of forests to switchgrass, the environmental impacts will be negative.
Valuable forest habitat will be lost and water quality will likely be degraded in the
land conversion process.

Finally, the location of the energy crops in relation to other land uses will
strongly influence water quality and wildlife impacts. Perennial energy crops such as
trees or grasses which receive low levels of fertilizers or pesticides can serve as
streamside filters if planted adjacent to streams. These crops can absorb nutrients
coming from more heavily fertilized conventional crops upslope and can catch
sediment as it moves downslope. Both actions can improve local water quality
(Ranney and Mann, 1994). If streamside planting is extensive and nonpoint source
pollution from agriculture is a regional problem, perennial energy crops could improve
regional water quality (OTA, 1993). A small amount of land in energy crops planted
adjacent to a region's streams could have a much larger influence on water quality
than double or triple that acreage planted upslope.

If planted in a largely agricultural landscape dominated by annual crops, energy
crops may promote regional and local wildlife. The addition of woody energy crops
in particular increases the structural diversity to agricultural landscapes which should
enhance biodiversity at the regional scale. Measurements of bird abundance, type and
number of species indicate that woody crops can serve some of the habitat functions
of natural forests (OTA, 1993; Wright et al., 1993; Hoffman et al., 1995). However,
woody energy crops are not a substitute for natural forests (Cook et al., 1991; Tolbert
and Schiller, In press). Producing energy crops can negatively affect wildlife if the
crops displace a food source that the original land use provided. For example, birds
migrating from Canada to Mexico and South America use the corn left in the fields of
the midwestern United States. If switchgrass displaced large acreages of corn in this
region, this food source would disappear with no obvious replacement.

Quantity of land dedicated to energy crops. The quantity or percent of land
converted to energy crops will clearly influence the impact that energy crops have on
a region. If energy crops are a minor component of the region, they will have less
impact on regional environmental resources. However, their impact cannot be
assumed to be simply a linear function of the amount of land planted to energy crops.
This is particularly true for wildlife and water quality impacts. However, even
impacts such as erosion that can be calculated on a per hectare basis and do not
depend on the relationship of the land-use change to other land uses, will not be
simply linearly related to the amount of land planted to energy crops in a region. Soil
types, topography, and former land-use will vary within a region and affect even these impacts (Graham and Downing, 1993).

Interactions among factors. The factors cannot be considered in isolation as they are highly related and interact in affecting the environment. For example, soil, climate and topography, crop type, and crop management will affect energy crop productivity and therefore the quantity of land needed to produce a specific supply. Even former land-use by itself can affect energy crop productivity. For example, soil compaction as a result of pasture use may reduce expected energy crop yields. Assessing the potential environmental impacts of energy crop production requires an integrated approach which considers all these factors. To be successful, however; the approach must also include the economic and policy drivers which will control where energy crops are most likely to be grown and what land uses they will displace.

IV. Quantitatively Predicting Environmental Impact

Quantitatively predicting the environmental impacts of cellulosic energy crop development at a landscape or regional scale is difficult as most cellulosic crops are not yet planted in regionally significant amounts. Thus at these scales empirical information on environmental impacts is lacking, and a modeling approach is needed to predict the effects these crops might have if planted to the scale of a major crop such as corn, or even a less important crop such as barley or oats. In this section we briefly outline a six stage modeling approach we have developed for assessing regional or landscape scale environmental impacts. This approach includes economic considerations as economics will determine 1) where energy crops are profitable and the conventional crops they will displace and 2) what management regimes will be used to produce energy crops. We then present some results from using this approach to assess the environmental consequences of growing switchgrass to supply bioenergy conversion facilities in North Dakota and Tennessee.

Characterizing the region. In the first stage, we characterize the region as to: climate and topography, soil quality, current land use types and location, management practices associated with current land uses, profitability of current land use. If possible the relationship between profit and soil type is determined. Understanding the relationship between potential profit from conventional land use and soil type greatly improves the projections of where energy crops would be grown.

Developing energy crop management scenarios and production costs. In the second stage we determine energy-crop management practices and estimate production costs. This determination is based in part on our characterization of the region. Some energy crops are more appropriate for some soils and climates than others.
Modeling crop yields and on-site environmental impacts. In the third stage, crop yield variations associated with soils and climates and crop-specific, on-site environmental parameters such as erosion, runoff, nutrient and pesticide losses are predicted using EPIC (Erosion Productivity Impact Calculator) crop simulation model developed by the U.S. Department of Agriculture (Williams et al., 1989). The model is sensitive to many of the factors controlling regional environmental impacts - soil type, topography, climate, crop type, and crop management. By running the model under many climate, crop, and soil regimes, we can predict not only crop yield but also the crop erosion (Mg soil/ha/yr), runoff (cm/yr), and nitrogen and phosphorous nutrient loss (kg/ha/yr) to runoff or groundwater as a function of climate, soil, and topography. Changes in the environmental values associated with a land use switch to a specific energy crop can be easily calculated by comparing the EPIC predictions for the conventional crop to those predicted for the energy crop. The crop yield information provided by EPIC is combined with empirical crop yield information to predict variations in yield associated with different soil and climate conditions.

Calculating probable farmgate biomass price. Using conventional crop profit information generated in Stage 1 and energy crops yield and production costs, we calculate the probable price of biomass at the farm (the farmgate price) in the fourth stage. This is the break-even price needed to ensure the farmer a profit equivalent to that produced by conventional crops and does not include the cost of transporting the biomass to the location where it is to be used. The break-even farmgate price is used to identify the lands most likely to be converted to energy crop production.

Determining where land use change will occur. In the fifth stage we predict land use changes based on the assumption that transportation costs to the conversion facility being equal, land with the lowest farmgate price will be the first land to go into biomass crop production as this land will produce the least expensive biomass for a conversion facility.

Evaluating environmental impacts. - Regional impacts on soil fertility, water quantity, and air quality largely depend on how much and what type of land is converted. They can be calculated by linking the per hectare environmental impacts determined in Stage 3 to the land-use change predictions determined in Stage 5. Regional wildlife impacts depend not only on how much and what type of land is converted but also the location of that land in relation to other land uses. To evaluate these impacts, one must create maps of the changes in landscape pattern created by the projected land use changes. These maps are then used as input to spatially explicit models of animal behavior and habitat to examine wildlife impacts. Regional water quality impacts depend on not only how much and what type of land is converted and where that land is in relation to other land but also the topographic position of the land in relation to streams and lakes. One must not only create maps of projected land use changes associated with biomass production but also link those maps with

Graham et al., p. 7
topographic maps of the same area. Water quality models such as AGNPS (Agricultural NonPoint Source pollution) which predicts stream water quantity and quality as a function of topography, climate and land use pattern (Engle et al., 1993) can then be used to predict regional impacts on water quality.

Some results from two environmental analyses using this six stage approach analysis are shown in Figure 1. Figures 1a and 1b show the predicted impact on regional soil erosion and nitrate loss from growing switchgrass to supply a hypothetical biomass energy facility near Fargo, North Dakota (English et al., 1993). The figures were created by comparing the total water erosion or nitrate loss in runoff expected from growing just conventional crops (wheat, oats, barley) on the cropland within 50 km of the facility with the erosion and nitrate loss expected if this land was also producing switchgrass to supply an biomass energy facility of varying biomass demand levels (1,000 to 10,000 Mg of switchgrass/day). The land requirements for these demand levels ranged from 47,000 to 320,000 ha. Switchgrass production is predicted to reduce soil nitrate loss and water erosion in this region but the absolute amounts (tonnes per year) are low as the land is flat and rainfall is limited.

Figures 1b and 1c show some results from a study designed to analyze the regional implications of growing switchgrass in two multi-county areas in Tennessee, one centered around Memphis and the other around Nashville (Graham and Downing 1993). Conversion of 20 percent of the cropland to switchgrass production in each region, is projected to reduce regional erosion by almost 20 percent (Figure 1c). The absolute erosion reduction (in tons of soil per year) is projected to be greater in the Memphis region because of the significantly higher initial erosion rates in this region. Increased switchgrass production reduces nitrate losses in runoff in both regions. Due to high predicted nitrate losses from soybean production, the benefits of producing switchgrass are higher in the Memphis region because of the greater displacement of soybean acres in that area (Figure 1d). Thus, conversion of 20 percent of the cropland to switchgrass production is projected to reduce regional nitrate loss in runoff by almost 20 percent in the Memphis region, but by only 10 percent in the Nashville region.

The study results illustrate the potential environmental benefits of switchgrass production but also emphasize the regional differences that may be expected. Biomass energy crop production has many environmental benefits if the crops are well managed and well suited to the site; however, they are not universally advantageous. Governments face a serious challenge to develop policies and regulations that take advantage of the potential environmental benefits of energy crops and minimize their potential negative impacts. The value of the environmental benefits needs to be quantified and incorporated in cost comparisons between biomass and other energy sources.
References


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Graham et al., p. 10
Figure 1. The regional effect of switchgrass production on erosion and nitrate losses in runoff from cropland at two locations - eastern North Dakota and Tennessee.