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THE USE OF MODELING AND GIS IN FOREST ECOSYSTEM MANAGEMENT: TWO CASE STUDIES

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ABSTRACT

Geographic information systems (GIS's) and ecosystem models are powerful tools for predicting the influence of environmental change on forests. When combined, these tools assist the land manager in examining how forest practices or perturbations modify ecosystem processes. This paper presents two examples of how land managers can use GIS/modeling outputs for forest land management planning purposes. First, we examined the use of a soil erosion model supported within a GIS to enable the land manager to evaluate the amount and spatial distribution of soil erosion for proposed management activities such as road construction and logging. This system could be used for risk assessment of the effects of alternative management scenarios on stream water quality. Second, we examined the use of a GIS and a forest process model (PnET-IIS) in assessing the influence of short and long-term climate change on forest productivity at the regional scale. This analysis could be used by forest managers to estimate the impact of short term climate on timber production. The system could also be used to generate alternative, long-term silvicultural prescriptions and planning associated with species response to climate change scenarios.

INTRODUCTION

Models are useful for integrating forest ecosystem processes at different temporal and spatial scales. All scales of models have some utility, ranging from representing physiological processes at the fine scale, to providing a tool for predicting forest function across regions at the large scale (Wessman 1992). At the watershed and larger scales, database management becomes one of the greatest challenges associated with model use and, therefore, requires the use of innovative methodologies to construct the databases, to execute and validate the models, and to display the results. A geographic information system (GIS) is a powerful tool that can be used for all scales of ecosystem modeling (Everham et al. 1991). Geographic information systems have existed since the early 1960's (Tomlinson et al. 1976), but reductions in software and hardware costs and increased program flexibility has made them viable for ecosystem research since the mid-1980's (Drayton et al. 1992). These improvements led Lanfear (1989) to conclude that the impact of a GIS in understanding environmental issues may be as great as that of the introduction of the FORTRAN programming language. The utility of a GIS is derived from its ability to store, manipulate, use, and display large, spatially explicit databases. This paper presents two examples of the combination of a GIS with forest models to better predict the influence of environmental impacts on forest processes.

CASE STUDY #1: SOIL EROSION

Soil erosion due to road construction, log removal, and site preparation can be the major forestry impact on water quality. The ability to estimate soil loss from the watershed due to past and proposed forest activities is an important tool for cumulative impacts assessment and management planning. Soil erosion models developed for agricultural practices have been adapted to the forest situation with varying success (Dissmeyer and Foster, 1980). Unlike in agriculture, forest soil disturbance is often patchy and discontinuous at the site level and the disturbed sites are separated over a watershed. Besides being spatially discontinuous, forest disturbances may be separated by long periods of recovery and non-disturbance. These factors make soil erosion modeling at the watershed scale difficult.

With a GIS, model outputs are displayed as maps. Maps of soil erosion will assist the land manager in identifying areas where sections of the watershed are most susceptible to soil erosion. The model could be rerun through a succession of alternative management scenarios, until a management strategy (e.g., using filter strips, brush barriers, or altering the season in which management activities are conducted) is found which minimizes (or reduces to an acceptable level) soil erosion and stream sedimentation.

Site Location

The data necessary to develop a spatially explicit soil erosion model was derived from preexisting digitized maps (e.g., soil series, forest compartment boundaries, roads, streams and topography) in the Wine Spring Ecosystem Management Project's 1140 ha basin in the Nantahala National Forest in western North Carolina (McNulty et al. 1995). Basin elevation ranges from 915 m at Nantahala Lake to 1655 m at Wine Spring Bald. About one-half the basin has been undisturbed by forestry activities for 60 or more years. Portions of the upper watershed have been actively managed for timber production within the last 25 years.

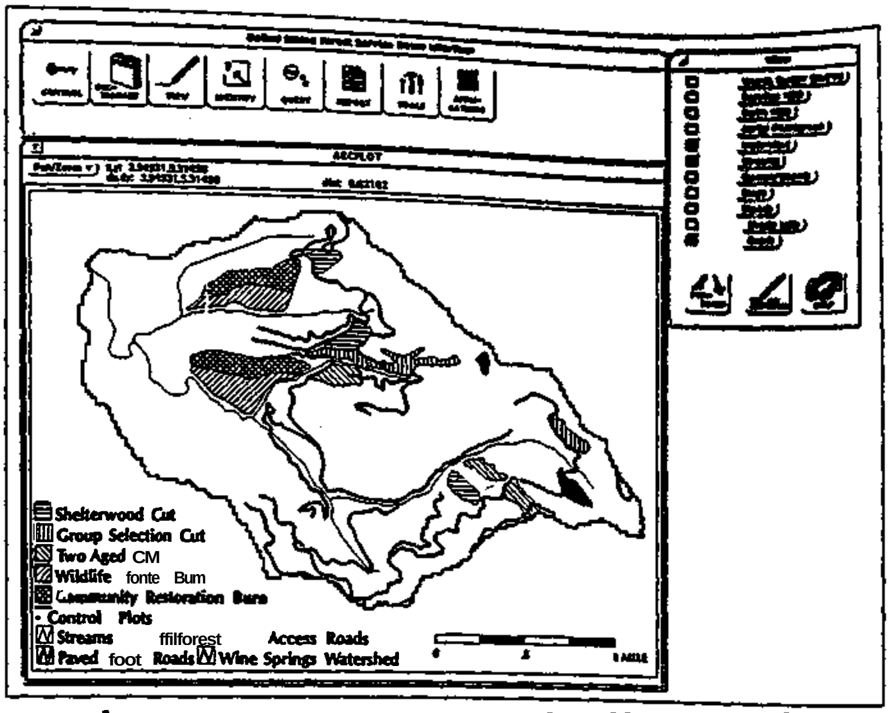

Figure 1. Forest management practices and road locations in the Wine Spring Ecosystem Management Project Basin.

Sediment Production Modeling

The universal soil loss equation (USLE) is used to predict erosion for each 900 m^2 (30 x 30 m)grid cell across the watershed. Ecosystem factors regulating the production of sediment are input to the model as GIS databases.

The USLE, which is a simple model to parameterize, is described in equation 1

$$A = R \times K \times LS \times C \times P \quad (1)$$

where A is seasonal or annual soil loss; R is the rainfall runoff factor; K is the soil erosivity factor; LS it a topographic factor that combines slope length (L) with slope steepness (S); C is the forest cover management factor; and P is the soil conservation practice factor.

Each factor is digitized into the GIS as an attribute from preexisting data. For example, rainfall intensity (R) is derived from regional values or data from climate stations near the watershed. The data can be extrapolated across the basin based on elevation and location of the rainfall collectors. Other factors such as the LS factor can be derived from preexisting DEM's, while the K factor is an attribute attached to digitized soil series maps.

Within the GIS system, forest managers can attempt to alter the sediment production rates through changes in the cover management factor (C), and the soil conservation practice (P). In our modeling project, forest management practices (e.g., road building, burning, timber harvesting) are entered into the GIS database (Fig. 1). Depending on the type of practice, the values for C x P are changed within affected cells. Forest managers can alter the predicted rates of soil loss by changing where, when, and how various forest management practices are conducted.

Management Scenarios

Two management scenarios were run using the USLE model with a **GIS** interface. In the first scenario, all forest logging roads were well-graveled surfaces with no ruts or exposed soil. Road maintenance in the first scenario is consistent with Forest Service "Best management **practices". In** the second scenario, forest logging roads were classified as rutted, with some exposed soil. This classification is typical of poorly constructed roads, or roads that have not been properly maintained. Both scenarios were run with average spring precipitation intensity and amount **(R),** and a variety of management cuts and regeneration bums (C and P) (Fig. 1). The only difference between scenario 1 and 2 was the degree of road maintenance.

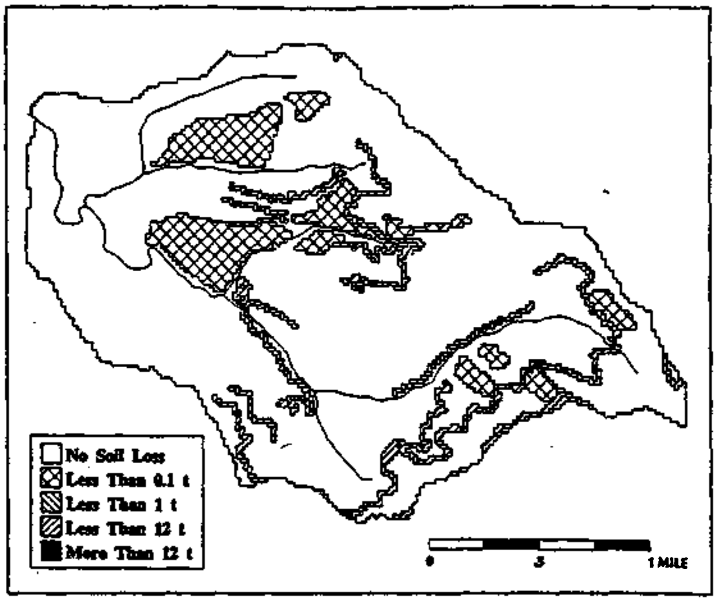

Figure 2. Predicted soil erosion across the Wine Spring **Ecosystem** Management Project Area using best management practice road **construction.**

RESULTS AND DISCUSSION

No sediment loss was predicted for most of the watershed using either management scenario. Small amounts of sediment loss **(< 0.2 t ha^{-1})** were predicted from **the** proposed prescribed burn areas and proposed timber cutting sites. However, most of the predicted soil loss came from road surfaces (Fig. 2 and **3)** .

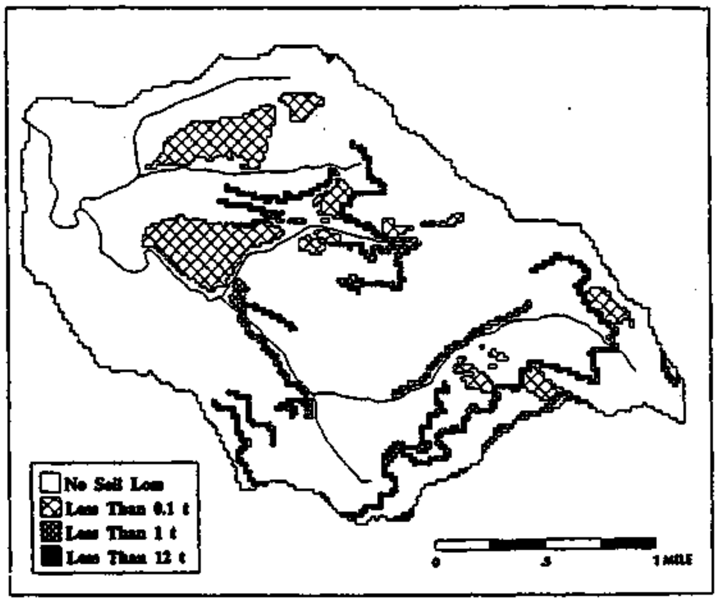

Figure **3.** Predicted sofl erosion across the Wine Spring Ecosystem Management Area using poor management practice road construction.

Soil erosion rates were higher for the poorly maintained road (Fig. 3), compared with the well maintained road soil erosion rates (Fig. 2). In the well-maintained road scenario, only 6 cells had estimated sediment production rates > **12 t $cell^{-1}$, (i.e., 133 t ha^{-1}),** while **in** the poorly maintained road scenario, several sections of road had estimated sediment production rates > 12 t cell^{-1}. The maximum amount of predicted sediment was 32 t cell^{-1} (i.e., 355 t ha^{-1}) and occurred on a poorly graveled road cell which was located on a steep slope.

Given that the USLE is a simple model, estimations of sediment loss should not be expected to match measured rates precisely. Instead, we envision the use of the model as a tool for predicting relative soil loss. Forest managers can use this model to predict areas with potentially high soil loss compared with other sections of the management area. By running the model multiple times under different management practices and seasons, this model would be useful for determining which conditions reduce total soil loss or soil loss in sensitive areas (i.e., near streams).

In this case study, A GIS provided both the platform for managing the database and a mechanism for spatially displaying the model outputs. Without a GIS, the USLE could only predict soil erosion rates for individual areas in the watershed, or predict whole watershed erosion. Selection of the areas to check for soil erosion are subjective. Running the model across the entire watershed removes the subjectively for the assessment and provides a more comprehesive analysis. If the model were to be run for the entire watershed as a single unit, the small area of high erosion would be lost in the overall low predicted soil erosion rates. More importantly, no determination could be made regarding the location of high erosion rate areas if the whole watershed were considered a single unit.

CASE STUDY #2 FOREST GROWTH MODELING

Forests cover approximately 55% of the southern U.S. land area (Flather et al. 1989), so short-term (i.e., monthly) and long-term (i.e., decadal) changes in air temperature and precipitation could substantially impact southern timber production and have serious economic implications (de Steiguer and McNulty 1996).

Models of forest response to environmental change will be useful tools in understanding and managing our nation's forest resources into the 21st century. PnET-IIS is an example of a regional scale forest process model developed using a GIS to predict forest productivity, hydrology and species survivability across a range of climates and site conditions (McNulty et al. 1996). We used a GIS and PnET-IIS to assess the impact of changing precipitation and air temperature on southern pine forest productivity.

Model Structure

PnET-IIS, uses site specific soil water holding capacity (SWHC), four monthly climate parameters (minimum and maximum air temperature, total precipitation, and solar radiation) and species specific process coefficients (McNulty et al. 1996) to predict hydrology and productivity at a 0.5° x 0.5° grid cell resolution (approximately 50 x 75 km) (McNulty et al. 1996) across the southern United States. Regional scale predictions require a GIS for database management and model output display.

Vegetation Data

PnET-IIS required no site specific vegetation indices. **Instead,** the model uses species specific vegetation coefficients. We derived these coefficients from field measurements and from the published literature (**Aber** and **Federer** 1992, **Aber et al.** 1995, **McNulty et al.** 1994, **McNulty et al.** 1996).

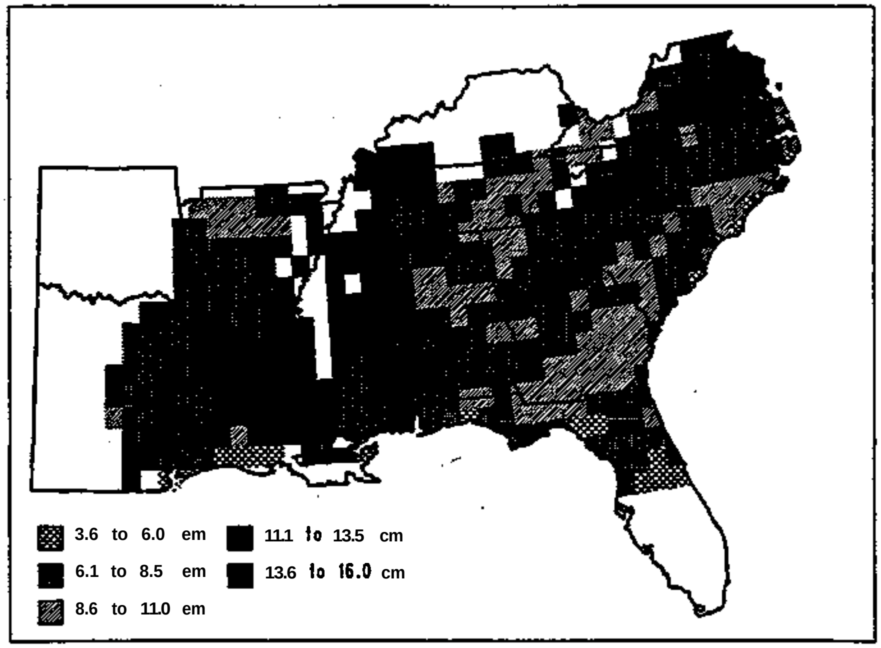

Figure 4. Regional estimation of soil water holding capacity to 102 cm.

Soils Data

Soil water holding **capacity** was the only soil parameter needed to run **PnET-IIS.** The model data were derived from a **GIS-**based Soils Atlas compiled by the Soil Conservation Service (Marx 1988).

Climate Data

To predict forest **growth,** we used monthly climate data from **1951** to 1984 as model inputs. We interpolated the 900+ cooperative climate station point databases on a 0.5° x 0.5° grid across the southern U.S. (Marx 1988). **The gridded** databases of minimum and maximum air temperature, relative humidity, and precipitation were compiled into a single database and run through a program to calculate average monthly solar radiation (**Nikolov** and **Zeller** 1992). We combined solar radiation values with monthly maximum and minimum air temperature, and total monthly precipitation as input for **PnET-IIS.**

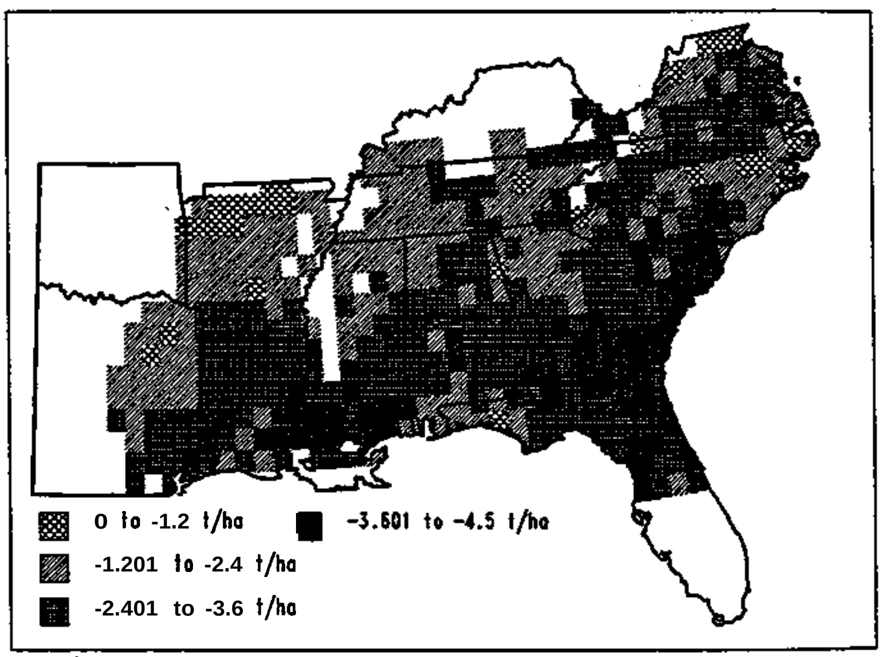

Figure 5. Change in predicted average annual **NPP** due to **a** one year drought.

Climate Scenarios

We used the model to predict how short and long-term changes on precipitation would influence regional scale forest productivity. For the short-term **predictions,** we ran **PnET-IIS** using the **1951 to** 1984 monthly climate data. However, in the first scenario, we decreased average annual precipitation by 25% during the last year to simulate the region wide drought that **occured** in 1985. In a second scenario we again **used the 1951 to** 1984 climate **data,** but during the final year we increased regional precipitation by 30% to simulate the record wet year of 1989.

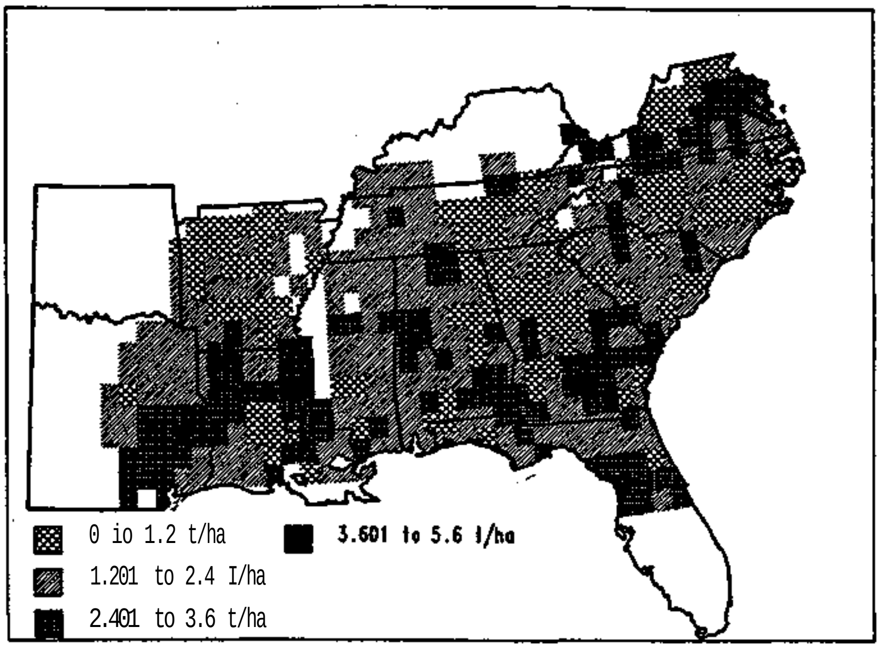

Figure *6.* Change in predicted average annual **NPP** due to one wet year.

A third scenario combined the Oregon State University General Circulation Model (OSU GCM) predictions of changing air temperature, precipitation and atmospheric **CO_2** with historic climate data. The OSU GCM predicted a **3.5°C** increase **in** air temperature and a 5% reduction in average annual precipitation. **Grid** data from OSU GCM monthly climate change data **(Cooter** et **al.** 1993) were added to historic (1951 to 1984) average monthly minimum and maximum air temperature or **multiplied** by historic monthly precipitation to produce 35 years of climate change scenario data. These data were then used with **PnET-IIS** to predict the influence of climate change and increasing atmospheric **CO_2** on regional scale forest productivity.

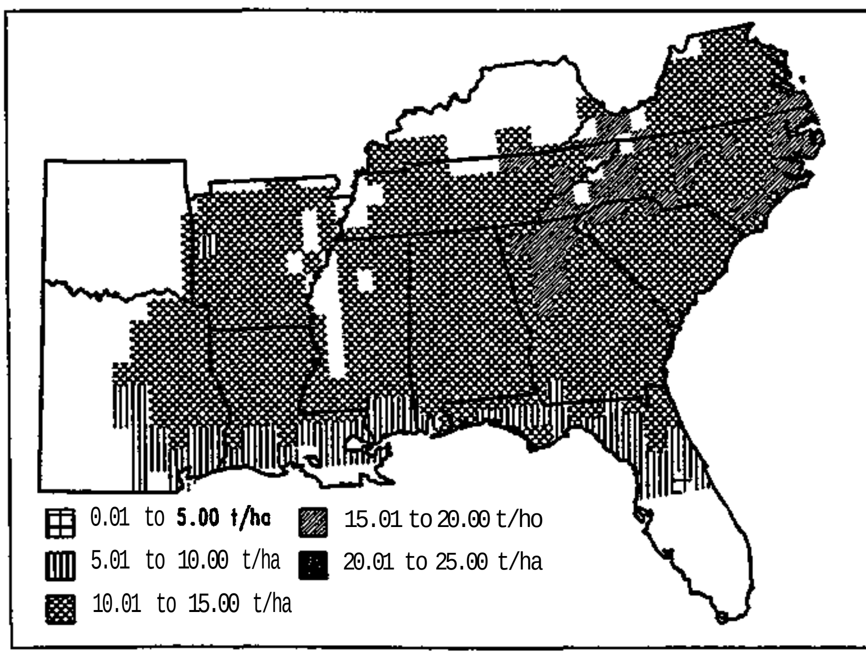

Figure 7. Predicted average annual NPP given a +2° C increase in average annual **air** temperature and a doubling of atmospheric **CO_2**.

RESULTS

The one year drought (i.e, -25% average annual precipitation) caused the model to predict a 32% reduction in NPP across the region. Areas that received high rates of precipitation were less affected than areas that received less precipitation (Fig. 5). Conversely, a 30% increase in average annual precipitation caused the model to predict a 14% increase in average regional NPP. Again, areas receiving historically more precipitation were less sensitive to increases in precipitation than those areas receiving less average annual precipitation (Fig. 6).

Long-term climate change had a larger impact on regional NPP. Besides the climate change influence, the level of atmospheric CO_2 is assumed to double. Using the OSU GCM, PnET-IIS predicted that NPP would increase by 47% across the region (Fig. 7). Increased air temperature was countered by increased atmospheric CO_2. The net effect was a decrease in plant water use and an increase in NPP.

When coupled with a GIS, these models could be used by state and federal agencies and private industry to forecast the influence of short and long-term climate change on forest resources. Spatially explicit maps provide improved assessment of areas which could benefit or suffer from climatic perturbations. In response, land managers could modify forest practices (e.g., species selection, thinning) in climatically sensitive areas.

CONCLUSIONS

In this example we used a GIS to link models and databases for the prediction of soil erosion and regional scale forest growth. Although the two case studies had very different objectives and temporal and spatial scales, the function of a GIS was very similar. As these model/GIS packages become more available, forest managers could use these systems to assess management practices that minimize sediment production and stream water impacts given alternative forest management practices, or to determine how forest growth could be impacted by changing climate. Understanding short-term climate change effects on forest growth are important for monitoring changes in standing stock volume. Model predictions of long-term influence on forest productivity is useful for planning yield and rotation lengths. Only with the assistance of a GIS are these assessments possible. Therefore, the utility of GIS in forest management will increase as a tool for land managers during the coming years.

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