Multidisciplinary modeling and GIS for landscape management.

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Abstract

Ecological dynamics in human-influenced landscapes are strongly affected by the socioeconomic factors that influence land-use decisions. Incorporating these factors into a spatially-explicit landscape-change model requires the integration of multidisciplinary data. We developed a model that simulates the effects of land use on landscape structure in the Little Tennessee River Basin in western North Carolina. This model uses a variety of data, including interpreted remotely-sensed imagery, census and ownership maps, topography, and results from econometric models. Data are integrated by using a geographic information system and translated into a common format, maps. Simulations generate new maps of land cover representing the amount of land-cover change that occurs. With spatially-explicit projections of landscape change, issues such as biodiversity conservation, the importance of specific landscape elements to conservation goals, and long-term landscape integrity can be addressed. In order for management to use the model to address these issues, a computer-based landscape-management decision aid is being developed. This tool integrates the models, associated data bases, and a geographic information system to facilitate the evaluation of land-use decisions and management plans. This system will estimate landscape-level consequences of alternative actions and will serve to focus coordination among different land-owners and land-use interests in managing the regional landscape.
The southern Appalachian landscape is a product of the interaction between ecological and socioeconomic processes. Effective landscape management in this region requires (1) an understanding of how these processes are linked in time and space to influence landscape dynamics and (2) a methodology that takes this knowledge about the landscape and makes it available to managers. One approach for linking the processes is to develop a spatially-explicit multidisciplinary model that can simulate landscape change induced by land use and then evaluate its impacts on ecological and resource supply variables. The advent of geographic information systems (GIS) and remote sensing makes construction of this model feasible. Applying this model in a landscape management program involves "packaging" it in a form that is desirable to the decision makers. Designing this "package" requires a cooperative effort among computer scientists, research scientists, and potential users of the model.

In this chapter, we present an approach for integrating ecological and socioeconometric information for application in a landscape management program. First, we discuss an approach for integrating information for use in landscape-level conservation planning. This discussion is placed in the context of a landscape-change simulation model being developed for the southern Appalachians and the Olympic Peninsula. Second, we present a methodology of how this model can be applied to address landscape-management and conservation questions. This methodology is
discussed in terms of a landscape management decision aid being developed called the Land Use Change and Analysis System (LUCAS). Linking ecology and socioeconomics for simulating landscape change

Landscapes traditionally are viewed ecologically as a mosaic of land cover types (Forman and Godron 1986). For example, in the southern Appalachians, the landscape can be characterized as forest with interspersed patches of agriculture, range or brushy lands, urban areas, and wetlands. Landscapes can also be viewed as a mosaic of socioeconomic units called ownership tracts. Individual tracts can be categorized as a subset of either public or private land (e.g., state, USDA Forest Service, residential, commercial, industrial). As management goals differ among the ownership categories, so too may the land use. Consequently, the structure and function of the landscape is directly related to the abundance and arrangement of land in each ownership category, in addition to the mosaic of ecologically defined patches. Combining these ecologic and socioeconomic views is necessary for a more complete understanding of landscape-scale processes and, therefore, more informed conservation-management decisions.

In the southern Appalachians, a model is being developed that integrates the socioeconomic and ecologic views of the landscape for the purpose of simulating the influence of land use on landscape change and its impacts. Model development revolves around two considerations. First, can we represent information derived from the
socioeconometric and biological disciplines as a common data structure to facilitate integration? Second, can solutions to landscape management and conservation problems be generalized? In other words, can a single generalized solution serve as a standard approach for addressing a broad array of landscape management issues.

**Integrating ecology and socioeconomics.** In the landscape-change model, integration is accomplished through the database, and the unifying data structure is the raster map. All data used and produced by the model is represented as a map. Maps created by the model can then be evaluated for specific purposes, such as an analysis on changes in the landscape's biodiversity.

Data layers included relate to land cover, land use, access or transportation costs, and land-use potential. The data used to create these layers originate in many forms, including remote imagery, digital elevation models, census tract data, TIGER/Line™ census files, county tax assessor maps of private ownership boundaries, and federal ownership maps. Some of the information is used directly, like the road network maps from the TIGER data. Other maps must be created, such as land cover (e.g., interpretations of remote imagery), land use (e.g., combination of county tax assessor maps, interpreted remote imagery, and TIGER data), land-use potential (e.g., composite of elevation and slope), and maps of access or transportation costs (e.g., the distance between each patch and a road or the nearest market or cultural center).
Land-cover maps were created by interpreting of Multispectral Scanner (MSS) images. Four MSS images from 1975, 1980, 1986, and 1990 were used to create a time series of land cover change for the Little Tennessee basin. This time series was used to derive probabilities of land cover change for input into the landscape-change model. The land cover classifications included forest, disturbed/unvegetated (includes urban and recently cleared areas), Agricultural/grassy/brushy (includes row crops, rangeland, lawns, young regrowth, etc), water, bare rock, and balds.

Land cover is an expression of land use. Different land uses, however, might occur within the same land cover class. For example, an area classified from a remote image as hardwood forest might be used as an unmanaged woodland, recreation area, plantation, or a wooded residential area. Although these areas might appear identical on the remote image, they probably function differently within the landscape. In the landscape-change model, a land use map is being constructed from county tax assessor maps and TIGER data. Land use classifications include commercial, residential, industrial, agricultural, cleared, other forested, and transportation. Land-use potential was represented as an overlay of elevation and slope maps derived from USGS 1:24000 DEMs.

Access and transportation cost maps were created using TIGER files of road networks. Access measures the cost associated with movement away from paved roads. This cost was estimated by creating a map of the distance that each pixel is located from a paved
road. Transportation measures the costs associated with distance along roads to specific points like market or cultural centers. In this map, each cell was assigned a value representing the shortest distance from a point on a road nearest to each pixel to the center of the closest major market and cultural center.

Of the data layers discussed above, the most fundamental to the model are the land cover maps derived from the remote images. It is through the selection of the type of imagery and the time periods that determine the spatial and temporal scale that land cover changes are measured by the model. Improvements in remote imagery and the software available for their interpretation have greatly enhanced our versatility to create land cover maps at a variety of scales and detail.

Linking the land cover maps with the other data layers is accomplished using a GIS. The GIS is used to overlay the data to construct a composite map. The composite map is represented as an ascii file for input into the model. "Cells" in the composite map are categorized by a string of characters called a landscape-condition label. Each character of this label is a category value from one of the original maps. For example, if the label for a cell from the composite map is 3264, the first position (4) (moving from right to left) might be a land-cover category, the second position (6) land use, the third position (2) distance-to-the-nearest-road, and so on. Because the landscape-condition label is a character string, its length (e.g., the number of data layers) is essentially not limiting. A time series of
the composite maps can then be used to estimate transition probabilities for land-cover change based on a wide variety of spatial information. They can also be applied in the landscape-change simulation or used to assess the environmental and socioeconomic impacts of change.

A General Solution. The southern Appalachians is a landscape dominated by humans. Much of the landscape remains unchanged from year-to-year, however, because decision making on the large public ownerships (Great Smokies National Park and National Forests) is oriented toward preservation, wildlife management, recreation, water resources, and forestry. Regardless, every hectare is under the stewardship of humans, and consequently landscape properties such as fragmentation, connectivity, and the degree of dominance of habitat types are influenced by market processes, human institutions, and landowner knowledge in addition to ecological processes. With this consideration, the following general solution was proposed for the landscape-change model (Lee et al. 1992) (Fig. 1). First, an econometric analysis for estimating the propensity for ecological processes, market forces, and social factors to influence land use in the region is conducted. Second, the results of the econometric analysis are passed to a landscape-change simulation model and changes in landscape structure based on land use are estimated. Third, the results of the landscape-change simulation are passed to models that estimate impacts of change on environmental integrity and resource supplies. Fourth, results of the
environmental- and socioeconomic-impact models are then analyzed for their influence landscape on sustainability. We will discuss the first 3 steps of the general solution as they are being applied in the southern Appalachian landscape.

The econometric analysis involves estimating probabilities of land-cover change as a function of selected socioeconomic driving variables. Presently, these variables include transportation networks (access and transportation costs); slope and elevation (indicators of land-use potential); ownership (landholder characteristics); and land cover. Preliminary analysis of the Little Tennessee river basin revealed that land-cover change is most likely to occur on private land, near a paved road, on flat low elevation land, and close to the major urban center, Franklin, NC. Most of the transitions in land cover are forest converting to agriculture/grassy/brushy and disturbed/unvegetated cover types.

Impacts of land use on landscape structure are estimated by applying the transition probabilities of land-cover change in a Markov model. Each grid cell in the map is evaluated for land cover change based on probabilities associated with its landscape condition label. Several simulations are run to produce a set of results representing a distribution of possible land cover maps for a future time. These maps are then evaluated for changes in specific environmental and resource supply variables. For example, risk to an endangered species can be examined by comparing the amount of
habitat or number, size, and distribution of habitat patches that are in the initial and simulated landscape.

**Landscape management application: The Knowledge System Environment.** Packaging the model so that it is useful to natural resource managers is a significant issue. Failure to address this issue will result in the model having limited utility and applicability in a management setting. Fortunately, techniques derived from artificial intelligence (AI) concepts and object-oriented programming fundamentals can be used to make contemporary modeling technology available to landscape managers (Tanimoto 1987, Saarenmaa et al. 1988, Folse et al. 1989, Flamm et al. 1991).

A modeling environment that employs AI and object-oriented programming techniques is called a Knowledge System Environment (KSE) (Coulson et al. 1989). A KSE is a computer-based methodology developed to address issues of integration and application of different forms of information to solve unstructured problems. A KSE being designed for addressing problems in landscape management for the southern Appalachians is called the Land Use Change and Analysis System (LUCAS) (Fig. 2). LUCAS has four distinct modules: a model base, GIS, data base, and a graphic user interface. The model base houses the quantitative models. The GIS manipulates the spatial data. The database serves as the reservoir for non-spatial data. The graphical user interface in LUCAS serves several functions: (1) it is the link between the system and the users, (2) it addresses issues of communication between system modules,
and (3) it contains the expert opinion represented as the contents of windows, the order that windows "pop-up" on the screen, and the interpretation of quantitative model results.

LUCAS has many attributes, all of them a function of object-oriented methodologies and AI concepts. First, recently acquired data or new technologies such as a simulation model can be incorporated with little impact to those components of the system not being changed. As such, LUCAS can serve as a warehouse for knowledge gained from research and development. Second, event-driven, in addition to time-driven, land-use scenarios can be evaluated. This feature is particularly beneficial to landscape management, because it allows for the examination of the impacts of a specific event or series of events, such as the construction of a road or the expansion of an urban area. Third, LUCAS can provide facilities for documenting the logic behind a decision as well as help guide a regional research and development program. Such documentation may be necessary in the advent of litigation or meetings with concerned citizens.

A KSE as a flexible management decision aid. Landscape management requires estimating impacts of specific actions as well as evaluating plans for achieving a desired future condition. Given that a landscape is a mosaic of private and public ownerships with different land-use goals, evaluating management alternatives or selecting a future condition must include those interests affected by the decisions. Furthermore, the complexity of landscapes and their
broad spatial scale prohibit traditional hypothesis testing as a primary tool for landscape-management decision evaluation. An approach that emphasizes input from interested parties, is sufficiently flexible for evaluating land-use options, and provides replication through simulation experiments is called adaptive management (Holling 1978, Lee 1986, Walters 1986). This approach is serving as the design concept for LUCAS.

In adaptive management, a small group of people with experience in integrating information and coordinating resources to solve problems is assembled (Holling 1978). Integration comes from the application of systems analysis techniques like computer modeling. Coordination involves identifying a series of steps needed to evaluate a desired future condition or management action. LUCAS is being designed to address both these tasks. As discussed previously, integration occurs through the transformation of data to a common scale and format and the links constructed between modules of the KSE. Coordination is accomplished by extracting knowledge about a specific landscape-management issue from land owners and managers, integrating this knowledge into LUCAS for experimentation, and then land owners and managers evaluating the results of the simulations and, hopefully, arriving at a consensus.

The success of LUCAS will depend on its functionality and acceptability. The primary function of LUCAS is as a facilitator for making a choice from a set of alternatives. Thus LUCAS must be capable of at least one or more of the following functions during a
decision evaluation. First, it must be able to generate estimates for a set of social, economic, and ecological indicators to use in an impact assessment. Second, LUCAS may need to calculate a frequency distribution and perform a sensitivity analysis on these indicators. Third, each management plan or action will need to be evaluated in terms of the behavior of relevant indicators over space and time. Fourth, LUCAS may need to consider trade-offs between one indicator and another during an analysis session. This may require ranking the indicators in order of importance. Fifth, LUCAS must serve to encourage communication and interaction among research scientists and developers, landscape managers and their staff, and those who must endure management policies or actions. For example, misunderstandings between sponsoring land-management agencies and research institutions about deliverables might be avoided if a standard existed for product specifications. A system like LUCAS can provide this standard.

System acceptability among users is just as important as functionality. For acceptability, LUCAS must maximize "user" involvement so that the local scientists, managers, owners and other interested parties specify system utility. LUCAS sessions also must be made fully transparent and interactive, typically done through the extensive use of graphics and an interactive computer environment. In other words, direct interactions with data bases and models are minimized, or made transparent to the user, while system flexibility is emphasized. An effective communication network
between scientists, managers, and land owners must be maintained. It is through this network where a foundation of confidence and understanding among system contributors is constructed. These networks are often initiated through workshops that include representatives of various landscape management, research and development, environmental, or ownership groups.

In the Southern Appalachians, efforts are being directed toward managing its landscape. These efforts benefit greatly from advances in remote sensing technology and GIS. Improvements in remotely sensed data have increased our ability to interpret changes in land cover. Geographic information systems have simplified the integration of multidisciplinary spatial information. We have described two approaches - spatially-explicit models and the KSE - that can take advantage of improvements in these technologies. We also described an application of these approaches and technologies, LUCAS, that will bring these new developments into practice by providing a flexible and interactive environment that is caters to those people interested in managing the landscape.
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References


Figure Captions

Fig. 1. The three principal modules of the general solution being applied in the landscape-change model in the southern Appalachians. The output of each module serves as the input to the subsequent module. The data base is shared by all modules.

Fig. 2. Schematic of the Land Use Change and Analysis System. In the general solution, diamonds represent actions and parallelograms symbolize products. The entire system is being developed within a graphic user interface.

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General Solution

Socioeconometric Model Module

Landscape-change Model Module

Impacts Model Module

Transition Probability Matrix

Land-use Land-cover Maps

Environmental & Resource Supply Impact Maps

Database

maps tabular data

Census data
as 1 23 1
we 2 43 2
re 4 43 1
yt 6 54 8
tr 6 43 1
pt 6 43 7
General Solution

- Calculation of transition probabilities
- Transition probability matrix
- Simulation of landscape change
- Map of landscape structure
- Simulation of ecological effects
- Map of ecological effects
- Δ in species abundance
- Δ in species diversity
- Δ in water quality
- other

System Components

- Expert Opinion
  - Socioeconomics of landuse decision making
  - Landuse classes
  - Economics
  - Institutions
  - Environmental awareness
  - Knowledge of implications of landowner's actions
  - Feedback processes
  - Other
  - Ecological impacts of landuse change
  - Ecological effects classes
  - Sediment transport
  - Biodiversity
  - Ecosystem classification
  - Habitat requirements
  - Feedback processes
  - Other

- Models
  - Simulation
  - Analytical
  - Other

- Geographic Information System
  - Spatial analyses and simulations

- Data Bases
  - Historical data
  - Land cover
  - Soil
  - Slope or altitude
  - Aspect
  - Ecological effects
  - Other