Eleventh Annual
Symposium
on Geographic
Information
Systems

97

Vancouver
British Columbia
Canada

A Coupled CENTURY Model-GIS Approach for Evaluation of the Sustainability of Canadian Boreal Forests Under a Changing Environment

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Abstract

Canada is custodian to about one-tenth of the world's forests and to approximately 25% of its boreal forests. The boreal forest region is the largest forest region in Canada and its long-term ecological variability and sustainability are influenced by many factors. One of the challenges for sustainable management and development of these forests is to predict their likely long-term and large-scale response to a rapidly changing environment, caused both by natural factors and by human activities, and to transfer that knowledge to forest managers, policy-makers, and to the decision-making public. Of particular interest is the imperfectly understood interaction between large-scale natural disturbances (such as wild fire and insect damage), climate change and the increasing pressures of human population increases (e.g., through harvesting and land-use change) on the forest resource. This paper addresses some of the major issues that need to be considered in the design of a Decision-Support System (DSS) for sustainable forest management under such conditions. As a specific example of such a DSS, the paper outlines the linking of an ecosystem model (CENTURY 4.0) with a Geographic Information Systems (GIS) to permit evaluation of likely future changes of boreal forest ecosystem under a changing environment.

Introduction

The word's population has increased from 1.6 billion at the beginning of the 20th century to some 5.6 billion today and is expected to exceed 6.0 billion before the year 2000. Along with this population increase, economic growth and industrialization have increased the per capita consumption of nature resources and simultaneously lead to increased environmental pollution and degradation. This has raised widespread awareness of the need for environmentally sustainable economic development (WCED, 1987). Of particular concern is the apparent degradation of global forests and loss of the essential environmental and economic services that they supply.

Canada is custodian to about one-tenth of the world's total forests and approximately 25% of its boreal forests. Forming a nearly contiguous circumpolar belt through Nordic Europe, Russia and North America, the boreal forest biome also comprises the largest forest region in Canada. The long-term ecological variability and sustainability of the boreal forest biome is influenced by many factors. Understanding the dynamics of boreal forest ecosystems and the factors that influence these dynamics, provides the basis for the sustainable use of these forest resources and the conservation of their environmental services. Of particular importance is the fact that they are subjected at aperiodic intervals to large-scale natural disturbances (such as wild fire, and insect outbreaks) whose relationship and interaction with environmental variability and change is imperfectly understood. Moreover, the same forests have come under increasing human population pressure both through the direct effects of harvesting and land-use change, for example, as well as from the indirect human effects of anthropogenic changes in the global climate system. The development of boreal forest ecosystems is a slow process, relative to other forest biomes, so it may be expected that the impacts of rapid changes in the global environment on both the structure and the function of these ecosystems may be both significant and complex (Apps *et al.*, 1995).

Sustainable forest management (SFM) represents a new paradigm for forestry in Canada (CCFM, 1992) and involves management of both temporal and spatial patterns of ecosystem conditions at both stand and landscape levels (Cocklin, 1989; Oliver and McCarter, 1995). In its broadest sense, SFM seeks to embrace both the concepts of ecosystem management (in which multiple resource values are made explicit) and the concepts of sustainable development (in which the needs of future generations are explicitly considered). With such broad aims, the development of measurable indicators for SFM represents a major on-going research challenge, and is a priority area of research (Panel, 1994).

Traditionally, forest science has focused on stand-level processes (Baskerville, 1986) and the prediction of forest growth and yield has been through use of the historical bioassay (Kimmins, 1990; Kimmins *et al.*, 1990). Many of the contemporary issues facing biological conservation and forest ecosystem management, however, cannot be handled solely at the stand level and do not have historical analogues for their solution. Rather, the issues are typically related to the landscape-level and the patterns of change at various spatial and temporal scales (Tuner, 1989). Some of the greatest challenges for sustainable development in the boreal forest biome are : to predict the likely long-term and large-scale response of forest ecosystems to a changing environment, such as changes in climate and natural disturbance regimes; to estimate the influence of human activities on these responses; and to effect the transfer of that knowledge to the forest manager, the policy-maker, and the public (Maini, 1990).

As part of a larger research program on the role of boreal forests in global change, a study was undertaken : (1) to examine the potential for coupling an existing ecosystem simulation model (CENTURY 4.0) with a geographic information system (GIS) to provide forest management decision-support; (2) to develop ecologically-based indicators for SFM of boreal forest ecosystems and to link these indicators with changes in ecological, economic and social factors, in term of both causes and effects; and (3) to use this decision-support information to help identify SFM strategies for the boreal forest region in Canada, in terms of forest net primary productivity (NPP), biomass, soil organic matter (SOM), nitrogen cycling and other ecosystem values. In this paper we focus on the coupling of the ecosystem model (CENTURY 4.0) with a GIS to include the influence of a changing environment in the DSS. We also present the results of validation of performance of CENTURY 4.0 for specific sites across the Boreal Forest Transect Case Study (BFTCS) in central Canada.

Study Area

The Boreal Forest Transect Case Study (BFTCS) extends over a distance of 1000 km and is oriented approximately southwest-northeast along a pronounced ecoclimatic gradient across the boreal forests of Saskatchewan and Manitoba (Figure 1). It was selected for this study for a number of reasons. First, the BFTCS is one of the Global Change and Terrestrial Ecosystems (GCTE, a core project of the International Geosphere Biosphere Program (IGBP)) high latitude transects (Koch *et al.*, 1996). The BFTCS was initiated in 1990 by the Canadian Forest Service as part of the Boreal Ecosystem-Atmosphere Study (BOREAS) (BOREAS Science Steering Committee, 1991). Second, detailed vegetation and soil databases are available across the BFTCS (Halliwell *et al.*, 1995; Halliwell and Apps, 1996a,b,c) against which to test the model's ability to predict aboveground biomass and soil C for different climatic conditions and soil types within the boreal biome. Third, the BFTCS represents a pronounced climatic gradient across the boreal forest landscape of Saskatchewan and Manitoba (Price and Apps, 1995). The northern limit of the boreal forest appears to be determined by low annual heat sums and temperatures (where soil moisture is non-limiting). Conversely, at the southern limit, conditions are warmer, but tree growth is evidently limited by growing-season soil moisture deficits (Hogg, 1994; Hogg and Hurdle, 1995). In addition, there is a pronounced gradient of land-use and land-use intensity across the transect

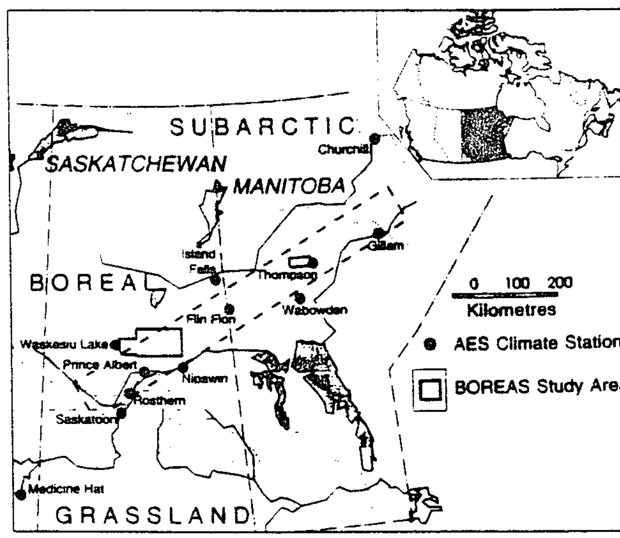

Figure 1. Map of Saskatchewan and Manitoba showing ecoclimatic provinces (subarctic, boreal and grassland) and the approximate positions of the Boreal Forest Transect Case Study (BFTCS), BOREAS study areas and the climate stations used in CENTURY 4.0 simulations.

ranging from modern forestry practices in the south (Prince Alberta Model Forest) to traditional native land practices in the north (Linklater, 1995). Fifthly, situated centrally within the continent, the BFTCS is expected to undergo the largest and earliest changes in global environment, changes that many (IPCC 1995) expect could take place during the lifetime of trees being planted today. Finally, earlier work (Price and Apps, 1996; Price *et al.*, 1996; Peng et al. 1996a,b) with ecosystem models (including CENTURY 4.0) have been performed in this region and provide a scientific foundation for development of scaling-up methods (coupling CENTURY model with GIS) at landscape-levels.

Century Model

CENTURY, as developed by Parton *et al.*, (1987, 1988, 1993), is a general computer model of plant-soil ecosystem which simulates the dynamics of C and N of various plant-soil systems including grassland, agriculture land, savannas and forests. It incorporates representations of key process relating to carbon assimilation, turnover and decomposition, based on a set of existing submodels. It also permits simulation of many management measures, including grazing, cropping, fertilization, irrigation, and control of wildfire. The model has been previously described in detail by Parton et al. (1987, 1993) and Metherell *et al.*, (1993).

Figure 2 shows the carbon pools and fluxes in version 4.0 of CENTURY which is used in the present study. The forest production submodel partitions tree biomass into several compartments: foliage, fine and coarse roots, fine branches, and large wood. Carbon (C) and nitrogen (N) are allocated to the different plant parts using a fixed allocation scheme. Gross primary productivity (GPP) is calculated as a function of maximum gross productivity, moisture, soil temperature and live leaf-area-index (LAI). Plant respiration is calculated as a function of wood N content and air temperature using a relationship developed by Ryan (1991) and subtracted from GPP to obtain net primary productivity (NPP).

The soil submodel consists of eight organic matter pools, four represent surface and root litter and the other four represent soil organic matter (SOM). The SOM pools include: two "active" fractions that have rapid turnover times (1-5 yr) and represent microbial biomass and metabolites divided into a surface and a soil pool; a "slow" fraction with an intermediate turnover time (20-40 yr) that represents stabilized decomposition products; and a "passive" fraction with a slow turnover time (200-15000 yr) that represents highly stabilized organic matter. As shown in Figure 2, C flows between these pools are controlled by decomposition rate and microbial respiration loss parameters, both of which are expressed as functions of soil texture. The turnover times of all pools vary with a soil abiotic decomposition parameter and are calculated as a function of monthly temperature and precipitation.

CENTURY 4.0, which operates on a monthly time step, also includes a water balance submodel which calculates monthly evaporation, transpiration, water content of soil layers, snow water content and water flow between saturated soil layers. Importantly for the present purpose, CENTURY 4.0 also includes some ability to simulate the influence of key resource management measures as mentioned previously (e.g. fire, grazing, cropping, fertilization, irrigation). The major input variables for the model include (1) monthly mean maximum and minimum air temperature, (2) monthly precipitation, (3) soil texture, (4) atmospheric and soil N inputs, (5) plant lignin content, and (6), initial soil C and nutrient levels.

Earlier versions of CENTURY have been used widely to simulate plant productivity, biomass and soil C and N dynamics in agroecosystem (Paustian *et al.*, 1992, Metherell, 1992), grassland (Parton *et al.*, 1993, 1995; Hall *et al.*, 1995; Xiao *et al.*, 1995), tropical forest (Sanford et al., 1991; Vitousek *et al.*, 1994; Townsend *et al.*, 1995), as well as savanna and tundra (Metherell *et al.*, 1993). More recently, CENTURY 4.0 has been validated for the boreal forest in Central Canada using field data of aboveground biomass, soil organic matter and net N mineralization and used for evaluating boreal forest response to climate change, doubled CO_2, and their combined effects (Peng *et al.*, 1996a,b; Price *et al.*, 1996). The model is not spatially oriented, however, and to our knowledge has not previously been used for evaluating the spatial patterns and dynamic processes of boreal forest ecosystem responses to possible management interventions at landscape levels.

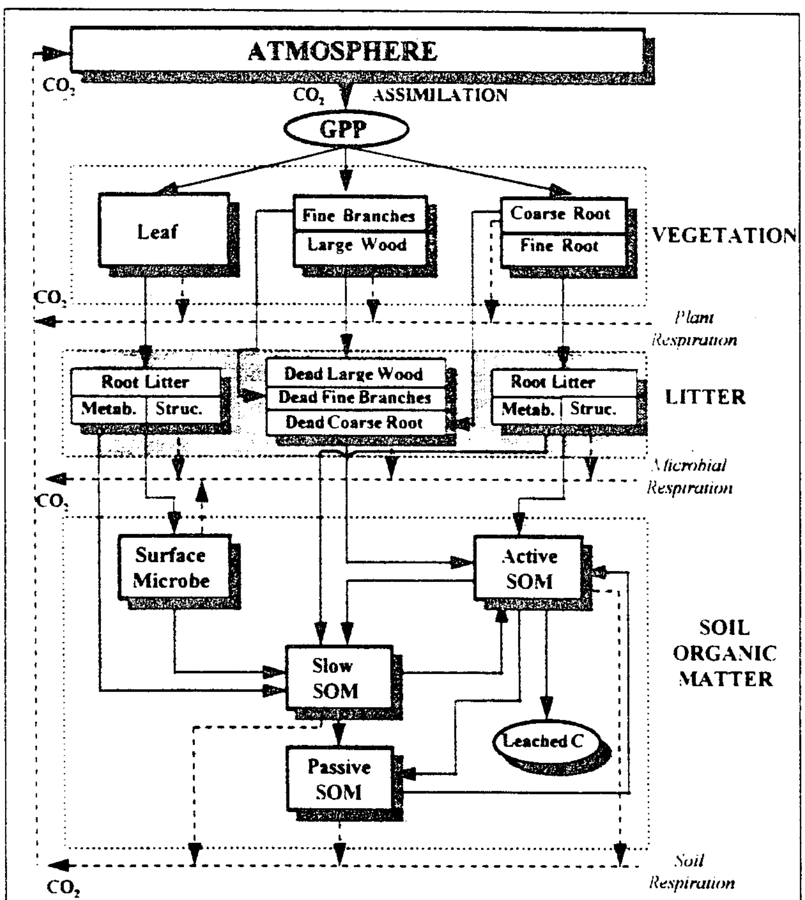

Figure 2. Carbon pools (boxes) and fluxes (arrows) in CENTURY 4.0.

Coupling Century with Geographically Explicit Information

Figure 3 shows a schematic representation of the information flow that underlies the DSS design. A DSS is generally comprised of sets of input data and assumptions; rule, or model, based operations for exploring alternative possible actions between which choices must be made; and various output indicators which present to the decision maker the expected responses to those actions. In Figure 3 the GIS-based database represents the data for the range of known spatial and temporal variability of the model driving variables across the study area. These data are then used as input for the central model to simulate expected changes in regional patterns and dynamics. The central component of the system shown in Figure 3 is an ecosystem model (in the present study, CENTURY 4.0) that permits simulation of future ecosystem development under different scenarios of present forest management and future environmen-

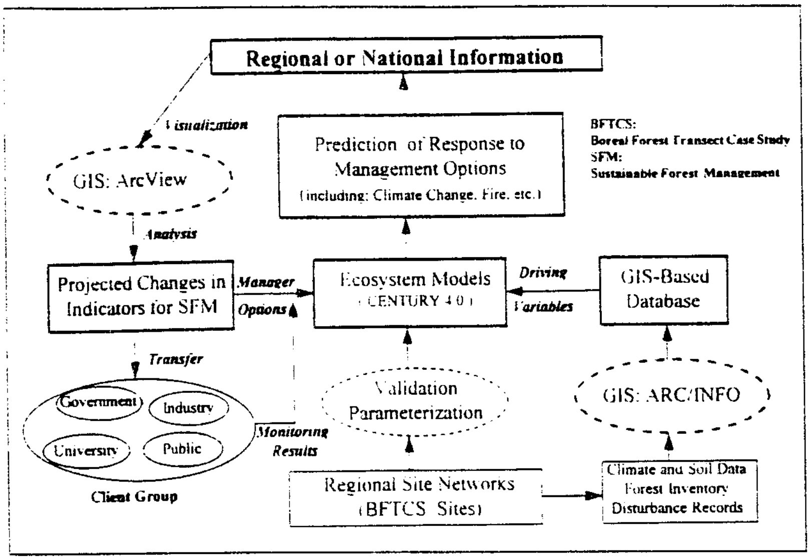

Figure 3. Flowchart of a Decision Support System (DSS) for assessment of sustainability of boreal forest landscape under a changing environment.

tal conditions. The output of the ecosystem model, which focuses on changes over time at a specific point on the ground, is combined with geographically explicit data to provide indicators of the spatial and temporal patterns at a regional or landscape scale, as needed to assist management choice.

1. Establishing the GIS-based Database

Climate Data

CENTURY 4.0 requires monthly values for maximum and minimum temperature and total precipitation. These values are usually provided to the model as historically recorded input from a user-supplied file. In addition, however, CENTURY can also stochastically generate precipitation data using historical mean and skewedness values computed from a user-supplied file or through direct user input. To examine future landscape dynamics, it is necessary to develop appropriate temperature and precipitation time series scenarios for the model. This must be done at spatial scales that recognize the climate variability throughout the study region and yet are consistent with the spatial resolution of both soil changing processes and disturbance regime scenarios.

A collection of historical climate data from the Atmospheric Environment Service (AES, 1983) for the study region were used to obtain 30 year normals (1951-1980) of monthly maximum and minimum temperature and total precipitation data for selected climate stations in and near the study region (Price and Apps, 1995). A GIS (ARC/INFO) was used to create the climate division (CD) boundaries, which form the spatial units of analysis for this study as described in section 3 below, and to generate contour maps of annual temperature and precipitation data.

The $2xCO_2$ climate scenarios generated from the selected general circulation models (GCMs) were obtained from the Canadian Climate Centre (CCC) (Boer *et al.*, 1992). An ARC/INFO grid map was created for the CCC GCM and the $2xCO_2$ climate data was linked to each grid cell of the CCC GCM. For example, in each grid cell the climate anomaly ($2xCO_2$ value minus $1xCO_2$ value) was added to the observed climate normal to calculate the climate under the $2xCO_2$ condition.

Soil Data

CENTURY 4.0 requires input data on soil texture (percent sand, silt, and clay), bulk density, and initial soil C and N levels. These data are taken from the Soil Maps of Canada (Clayton *et al.*, 1977), the BFTCS data bases of Halliwell and Apps (in press, c) and the national scale soil database of Siltanen et al., (in press). The later contains soil and environmental data for over 1400 pedons (comprising more than 7000 soil horizons) at non-agricultural sites across Canada (Siltanen *et al.*, in press) and provides a comprehensive data set to validate model simulations of soil C at regional scales. This database contains soil profiles, relatively undisturbed by direct human activities, that represent the processes of soil development that occur in a natural environment.

2. Validation of the Ecosystem Model CENTURY 4.0

Validation of CENTURY 4.0 along the boreal forest transect case study (BFTCS) is a necessary first task. Figure 5 and 6 show comparisons of the simulated soil C and aboveground biomass with independent observations. The results indicate that CENTURY 4.0 simulates both aboveground biomass and soil C reasonably well across the range of present climatic conditions represented in the transect. As reported earlier (Peng *et al.*, 1996a,b), it appears that the overall representation of biogeochemical processes in CENTURY 4.0 is adequate for simulating the C and N dynamics of boreal forest ecosystems. These previous works provide a scientific foundation for using CENTURY 4.0 to examine the spatial-temporal response of the boreal forest landscape to changes in climate, natural, and human disturbances. By monitoring the changes in the BFTCS as they occur over time, and testing the DSS model predictions against these changes, refinements to the model can be made, thereby improving the DSS services in an adaptive manner.

3. Linkage Between the CENTURY and GIS-Based Database

Figure 4 shows the basic steps in applying the modeling methodology to the BFTCS. These steps are discussed in more detail below:

(1) The study region is divided into "Climate Divisions" (CD) (or GIS polygons) each of which has can be assigned an individual climate time series of the monthly max/min air temperature and precipitation data needed by CENTURY. The CD boundaries are defined as the intersection of ecoclimatic region (Ecoregions Working Group, 1989) and administrative (provincial) boundaries to facilitate the transformations (i.e. aggregation/disaggregation) of fire disturbance, harvesting and soil data. The CD is the basic spatial unit of analysis for this study and no higher level of spatial resolution is maintained. For the BFTCS hundreds of unique polygons are defined by this process.

(2) Within each CD, the frequency distribution (in area units) of soil textures, percent distribution of clay, silt and sand that are present are defined by the data in the soil data sets base. These are used to assign parameter sets for statistical sim-

ulation samples for CENTURY. Area weighted averages are used to determine the indicator values for the CD.

(3) For each CD, natural disturbance regimes, such as fire frequency and intensity and insect epidemic events, are specified as historical records or as future scenarios. These scenarios may be generated by external disturbance models or as prescribed "what-if" data sets. Human activities, including different harvesting regimes (such as clear-cut, selective logging, and variable rotation period), specific practices (e.g., whole-tree harvesting or conventional stem-only harvesting), and resource preservation measures (such as fire and pest suppression) may similarly be included as historical records or future scenarios.

(4) Establish initial conditions for vegetation composition, SOM, N, and other needed model variables for each soil texture

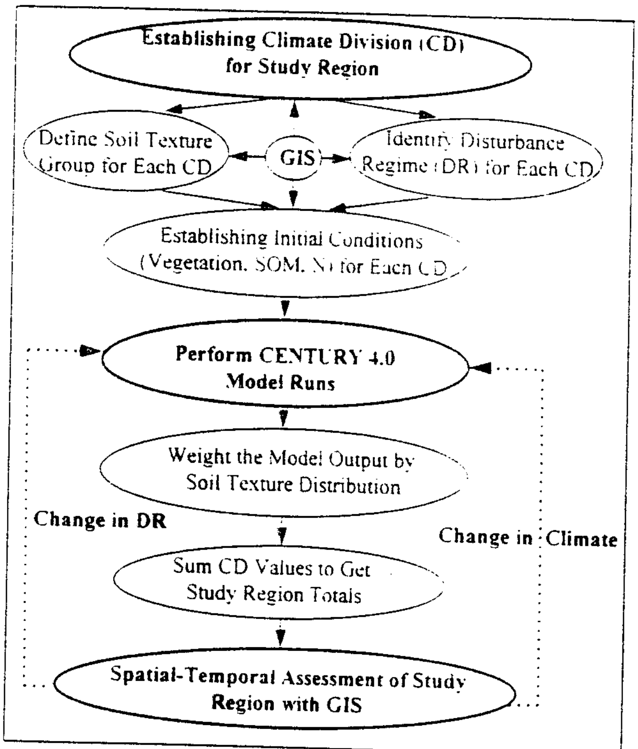

Figure 4. Flowchart of a coupled CENTURY-GIS modeling method-

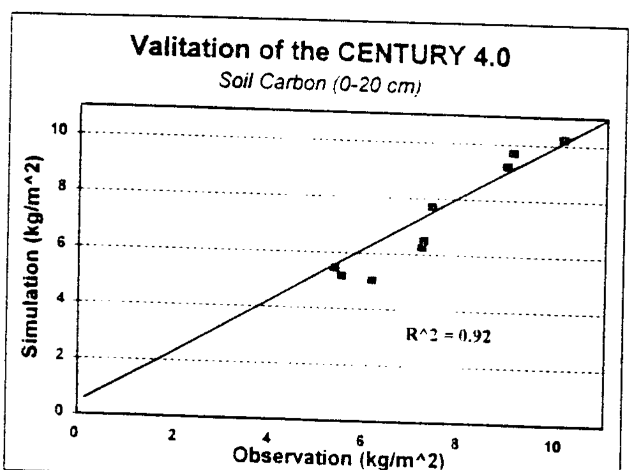

Figure 5. The simulations of soil carbon (0-20 cm) from CENTURY 4.0 are compared to nine observations reported from Siltanen et al., (in press). Simulated and observed values are strongly correlated (R2 = 0.92).

within each CD. This task has very high data demands and often requires a set of assumptions or subsidiary models to fulfill (Kimmins *et al.*, 1990).

4. Projection of Climate Change, Disturbance Regimes, and Management Scenarios

(1) For each CD, initial conditions are established by running CENTURY 4.0 for about 5000 years using the repeated mean monthly temperature and stochastic precipitation generator. The resulting model state variables of interest (such as NPP, biomass, SOM, net N mineralization) are analyzed to check that the model simulation has indeed reached an equilibrium state; this equilibrium is assumed to represent the state of the present forest under natural boreal forest conditions in each CD. Subsequent application of different climate, disturbance regimes, and management scenarios are then used to make projections of alternative future states of the forest landscape.

Two examples are provided in Figures 7 and 8. Figure 7 shows the response of biomass, litter and SOM to climatic change scenarios generated by the GISS general circulation model (GCM) (Hansen *et al.*, 1988). Figure 8 shows the sensitivity of total biomass to a changing fire frequency. The detailed analysis of fire disturbance and management regimes will be provided in a separate manuscript elsewhere (Peng and Apps, 1996c).

(2) Sets of CENTURY simulations are performed using different soil texture values. The outputs from each CENTURY run are weighted by the soil texture distribution for that CD to obtain averaged response curves for the output variables (indicator) within each CD. This is done for each of the different treatment scenarios to be assessed. These treatment scenarios may

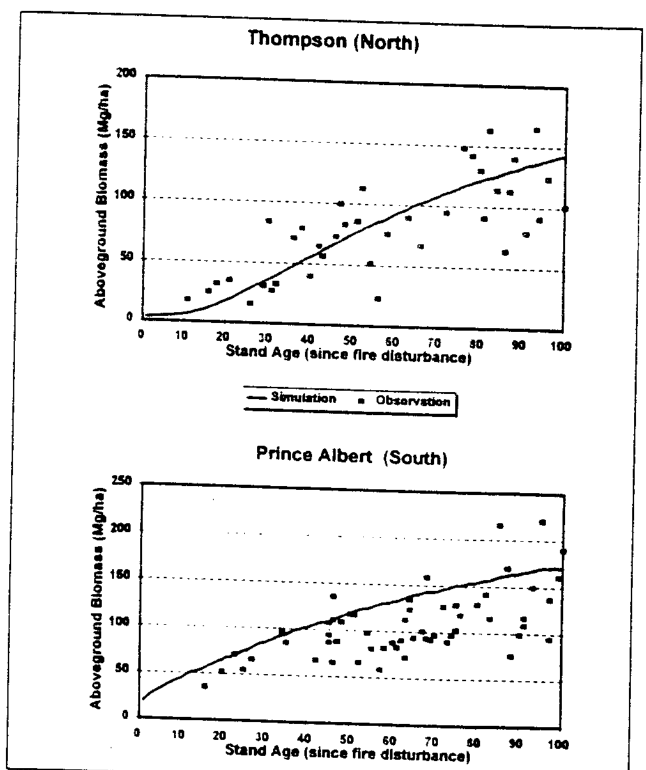

Figure 6. The CENTURY 4.0 simulations of aboveground biomass with different stand ages are compared the observed data reported by Halliwell et al., (1995).

include direct management actions (such as harvest intensity or type) as well as concurrent changes in climate or natural disturbance regimes (with various levels of protection or suppression).

(3) For each simulation scenario, the weighted average response curves are scaled up to the CD level by multiplying by the treatment area for that scenario. The totals for each CD are then summed to provide totals for the entire study region and for the projection period of interest.

(4) The final quantitative evaluation of baseline conditions, and comparison of each alternative scenario is visualized using the ArcView-based GIS interface as a navigation and information-display tool. These assessments focus on the spatial-temporal impacts on NPP, biomass, SOM, net N mineralization and nutrient cycling.

5. Building on Accumulation of Experience in the DSS

Human knowledge and experience is explicitly embodied in the DSS system in many places, but most explicitly in the structure of the ecosystem model (here, CENTURY 4.0), in the formulation of potential management scenarios, and in the ultimate selection of the treatment or management intervention. The response of the real system to the carrying out of this management action, if regarded as an experiment, can be used to add to the depth and scope of this knowledge and experience. Success or failure in meeting management objectives clearly contributes to the manager's ability to formulate potential future actions.

The feedback of information to the decision-maker—and need for such feedback—is greatest however if the external environment is changing rapidly. Given the premise that the rapid changes in the environment will introduce spatial and temporal patterns with which there has been limited, or no, direct human experience, optimizing the information received from such experiments can provide multiple benefits. First it permits a certain degree of 'adaptive management' to be practiced by encouraging the decision-maker to re-assess the system response and take corrective measures as appropriate. Secondly, by monitoring selected landscape indicators and comparing these against projected values, warnings of possible failure (or missed opportunity) may be detected. This provides both an opportunity for further management intervention and, perhaps more importantly, for modifying and improving the predictive ability of the ecosystem model. Thus the DSS system can help in the design of appropriate monitoring systems by indicating changes in auxiliary ecosystem indicators that may not be of immediate interest to the decision maker, but which may provide early warning 'flags' or lead to significantly increased understanding of the ecosystem processes—and improved predictive ability in the ecosystem model.

Discussion

Current concerns about likely long-term and large-scale response of forest ecosystems to a rapidly changing environment are enlarging the spatial scale of the information needed about ecosystem structure and function. The inherent spatial heterogeneity in biotic and abiotic variables, however, makes it difficult to meaningfully use the small numbers of empirical site-level field studies to evaluate large-scale responses to perturbations over time. There are two aspects to this 'scaling problem': dealing with the spatial heterogeneity and dealing with the temporal changes within the heterogeneous spatial pattern. To deal with the first of these, ecologists have recently begun using larger numbers of spatially dispersed sites (Sala *et al.*, 1988, Burke *et al.*, 1989) with tools such as remote sensing and geographic information systems (GIS), which permit the analysis and management of spatial data.

As a means for dealing with temporal dynamics, the linkage of ecosystem models within a GIS is presently receiving a great deal of attention (Buckley *et al.*, 1994; Oliver and McCarter, 1995). GIS is a powerful tool for the integration of different spatially-referenced databases as multiple layers of driving variables. These linked multiple layers can be used for modeling the responses of ecosystems to different perturbations. GIS technology enables the investigation of large spatial scale environmental issues by facilitating the analysis of the heterogeneous patterns and processes that are present at lower (finer) spatial scales.

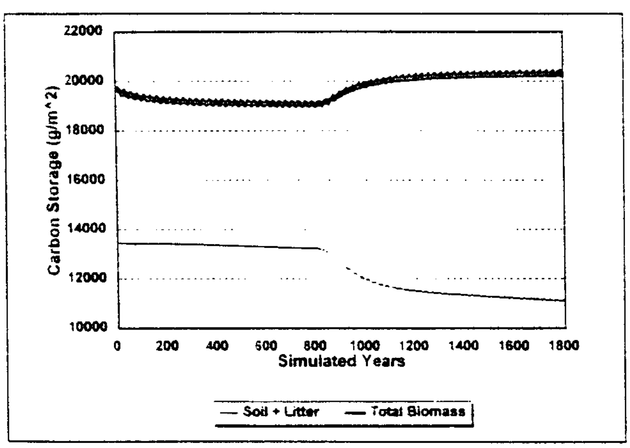

Figure 7. Total (above- and belowground) biomass, litter and soil carbon density simulated by CENTURY 4.0 at Thompson, Manitoba (55(48' N, 97(52'W), using a average monthly climate record from the period 1958-1990. A simulated change in climate derived from the GISS general circulation models (Hansen et al., 1988) was applied beginning at year 801, continuing until year 900, followed by 800 year assuming a stable 2xCO2 climate scenario.

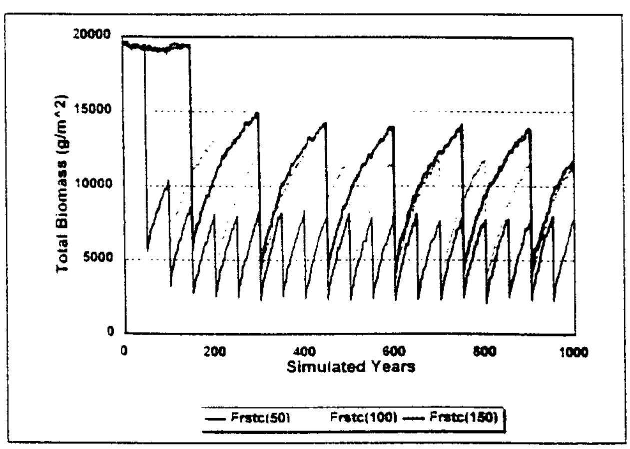

Figure 8. Sensitivity analysis of total biomass, simulated by CENTURY 4.0 using a average monthly climate record from the period 1958-1990, to changes in fire disturbance regimes at Flin Flon, Saskatchewan (54(46' N, 101(51'W). Frstc(50), Frstc(100), and Frstc(150) represent simulations with fire return intervals of 50, 100, and 150 years, respectively.

GIS systems, however, deal only with spatial scaling issues. They can not, on their own, deal with the issues of temporal scale or provide spatially-explicit development patterns of ecosystem structure and function. The obvious solution to this limitation has been a linkage between GIS and stand-level models. In forestry this generally has involved traditional growth and yield models (e.g., Oliver and McCarter, 1995). While such models when imbedded in a GIS predict timber production from a landscape over time, the predictions have questionable value in the face of a rapidly changing environment. Thus to use a boreal forest example, traditional growth and yield models fail to account for changes that might be associated with changes in climate, changes in the natural disturbance regime or associated changes in nutrient cycling. In particular, without considering soil nutrient and organic matter dynamics—and the feedback between plant productivity and soil decomposition—it is unlikely that robust long-term projections of stand-level or ecosystem-level forest growth will be obtained.

Some of the shortcomings just mentioned can be overcome by using an process-based, coupled vegetation plant-soil model that includes such ecosystem feedback mechanisms as nutrient cycling (Kimmins, 1990). CENTURY 4.0 is one such model but it is a point based model and is not spatially oriented. Linking CENTURY 4.0 into a GIS takes advantage of both the temporal dynamics of CENTURY and the spatial integration powers of the GIS. With such a coupled system, it is possible to examine the possible effects of global climate change on net primary productivity, biomass and soil organic matter and to link such information to the spatial characteristics at the landscape level.

By also providing visualization tools and spatial integration of responses to alternative management scenarios, this approach also can assist forest resource managers. By assisting them in the evaluation of the impacts of alternative management strategies, it can help them to make informed decisions in an increasingly complex and rapidly changing decision-making environment.

Acknowledgments

We thank The CENTURY Model group for free access to CENTURY 4.0 and acknowledge valuable discussions with X.H. Wei and I. A. Nalder. This work was supported in part by Natural Resources Canada, Canadian Forest Service through a Government Laboratory Visiting Fellowship from the Natural Sciences and Engineering Council of Canada to C.H. Peng.

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