

# *Applications of GIS in Forestry: A Review*

*Jean E. McKendry and J Ronald Eastman*

## **Introduction**

A review of forestry applications in GIS reveals an extensive range of activities. Geographic Information Systems for forest management may be characterized by two broad and related categories:

1. resource inventory and monitoring;
2. analysis, modeling, and forecasting to support decision making.

In fact, the development of a fully operational GIS for forest management will likely incorporate each activity as two distinct stages in its development (see Crain and MacDonald 1983, Jordan and Erdle 1990). For example, spatial data input, editing, and simple maps characterize the inventory and monitoring stage. In the modeling stage, overlays, reclassifications and suitability analyses are increasingly included as part of the decision making process. More sophisticated forecasts and "what if" simulations may then be used to assess management decisions before any changes or interventions are made on the ground. The boundaries between these activities, however, are not distinct. Monitoring, for example also includes an analytical component to assess change or the result of specific interventions.

With these two types of broad activities as a guide, this paper is organized into two parts – resource assessment (including inventory and monitoring) and resource management (including the full range of analysis and modeling concerning the evaluation and testing of specific interventions). In each part, general concepts are introduced and then specific examples are summarized.

## **Resource Assessment**

Resource assessment activities include: 1) inventorying forest resources available for harvest, fuel, food, recreation, or conservation purposes, along with related data such as topography, soils, roads, and hydrology, 2) monitoring changes that occur to these resources over time, and 3) evaluating potential land productivity for forest types given certain biophysical and climatic factors. It is in forest resource assessment that other technologies related to GIS, remote sensing, and global positioning systems, make direct and substantial contributions.

## **Inventory**

The acquisition of basic inventory data is fundamental to timber management as well as efforts to conserve certain forest ecosystems. Data include soil type, species type, size, class/stand structure, crown closure, density, and the boundaries of management units (e.g., stands). Once data are entered in a GIS, maps can be displayed showing general species distributions and the

area of stands can be calculated (see, for example, Green and Congalton 1990). As the data are updated over time, changes in these distributions can be recorded and analyzed. More customized maps may be created to answer specific resource questions, such as a map that displays the locations of only stressed or diseased species. Creating maps that show the spatial relationships between harvestable tree species and other features such as mills, steep slopes, or even ecologically sensitive riparian areas are possible and useful to managers (Sheffield and Royer 1989).

Data collection techniques for forest inventories range from selecting sample plots for ground surveys to using topographic maps, remote sensing, and emerging global positioning systems (GPS). While a range of techniques is critical for comprehensive inventories, particularly ground surveys, remote sensing will be highlighted here.

Historically, remote sensing has been important in data collection activities and includes black and white, color and infrared aerial photography, radar, imaging spectrometers, laser altimetry, video imaging, and multispectral digital satellite imagery (Duggin et al. 1990, Leckie 1990). Integrating data from different types of remote sensors for forest inventory is strongly encouraged (Leysen and Goosens 1991, Leckie 1990). However, since the structure of satellite data (pixels) permits the input of these data directly into a GIS for processing, satellite remote sensing for inventory will be emphasized in the examples that remain.

Satellite imagery is available at varying spectral, spatial, and temporal resolutions and is useful to map broad forest types and to detect and delineate major forest changes over time (Leckie 1990). The primary sources and types of imagery available include Landsat Multispectral Scanner (MSS) imagery (80-meter resolution), Landsat Thematic Mapper (TM) imagery (30 meter resolution), SPOT panchromatic (10 meter resolution) and multispectral imagery (20 meter resolution), and NOAA Advanced Very High Resolution Radiometer (AVHRR) imagery (one kilometer resolution).

Satellite imagery provides several possibilities for inventorying. The United States Environmental Protection Agency (EPA) tested a method to identify xeric riparian (dry riverbed) habitats using Thematic Mapper imagery (Hewitt 1990). These riparian zones are important for plant and animal diversity and are more productive (amount of biomass) than bordering terrestrial habitats. They also serve as a permeable buffer between aquatic and terrestrial systems. Healthy riparian vegetation moderates sediments, nutrients, temperature, and bank erosion. Using three bands of TM imagery, the EPA focused on an area in eastern Washington State, USA. Sixteen distinct spectral classes were identified and then eventually aggregated to three classes indicating water, riparian, and non-riparian areas. Ground verification established a final accuracy of 81 percent. This approach potentially could be used to identify riparian areas that should remain undeveloped.

As deforestation in South and Central America, Malaysia and elsewhere has become a significant international concern (see Carneiro 1991, Lugo 1991, Brundtland Commission 1987 and world Resources Institute 1985 for discussions), inventories of tropical forests have become an urgent priority. The utility of satellite remote sensing to inventory large, sometimes remote areas proved itself early in the development of the technology. For example, in the 1970s, the Philippine government estimated that 57 percent of the national territory was covered by

forests, mainly evergreen rainforests. However, a 1976 remote sensing survey revealed that forest cover was only 38 percent (Myers 1988).

To inventory the vast area of the tropics, a strategy using multiple satellite sensors has been suggested (Sader et al. 1990). Coarse resolution scanners with high temporal resolution are needed to reduce data volumes and increase the probability of cloud free data—a persistent problem in the tropics. With its 12-hour global coverage frequency (repeat cycle), NOAA satellite AVHRR sensor data provides this capability. High-resolution scanners, such as SPOT and TM with repeat cycles of around two weeks, are required to record spatial and spectral detail. Coarse resolution data may be used to stratify areas as the first step in a multi-stage sampling design. More detailed identification of forest parameters can then be made in specific locations at later stages with the higher resolution sensors. In fact, TM imagery has been used in several efforts to interpret the accuracy of and even calibrate AVHRR imagery (Stone et al. 1991, Cross et al. 1991, Teuber 1990, Iverson et al. 1989).

In addition to remote sensing, spatial positioning technologies have begun to influence surveying techniques and, thus, resource inventories. GPS (Global Positioning System) technology is based on a set of orbiting satellites (a total of 24), operated by the United States Department of Defense. They provide 24-hour, three-dimensional positional fixes with an accuracy of within tens of meters. With four or more satellites in view, a GPS receiver can interpret the carefully timed satellite signals to determine geometrically the latitude, longitude, and altitude at the operator's location.

GIS applications of GPS include georeferencing of satellite imagery and navigating to sample sites for ground truth (Lange and Stenberg 1990)—operations particularly relevant for forest inventories. As both the cost and weight of GPS receivers continue to decline, its greatest value will be as a real-time mapping tool to update GIS inventory data concerning specific forest management areas (Duggin et al. 1990). In remote tropical areas where base maps are lacking, GPS will provide an opportunity to establish ground control points to locate field plots and to rectify satellite imagery (Sader et al. 1990). On a cautionary note, GPS technology is not entirely trouble-free with respect to forest inventories. Receivers may not work well under forest canopies (Herrington, pers. Comm. 1992).

## **Monitoring**

While an initial inventory of forest resources stored in a GIS is an important step, changes occur that need to be monitored and recorded. For example, silvicultural activities to manage timber involve complex and specific interventions to control stand structure, stand density, species composition, length of harvest rotation, and to maintain site quality. Other changes may result from sudden, discrete events or disturbances, such as massive deforestation or pestilence that initiate new development patterns in the affected areas.

Examples of how GIS is used to monitor changes resulting from large-scale deforestation and pests and pollution are explored in the following pages. Again, remote sensing technology makes important contributions.

## ***Deforestation***

Since deforestation is a continuing process, efforts to inventory and monitor changes are very closely related. There are many uncertainties about actual rates of deforestation (Sader et al. 1990), hence the need for accurate, up-to-date monitoring schemes. Techniques used to inventory these areas also can be applied in their systematic monitoring to create a time-series of data describing rates and magnitudes of deforestation.

In Rondonia Brazil, for example, Landsat MSS (1980) and TM (1986) imagery were used to define the area and deforestation rates for a study area of approximately 30,000 square kilometers (Stone et al. 1991). The researchers found that 3168 square kilometers (528 square km/year) of new clearing occurred between 1980 and 1986. Earlier research (Woodwell et al. 1987) had revealed a rate of clearing of 14 square km/year from 1972 - 1978 and 79 square km/year from 1978 - 1980.

Historical records have also been used in GIS to identify changes in forest cover. Between 1979 and 1984, a land resource inventory project was completed in the Jhikhu Khola watershed in Nepal (see Schreier et al. 1989). Land use information was digitized using 1:50,000 scale topographic maps as the base for information collected by surveying 1980. Land use data that had been divided into three broad categories in the original 1950 topographic map were also digitized. The area of each land use type was calculated in the GIS and then the two layers were subtracted. "Although somewhat crude, this information was found to be very useful in producing a land use change overview map" (Schreier et al. 1989). The thirty-year interval revealed that about 50 percent of the forestland has been lost to shrub and agriculture.

A second three-year project was initiated in 1988 to "examine processes relating to soil erosion, sediment transport, soil fertility changes and land use changes in a quantitative way" in the Jhikhu Khola watershed (Schmidt and Schreier 1991). Forest and agricultural land uses were mapped and digitized using 1:20,000 scale and aerial photographs taken in 1972 and 1989. Changes in the area of four land uses were calculated for each date: forest, grassland, irrigated agriculture and sloping terraces. In this case, using a larger scale and a different land cover scheme, the researchers found that the forest area had not decreased substantially (only 1 percent) during these 17 years.

## ***Damage From Pollution and Pests***

Gradual forest decline is another type of change that can be monitored. Vegetation is sensitive to stress factors associated with changes in moisture, temperature, as well as anthropogenic factors, such as air pollution, forest pests and disease. GIS together with remote sensing offers the means to monitor the magnitudes and rates of decline (Rock and Vogelmann 1989).

In Germany and Poland, forests have been dying gradually due to industrial air pollution (Landauer 1989, Zawila-Niedzwiecki 1989). In Germany, a three-year project was initiated in 1986 to establish methods to detect, classify, and map forest decline using a combination of Landsat MSS and airborne multi-spectral imagery. The researchers found that characteristic spectral signatures could be identified for different tree species (spruce, pine, and beech) depending on the degree of decline (Landauer 1989). Similarly, in Czechoslovakia, Trezzi

(pers. comm. 1991) found that the extent of pollution-damaged forest stands near Liberec could easily be measured because of their distinctive contrast to undamaged areas.

In another example, Landsat TM data was used to assess and monitor damage in coniferous forests in the state of Vermont, USA (Rock and Vogelmann 1989). Researchers found that the most useful spectral reflectance data were TM4 (near-infrared) and TM5 (short-wave infrared). A ratio of TM5/TM4 was used to highlight the differences in spectral regions. Bank four displayed changes in canopy biomass and structure and Bank five indicated loss of foliage and changes in canopy moisture. The higher the ratio, the higher the damage that had occurred. Damage patterns suggested that factors associated with clouds and weather patterns from the west may influence forest decline. In a comparison of Landsat MSS data from 1973 and 1984, they also found a decrease in near-infrared reflectance for red spruce on west-facing slopes and for lower elevation hardwoods.

Pests and disease are another source of forest decline. A diversity of insects, fungi, bacteria, and viruses occur in forests and may be beneficial. More destructive pests may be controlled by natural enemies or an unfavorable environment. In the economics of timber harvesting, small losses due to pests and diseases are generally acceptable; losses that significantly affect timber production are not. Therefore, monitoring pest and disease infestations is a concern for private and national timber interests. GIS and remote sensing are becoming important tools to identify, monitor, and anticipate the spread of infestations. An example from Canada illustrates this application.

Since 1936, the Forest Insect and Disease Survey (FIDS) of Forestry Canada has annually collected and recorded data on forest pest conditions. The Pacific regional database includes 171,000 disease and 295,000 insect and parasite records with host and location information. Approximately 6,000 new records are added each year. Since 1986, the Pacific Forestry Centre (PFC) has used a GIS to store data from annual ground and aerial surveys and added data from historical maps.

With this information, the area of each pest's infestation is calculated annually for each forest region. Overlays of yearly defoliation maps then become quite useful to identify areas of greatest damage. These identifications can then assist managers in making decisions about salvage or treatment. Silvicultural planning efforts can benefit from the patterns revealed by long-term pest and disease occurrence records.

Defoliation also can be related to factors such as climate, forest types, ecozones, slope, and aspect and this analysis can be accomplished with a GIS. Van Sickle (1989) suggests that this provides a useful source of information for management:

Identification of the most susceptible areas and stand types focuses and improves monitoring techniques, provides a basis for risk assessment and identifies the probable need and frequency for direct control of infestations in future rotations. Information on the environmental requirements and limitations for outbreaks can improve predictions of where and when future outbreaks will occur and is basic to estimating damage which may be expected with climatic shifts because of atmospheric pollution or global warming effects.

## Suitability and Productivity Assessment

Another factor in resource assessment includes efforts to identify biophysical and climatic factors suitable for the regeneration of tree species. This can be important for establishing tree plantations, for afforestation programs, for re-establishing endemic species following severe over-utilization and for timber harvesting. The information obtained from assessing the potential productivity of a site can be used to manage it for optimal harvest.

In one example, Booth (1990) describes a technique to identify and map locations satisfying up to six climatic criteria where plantation species could be cultivated. Three plantation species were used to demonstrate the technique: *Eucalyptus grandis*, *Eucalyptus tereticornis*, and *Pinus radiata*. The six climatic criteria were mean annual rainfall, rainfall regime, dry season length, mean maximum temperature of the hottest month, mean minimum temperature of the coldest month and mean annual temperature. This approach has been demonstrated at the global and continental scales (Booth 1989, 1990).

This technique may be used with afforestation projects at more local levels as suggested by the efforts of Schreier et al. (1989). As part of the land resource inventory in Nepal (1979-1984), data on land use, topography, land systems, and land capability were collected. Based on available climatic information and elevation data, the Jhikhu Khola watershed was divided into elevation, slope, and aspect categories. This was done to create physiographic subdivisions reflecting local micro-climatic conditions. (During the project, these classes were calibrated with climatic information collected in the field.) The locations of these combined elevation/slope/aspect categories were compared with crop and forest classes. The distribution of forests and crops was then compared with land capability ratings. Schreier et al. (1989, p. 181) explain the value of this approach:

These combined maps are of interest in afforestation programs that are initiated in many parts of Nepal to overcome chronic fuelwood and fodder deficits. Tree seedling survival is a serious problem. Heavy grazing, difficult climatic conditions and poor site and soil conditions are the main reasons for this difficulty. The elevation/slope/aspect map in combination with forest cover and capability can greatly assist in the afforestation program. It provides a crude basis for matching tree species with appropriate environments and new crops and cropping systems, such as fruit and vegetables with the most appropriate site conditions.

## Resource Management

Collecting forest inventory data and monitoring changes are critical to forest management activities. Yet, a GIS can build on these activities by incorporating models to guide, for example, timber harvesting, silviculture and fire management activities, or predict fuel wood and other resource supplies. Other priorities, such as providing for wildlife habitat, ensuring recreation opportunities and minimizing visual impacts of harvesting, are also growing in importance.

In this section, examples of resource management applications in forestry will be described. Some applications deal with single management issues, such as timber production, while others illustrate how a mix of management concerns can be integrated through the use of GIS, such as timber production combined with habitat protection.

## Timber Harvesting

Timber management focuses on efforts to provide a continuous supply of trees for economically optimal wood production. In the recent past, foresters have relied on wood supply models to guide planning for optimal harvests that typically ignore specific geographic locations (Jordan and Baskent 1991, Moore and Lockwood 1990, Reisinger et al. 1990, Reisinger 1989, Reisinger and Davis 1987). These simulations (WOSFOP, OWOSFOP, NORMAN, FEM, FORMAN, and FORPLAN), developed over the past 10 years, use an aspatial optimizing approach. Jordan and Baskent (1991, p. 150) describe the problem as follows:

While today's models are sufficient for defining and developing aspatial management design strategies for wood supply, they lack consideration of the geographic structure of forests and are insufficient for design of wildlife sensitive and operationally, i.e., economically, acceptable management.

GIS has now made it possible to incorporate spatial components into harvest planning and simulation models. In some cases, the modeling capabilities of a particular GIS may be used directly to aid decisions about timber harvesting; in other cases, an external model is linked to a GIS database. These models are typically called Decision Support Systems (DSS) or Spatial Decision Support Systems (SDSS). In any case, the analytical goals are quite similar, as several examples will illustrate.

Herrington and Koten (1988) assert that harvest planning requires knowledge of individual stand or compartment status and the geographical relationships between compartments. They developed a harvest model using a raster GIS to create a map showing the relative maximum potential stumpage (MPS – the market value of standing timber) for all compartments in a forest. Harvesting costs were derived from topography, forest type, soil classification, management compartments, roads, and streams. Total cost was based on cost to landing (road) and cost to mill. In their harvest model they:

1. cut all the merchantable trees in a compartment,
2. skidded the stems downhill to the nearest road,
3. transported saw logs to a sawmill, and
4. transported pulpwood to a pulpmill.

The model assumed that loading logs onto transport trucks had no cost and that skidding across streams and lakes was not permitted. Skidding cost also varied due to obstacles created by steep slopes. The market value of the timber was derived from compartment and forest type maps and based on volume. In their final MPS map, each grid cell had a value representing the price at the mill for all products minus the costs of harvesting the products on that grid cell, that is, profitability from the harvest.

Using regression models developed by McGreer (1974), Berry et al. (1980) evaluated timber loss due to felling breakage during harvesting for both tree pulling and conventional felling techniques. The independent variables used in the two regression models were topographic slope, tree diameter, tree height, amount of wood defect and tree volume. Each regression variable was treated as a separate map and multiplied by the corresponding regression coefficient derived from McGreer's models. The resulting weighted maps were summed to create predicted breakage maps for each technique. The researchers suggested that the analysis

was useful to the harvest planning process in its potential to identify locations of potentially high breakage.

Jordan and Baskent (1991, p. 150) describe a spatial wood supply simulation model, GISFORMAN, which is linked to a GIS database. It forecasts in selected yearly increments (for instance, five-year period), “forest response to harvesting and silviculture of types, amounts, timings, and geographic locations”. Management strategies can then be translated into very specific mapped schedules. Similarly, Moore and Lockwood (1990) developed a planning system known as the HSG Wood Supply Model that directly incorporates a GIS to assist in the design and evaluation of long-range timber harvest schedules.

In the HSG system, the fundamental GIS data layer is a forest stand inventory in which each stand is assigned attributes of the year of stand origin, site class (productivity of the site), area, relative stocking factor, and silvicultural treatment class. The model then repetitively adds a certain time interval (e.g., five years) to the stand origin date to produce a sequence of stand ages (e.g., over a 100-year interval). It then uses a look-up table to relate stand age, site class, and silviculture treatment class to estimate a yield factor. This is then multiplied by the stocking factor and area to produce an estimated yield. As Moore and Lockwood (1990) point out, although the yield table will most commonly describe merchantable volume development of a tree species, it could equally well describe such factors as wildlife habitat characteristics.

Through its progressive aging of the stand, the HSG model simulates the development of the forest on a stand-by-stand basis. At each stage, the effects of disturbances such as harvesting, silviculture treatment, and ecological succession are incorporated. For example, Moore and Lockwood (1990) give the illustration of a rule that results in the breakup of a 140 year old black spruce stand on a particular site class and its replacement through regeneration over 40 years. For harvesting, the model allows a variety of rule logics. One, for example, allows the model to evaluate the effects of a specific harvest quota. Stands are then numerically rated at each stage for their suitability for harvest and then selected to meet the quota. Similarly, the model incorporates the ability to select the most suitable stands for silviculture treatment (such as renewal treatments on harvested stands) based on a fixed budget.

The HSG model illustrates the potential utility of simulation models in GIS. At present, GIS is largely used for database development and the spatial representation of results during the run of the model. However, there is little to prevent it from incorporating specific spatial disturbance rules (such as economic factors of harvesting related to distance, terrain characteristics and the like). Simulation models are still fairly rare in GIS, but the potential that the technology offers for the evaluation and assessment of varying management scenarios is enormous.

### **Fuel Wood Supplies**

The availability of fuel wood supplies for local use is an important forest management issue in many parts of the world. GIS can contribute to assessments of fuel wood supply and demand and offers the potential to predict future needs. Several examples illustrate this type of approach.

As part of the land resource mapping project in Nepal, fuel wood sufficiency for the 75 districts in the country was evaluated and mapped using GIS. This was part of a larger resource

overview for national land use planning that also included food and fodder resources (Schreier et al. 1990). Fuel wood production was estimated using yield data for each forest type included in the inventory: shrub, grassland, and four forest maturity classes. To calculate fuel wood supplies, the yields were multiplied by area data for each land use category. To calculate fuel wood demand, estimates for each district were supplied by the domestic energy model of the Water and Energy Secretariat. Surplus and deficit figures were calculated and each district was assigned a surplus, sufficiency, or deficit rating. Figures for 1981 were based on the resource survey. Figures for the year 2000 were calculated based on an unchanging resource base and two changing variables, increases in population and livestock. The fuel wood assessment was also combined with the fodder and food assessments to create an overall evaluation of resource poverty.

The calculations for the future were not actual predictions but a test to examine the model's response to population and livestock growth. The researchers suggested that the projection maps could be used to direct attention to districts that will likely experience severe resource deficits. Also, GIS capabilities could be used to develop:

...deficit elimination scenarios. If we assume current growth and consumption rates, the model can calculate what changes in key variables would be required to eliminate the deficits in each critical district.... To eliminate such deficits, we can calculate by how much we would have to increase the tree biomass production or how much we would have to enlarge the area of tree planting (Schreier et al. 1991).

In a similar example, Olsson (1986) used a GIS to examine the balance between supply and demand for fuel wood. Using Landsat MSS imagery, Olsson first used the infrared and red image bands to produce a vegetation biomass map (there are several procedures for doing this, the simplest of which simply divides the infrared reflectance for each pixel by the red reflectance). Using ground-truth data he then scaled the data to yield a map of woody biomass supply. He then took a map of village locations and populations, along with an interpolation rule based on the gravity model (a potential model) to create a population surface. Based on field studies, he then assigned to each person a demand for fuel wood. This was then compared to the woody biomass supply map through a procedure that had individual pixels simulate the action of humans gathering wood in a radial pattern from their homes, with full competition for resources. He then specified a maximum distance that an individual could walk with their required wood and produced a final map illustrating areas of surplus, areas in balance, and areas of deficit.<sup>1</sup>

## **Fire Management**

The effect of fire on forest resources is another important management concern. Management activities include fire prevention, wildlife control, prescribed burning, and post-fire recovery actions. The modeling capabilities of GIS have been quite effective in this context. Forest fire managers have used GIS for fuel mapping, weather condition mapping, and fire danger rating (Holder et al. 1990). Several examples illustrate a range of fire applications.

At Cuyamaca Rancho State Park in California, USA, GIS has been used to guide prescribed burning. After decades of wildfire suppression in the park, fuel loads had dramatically

increased, chaparral had replaced other vegetation, biotic diversity had decreased and exotic grasses dominated the park's grasslands (Wells and McKinsey 1991). Beginning in 1970, fire was reintroduced into the park's ecology.

The key to managing prescribed burning activities was the ability to anticipate fire behavior after ignition. Fire behavior models have been developed from fuel models to predict the fire intensity based on factors such as slope, elevation, site exposure, wind speed, relative humidity, cloud cover, temperature, and live and dead fuel moisture. These models are not spatial, however, and are typically used to predict fire behavior for a fairly large area. To increase the sensitivity of the fire behavior models to spatial variability within the park, fire behavior models were run with a raster-based GIS. With input layers stored in the GIS, its mathematical modeling capabilities, along with selected lookup tables, were then used to implement several fuel and fire intensity models. By comparing the predicted fire behavior with actual burn conditions, Wells and McKinsey (1991) concluded that the GIS implementation of fire behavior models was useful in locating potential control areas, planning ignition patterns, and accommodating sensitive areas that would be adversely affected by high fire intensities.

In a different study, Chou (1990) describes an effort to construct a probability model of fire occurrence based on logistic regression. The goal was to develop a map showing areas of extremely high fire danger. Alternative management strategies could then be developed to reduce overall fire danger. The study area was in the San Jacinto Ranger District of the San Bernardino National Forest, California, USA. The independent variables included environmental and human factors: temperature, precipitation, vegetation, transportation and structures (building or campgrounds). Vegetation was converted to fire potential weights based on fuel models. Fire potential and a second variable measuring "neighborhood effect" (a polygon surrounded by adjacent polygons with a high fire danger would have a higher probability of burning than one that was not) were found to be statistically significant. The resulting regression coefficients were used to create a map showing probabilities of fire occurrence.

In a third example, a pilot project in Canada linked a fire growth model with a GIS (Holder et al. 1990) to evaluate its potential to minimize the costs of controlling and managing forest fires. The researchers described a two part demonstration in which, 1) only a GIS was used and 2) a forest growth model was combined with a GIS.

In the first part, data for fuel types, weather parameters and lightning strikes from the North Central Fire Region in Ontario, Canada were entered into a GIS. Canadian Forest Fire Weather Index codes and indices related to weather observations were calculated as well as Fire Behavior Prediction System-defined Rate of Spread (ROS) conditions. A map showing the density of lightning strikes over a one-day period was generated from a data set of almost 6500 points. In a two-part analysis, the distribution of ROS conditions was first compared with forest fire fuel types. Then a map containing airport locations was added to the database, distance buffers were created based on 15 minute flying intervals and this buffer map was matched with the ROS map to identify potential hazard zones that did not have adequate coverage by air.

In the second part of the demonstration, a subset of the North Central Fire Region was used. Digital terrain data and forest fire fuel types were moved from the GIS to fire growth modeling software. Data on wind speed and direction as well as Fire Fuel Moisture Codes were added to the model. Several fires were ignited and their growth modeled. When the model was halted,

the result was moved back into the GIS. The burns were classified into intervals, areas were calculated and the results compared, using cross-tabulations, with forest types to identify the effect of the fire over time.

In a final example, GIS was used to analyze environmental impacts resulting from a fire and to develop management strategies to deal with the impacts. Scher (1990) describes a devastating wildfire that occurred in the Lowman Ranger District of the Boise National Forest in Idaho, USA where over 46,000 acres burned. Managers were concerned about the effects of the fire on streamside vegetation and corresponding erosion problems. The effects of accelerated sedimentation on stream channel stability and fish habitat were a related concern.

Data collection included a survey of post-fire vegetation that was divided into four density classes and four burn intensity classes: high, moderate, low, and no burn. Data on aspect, slope, and stream classes also were used and buffers were generated for each stream class to identify riparian management zones. Examples of the analysis included a comparison of burn intensity with stream management zones. This provided information on the location of areas deficient in riparian vegetation. A comparison of conifer density classes with stream management zones helped identify riparian areas deficient in woody debris that traps sediment and contributes to quality fish habitat. A comparison of slopes with burn intensity led to the identification of areas where the potential for post-fire erosion was high. This information guided the development of recovery plans for the post-fire situation.

### **Multiple Resource Management**

Most of the studies presented so far have emphasized single management concerns. However, contemporary forest management should incorporate non-timber values and multiple resource concerns. In some situations, sites to be protected for non-timber uses are defined before a harvest supply model is implemented (Dippon and Cadwell 1991). In other cases, issues of visual quality or habitat requirements are integrated as constraints in overall harvest plans (Johnston 1987). This clearly involves a more complex analysis.

Fortunately, the ability of GIS to simulate ecological, social, and economic changes lends important support to multi-resource management (Levinsohn and Brown 1991, Behan 1990). The following discussion, then, provides some examples of the emerging potential of GIS in multi-objective resource management situations.

In one broad category of multi-objective applications non-timber issues are directly incorporated into timber management planning. Duinker et al. (1991), for example, are developing habitat simulations for moose and marten in Ontario, Canada. They argue that integrating timber and wildlife needs will not occur without GIS-based habitat supply analyses. They plan to follow five criteria in their research:

1. the habitat model must rely on easily obtained data describing landscape vegetation patterns,
2. it should incorporate the dynamic evolution of forests on a stand by stand basis, including the stands that have been harvested and those left alone,

3. it should be able to accept the input of forest management interventions, forecast habitat response and generate alternative timber strategies if necessary,
4. the model should consider that wildlife species often have home ranges that include many forest stands and range in spatial patterns that are difficult to predict, and
5. finally, the model should deal with the link between food sources and proximity to cover, important for many species.

In an example from Tasmania, conflicts between land preservation and timber management were the focus. Blakesley (1990) described an effort by the Forestry Commission to balance timber and non-timber uses of the Southern Forests, a strip of land about 20 kilometers wide and 85 kilometers long. This area supplied timber to sawmills, a newsprint mill, a pulp mill and two export woodchip plants. Yet conservationists also wanted to preserve the tall, old growth eucalyptus forests and existing wilderness qualities in the area.

The Forestry Commission, responsible for managing state forests, acquired a GIS in 1982 and began work on a new Forest Management Plan for the southern Forests. Wood and non-wood uses were evaluated. The unit of analysis was the basic logging unit or *coupe* and areas already developed for wood production were removed from further analysis. Each of the coupes was assigned a wood and a non-wood value derived from a specific set of criteria. Based on these values, different boundary options between timber and non-timber areas were presented to managers. The managers selected a “limit to logging line” for the Southern Forests that was then made available for public comment. During this planning process, the GIS was also valuable in expanding the boundaries of the Tasmanian Wilderness World Heritage Site nomination to include areas in the Southern Forests.

In a third example, ecologically based forest planning was the goal in a project undertaken in Vermont, USA to examine competing land uses. For the Mad River Valley, a forest site index (based on the average height of trees at a site at a given age) and soil erosion estimates were combined to produce land suitability classes of resource protection, forest management, multiple-use, and trade-off (Hendrix and Price 1986). Using data layers that included soils, land use, elevation, slope, aspect, roads, and water course, the project considered forest productivity, soil erosion potential, and management opportunities and constraints.

Forest productivity was used as an indicator of ecological conditions. It was estimated by using previously computed regression equations that incorporated site index as the dependent variable and topography, altitude, and soil series groups as the independent variables.

Soil erosion was used as an indicator of a site’s sensitivity to disruption. Sites with high erosion potential required protection or special management techniques. Soils were divided by their soil erodibility factors, or K-Factor estimates, a variable used in the Universal Soil Loss Equation (USLE) developed by the US Department of Agriculture. K-Factor and slope categories were combined in a matrix and empirically assigned a rank (very low to very high) corresponding to their erosion potential.

To identify management options, the productivity and erosion potential maps were compared. The resulting combinations and the judgement of managers produced the following options: lands with high erosion potential were classified as resource protection areas, lands with low

erosion potential and high site index were classified as forest management areas and sites with low erosion potential and low site index were considered a trade-off. Sites in the forest management category were further refined by relating these areas to existing land uses, elevation, and access to roads. A map was created showing only the forest management sites that were in forest cover, below 2500 feet in elevation and within one kilometer of existing roads.

For a final example, a study described by Johnston (1987) provides a much broader perspective on the problems of multi-resource planning. For a project in the Kedgewick River Area of Edmunston, New Brunswick, Canada a series of natural resource models were developed to test a variety of management priorities (Johnston 1987). Although timber management was an important objective for the Fraser Timber company, the models were designed to be flexible, running management scenarios (submodels) that could completely exclude timber production and economics to focus on visual quality, landscape ecology, potential natural vegetation, fire management, wind management, or any combination of objectives.

In the first step of the project, managers were asked to define the design objectives of the study, those actions that would or would not be allowed in the area. This guided the creation of the database. The database included base maps for deeryards, topography, soils, deposits, many different species of trees, windthrow affected areas, crown closure, forest codes, development stage, waterways, and roads.

With the database complete, suitability maps were produced from each submodel using a raster GIS. For example, a visual quality submodel produced a map where each cell contained a suitability rating for its visual quality. Then, a decision was made about the percent of lands that would be allocated to different uses given the objectives of the management plan. In this project, five land uses were considered and assigned the following proportional areal coverages: logging (45 percent), ecology (35 percent), visual quality (10 percent), controlling fire (5 percent), and reducing windthrow (5 percent). As the model was run, cells with the highest weight on each suitability map were selected for placement on the output map until the total number of cells selected in each category matched the original percentage. If any cells were assigned two or more land uses in the result, the conflict would be resolved by iteratively choosing the land use for which the cell was most suited while adjusting other assignments to keep as close to the final proportion as possible.

The procedure highlighted, however, the fact that most GIS software systems do not have automated procedures for the optimum allocation of land to meet multiple objectives. Despite this, Johnston (1987) felt that use of this technology allowed the manager to examine different management scenarios in a manner that would be difficult without a GIS.

## Conclusions

The range of applications reviewed in this paper is clear testament to the significant value of forests and the potential of GIS to aid in their management. Despite the diversity of applications, however, a number of broad conclusions can be reached about the role of GIS in forestry:

1. GIS applications can strongly benefit from remote sensing and image processing technologies. Forests are complex assemblages of species that lend themselves well to broad-level inventory through remote sensing. However, the need for strong ground-truth remains paramount and it is likely that satellite positioning systems (such as GPS) will play an important role in augmenting traditional forest survey activities.
2. Forests are a dynamic resource, affected by many concurrent ecological processes and direct management interventions. Simulation modeling has been applied in forestry to a degree that is substantially higher than in many other disciplines. Simulation or *process* modeling is one of the more challenging areas of GIS applications and it is likely that this activity will increase as the research and tools to support this kind of application become more prevalent.
3. It is clear that throughout the world, forests are subject to many demands. As a result, many forest management problems have the nature of multi-objective planning procedures. Unfortunately, GIS is not well developed for multi-objective planning. Stronger tools are necessary for the analytical resolution of conflicting suitabilities and choices in resource allocation.

In a sense, forestry applications embody the full scope of GIS technology. Thus its study provides an excellent overview of the state of the technology and its potential as a management tool for natural resource concerns.

## References

- Behan, R.W., 1990. "Multi-resource forest management: A paradigmatic challenge to professional forestry", *Journal of Forestry*, April: 12-18.
- Berry, J.K., L.D. Nott, C.D. Tomlin, and A. Mansbach, 1980. "Computer-assisted map analysis of predicted timber felling breakage", Presented at IUFRO Symposium on Forest Management Planning, Virginia Polytechnic Institute and State University, 16 pages.
- Blakesley, A.J., 1990. "The use of GIS in the resolution of land use conflicts in Tasmania", In *Making It Work, GIS 90 Symposium Proceedings*, Vancouver, Canada, March 13-16, 1990. Vancouver, BC: Forestry Canada, 339-343.
- Booth, T.H., 1990. "Mapping regions climatically suitable for particular tree species at the global scale", *Forest Ecology and Management* 36: 47-60.
- Booth, J.H., J.A. Stein, H.A. Nix, and M.G. Hutchinson, 1989. "Mapping regions climatically suitable for particular species: an example using Africa", *Forest Ecology and Management* 28: 19-31.
- Brundtland Commission, 1987. *Our Common Future*, Oxford: Oxford University Press.
- Carneiro, C.M.R., 1991. "The Tropical Forestry Action Plan and the monitoring of the tropical forest cover of the Amazon region", Presented at the Symposium of Applied Remote Sensing in Forestry: Status and Developments, Albert-Ludwigs University of Freiburg, Germany, October 10-11, 1991, 11 pages.

- Chou, Y.H., 1990. "Modeling fire occurrence for wildland fire management: GIS spatial analysis for fire control and prevention", In *Proceedings, GIS/LIS '90, Vol. 1*, Anaheim, California, November 7-10, 1990, ACSM, ASPRS, AAG, URISA, AM/FM International, 440-449.
- Crain, I.K. and C.L. MacDonald, 1983. "From land inventory to land management: The evolution of an operational GIS", In *Automated Cartography: International Perspectives on Achievements and Challenges, Vol. 1*, B.S. Weller, ed. Ottawa: Steering Committee for the Sixth International Symposium on Automated Cartography, 41-50.
- Cross, A.M., J.J. Settle, N.A. Drake, and R.T.M. Paivinen, 1991. "Subpixel measurement of tropical forest cover using AVHRR data", *International Journal of Remote Sensing* 12(5): 1119-1129.
- Dippon, D. and C. Cadwell, 1991. "Resource management planning – Linking a land information system to a harvest scheduling model", In *Applications in a Changing World, GIS '91 Symposium Proceedings*, Vancouver, Canada, February 12-15, 1991. Vancouver, BC: Forestry Canada, 157-166.
- Duggin, M.J., P.F. Hopkins, and R.H. Brock, 1990. "A survey of remote sensing methodology for forest inventory", In *Proceedings, State-of-the-Art Methodology for Forest Inventory: A Symposium*. USDA Forest Service, Pacific Northwest Research Station, General Technical Report, PNW-GTR-263, 267-285.
- Duinker, P., P. Higgelke, and S. Koppikar, 1991. "GIS-based habitat supply modeling in northwestern Ontario: Moose and marten", In *Applications in a Changing World, GIS '91 Symposium Proceedings*, Vancouver, Canada, February 12-15, 1991. Vancouver, BC: Forestry Canada, 271-275.
- Erdle, T.A. and P.W. Andrews, 1990. "Updating and maintenance of a GIS-based forest inventory", In *Making It Work, GIS '90 Symposium Proceedings*, Vancouver, Canada, March 13-16, 1990. Vancouver, BC: Forestry Canada, 197-206.
- Green, K. And R. Congalton, 1990. "Mapping potential old growth forests and other resources on national forest and park lands in Oregon and Washington", In *Proceedings, GIS/LIS '90, Vol. 2*, Anaheim California, November 7-10, 1990. ACSM, ASPRS, AAG, URISA, AM/FM International, 712-723.
- Hendrix, W.G. and J.E. Price, 1986. "Application of geographic information systems for assessment of site index and forest management constraints", In *Proceedings of Geographic Information Systems Workshop*, Atlanta, Georgia, April 1-4, 1986. Falls Church, VA: American Society for Photogrammetry and Remote Sensing, 263-272.
- Herrington, L. And D.E. Kotten, 1988. "A GIS-based decision support system for forest management", In *Accessing the World, Proceedings, GIS/LIS '88, Vol. 2*, San Antonio, TX, November 30-December 2, 1988. ACSM, ASPRS, AAG, URISA, 825-831.
- Hermansen, C., 1989. "The practical application of GIS in forest resource management", In *A wider Perspective, GIS '89 Symposium Proceedings*, Vancouver, Canada, March 7-10, 1989. Vancouver, BC: Forestry Canada, 89-101.
- Hewitt, M.J., III., 1990. "Synoptic inventory of riparian ecosystems: the utility of Landsat thematic mapper data", *Forest Ecology and Management* 33/34:605-620.

- Holder, G., R. Van Wyngaarden, S. Pala, and D. Taylor, 1990. "Flexible analysis through the integration of a fire growth model using an analytical GIS", *Proceedings, GIS '90 Symposium*, Vancouver, BC: Forestry Canada, 153-157.
- Iverson, L.R., E.A. Cook, and R.L. Graham, 1989. "Estimating forest cover over southeastern United States using TM calibrated data", In *Proceedings, Global Natural Resource Monitoring and Assessments: Preparing for the 21<sup>st</sup> Century, Volume 3*. Bethesda, MD: American Society for Photogrammetry and Remote Sensing, 1252-1262.
- Johnston, K., 1987. "Natural resource modeling in the geographic information system environment" In *Technical Papers, Vol. 5, ASPRS-ACSM Annual Convention*, Baltimore, Maryland, March 29-April 3, 1987. Falls Church, VA: American society for Photogrammetry and Remote Sensing and American Congress on Surveying and Mapping, 99-109.
- Jordan, C.B.K., 1988. "Forestry program fights rural poverty", *Journal of Forestry* 86(5):37-41.
- Jordan, G.A. and E.Z. Baskent, 1991 "GISFORMAN – A next generation wood supply model", In *Applications in a Changing World, GIS '91 Symposium Proceedings*, Vancouver, Canada, February 12-15, 1991. Vancouver, BC: Forestry Canada, 149-156.
- Jordan, G.A. and T.A. Erdle, 1989. "Forest management and GIS: What have we learned in New Brunswick?", *GISM Journal* (Canadian Institute of Surveying and Mapping) 43(3):287-295.
- Landauer, G., 1989. "Detection, classification and mapping of forest decline by means of multispectral remote sensing", In *Proceedings, Global Natural Resource Monitoring and Assessment: Preparing for the 21<sup>st</sup> Century, Vol. 1*. Bethesda, MD: American Society for Photogrammetry and Remote Sensing, 468-472.
- Lange, A.F. and J. Stenberg, 1990. "An introduction to the global positioning system and its use in ground truth in SPOT satellite imagery", In *Making It Work, GIS '90 Symposium Proceedings*, Vancouver, Canada, March 13-16, 1990. Vancouver, BC: Forestry Canada, 403-405.
- Leckie, D.G., 1990. "Advances in remote sensing technologies for forest surveys and management", *Canadian Journal of Forest Research* 20:464-483.
- Levinsohn, A.G. and S.J. Brown, 1991. "GIS and sustainable development in forest management", In *Applications in a Changing World, GIS '91 Symposium Proceedings*, Vancouver, Canada, February 12-15, 1991. Vancouver, BC: Forestry Canada, 181-185.
- Leysen, M.M. and R.E. Goosens, 1990. "Forest map updating in a GIS using high spatial resolution satellite data", in *EGIS '91, Second European Conference on Geographical Information Systems*, Brussels, Belgium, April 2-5, 1991. Utrecht, The Netherlands: EGIS Foundation, 653-661.
- Lugo, A., 1991. "Tropical forestry research: Past, present and future", *Journal of Forestry* 89(3):10-22.
- McGreer, D.J., 1974. "Stream protection and timber felling techniques: A comparison of costs and benefits", M.S. Thesis, Oregon State University School of Forestry, 1-80.
- Mitchell, A., 1989. "Harvest Planning on a micro-based GIS: A description of the Ministry of Forest' "Harvest Management System' ", In *A wider Perspective, GIS '89 Symposium*

- Proceedings*, Vancouver, Canada, March 7-10, 1989. Vancouver, BC: Forestry Canada, 145-150.
- Moore, T.G.E. and C.G. Lockwood, 1990. *The HSG Wood Supply Model: Description and User's Manual*, Chalk River, Ontario: Petawawa National Forestry Institute, Forestry Canada, Information Report PI-X-98.
- Myers, N., 1988. "Tropical deforestation and remote sensing", *Forest Ecology and Management* 23:215-225.
- Olsson, L., 1985. *An Integrated Study of Desertification: Applications of Remote Sensing, GIS and Spatial Models in Semi-Arid Sudan*, Monography No. 13, Series C, General and Mathematical Geography, Lund University, Sweden.
- Reisinger, T.W., 1989. "GIS-based decision support systems: A forest industry perspective", In *A Wider Perspective, GIS '89 Symposium Proceeding*, Vancouver, Canada, March 7-10, 1989. Vancouver, BC: Forestry Canada, 171-177.
- Reisinger, T.W., K.B. Coode, and J.L. Smith, 1990. "GIS-based forest management planning on the Jefferson National Forest", In *Proceedings, Application of Geographic Information Systems, Simulation Models and Knowledge-based Systems for Landuse Management*, Blacksburg, Virginia, November 12-14, 1990. Blacksburg: Virginia polytechnic Institute and State University, 255-264.
- Reisinger, T.W. and C. Davis, 1987. "Integrating geographic information and decision support systems: a forest industry application", In *GIS '87, Vol.2, Second annual International Conference, Exhibits and Workshops on Geographic Information Systems*, San Francisco, California, October 26-30, 1987. Falls Church, VA: American society for Photogrammetry and Remote Sensing and American Congress on Surveying and Mapping, 578-584.
- Rock, B.N. and J.E. Vogelmann, 1989. "The use of remote sensing for the study of forest damage", In *Proceedings of the Global Natural Resource Monitoring Assessments: Preparing for the 21<sup>st</sup> Century, Vol.1*. Bethesda, MD: American Society for Photogrammetry and Remote Sensing, 453-467.
- Sader, S.H., T.A. Stone, and A.T. Joyce, 1990. "Remote sensing of tropical forests: An overview of research and applications using non-photographic sensors", *Photogrammetric Engineering and Remote Sensing* 56(10): 1343-1351.
- Scher, L.H., 1990. "Post-fire recovery of riparian resources on teh Idaho Batholith: A geographic information system analysis", In *Making It Work, GIS '90 Symposium Proceedings*, Vancouver, Canada, March 13-16 1990. Vancouver, BC: Forestry Canada, 161-166.
- Schmidt, M. And H. Schreier, 1991. "Quantitative GIS analysis of the forest resources in a mountain watershed in Nepal", In *Applications in a Changing world, GIS '91 Symposium Proceedings*, Vancouver, Canada, February 12-15, 1991. Vancouver, BC: Forestry Canada, 227-232.
- Schreier, H., S. Brown, P.B.Shah, and G. Kennedy, 1991. "Nepal 2000, a GIS evaluation of the major land resources", In *Applications in a Changing world, GIS '91 Symposium*

- Proceedings*, Vancouver, Canada, February 12-15, 1991. Vancouver, BC: Forestry Canada, 221-225.
- Schreier, H., P.B. Shah, M.Schmidt, and G. Kennedy, 1989. "Himalayan-scale problems and micro-GIS solutions", In *A Wider Perspective, GIS '89 Symposium Proceedings*, Vancouver, Canada, March 7-10, 1989. Vancouver, BC: Forestry Canada, 179-184.
- Sheffield, R.M. and L.A. Royer, 1989. "GIS: A broad-scale inventory perspective", In *Proceedings, Society of American Foresters National Convention*, Spokane, Washington, September 24-27, 1989. 38-42.
- Smith, D.M., 1986. *The Practice of Silviculture*, New York: Wiley.
- Stone, T.A., I.F. Brown, and G.M. Woodwell, 1991. "Estimation, by remote sensing, of deforestation in central Rondonia, Brazil", *Forest Ecology and Management* 38:291-304.
- Teuber, K.B., 1990. "Use of AVHRR imagery for large scale forest inventories", *Forest Ecology and Management* 33/34:621-631.
- Van Sickle, G.A., 1989. "GIS – A tool in the forest pest management", In *A Wider Perspective, GIS '89 Symposium Proceedings*, Vancouver, Canada, March 7-10, 1989. Vancouver, BC: Forestry Canada, 213-219.
- Wells, M.L. and D.E. McKinsey, 1991. "Using a Geographic Information System for Prescribed Fire Management at Cuyamaca Rancho State Park, California", In *GIS Applications in Natural Resources*, M. Heit and A. Shortreid, ed. Fort Collins, Colorado: GIS World.
- Woodwell, G.M. and T.A. Stone, 1990. "The global forest inventory: Measurements using satellite imagery and geographic information systems in Amazonian forestry", In *Making It Work, GIS '90 Symposium Proceedings*, Vancouver, Canada, March 13-16, 1990. Vancouver, BC: Forestry Canada, 345.
- Woodwell, G.M., R.A. Houghton, T.A. Stone, R.F. Nelson, and W. Kovalick, 1987. "Deforestation in the tropics: New measurements in the Amazon Basin using Landsat and NOAA AVHRR imagery", *Journal of Geophysical Resources* 92(D2):2157-2163.
- World Resources Institute, 1985. *Tropical Forests: A Call for Action, Part I: The Plan*, Report of an International Task Force convened by the World Resources Institute, the World Bank and the United Nations Development Programme.
- Zawila-Niedzgiecki, T., 1989. "Satellite images for forest decline assessment", In *Proceedings, Global Natural Resource Monitoring and Assessment: Preparing for the 21<sup>st</sup> Century, Vol. 1*. Bethesda, MD: American Society for Photogrammetry and Remote Sensing, 473-478.