FIRE MANAGEMENT UNDER FIRE (ADAPTING TO CHANGE)

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Boreal Forest, Fire and Climate: Development of an Integrated Terrestrial Landscape Model

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ABSTRACT

Recently, members of the Forest Fire Behavior and Ecology project of the Petawawa National Forestry Institute) undertook development of an integrated terrestrial landscape model (INTELAND). The aim of the project is to develop a simulation model for the boreal forest that integrates the effects on forest landscapes of biotic components, abiotic components, climatic components, and disturbance components in a spatially defined context. This model will be designed to mimic natural processes in boreal forest systems. Initially, the model will focus on the relationships among factors such as fire, surficial deposit types, and forest vegetation in the boreal forest. Work in modelling fire occurrence and behavior, forest dynamics, and climate is currently ongoing. The INTELAND model will be used to define the "natural system baselines" in terms of biodiversity; disturbance regimes; forest composition, age structure, and distribution; minor vegetation composition; and faunal populations. This baseline information is essential in evaluating the impact of past and future forestry practices, land use, and other human impacts on forest health and sustainability, fire regimes and landscape biodiversity. The model could also address questions about the effects of global change both on the disturbance regimes and on the biotic components of the landscape. After development, the model could be extended to other biomes to provide forest managers with a tool to evaluate forest management policy. The general framework of the model and some preliminary results and applications will be presented and discussed.

INTRODUCTION

Sustainable forest management is contingent upon: 1) a clear understanding of forest dynamics under natural disturbance regimes, and 2) an ability to forecast the ecological impacts of forestry practices. In our study, we will develop a general model based on natural disturbance regimes that will integrate current knowledge of forest biology. Using this model we will predict factors pertinent to the sustainability of the forest resource, and the impact of current forestry practices on ecosystem and landscape characteristics such as biodiversity. Biodiversity can be measured at different levels such as genetic, species, ecosystem, and landscape (Canadian Forest Service 1993). However, a species-by-species approach for measuring biodiversity is difficult because there are numerous species (many unknown), it is costly, and it is time-consuming

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(Franklin 1993). Assuming that a forest management strategy that conserves patch diversity in landscapes is means of ensuring the maintenance of a level of biodiversity similar to that under natural conditions, a landscape-level approach was suggested (Franklin 1993, Noss 1983, 1987, Mladenoff and others 1993, Attiwill 1994). In our project, we adopted an hierarchical approach (Urban and others 1987) where different levels (species, stands, ecosystems, and landscapes) reflect the spatial scale of the important processes (e.g. stand: competition; landscape: disturbance).

Our study attempts to better understand the relationships among abiotic factors, biotic factors, disturbance, and climatological factors that affect forest diversity both in space and time, at the landscape level. For example, weather, vegetation, and abiotic conditions all have effects on the probability of fire occurrence and subsequent rate of fire spread and intensity. The type of disturbance (fire, insects, or diseases) and its intensity have an effect on vegetation composition and succession, that in turn, affect the abundance and composition of associated wildlife. Various types of disturbances may also act synergistically (Pickett and White 1985). For instance, the occurrence of a spruce budworm outbreak may affect the occurrence and intensity of fires (Bonan and Shugart 1989, Stocks 1985). Further, the spatial relationships among vegetation stands may have an effect on subsequent regeneration processes following a disturbance. For instance, the presence or absence of seed sources from a particular species may lead to differences in species composition after a disturbance among similar sites types (abiotic conditions). The dynamic (temporal) aspect of the biotic components is also very important. For instance, the management of large mammals requires knowledge of vegetation dynamics through time and space. Finally, the interaction among components has an impact on landscape biodiversity, site productivity and forest health. In this investigation we will focus on the boreal forest because of its relative simplicity and its national and global importance. However, in future, we expect to extend our model to other forest regions of Canada.

Our central emphasis is to improve knowledge of landscapes in the boreal forest prior to widespread human intervention (European settlement) in order to define the "natural baselines" for biodiversity (at species, stand, ecosystem and landscape levels) and disturbance regimes. These baselines will be used to assess how current disturbance affects biological diversity, thereby improving management by providing a basis for biodiversity objectives. Because most of Canada's forest ecosystems have already been affected by humans, the development of process models and simulations is a viable means to assess pre-settlement biodiversity. Models predicting successional patterns (gap models) have already been defined for several vegetation types (Shugart 1984, Leemans 1992, Bonan and Shugart 1989, Bonan 1992). Disturbance behavior models are also available (Forestry Canada 1992, Andrews 1986) and general circulation models (GCMs) are designed to assess the effects of CO_2 increase on climate change (Hansen and others 1988, Manabe and Weatherald 1980). However, the integration of these models in a spatially-defined context is lacking (Leemans 1992, Solomon and Shugart 1993, Levine and others 1993). A good integrated landscape model should include process models that incorporate the interaction between climate, disturbance, abiotic conditions, and biota. The model should also describe and simulate the changes ongoing within each component. There is also a need to increase our understanding of how spatial integration of environmental factors affects the landscape. The role of disturbances in creating and maintaining spatial mosaics is well recognized (Pickett and White 1985), but the way in which the landscape structure and heterogeneity affect the spread of disturbance, the distribution of organisms and, thus, biodiversity, is not well understood (Turner 1989, Wiens and others 1993). Thus, to gain a good understanding of the underlying processes, a better knowledge of the interrelationships both within and between components is required. In practice we expect our model to predict relative species presence and abundance, as well as ecosystem and landscape characteristics following different types of human intervention. This effort will constitute a solid basis for implementing of forest management programs.

Objectives

The general objective of our study is to produce a Geographic Information System (GIS)-based integrated terrestrial landscape model for the boreal forest that helps define "natural system baselines" for disturbance regimes, vegetation composition and dynamics, forest-level wildlife species composition, and landscape diversity (Figure 1). This model will relate biota (flora and fauna), climate, abiotic factors, and disturbances at the landscape level in order to:

1) define the relationships among the environmental components at the landscape level both in time and space;

2) predict the impacts of past, present, and future human interventions such as fire suppression,

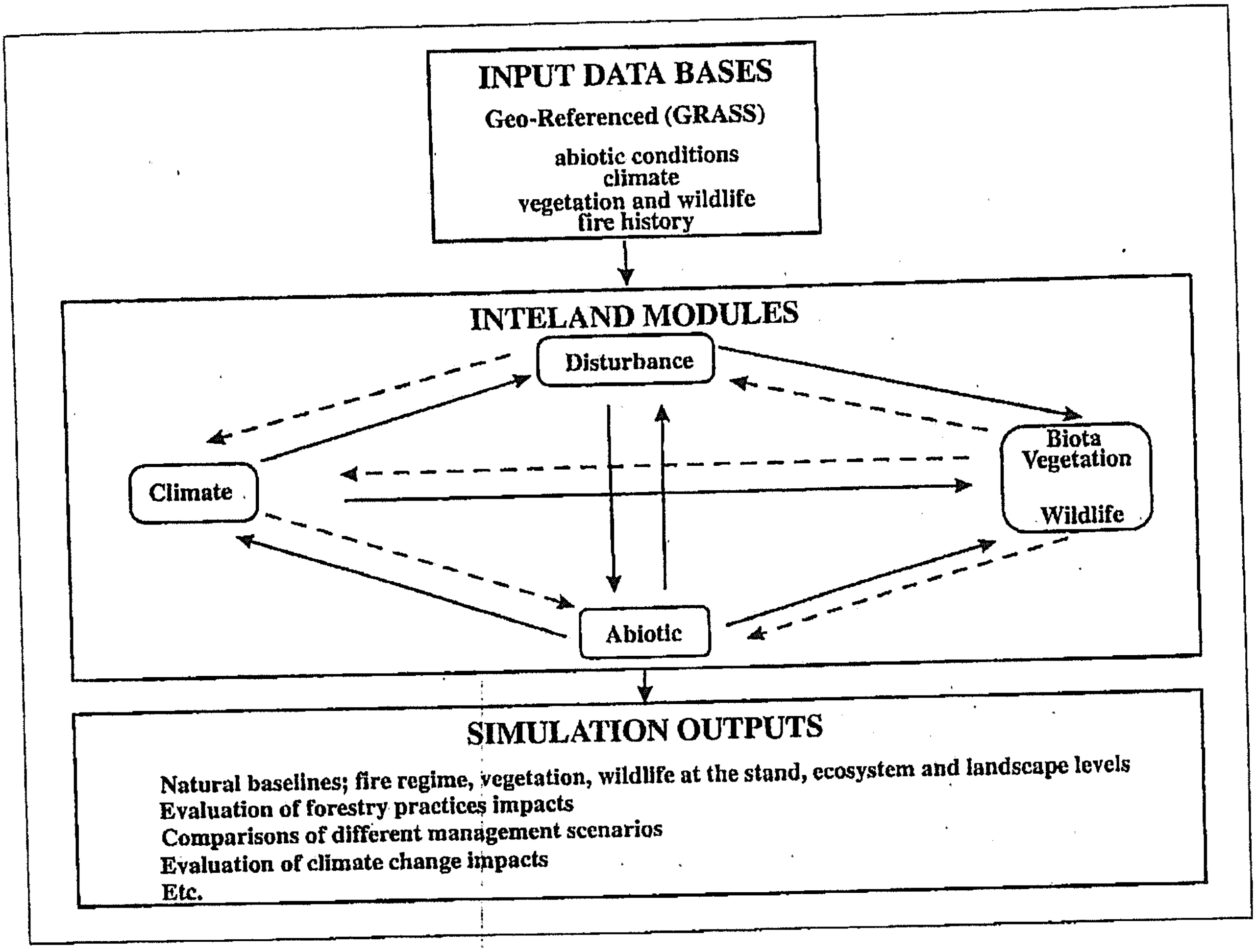

Figure 1.

forestry practices, and land use, on disturbance regimes, vegetation dynamics, forest wildlife species composition and landscape diversity; and

3) predict the effects of global climate change on disturbance regimes, vegetation dynamics, stand wildlife species composition, and landscape diversity.

Methods

The boreal biome was selected for several reasons:

1) it is widely represented in the Northern Hemisphere;
2) forest dynamics are closely linked to disturbances (Bonan and Shugart 1989);
3) at the landscape level, the mosaic created by fires and insect outbreaks maintains a diversity of stands of different ages and species compositions;
4) its stand diversity influences wildlife species in space and time; and, finally,
5) the number of species (trees and understory) is low making the model development relatively simple.

GIS-based simulation models are currently being developed and tested on a study area of about 20,000 km² in northwestern Québec (78°30'-79°30' W, 48°00'-50°00' N), from the southern fringe of the boreal forest extending northward to encompass several ecological regions.

Data Inputs

Data bases from different sources will be used in a raster-based GIS (GRASS) to characterize the spatial component of the environment. The abiotic component data base includes soil characteristics, drainage, surface geology, hydrology, and topography (elevation, slope, orientation). Data from 14 climate stations and five weather stations throughout the study area will provide climate/weather information. Interpolation techniques will be used to estimate climate fields for any particular cell. Historic daily weather variables such as temperature, relative humidity, wind speed and direction, and precipitation will be used to drive the fire occurrence and behavior module. For the vegetation dynamics routine, annual climate values will be used such as minimum temperature, frost free period, snow depth, growing degree day, precipitation and growing season length (available from Environment Canada). Fire history reconstruction maps will be integrated into the GIS data base. Eventually other disturbance types such as insect outbreaks and diseases will be added to the model. For the vegetation component, available data such as provincial forest inventories or ecological classifications will be used. Available data on wildlife species composition and relative abundance will also be integrated into the data base.

MODEL COMPONENTS

Fire Occurrence and Behavior Module

The disturbance component will initially focus on fire disturbances and will be linked to the climate, vegetation, and abiotic components (Fig. 2). There are two aspects to simulating fire as a landscape level disturbance. First, fire occurrence must be simulated consistent with climatic norms (ignition source patterns and fuel ignition potential) for the area of concern, the vegetation composition, and the time of year. Second, once ignited, the fire must be allowed to grow or be extinguished, given the fuel complex and the prevailing weather conditions. For the simulations, the annual number of fires for each year will be determined from historical fire incidence data for the region. Potential ignition sources will be stochastically constructed for location and date, and available models for ignition probability will be used. Spread potential for the date and location of the potential ignition will be determined from the data bases (vegetation, climate, current and past weather) to ascertain if the fire will spread. If the fire occurrence model indicates a fire ignition, then a fire growth model, driven by vegetation and daily weather, will be run. The fire growth model will continue to run allowing the fire to spread from cell to cell, based on daily weather from the weather data base, until some predetermined conditions are met. These predetermined conditions could be, in the case of the baseline "natural" situation, a substantial rain event or a

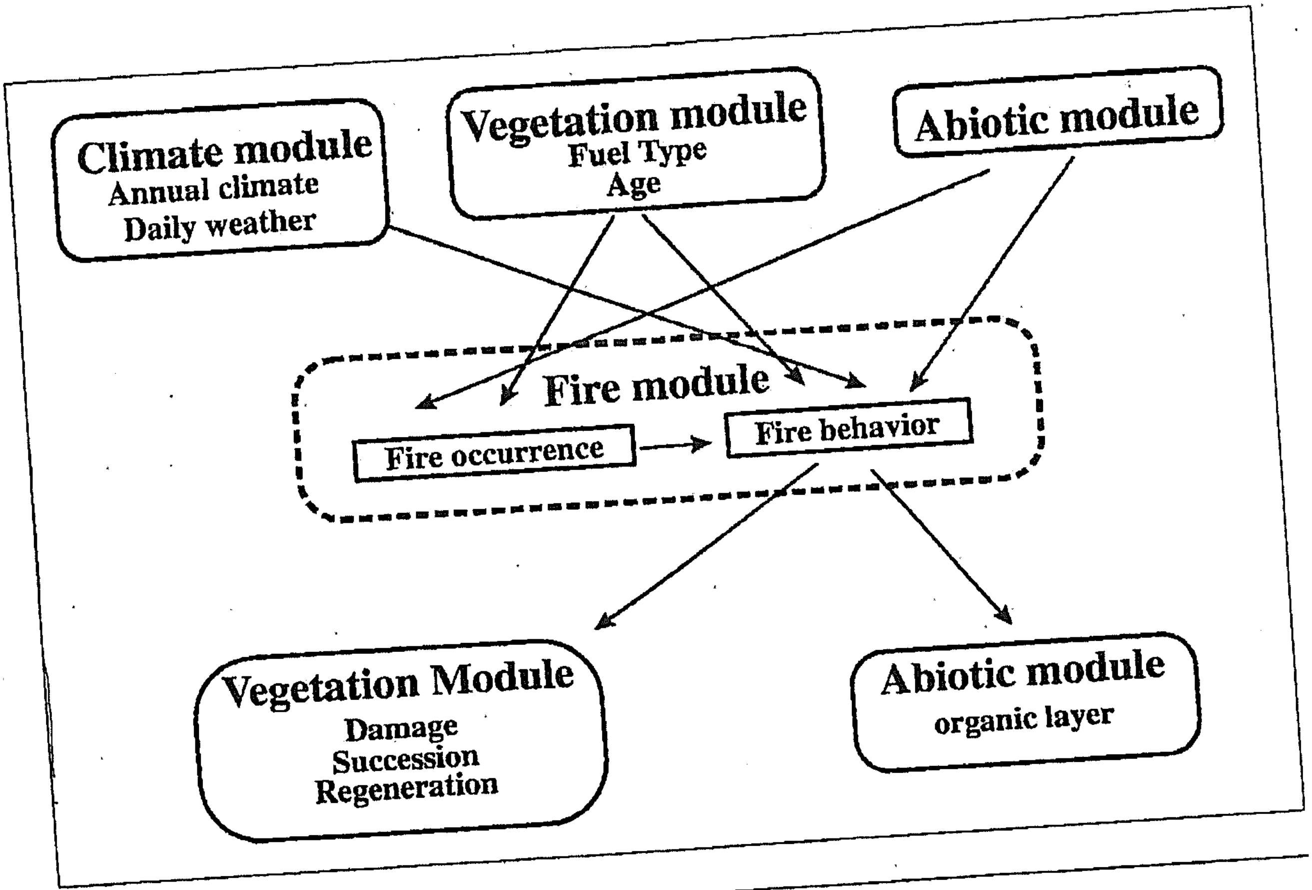

Figure 2.

natural fire break (a large lake). A requirement of the fire behavior outputs of the growth model will be the forest condition following the passage of fire. Most, if not all of the requirements, will be met by the Fire Behavior Prediction System (Forestry Canada Fire Danger Group 1992).

Biotic Models

Vegetation Module

At the landscape/regional level, the diversity of forest types results from four sets of components:

1) climatic factors;
2) abiotic conditions (geology, parent material, etc.);
3) disturbance events (fire, insects, diseases, etc.); and,
4) chance events (dispersal, pre-disturbance forest composition, etc.; Fig. 3).

Thus, modelling the vegetation dynamics will have to take into account these four sets of components at the landscape level, plus within-stand (cell) dynamics where life-history characteristics of the species are considered. For modelling vegetation dynamics, we selected an existing model derived from gap models for multi-species vegetation types (General Vegetation Model or GVM, Fulton 1993). The vegetation species are divided into three strata:

1) overstory (trees species),
2) understory perennials, and
3) understory annuals.

In GVM, each individual in a cell (stand) is not considered but stand variables are computed: species composition, density and volume per layer classes (height) for the overstory vegetation and, the species composition and cover, for the understory vegetation (Fulton 1993). The GVM model will be modified to take into account chance factors such as the pre-fire composition and interval between 2 successive fires in a cell, and the spatial distribution of vegetation species in the surrounding cells of any particular cell. These

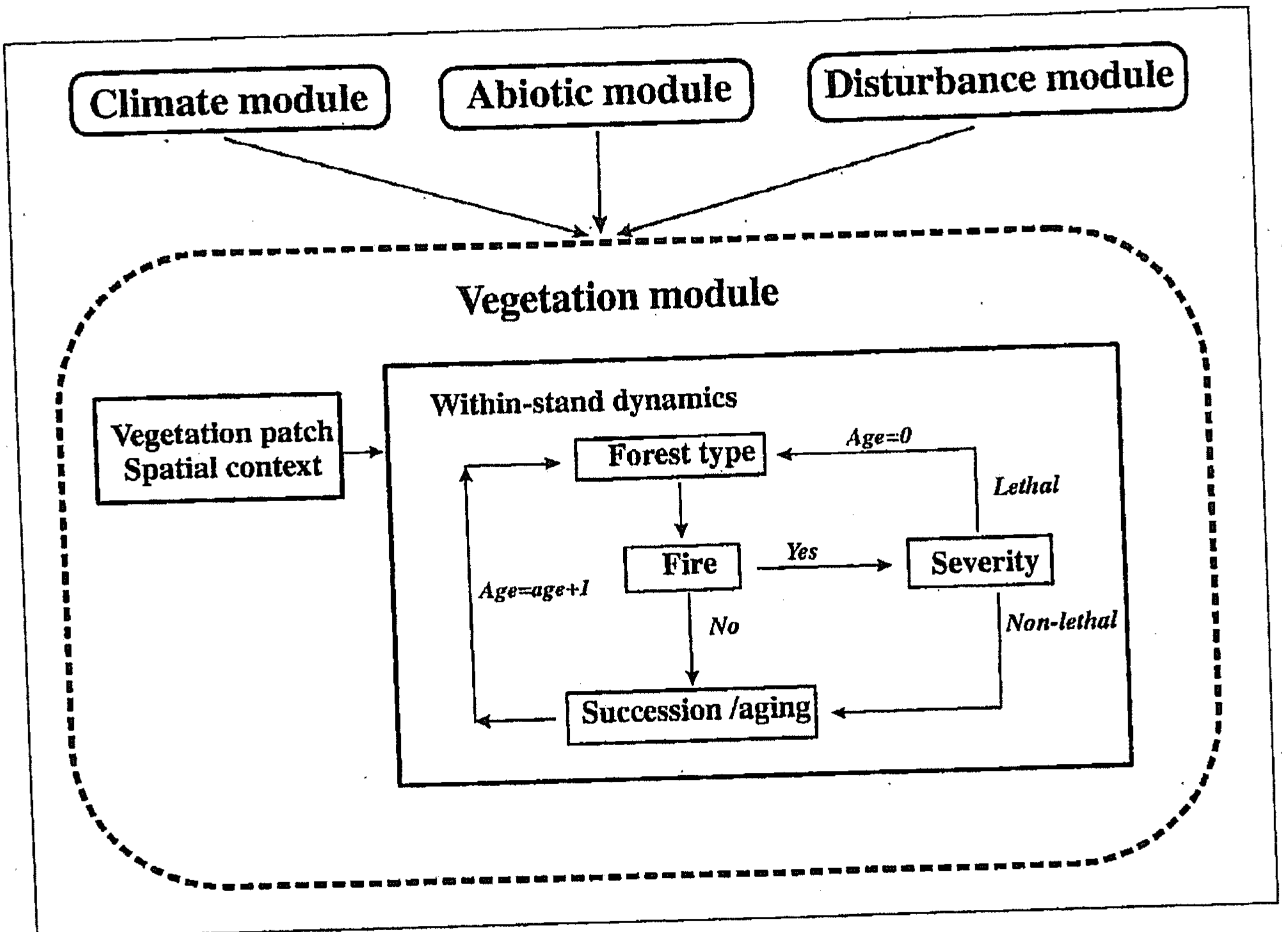

Figure 3.

two aspects are very important in explaining different successional pathways observed in stands under similar abiotic conditions (Rebertus and others 1991, Attiwill 1994, Noss 1983, 1987). There are two main components in the vegetation model, 1) a succession routine (aging / development without disturbances), and 2) a regeneration routine (stand evolution following disturbance; Fig. 3).

Within a stand, forest succession is the result of differences in recruitment, differential growth rates, mortality, and tolerance (shade and competition) among species (Shugart 1984), and will thus be modelled according to these factors. Modification of the GVM include accounting for the effects of neighbourhood species composition to determine species probability of recruitment within each cell. Chance events such as the presence or absence of species in the neighbourhood and seed crop production will also be included in the model. The regeneration routine considers the occurrence of fire in a stand as it affects forest composition. The fire model outputs will define the intensity of the disturbance and its impacts on vegetation. We recognize that, for most of the eastern boreal species, the relationship between fire intensity, tree size (DBH or height), and survival is poorly known. Data analysis, similar to the work of Van Wagner (1973) and Ryan and Reinhart (1988), was undertaken to assess the effects of fire intensity, tree size, crown scorch, scorch height, and bark thickness on tree survival. Field work will be necessary to complete this information. Post-fire regeneration will be predicted according to fire intensity, pre-fire composition and age, species propagule (seeds and protected buds) availability within the cell and its neighbouring cells (considering also the fire date), type of soil, drainage, depth of organic layer, and shade levels. Thus historical factors (pre-fire composition), chance factors, and more mechanistic factors will be integrated into the model. Once the overstory model is completed, the understory vegetation will be included in the modelling effort. The successional routine will be based on current knowledge (eg., the work of Racey and others 1989, Sims and others 1989, Bergeron and Bouchard 1983, De Grandpré and others 1993).

Fauna Module

Wildlife species' composition responds to site, stand, ecosystem, and landscape influences depending largely on body size. In some cases, notably animals with large body size, selection of habitat may be made at several scales (eg., caribou need large expanses of old forest, suitable stands are conifer- dominated, and more productive sites influence food production). Therefore, we intend to model habitat requirements of particular species at the stand and ecosystem levels (certain bird species, small mammals, hare, lynx, and marten) and at the ecosystem / landscape level (marten, caribou, and moose). Models will reflect life history requirements, food needs, and habitat requirements relative to minimum populations. Population models will be driven by rules relating to habitat capability at each scale, and summed for model cells. We anticipate little field work for this component, and we will link up with ongoing programs of Ontario Ministry of Natural Resources in the Lake Abitibi Model Forest, DSS modelling for songbirds by Canadian Wildlife Service at Rinker Lake, marten research by Ministère de l'Environnement et de la Faune du Québec at Val d'Or, and moose modelling by Lakehead University.

Climate Module

The climate data have three main applications: 1) it will be used to drive the fire/ behavior routine using daily data for the Fire-Weather Index (FWI, Van Wagner 1987) system inputs (Fig. 2); 2) the available species for recruitment and population dynamics in any cell (both fauna and flora) will be defined based on annual data such as precipitation, maximum temperature and depth of snow, etc. (Fig.3); and 3) the effect of climate change on fire regimes, species persistence and migration, and forest dynamics will be investigated using available outputs from general circulation models (GCMs; Fig. 4).

Abiotic Module

For the time scale under study, most of the abiotic variables will be considered to be in a static state and will be used as inputs in the other modules (Fig. 5). However, for characteristics that change with succession, fire and/or forestry practices, a model could be developed to change, for instance, soil characteristics such as pH, organic layer depth, and cation availability.

VALIDATION

The fire component of the model will be validated by reconstructing the fire history and climate of the past 200-300 years. Past fire history is currently reconstructed using standard techniques including use of archives, aerial photographs, and dendroecological studies and interpretation will be confirmed using pre-logging aerial photographs and samples from mesic forests. A stand-initiation map (Johnson 1992) will be used to compute fire frequencies. In order to reconstruct the climate, cores will be taken from long-lived conifers in a representative number of outcrops along

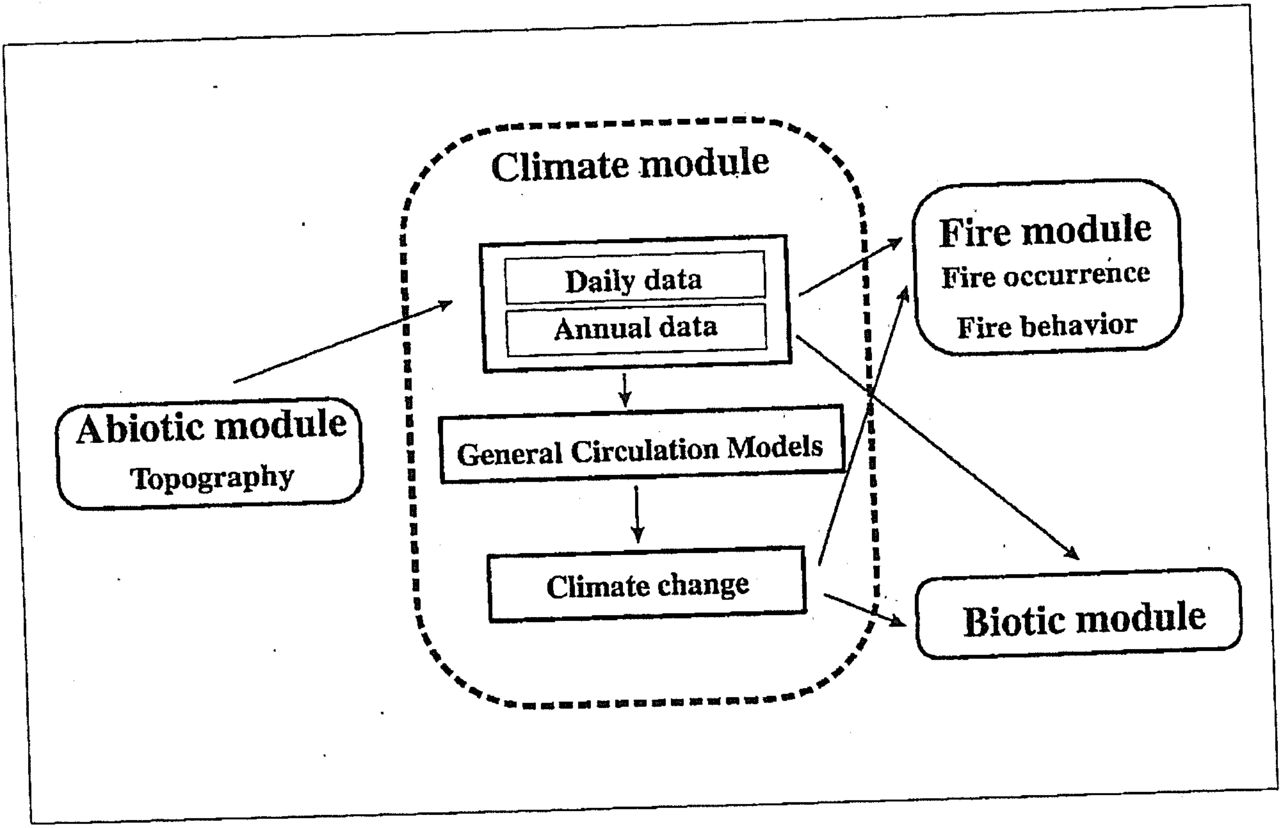

Figure 4.

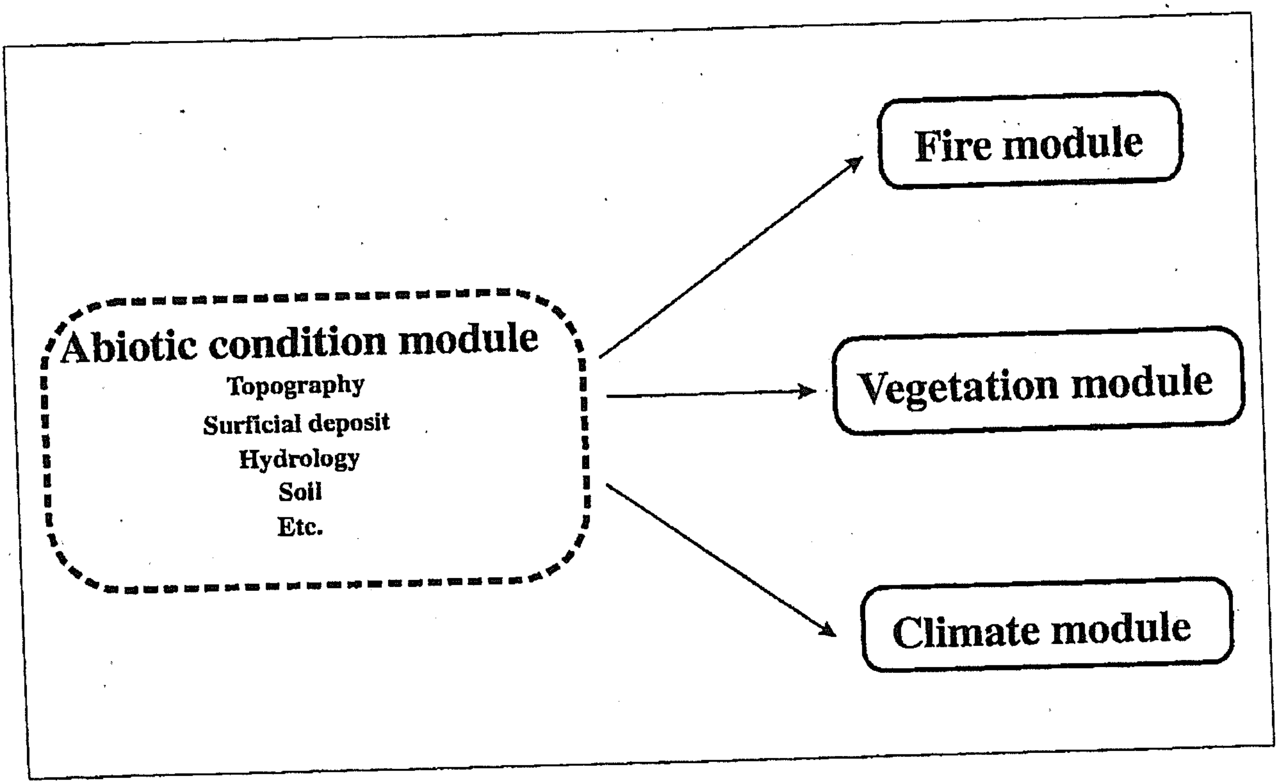

Figure 5.

the latitudinal gradient. This climate-fire reconstruction is being done by Yves Bergeron and others from Université du Québec à Montréal as part of a research effort on fire frequency and climate change in the boreal forest. Using this fire history and climate reconstruction we will test our fire model in terms of fire occurrence and area burned. Additionally, fire-climate relationships can be developed and tested. This validation is not site specific but is at the landscape level. Validation of the vegetation components of the model (succession and regeneration) will be accomplished by reconstructing the vegetation using forest inventory data and aerial photographs, and by inference from the fire history and known successional pathways (Arno and others 1993). Using vegetation reconstructions from the mid 1700s to initialize the model, it would be possible to compare the simulated vegetation for 1930 to the observed (1930), at the landscape level. Additionally, we shall try to validate the vegetation components of the model by using the climate and fire regime for the 100 years prior to 1930 with vegetation randomly assigned across the landscape, and then run the model for a long period (e.g. 1000 years) and compare the output with the 1930 data. Other avenues for validation such as paleoecology will be explored.

SIMULATIONS

Simulations can be powerful tools in evaluating the influence of various input parameters such as climate and forest management policy. By sequentially modifying input parameters, various scenarios can be explored and compared. Our goal is to use simulations to establish "natural system baselines" for the fire regimes, vegetation composition and dynamics, stand wildlife species composition, and landscape biodiversity. These "baselines" will represent an estimate of what would have been observed without anthropogenic influence in the study area. The effects of past and present forestry practices, such as fire suppression, on the landscape vegetation mosaic will also be investigated. Further, simulations could be used to compare the impact of different forestry practices options on important landscape features. Simulations using GCMs will be used to evaluate the effects of climate change on disturbances regimes, forest composition and dynamics, species maintenance and vegetation regions. In the model development, we will take into account the possibility of resolution improvement in remote sensing data collection. Simulations and research may be undertaken to investigate the influence of spatial resolution on the model solutions and to evaluate the changes that occurred through time in climate, fire regime, and vegetation since the last glaciation. The time scale can be adjusted according to specific goals.

CONCLUSION

The main outcome of this project will be the development of a generic integrated landscape model that could be used as a research and/or decision-making tool. This study will provide insights into the relationships among fire regimes, climate, abiotic conditions, and biodiversity at the stand, ecosystem, and landscape levels. The model will help assess the effect of past and current forestry practices on biodiversity and landscape heterogeneity as compared to the natural pre-settlement condition. The results may also help to understand the combined effects of climate change and forestry practices that might affect the rate of change in landscape biodiversity and heterogeneity of natural systems. For instance, simulations from this model will enable managers to make comparisons between the present forests and "natural baselines" in order to assess the impact of forestry practices (fire suppression, prescribed burning) and climate change on forest biodiversity, health, and disturbance regimes or to determine the best policy to maintain/restore the natural biodiversity in boreal systems. This research will be applicable, after calibration, to other regions of the boreal forest biome which encompasses approximately 60% of Canada's productive forests. Component modules used in this model will also be transportable and applicable to other forest regions of Canada. Further, it could be used as a public information tool describing, for example, the effects of natural disturbances on terrestrial ecosystems, the effects of forestry practices on ecosystem parameters such as forest health and biodiversity, and the potential effects of global change on terrestrial ecosystems.

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