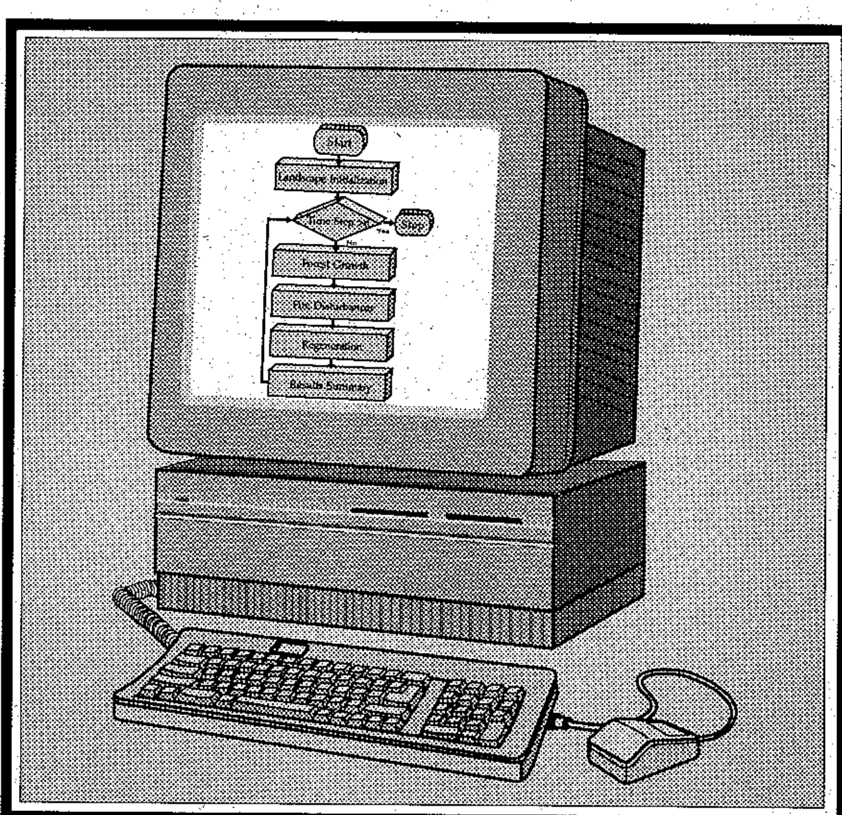
FOREST LANDSCAPE ECOLOGY PROGRAM

FOREST FRAGMENTATION AND BIODIVERSITY PROJECT

Report No. 25



ONTARIO FIRE REGIME MODEL:

ITS BACKGROUND, RATIONALE, DEVELOPMENT AND USE

Ontario

Ontario Forest Research Institute

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ONTARIO FIRE REGIME MODEL: ITS BACKGROUND, RATIONALE, DEVELOPMENT AND USE

Chao Li
Michael Ter-Mikaelian
and
Ajith Perera

(Ontario Forest Research Institute, Ministry of Natural Resources)

Ministry of Natural Resources
Ontario

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Ministry of Natural Resources
Ontario Forest Research Institute
P.O. Box 969
1235 Queen St. East
Sault Ste. Marie, Ontario
P6A 5N5

Telephone: (705) 946-2981
Fax: (705) 946-2030

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ABSTRACT

This report describes a study of forest fire dynamics at the landscape scale. The objective of this study was to develop a spatially-explicit model that can simulate long-term fire dynamics in Ontario, especially in the boreal region. Here we present background information, a brief review of existing fire models, the logic of model development, such as ecological foundation and descriptors for a fire regime, and potential uses of the model.

The role of forest fire is two-fold. On one hand, fires burn forest biomass, consume timber resources, and destroy properties; fires disrupt the forest's successive renewal cycle and function as a timer for succession, *i.e.*, reset the succession cycle to a particular point. On the other hand, however, frequent fires could help to maintain the diversity of landscapes, and may even be a "normal" component of forest ecosystems, maintaining their structure and function.

A fire regime is usually described by fire frequency. We propose a combination of fire return interval and size distribution for characterizing a unique fire regime. This combination describes the proportions of large and small fires.

A review of fire models in the literature suggests that none of the existing fire models could meet all of the expectations of the study. Most existing fire models either deal with scientific problems with different temporal and/or spatial scales, or with prescribed fire regimes, or are unable to link to a Geographic Information System (GIS) database. Therefore, a new model is needed.

ON-FIRE (ONtario FIre REgime model) was developed for simulating fire regimes that result from the interaction between fire events and forest landscapes, as influenced by weather. Three main components of ON-FIRE are looped for each time step: forest growth, fire disturbance, and regeneration after the burn. Age-dependent fire probability is a major assumption of ON-FIRE. The idea behind this assumption is that the processes of fire ignition and spread are mainly controlled by a variable that changes slowly -- amount of fuel accumulated across a landscape. Other factors (such as

vegetation cover type, topography, moisture regime, and weather) will modify the fire probability across the landscape and contribute to fire ignition and spread processes.

The philosophy guiding the development of ON-FIRE is that any of the existing hypotheses in the field of fire modelling, such as weather-driven and fuel-driven fire processes, should not be pre-accepted or pre-rejected. On the contrary, ON-FIRE tries to incorporate the effects of both weather and fuel conditions on fire regime, and provides a framework with which users will be able to test different hypotheses. We believe this modelling approach is appropriate because the current knowledge of fire process is so limited that the existing hypotheses were not well supported by observations.

ON-FIRE has many potential applications in different fields of forestry including forest policy, resource management, fire management, and wildlife and habitat management.

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1. INTRODUCTION

This report describes a study of forest fire dynamics at the landscape scale -- ON-FIRE (ONtario FIre REgime model), initiated within the Forest Landscape Ecology Program (FLEP) at the Ontario Forest Research Institute (OFRI). The objective of this study is to develop a spatially explicit model that can simulate long-term fire dynamics in Ontario, especially in the boreal region. Here we present background information, a brief review of existing fire models, the logic of model development, such as ecological foundation and descriptors for a fire regime, and potential uses of the model.

The study originated from the requirements of Ontario's current forestry policy, which requires that resource management should mimic natural disturbance patterns for ensuring sustainable resources and maintaining biodiversity (Environmental Assessment Board 1994). The intent of the policy was to maximize the long-term timber resource supply and to conserve biodiversity.

To implement this forestry policy, however, we must understand the patterns of natural disturbances (including fires, insect pests, diseases, windstorm, *etc.*). Natural disturbance patterns are still poorly understood. For assisting forest management decision-making, a tool is needed to answer "what - if" questions. The tool must be able to simulate natural disturbance patterns and allow users to compare outcomes from different management options with these patterns. ON-FIRE is one of the tools designed to reach this goal.

Ontario's forestry policy is consistent with the ones in other provinces and countries. For example, timber oriented forest resource management has been widely replaced by multiple use management goals (Lämås and Fries 1995). Tools that can simulate natural fire regime will also contribute to forest policy outside Ontario.

Two important characteristics have been defined for the study in the original design: landscape scale and long-term dynamics.

Focusing on the spatial scale of the landscape means that spatial heterogeneity has to be incorporated into the development of a simulation model, and the model must be spatially explicit. This approach enables us to link the developed model to a geographic information system (GIS) database, so that realistic results can be obtained. In other words, users of the developed model would be able to address the question of whether a fire regime could be modified by different landscape structures.

The emphasis on long-term dynamics enables us to evaluate the impacts of climate change and other management policies on the dynamics of simulated forest landscapes. For this evaluation, a natural disturbance model is needed as a baseline. From these perspectives, the study's objective can be written as: to develop a spatially explicit model that can simulate long-term fire dynamics in Ontario, especially in the northwest (boreal region). The model should be focused on simulating stand-replacing forest fires (mainly lightning-caused fires), including crown fires and intensive surface fires, that have shaped the structure of boreal forest landscapes in terms of stand age and species composition.

We will first address the question of why the fire model is so important, by describing the roles of disturbances on the dynamics of forest landscape. The question, thus can also be rephrased as: in what ways will the disturbances influence forest succession and hence the structure of the forest landscape?

2. ROLES OF DISTURBANCE ON FOREST DYNAMICS

It is necessary to introduce the concept of forest succession to understand the role of disturbance in forest dynamics.

2.1. Forest succession theory

Traditional forest succession theory (Clements 1916) tells us that the assemblages of forest species move toward a sustained climax species assemblage in a highly ordered sequence, and the resulting climaxes are primarily determined by climate and soil conditions. Clements (1916) sees the forest community as a supraorganism, and the various stages of succession are equivalent to the birth, growth, maturity, and death of an organism. This traditional view of ecosystem successional process could be seen as controlled by two functions: exploitation, which emphasizes the rapid colonization of recently disturbed areas, and conservation, which emphasizes slow accumulation and storage of energy and material.

This viewpoint, however, has been revised to include two additional functions (Holling 1986, 1992). One is release (or creative destruction), *i.e.*, the tightly bound accumulation of biomass and nutrients become increasingly fragile, until it is suddenly released by disturbances such as forest fires and insect pests. Another one is reorganization (or mobilization), *i.e.*, soil processes minimize nutrient loss and reorganize nutrients; so the nutrients become available for the next phase of exploitation. The revised viewpoint has incorporated the results from extensive comparative field studies and experimental manipulations of watersheds.

A renewal cycle, therefore, is composed of four ecosystem functions: from exploitation, slowly to conservation, very rapidly to release, rapidly to reorganization, and rapidly back to exploitation. This is the so-called "4-box" model, illustrated in Figure 1.

The identification of the two additional functions has clarified the roles of disturbances on forest dynamics. Forest fire, as one of the release agents, usually disrupts the forest renewal cycle and acts as a timer for succession processes.

2.2. Roles of forest fires

Forest fire is one of the major disturbances that have been shaping the structure of landscapes. In 1995, for example, serious forest fires occurred across Canada, from British Columbia to Ontario and Quebec. Many of them were out of control. The fire occurrences have been summarized (Canadian Forest Service 1995). Figures 2 and 3 show the fire situations in six provinces and two territories of Canada where most of the fires occurred, compared with the past 10 year's averages. Figure 2 shows the number of fires, and Figure 3 shows the area burned in thousands of hectares. Area burned in 1995 was higher than the average for the last 10 years, in spite of only three provinces (Manitoba, Ontario and Quebec) having higher than the average fire numbers. In Ontario, the total area burned in 1995 was 3.2 times the average value, though the number of fires was only slightly higher than average.

Fire has many negative impacts from the viewpoint of human society. Fire usually burns forest biomass, consumes timber resources, and destroys properties and valuables. Fire also transfers carbon from forest biomass to soil carbon and rapidly releases some ecosystem carbon into the atmosphere (Kurz *et al.* 1992). The transformation processes contribute to increases in CO_2, and thus may increase average global surface temperature.

The increase in global surface temperature will influence the growth of forests and may trigger more frequent natural fire ignitions. The use of prescribed fires to pre-treat regeneration sites and reduce slash fuel could decrease the fire probability for a quite while (delay the timing of next large fire).

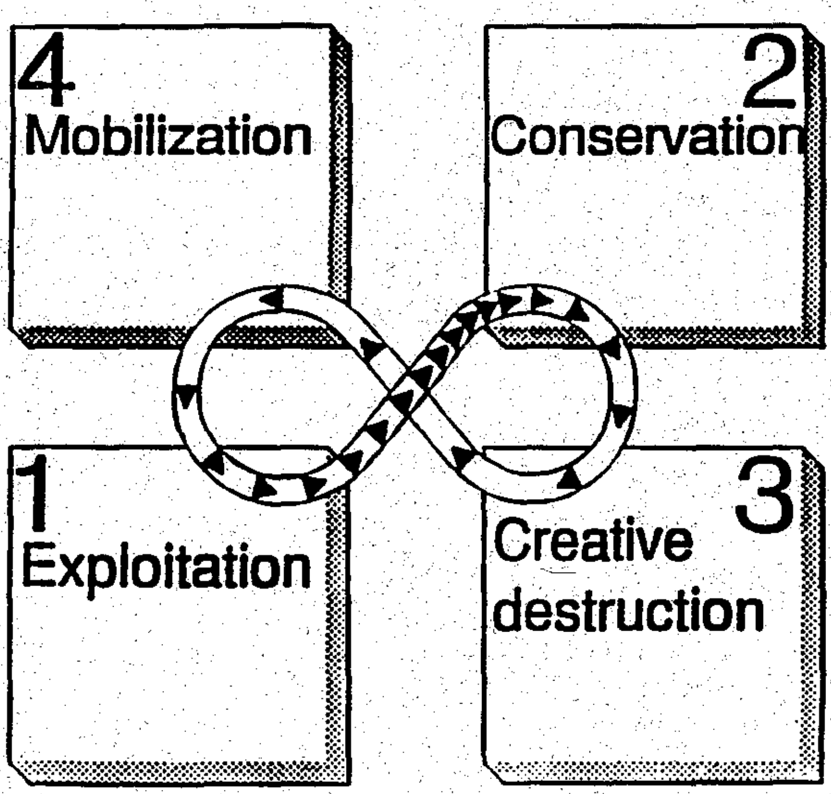

Figure 1. The four ecosystem functions and their relationship to the amount of stored capital and the degree of connectedness. The arrowheads indicate a renewal cycle. The distance between arrowheads indicates speed, *i.e.*, a short interval means slow change, a long interval, rapid change (reproduced with permission from Holling (1992)).

Forest fires, however, may not be completely harmful to the forest landscape. For example, frequent fires could help to maintain diversity of landscapes: short return fire cycle favors vegetation with short life spans, and long return fire cycles allow forest species to develop towards climax species assemblages determined by climate and soil conditions. Fire may increase nutrient availability for plants by direct addition of nutrients in ash (Christensen 1987).

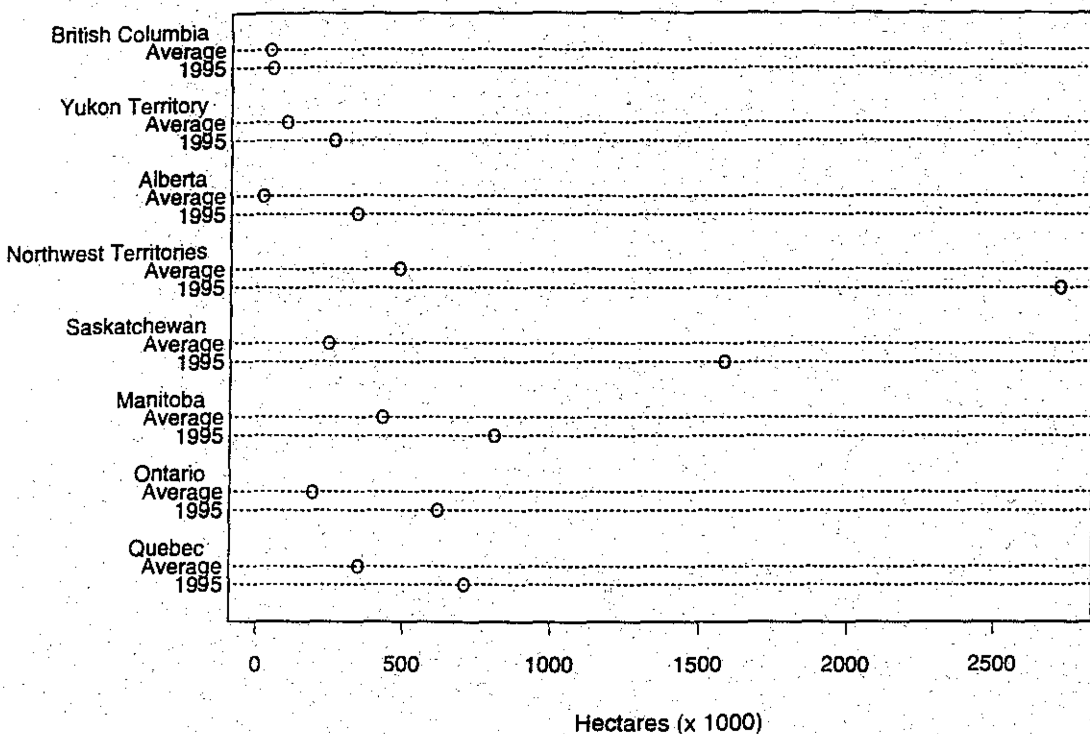

Figure 2. A comparison of number of fires in 1995 with the last 10 year's average values in six provinces and two territories of Canada, using data from the Forest Fire Research Group (Canadian Forest Service 1995). (1995 data are up to September 21.)

Forest fires may even be a "normal" component of forest ecosystems in the boreal region. Fires may be necessary to maintain ecosystem structure and function. For example, serotinous species, such as jack pine (*Pinus banksiana* Lamb.), are adapted to frequent burning. Heat from fire causes their cones to open and release seed.

The assessment of fire impact could be different under different spatial scales. For example, Figure 4 represents hypothetical fire maps for a landscape at three different spatial scales. The fire map on the right represents a large spatial scale composed of 20 by 20 pixels. Among these pixels, 26 are burned, which represents 6.5% of the total area of the landscape. This landscape was not burned severely. From a small spatial scale (indicated at the middle), which is a part of the larger landscape, however, the selected area was severely burned because 75% of the total area was burned. Furthermore, if each pixel is assumed to represent a forest stand (showed on the left side), then it is either not burned or burned completely. Thus, the fire's impact on a stand could be either none or extremely large.

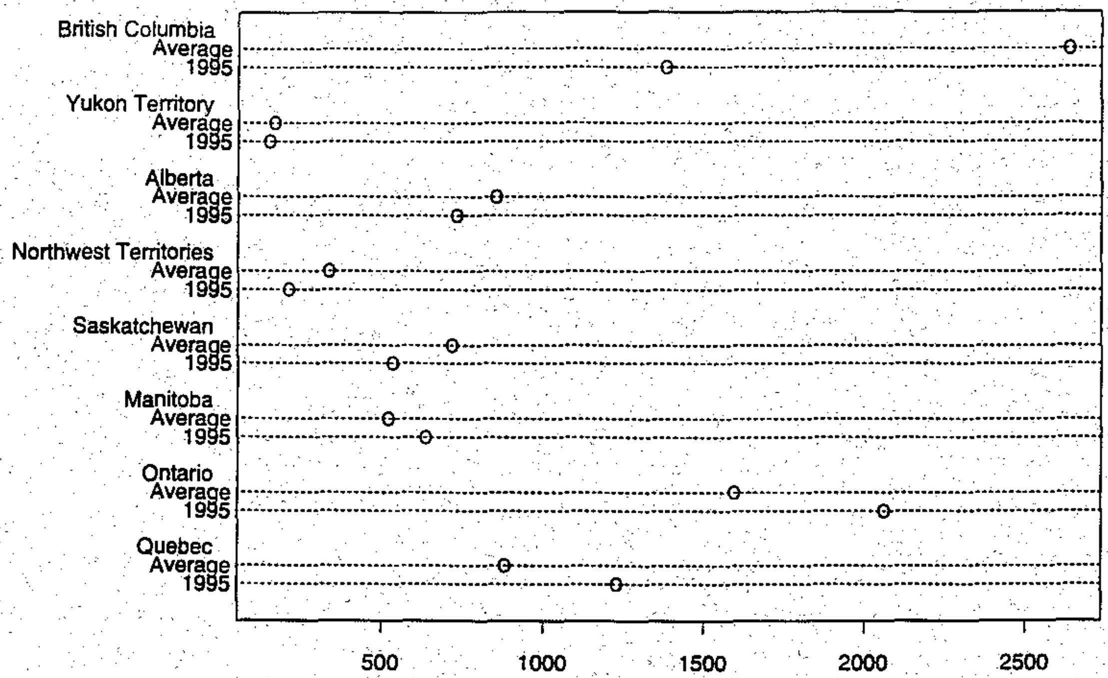

Figure 3. A comparison of area burned in 1995 with the last 10 year's average values in six provinces and two territories of Canada, using the data from the Forest Fire Research Group (Canadian Forest Service 1995). (1995 data are up to September 21.)

In spite of the dual roles of fire, the important thing in implementing Ontario's current forest policy, is to find out the potential consequences of fire events occurring at different stages of forest succession, and determine how forest ecosystems recover from disruptions of their successional processes. In the following sections, we discuss ways to describe a fire regime, why a new fire model has been developed, and how a natural fire regime could be simulated.

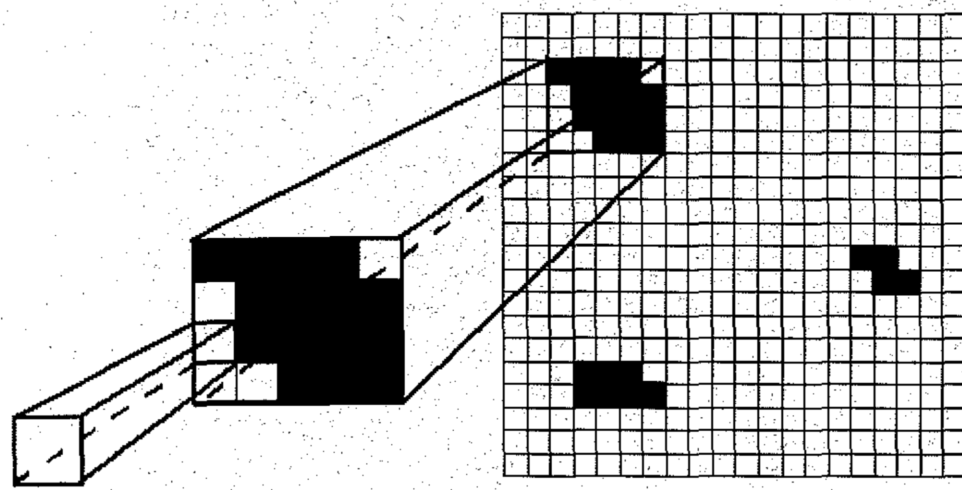

Figure 4. Hypothetical fire maps for a landscape at three different spatial scales.

3. FIRE REGIME

Fire regime differs from fire behavior in temporal scale. Fire regime usually refers to a "system" that can be described by a number of characteristics over a long period, such as a few decades or even centuries. The descriptions of fire regimes in both time and space are called patterns of fire disturbance. Fire behavior usually refers to fire intensity and how fires are ignited and spread in a short period, such as days or hours, even minutes or seconds. These are typically expressed in fire behavior models.

A change in fire regime is a function of climate. In a study of fire scars from giant sequoia, *Sequoiadendron giganteum* (Lindley) Buchholz, Swetnam (1993) found that the frequency of long-term fire occurrence at the regional level was mainly determined by climatic conditions. During a warm period from about A.D. 1000 to 1300, frequent small fires occurred; and during cooler periods from about A.D. 500 to 1000 and after A.D. 1300, less frequent but more widespread fires occurred. This shows how current fire regimes could be changed by projected global climate change.

3.1. Natural fire regimes

More attention should be paid to natural fire regimes in the boreal forest region, because lightning-caused (a natural source of forest fires) fires played a more important role in boreal forests than in other forests, *e.g.*, in United States. In Canada in 1995, 42% of the total number of fires were caused by lightning, or 85% of the total area burned (see Figure 5). In the US, lightning-caused fires are more important in the north than the south. During the period from 1917 to 1966, for example, lightning accounted for 64% of fires in the Rocky Mountain Group (12 States), 31% in the Pacific Group (five States), and one to two % in the rest of the US (Brown and Davis 1973) (see Figure 6).

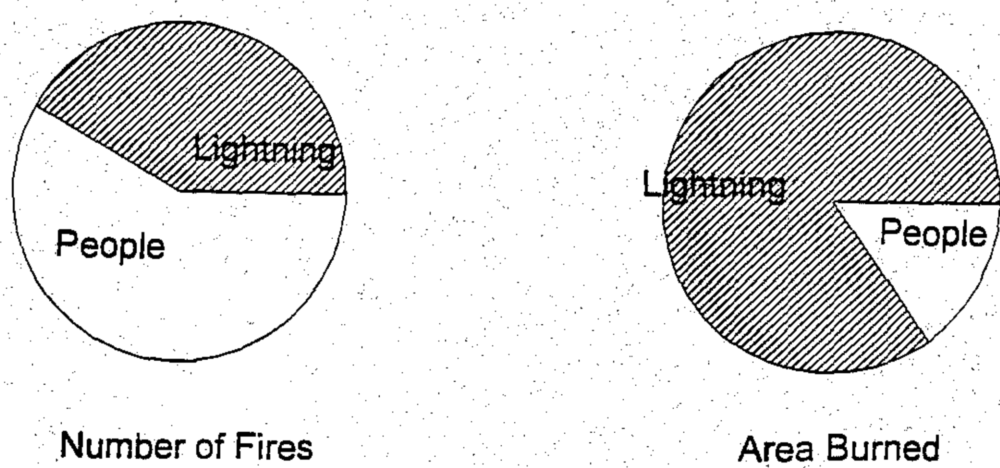

Figure 5. The percentages of lightning and human activities caused forest fires in 1995 in Canada, according to data from the Forest Fire Research Group (Canadian Forest Service 1995). (1995's data are up to September 21.)

The relative importance of lightning-caused fires in the Canadian boreal forest region, however, does not necessarily indicate a natural fire regime. The fire regime observed in the region may be closer to a natural fire regime than that in other regions, because it excludes many fires caused by anthropogenic factors.

Natural fire regimes occurred before European Settlement when most fires were caused by lightning strikes. At that time, forests could have been continuously going through the succession processes described in the previous section: the patches created by fires provided space for natural regeneration including seed germination, survival, seedling, and then species competition processes. Eventually, the species most adapted to the patches would become the dominant species and remain until it dies or a disturbance occurs.

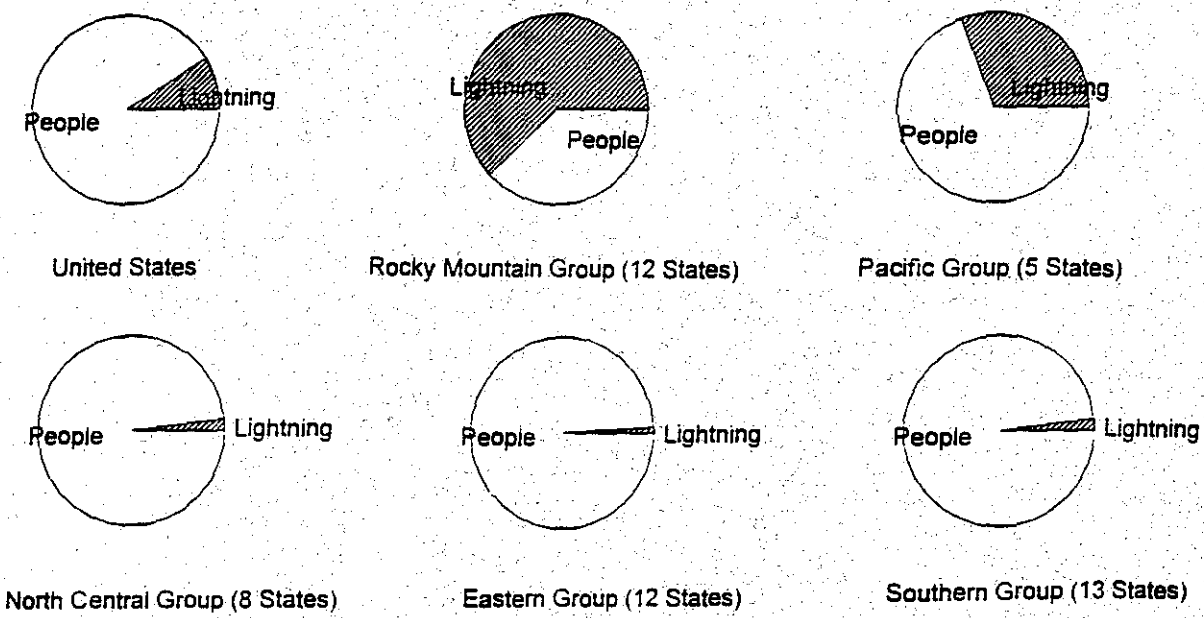

Figure 6. The percentages of lightning and human activities caused forest fires during the period of 1917-1966 in the United States (Brown and Davis 1973).

Natural disturbances (fire, insects, disease, windstorm, *etc.*), however, may hit these patches at any time during their slow conservation process, and restart the succession cycle. Fires can alter forest landscape structure immediately and change the fire probability across the landscape.

The fire probability of a forest stand, or its flammability, is a difficult concept to define. It is influenced by many factors related to the quantity and quality of existing fuel, and by the fact that not many field datasets could be used to evaluate the quantitative relationships between this probability and forest status. For our purposes, fire probability is defined in a relative sense as the probability that one forest stand burns more readily and with greater intensity than another within the same landscape.

The differences in changing pattern of fire probability across a landscape depend on the temporal scale of the investigation. In fire behavior models, the fire probability is mainly determined by fuel quality-related factors such as moisture content near the surface and the amount of precipitation. In models of long-term fire dynamics, however, fire probability is determined by both fuel quantity and quality-related factors. With increasing stand age, the increased fire probability may be caused by the amount of fuel accumulated and structural changes of trees such as branching patterns that carry fire from the ground to the canopy (Rundel 1981, Papio and Trabaud 1991).

The resulting structure of the landscape would determine the numbers and locations of fire ignitions* and even the extents of spread processes, thus influencing the fire disturbances in the years following. For example, newly burned stands will less likely be re-burned the following year than non-burned stands, simply because the amount of fuel is reduced. Less intensive or small fires will consume a small amount of fuel, and the total amount of fuel within the landscape will increase continuously, until an intensive or large fire occurs. An intensive or large fire will consume a large amount of fuel accumulated within the landscape, and thus greatly reduce the probability of any large fires reoccurring within the landscape in following years. In other words, the unavailability of fuel results in a smaller probability of ignition and spread. Thus, the fire probability map will change after every fire event.

Thus, a fire regime emerges that consists of a large number of small fires and few very large fires. This is what is perceived as patterns of fire regimes. A natural fire regime simulation should be able to generate such scenarios.

3.2. Description of fire regime

To simulate natural fire regimes, first determine the appropriate descriptors of a fire regime. In the development of ON-FIRE, we proposed that a combination of fire return interval and size distribution should be used to describe a fire regime and validate the model.

There are two common questions that resource and fire managers have about a fire regime: (1) how often fires would happen in a particular study area; and (2) how severe

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* The word "ignition" is used in our study in reference to a small area of forest being burned. Defined in this way, its usage will be consistent with the historical fire records in Ontario's Fire Management Branch (not less than 0.1 ha).

(including frequency and intensity) those fires would be. To answer these questions, fire researchers have been using technologies and data collected from other disciplines, *e.g.*, fire scars and sediment records (MacDonald *et al.* 1991), to complement lacking historical fire data.

Fire return interval could be used to address the first question. It can be defined as the time required to burn an area that equals the whole study area. Fire frequency, another often used descriptor, is the reciprocal of fire return interval. Either fire return interval or fire frequency may provide information about the historical fire occurrence situation for a given study area.

Fire return interval can also partially address the second question. For example, if fires are severe and burn large areas, then the calculated mean fire return interval will be shorter than when fires are not severe. Therefore, this measurement of fire regime has long been used in describing a fire regime. However, the measurement does not provide information about the proportions of large and small fires, and cannot describe a fire regime in a unique way. Consequently, difficulties will appear when resource managers try to mimic natural fire regimes using the mean fire return interval.

Below, we present a simple numerical example to explain why the mean fire return interval will provide only very little information to resource managers deciding how large an area of forest should be harvested at one time. Let's calculate the mean fire return interval for four different scenarios: (1) five % of a landscape burned every year; (2) 10% of the same landscape burned every the other year; (3) 20% of the same landscape burned every four years; and (4) 40% of the same landscape burned every eight years. Unsurprisingly, the mean fire return intervals are the same -- 20 years, for all of the four scenarios. That is to say, a single mean fire return interval value could result from many different scenarios. What this simple example tells us is that if a fire regime is only described by the mean fire return interval, or fire frequency, then the impact of the fire regime on the landscape cannot be adequately evaluated, except assuming similar landscape structures would result from the four scenarios.

To avoid such confusion, a description of fire sizes has to be introduced. Fire size distribution has usually been assumed as a negative exponential in many fire models, although the sources are not clear (Baker 1989). The distribution can successfully account for the large number of small fires, but cannot predict the few large fires. We collected a number of datasets of historical fire occurrences to see what the patterns of fire size distributions would be, and found a consistent discontinuous pattern for most of the datasets (Figure 7).

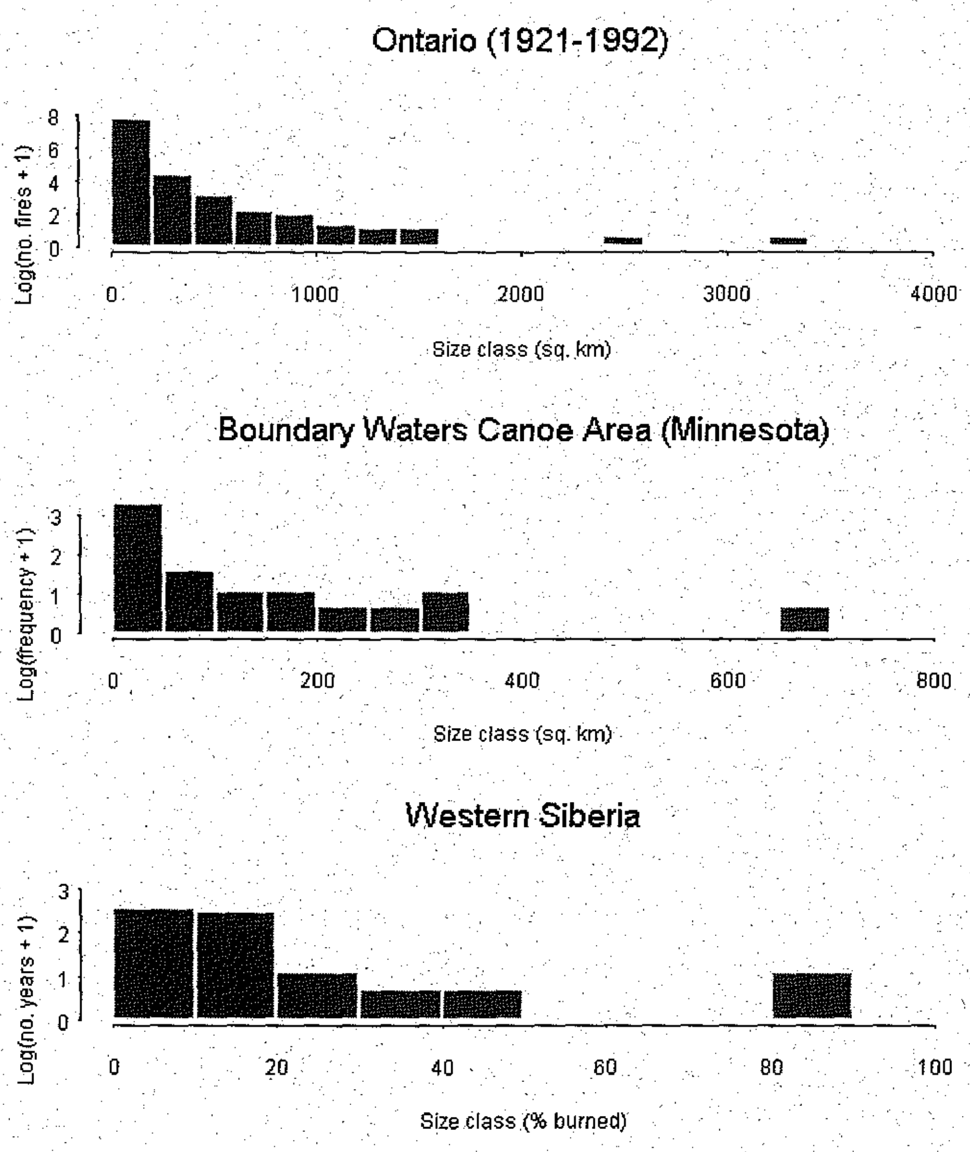

Figure 7. Discontinuous fire size distributions from various historical fire data: (a) historical fire records (> 200 ha) from Ontario (1921-1992) (unpublished data); (b) historical fires in Boundary Waters Canoe Area of Minnesota (Heinselman 1973); and (c) fire sizes in West Siberia (1700-1956) (Antonovski *et al.* 1992).

The discontinuous pattern of fire size distribution is not a new phenomena. The only reason it has not been thus described in the literature is that historically a different method of calculating fire size distribution was used. Some fire researchers, for example, grouped fire records by uneven size class interval. This usually results in a continuous pattern of fire size distribution, and thus satisfies the theoretical assumption of negative exponential fire size distribution. When even size class interval -- the most common method for calculating size distribution in statistics -- was applied to historical fire data, the discontinuous pattern appeared.

We are not criticizing the use of uneven size class interval for describing fire size distribution in order to meet the theoretical fire size distribution assumption, but are proposing an alternative way of looking at the problem. We think the even interval method describes a fire regime in a more unique way than the uneven interval method. For generating a negative exponential fire size distribution, a much wider range of large fires may have to be grouped into one size class, to compare with the ranges of small fires. For example, the size classes used in characterizing Ontario's fire size distribution were usually: 0.1, 0.2-4, 4-40, 41-200, 201-1,000, 1,001-10,000, and >10,000 ha (Ward and Tichecott 1993). The range of the largest size class is much wider than that of the smallest size class. It is not easy to evaluate the impact of a fire falling into this size class on a landscape, unless we assume a fire of 10,000 ha and another of 320,000 ha (the largest fire in Ontario, see Figure 7a) have similar impacts on a landscape. In summary, the even interval method describes a fire's impact on a landscape more precisely than the uneven interval method.

To apply fire size distribution, the issue of how to determine the appropriate number of the size classes has to be addressed. If the number of size classes is very large, then the size distribution will likely show some discontinuity; but if only two size classes apply, then it is impossible to identify any discontinuity. The question becomes: how many size classes are appropriate for historical fire records? From the viewpoint of statistics (Venables and Ripley 1994), the number of size classes could be determined by sample size. For a dataset with a normal distribution, this relationship could be expressed as Sturges' rule. For a non-normally distributed dataset with the same sample size, the number of size classes should be a couple more than what is expressed by Sturges' rule, as indicated by Doane's rule (Venables and Ripley 1994).

The problem of determining appropriate number of size classes also existed when the uneven interval method was used to characterize fire size distribution. Another problem to be addressed is how to determine the appropriate boundaries for each of the size classes. The fire size distribution will change with different boundaries, although there may not be any size classes missing between the small and large fires. The boundaries of uneven interval size classes in the literature might be randomly determined, since there is no appropriate statistical theory for generating a size distribution using the uneven interval method.

4. WHY A NEW MODEL?

Why are we developing a new model when so many fire models already exist in the literature? This question can be answered by a review of existing fire models; comparing a number of model characteristics, including the spatial and temporal scales that the models focused on; the questions that the models addressed; and the assumptions that the models used.

For the purposes of our study, an appropriate model should be able to:

(1) simulate long-term dynamics at the landscape scale with temporal resolution of a fire season and spatial resolution of one ha;
(2) incorporate the impacts of both age (*i.e.*, fuel accumulation) and weather (*i.e.*, fuel quality);
(3) incorporate impacts from other factors including fuel type, topography, and soil moisture;
(4) link to GIS databases;
(5) produce simulated fire regimes that are consistent, in terms of frequency and size distribution, with observations made in Ontario;
(6) simulate irregular final fire shapes;
(7) simulate the processes of spatial pattern formation and dissolution;
(8) produce simulation results that show a pseudo-cyclic pattern in temporal dynamics of pattern indices;
(9) generate relative fire hazard maps* within user-defined temporal frameworks, for assisting management decision-making.

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* A relative fire hazard map shows the relative probability of burning across the landscape. The map will provide a new dimension for assisting resource and fire managers in decision-making processes. Areas with high probability of being burned will not necessarily be the main targets of any fire suppression actions.

We can classify existing models of fire dynamics as short-term or long-term, and as spatial or non-spatial. A long-term model simulates fire dynamics over tens or hundreds of years, whereas a short-term model simulates the changes in forest pattern during one fire season (year). A spatial model simulates the interactions between adjacent landscape units, whereas a non-spatial model does not account explicitly for these interactions; here, "interaction" means primarily that the fire spreads across a forested landscape. In Table 1, we grouped models into four categories according to these spatial and temporal criteria. Our discussion of each group is driven by its relevance to our objectives. Therefore, we pay relatively little attention to the short-term models and focus mainly on the long-term ones.

Table 1. Categories of forest fire models.

	Short-term	**Long-term**
Non-spatial	Fire behaviour models: Rothermel (1972) Albini and Stocks (1986) Weber (1991)	Markovian models: Shugart *et al.* (1973) Kessell (1979) Hall *et al.* (1991) Fire frequency models: Van Wagner (1978) Johnson and Van Wagner (1985) Masters (1990) Johnson and Larsen (1991) Johnson (1992) Gap models: Kercher and Axelrod (1984) Keane *et al.* (1989) Prentice *et al.* (1993)
Spatial	Fire spread models: Turner et al. (1989) Turner and Gardner (1991) Hargrove *et al.* (1995) Vasconcelos and Guertin (1992)	Antonovski *et al.* (1992) Baker (1992) Peterson (1995) Green (1989) Ratz (1995) Boychuk *et al.* (1995, in press) Li and Apps (1995, 1996)

4.1. Short-term, non-spatial

Models in this group are related to fire ignition and spread in a particular environment. Well-known fire behavior models belong to this group.

Fire behavior models focus on surface fires and predict rate of fire spread and intensity for various fuel types and terrain. The rate of spread is a function of weather for a given fuel type and terrain. Rothermel's (1972, 1983) fire behavior model has been widely used for constructing other fire models, such as the Fire Danger Rating System at the national level and FIREMAP at regional to local levels.

Rothermel's (1983) model requires input information about fuel type, fuel moisture, wind speed, wind direction and slope. The output of the model is a single value that represents the rate of spread of the flame front for surface fires in homogeneous conditions. The calculations of fuel type influence are chosen from 13 standard fuel models that represent most of the situations likely to be found in the United States. The slope is fixed for a particular site. The variation in the rate of spread largely depends on the weather, which determines fuel moisture and the speed and direction of wind. Obviously, the accuracy of the prediction relies heavily on a precise weather forecast.

Fire behavior models simulate the combustion process based on physical and chemical principles (Rothermel 1972, Albini and Stocks 1986, Weber 1991). Such models are useful in fire suppression efforts, but their application is usually limited to short time periods.

4.2. Short-term, spatial

Models in this group simulate how a fire spreads over a landscape. The majority of the models are "grid-cell" models that simulate a landscape as a grid of cells of equal size. The fire-spread algorithms differ in several aspects: (1) fire spread to an adjacent cell is "randomly" generated using a set of probabilities or is calculated using current weather data; (2) fire shape is predefined or simulated randomly; (3) the simulated landscape is assumed to be homogeneous or not. A simplified analog of these fire-spread algorithms is used in some long-term models (*i.e.*, EMBYR); but the application is questionable because of the high requirements for input data (primarily weather data).

Short-term spatial fire models are typical of disturbance models found in the landscape ecology literature. These models are developed based on the methodology used in theoretical percolation studies to investigate how landscape heterogeneity will influence the spread of a disturbance. The goal of the investigation is to find a critical value of probability, under which a disturbance cannot spread from one edge to another, and above which a disturbance starting from any point spreads across the landscape (O'Neill *et al.* 1992, Turner and Gardner 1991). These studies are based on a much simplified landscape scenario that consists of cells that are either sensitive or non-sensitive to disturbances. These models are not specific to fire, but include all kinds of contagious disturbances. Results obtained from such studies are highly theoretical, and might not be realistic.

4.2.1. EMBRY

The methodology used in disturbance models of landscape ecology has been modified to simulate the causes and consequences of large-scale fires, like those that burned in the Great Yellowstone National Park during 1988, in models like EMBYR (an Ecological Model for Burning the Yellowstone Region) (Hargrove *et al.*, unpublished manuscript). The major modifications in EMBYR are the ability to link to a GIS database and improvement in the fire spread algorithm. The algorithm assumes fire can spread to all its neighboring cells including those sharing a common edge and those sharing a common corner, instead of the assumption that fire can only spread to cells sharing a common edge. The fire spread probability is summarized in a look-up table and each element in the table is a function of successional stage (forest age).

The modelling approach used in EMBYR was similar to other short-term spatial fire models, such as FIREMAP described below. However, it is also used in long-term simulations for investigating the relationships among global change, disturbance, and landscape (Gardner *et al.*, unpublished manuscript).

4.2.2. FIREMAP

The direction for developing short-term spatial fire models is similar -- trying to incorporate as much detail as possible of fire spread processes, such as fuel type, fuel consumption, and weather. We use FIREMAP as an example of such models (Vasconcelos and Guertin 1992).

FIREMAP is a combination of the fire spread algorithm of the BEHAVE system and a raster-based GIS -- the Map Analysis Package. A friction surface is calculated first in FIREMAP. The friction is defined as the time it takes the fire front to consume a cell and is computed by dividing a cell's length by the fire's rate of spread. Once a fire source point is defined, FIREMAP can calculate fire spread according to the number of time units the fire takes to consume each of the cells under the given conditions. The time units associated with each cell are recalculated for changes in weather.

FIREMAP is designed to simulate fire dynamics during a very short period. Required weather data input are high in temporal resolution. In the example that Vasconcelos and Guertin (1992) give, the input of fuel moisture and wind direction and speed need to be updated hourly. In five time steps, FIREMAP simulated a final fire shape similar to a real fire that occurred between June 10-14, 1988 in Ivins Canyon in the Fort Apache Indian Reservation of east-central Arizona.

FIREMAP is apparently designed to be used by fire managers at an operational level. However, the lack of such high resolution weather forecasts may limit the accuracy of the simulation. Another questionable point is the prediction of fire source point -- effective technology that can provide the exact fire source point before a fire occurs is still unavailable. These limitations could apply to all the short-term fire behavior models, and leave unanswered the question of the ability to predict exact time and locations of fire ignition and hence the exact final fire shapes and sizes.

4.3. Long-term, non-spatial

Models in this category simulate the long-term fire dynamics of a single or multiple forest patches. The lack of interaction between patches makes these seemingly different models similar from our point of view. Indeed, simulating "multiple-patch" landscape dynamics with a non-spatial model is equivalent to applying the model separately to each patch in the landscape. The model's parameters may depend on the type of patch and its initial state, but simulation of the dynamics of one patch is not affected by any changes in the state of an adjacent patch.

Long-term non-spatial models can be divided into three subgroups, each with its own specific features. The first subgroup includes Markovian models (Shugart *et al.* 1973, Kessell 1979, Hall *et al.* 1991). These are "grid-cell" models that simulate the dynamics of each cell with a matrix of probabilities for the transitions from one state to another. Both the initial state of a landscape and the transition matrix account for the spatial variability in cell types (such as vegetation type, fuel load, slope, *etc.*); for this reason, some authors refer to these models as spatial models. This approach probably originated with a model presented by Shugart *et al.* (1973); this model did not simulate the transitions corresponding to the burning of a cell, but had all the key features that distinguish Markovian models.

The second subgroup is the largest one and contains models that use the "fire-frequency" approach. This approach was introduced by Van Wagner (1978) and was further developed and applied in numerous studies on fire frequency distributions (Johnson and Van Wagner 1985, Masters 1990, Johnson and Larsen 1991). In these models, the frequency distribution for the interval between fires is described using either negative exponential or Weibull distributions. The models are effective in analyses of changes in fire frequencies induced by climatic change.

The third subgroup includes so-called gap models (Kercher and Axelrod 1984, Keane *et al.* 1989); these individual tree-based models simulate the long-term dynamics of a small forest patch (usually 1/12 ha). Gap models are mainly applied to simulate successional changes (species composition and replacement) under various climatic scenarios.

Gap models have been widely used in the study of forest succession. The research goal of gap models is to simulate forest succession through species competition at a small spatial scale -- usually about 1/10 to 1/12 ha. Most gap models are called conventional forest gap models, which are the variations of the JABOWA model (Botkin *et al.* 1972). Non-conventional forest gap models are those not derived from JABOWA.

Gap models aim to simulate forest growth through individual trees competing for resources such as light, after a mature tree dies and leave space for small trees to grow. The spatial scale of gap models is generally consistent with the size of the space after a mature tree dies. Fast growing species tends to dominant the gap first, but long-lived species will eventually dominate. Weather changes will determine the rates of growth and survival of the tree species and result in different succession processes. The differences between conventional and non-conventional gap models are in the ways they simulate growth and competition among individual trees.

Disturbance (including forest fires) impacts on gap dynamics are usually expressed as a function of the gap's age (time since last disturbance), *i.e.*, the older the gap, the higher the probability of being disturbed. Once the disturbance happens, all the trees will die and gap dynamics will start again.

The landscape version of the gap model is non-spatial, because they assume that forest dynamics on a landscape can be adequately represented by aggregating a large number of independent samples of small gap dynamics. In other words, each of the fire disturbances will only destroy the forest within one gap, and no propagation will be considered. FORSKA2 (Prentice *et al.* 1993) can serve as an example of the landscape version of a gap model. The model aggregates the dynamics in 100 gaps that are independent of each other, to represent the dynamics of the landscape. Each gap is subjected to disturbances according to a Weibull function linked to age.

Despite differences in approach, the common feature of these three subgroups of models is the lack of any spatial interaction between landscape patches. Consequently, these models correctly describe long-term average landscape patterns under certain conditions as well as trends in these patterns caused by macro-scale processes such as climatic change, but do not capture spatial variation in the patterns. This can be illustrated as follows: the application of a typical long-term non-spatial model to an individual patch produces a stable probability distribution for the patch's age or state; here "stable" means that the distribution does not change with time. When applied to a "multi-patch" landscape, this stable distribution transforms into a stable landscape age structure, which can be understood as the share of the area occupied by forest of given age; the age of a patch is the time since the last catastrophic fire. It is obvious, that in order to be stable, the age structure should have a monotonically decreasing shape. Although this shape has been observed in the age structure of some areas (Yarie 1981), it is inconsistent with the irregular occurrence of major fires reported in many studies of long-term forest fire history (Heinselman 1973, Tande 1979, Antonovski *et al.* 1992): a major fire inevitably distorts the monotonically decreasing shape of the age structure.

4.4. Long-term, spatial

Models in this group simulate long-term fire dynamics by accounting explicitly for spatial interactions between landscape patches. These models meet the expected spatial and temporal scales of our study. All models that we are aware of are "grid-cell" models, with the dynamics of an individual cell related to its neighbor cells through fire spread processes (*e.g.*, Green 1989; Antonovski *et al.* 1992; Baker 1992; Ratz 1995; Peterson 1995; Li and Apps 1995, 1996; Boychuk *et al.* 1995, in press). Any of these models, however, can only partially meet our expectations. Here we summarize two models as examples of long-term spatial fire models: FORLAND (Antonovski *et al.* 1992) and DISPATCH (Baker *et al.* 1991).

4.4.1. FORLAND

Although the fire model for boreal forests in western Siberia was finally published in a book chapter in 1992, the structure of the model was published in an internal working paper at the IIASA (International Institute for Applied Systems Analysis) in 1987. The model was named FORLAND (FORest LANDscape) in research papers published in Russian, however, the name has not been used in papers published in English yet. The model simulates a forest territory as a grid of cells. Each cell is characterized by its age (successional stage). The fire source for each cell is assumed equal during a single fire season. The probability of fire maturity of a particular cell will determine whether a forest fire would be ignited in that cell. This probability is a function of the cell's successional stage and weather, which includes seasonal temperature, maximum seasonal period between two successive rains, and seasonal precipitation. Once a fire is ignited, it will propagate to its neighbor cells, according to another set of probabilities -- called fire spread probability. The fire spread probability is a function of successional stage. The values of fire spread probability and fire source probability are determined by the best fit of observed percentage of area burned per year and the results from numerous computer experimental runs.

The model was applied to a forested area (165,000 ha) on Kas-Eniseyskaya plain in western Siberia. The study area was simulated by a grid of 25 by 25 equal sized cells. Each cell represents a forest size of 264 ha. A yearly time step was used in the model. Within a time step, the program checks every cell to see if it is a fire source. If it is, then the probability of fire maturity of that cell will determine whether a fire will ignite. Once a fire ignites, it may spread to adjacent cells according to the probability of fire spread of the burning cell. There was no pre-determined fire size to limit fire spread, so final fire size will be determined by the cell-age (or successional stage) mosaic of the landscape. In other words, the fire would spread continuously until stopped by low fire spread probability in all adjacent cells. The simulation results showed a bimodal shape distribution of area burned per year, which corresponds to a fire regime consisting of many small fire-years and few irregular large fire-years.

The unique feature of FORLAND is that the simulated fire regime is not prescribed by the users, but generated by the interaction between fire events and the cell-age mosaic of the landscape. This modelling approach emphasizes the interactions among system components, and investigates system dynamics from an evolutionary perspective. However, FORLAND was unable to output data on landscape structure and was unable to link to a GIS database. These weaknesses greatly limited further development of the model and its potential applications. Consequently, the model was generally used in theoretical research.

4.4.2. DISPATCH

DISPATCH (DISturbance PATCH) was developed for studying the effects of climatic change on the landscape's structure when subject to large disturbances (originally oriented to floods and later modified for fires). The model is a combination of several existing software packages and some additional locally written code.

The model consists of five major components: (1) the climatic regime: a probabilistic way to model the occurrence of a variety of weather on a seasonal time scale; (2) the disturbance regime: a negative exponential distribution of disturbance size; (3) GIS map layers including vegetation type, patch age, elevation, slope, and aspect; (4) a disturbance probability map that is a user defined combination from the five map layers; and (5) a structure analysis program that outputs quantitative indices and measures of the landscape.

A landscape was simulated as a grid of 200 by 200 cells. Each cell has a randomly determined age between 0 and 250 years old as the initial landscape structure. The model simulates weekly changes in the landscape. If the simulated week is within a disturbance period, then the model checks to see whether antecedent conditions favor a disturbance. If they do, then a disturbance size distribution will be generated from one of the four negative exponential distributions, which correspond to the four seasons. A disturbance probability map will then be calculated. The location of a disturbance is determined by either the cell with the highest disturbance probability, or randomly chosen among cells containing disturbance probabilities above some user-defined minimum value. Following a disturbance ignition, the disturbance may spread to one of the eight neighboring cells, which has the highest disturbance probability, or to a randomly chosen neighbor that has a disturbance probability above some user-defined minimum value. The algorithm will continue until either the potential disturbance size is reached, or there are no neighboring cells with the minimum probability of being disturbed.

DISPATCH is a GIS model. It runs within a raster-based GIS package -- GRASS. It is able to link to a real GIS database, but lacks the explicit functions and verification of FORLAND (Baker 1995). It can simulate the impact of a user-defined fire regime on landscape dynamics, but is unable to generate a natural fire regime as FORLAND did.

4.4.3. Manitoba model

The Manitoba fire model (Peterson 1995) was a theoretical model based on highly abstract situations from the boreal forests of Manitoba, Canada. The Manitoba model was developed within a cross-scale theoretical framework for testing two hypotheses. The first hypothesis is called the interaction hypothesis -- fire produces and is influenced by forest pattern. This hypothesis was supported by the simulation results. The second hypothesis is called the lump hypothesis, *i.e.*, the interaction of forest and fire processes produces spatial and temporal discontinuities in forest landscapes. It was weakly supported by the simulation results.

The methodology used in constructing the Manitoba fire model was similar to that in percolation studies. The model assumes that a fire is able to spread to all neighboring cells with a probability that is a function of cell age. A fixed number of ignitions is assumed, and the final sizes of the fires are determined by the cell-age-mosaic of the hypothetical forest landscape. The model was not designed for linking to a GIS database, and was solely for simulating age-dependent fire disturbances.

The idea behind the Manitoba model is that fire processes are fully determined by the amount of fuel accumulated across forest landscapes.

4.4.4. Other models

In other long-term spatial fire models, Green (1989) examined the potential consequences of species competition in a tropical forest with a model that accounted for fire occurrence and seed dispersal. The study showed that a random initial spatial pattern converges on various patterns as a result of a series of fire disturbances. A model by Ratz

(1995) simulated a spatial pattern of successional stages under two scenarios: constant and age-dependent flammabilities. A model by Li and Apps (1995, 1996) simulated fire disturbance using stand age-related ignition, while the spread was determined by the distance from a disturbance center. The study demonstrated that errors in simulating forest biomass may be caused by neglecting cell interactions. Finally, a theoretical model, FLAP-X, was developed for investigating the effects of long-term fire dynamics on forest age distribution (Boychuk *et al.* 1995, in press).

Some of the assumptions used in these models seem too simplistic, *e.g.*, the assumption of a fixed final shape for an individual fire in the models by Green (1989) and Boychuk *et al.* (1995, in press), and the user-defined shape in Baker's (1992) model. The fixed elliptical or circular final fire shape assumption does not explain some observations. For example, the mosaic of forest pattern may result in only about a third of the vegetation burning within the perimeter of a large fire. For the 1987 Deadwood Fire in the Boise National Forest, 16% burned at high intensity, 18% at moderate intensity, and the remaining 66% either burned at low intensity or did not burn at all (Fuller 1991). This kind of observation suggests that fire models using the fixed elliptical fire shape assumption may overestimate total burned area up to one third. However, this does not negate the major advantage of these models, *i.e.*, their ability to simulate spatial variations in fire regime and/or landscape patterns.

4.5. General comments on existing fire models

Each of the existing fire models was developed for its own purpose, and may not be inclusive or suitable for other research goals. The following general comments pertain only to the criteria for choosing a model for our present research objectives only.

Short-term non-spatial models try to determine the rate of spread from details in physical and chemical processes of combustion. The questions addressed by these models are mostly deterministic and static, *e.g.*, what is rate of spread under a set of given weather and fuel conditions.

Short-term spatial models try to simulate a particular fire event under a set of given conditions. For theoretical purposes, fire models belonging to this group could usually provide useful insight on how a fire event would behave. For practical purposes, fire models belonging to this group usually demand highly accurate weather data. Since such data would most likely be available after the fire event, the major function of these models would be to provide explanations of why the fire event behaved as it did. These models will be able to predict a fire event only when such highly accurate weather data is available.

Long-term non-spatial models are fundamentally based on point-based random sampling theory. These models cannot incorporate the spatial correlation among disturbed sites. Li and Apps (1995, 1996) studied the consequences of spatial and non-spatial modelling approaches on forest dynamics, and found that the mean biomass simulated using a spatial modelling approach was significantly higher than that found using a non-spatial modelling approach. In the spatial modelling approach, fire propagation was simulated by a distance-dependent function. The non-spatial model assumes fire does not propagate like in the landscape version of gap models. The different simulation results suggest that spatial correlation among disturbed stands may play an important role in simulating long-term dynamics of fire and forest landscapes. The long-term non-spatial models, therefore, are usually not adequate for addressing questions related to those disturbances with spread property.

The temporal and spatial scales of long-term spatial fire models are consistent with our research objectives. However, none of the existing models were able to meet all of our expectations. For example, Green's (1989), Baker's (1992), Peterson's (1995), and Boychuk's *et al.* (1995, in press) models assume prescribed fire regimes such as fixed fire ignitions per fire season, fixed circular or elliptical final shapes, and negative exponential size distributions. These models were designed to simulate built-in prescribed fire regimes, not natural fire regimes. Most models were unable to link to any GIS database, except Baker (1992). Therefore, they may not be suitable for predicting the forest patch mosaic patterns after fire disturbances and the changes of the mosaic patterns over time.

Fire models could be used for theoretical and/or practical reasons. In theoretical research, a hypothetical landscape is usually assumed in the models. For practical purposes, however, a fire model has to be able to link to a spatial dataset such as a GIS. However, some fire models that link with a GIS dataset, can also be used in theoretical studies.

Results from this literature review and the description of a fire regime in the previous section, have indicated that none of the existing models could meet our research objectives and expected characteristics. A new fire model is needed to simulate natural (not prescribed) fire regimes, which could be described by a combination of fire return interval and discontinuous size distribution, based on realistic forest landscapes (*i.e.*, with the ability to link to a GIS database). In the next section, we give a brief description of the model ON-FIRE, focusing on its structure and main assumptions. For technical details, see Li *et al.* (1995).

5. ON-FIRE MODEL

ON-FIRE simulates the changing patterns of final fire sizes and shapes at the end of each fire season over a long-term period. Readers should keep in mind that we are not attempting to simulate fire behavior for every individual fire event.

5.1. Model assumptions

Two kinds of assumptions were used in existing fire models based on different understandings of fire processes: fire is a function of climate or weather, and fire is a function of the amount of fuel accumulated in the forest. The methodology used in developing fire models is partly dependent on the understanding of fire processes and the spatial scale concerned.

Researchers who believe fire processes are fundamentally determined by the amount of fuel accumulated across the landscape will likely simulate fire ignition and spread as a function of forest age, such as in Peterson's (1995) Manitoba fire model. These researchers usually simplify the complicated dynamics in local weather and pay more attention to the effects of baseline fire probability, which is a function of fuel quantity. They tried to focus on fundamental processes that shape the landscape structure, and to understand the long-term dynamics of a landscape. The major weakness of these models is oversimplifying the effects of other factors, such as fuel quality, that influence baseline fire probability.

Researchers who believe fire processes are mainly controlled by local weather will probably simulate fire ignition and spread as a function of fuel moisture content, such as in McAlpine's (pers. comm. 1995) model. These researchers usually try to apply short-term non-spatial fire models, reported in fire behavior studies, to landscape scale. The major difficulties involved in these applications are satisfying the demand for local weather data at high temporal and spatial resolutions, and scaling-up small scale results to the landscape level (see King 1991, Shugart *et al.* 1992, Li and Apps 1995).

The role of climate and weather in the occurrence of forest fires has been studied extensively by numerous authors. Climate-related fire characteristics that are explicitly simulated by the model (fire frequency and fire size distribution) are most important.

An overview of the studies on the relationship between climate and fire frequency was given by Johnson (1992), who concluded that (1) fire frequencies are climate-dependent, and (2) fire frequency is reasonably constant over periods of stable climate, with changes in fire frequency caused by changes in climatic conditions. Swetnam (1993) found an inverse relationship between fire frequency and fire size. He interpreted the increased fire size following periods of low fire frequency as a synchronization with fuel accumulation. Substituting age for fuel, one may rephrase the latter effect as a "synchronization" with forest age: large fires occur when contiguous areas (cells) become old as a result of insufficiently frequent small fires; such small fires burn only single cells, resulting in a mosaic of cells of different age rather than broad expanses of "even-aged" old forest.

The relationship between seasonal weather condition and fire size distribution is substantially less evident. Flannigan and Van Wagner (1991) studied the relationship between the seasonal severity rating (SSR) (a component of the Canadian Forest Fire Weather Index System) and burned area for nine major divisions of Canada from 1953 to 1980. They found a very poor correlation, with 0 to 34 % of the variance explained. Harrington *et al.* (1983) obtained similar results using components other than SSR. These results suggest that the influences of climate and weather on fire dynamics are different; and seasonal weather condition may not be the only dominant factor determining fire dynamics.

The relationship between climate and fire size may be approached using the observed fire size distributions. Figure 7a presents the fire size distribution for Ontario; this distribution uses data on fire size from 1921 to 1993 (Ontario Forest Research Institute, Forest Landscape Ecology Program, unpublished data). The presented fire size distribution has a discontinuous pattern, with the three peaks corresponding to small (2-1,600 km^2) and large (2,400-2,600 km^2 and 3,200-3,400 km^2) fires. Fires were absent from the size classes 1,600 to 2,400 km^2 and 2,600-3,200 km^2. Similar discontinuous patterns can be observed for distributions of annual burned area in other regions (Heinselman 1973, Tande 1979, Antonovski *et al.* 1992).

If fire size were driven solely by a hypothetical climatic factor, the frequency distribution of the climatic factor built over a long time would also have a discontinuous shape; any "unimodally" distributed factor would result in a fire size distribution with one peak. (Here we must say "hypothetical" since, as mentioned above, the climatic factors studied so far cannot be used as predictors for fire size.) An explanation similar to that of Swetnam (1993) seems to be more probable: Frequent small fires consume a certain part of the fuel load within the landscape, but the total fuel load still accumulates gradually; the vulnerability of the forest landscape to large fires thus increases over time. Eventually, a large fire occurs and consumes a large amount of fuel, significantly reducing the chance of the landscape being disturbed by another large fire for a while. Consequently, small fires are more likely to occur than large fires. Thus, any given climatic situation is sufficient for a large fire only if the primary condition is met, *i.e.*, the landscape has accumulated a certain level of fuel.

One more argument comes from the experience of one of the co-authors in developing FORLAND for western Siberia (Antonovski *et al.* 1992). During this study, all experiments with climate-driven probabilities of fire ignition failed to produce the observed distribution pattern of annual burned area if the probability of fire spread was set to zero (*i.e.*, interaction between cells was ignored). On the other hand, constant age-dependent probabilities of fire ignition and fire spread were sufficient to simulate the observed bimodal distribution pattern of burned area.

To prioritize the relative importance of climate and spatial interaction, we add processes to the model in a stepwise manner. Testing the individual contribution made by each process allows us to separate those processes that significantly improve the model from those that do not. We have no intention of denying the effects of climatic factors on fire regime, but we do not overemphasize the effects.

Fire, climate, and weather are external factors that influence forest dynamics, including forest growth and regeneration. If the forest dynamics under no fire and constant weather can be called "normal", then changes in the external factors will be the sources that initiate changes in the normal forest dynamics. The impacts of these sources would be determined by the response of the forest landscape through its structure (O'Neill *et al.* 1991). For a landscape with a higher average fire probability, for example, an ignited fire would likely burn a large area and dry-warm-windy weather would probably increase the area burned.

If natural fire regimes can be described by the processes explained in the Section 3.1 and forest stand-age could serve as an approximation of fuel accumulation, then stand age-dependent functions would describe the fire probability across a landscape. Age-dependent fire probability is the major assumption employed in ON-FIRE. The idea behind this assumption is that the processes of fire ignition and spread are mainly controlled by a variable that changes slowly -- amount of fuel accumulated across a landscape.

The assumption is derived from a basic ecological theory that says the dynamics of a system are fundamentally controlled by its slow variable(s). The theory is supported by a number of studies about individual ecosystem dynamics (Odum 1971, Holling 1986). We applied this theory to the fire disturbance situation. If a forest landscape and its associated fire events can be seen as an abstract system, then the dynamics of the system at the temporal scale of a few decades to a few centuries, will be fundamentally controlled by the slow variable -- amount of fuel accumulated across the landscape, which can be approximated by forest succession processes related to forest age.

The assumption is also supported by empirical observations. Balling *et al.* (1992) reported the influence of forest successional stage on the flammability of Yellowstone lodgepole-dominated forests. They found the fire regimes in these forests are characterized by stand-replacing fires that occur at relatively long intervals of 150 to 300 years or more, and flammability tends to increase as stands approach maturity over these intervals. However, a big fire year may not immediately occur once the stands are mature. For example, the burn area data presented in the study do not show a simple increasing trend over the study period (1872-1990), *i.e.*, many stands would have reached a mature and flammable state by the beginning of the study period. The area of mature forest, nevertheless, may have increased over the study period, resulting in an increasing probability of large fires.

The age-dependent fire probability has also been widely used in short-term spatial fire models and long-term non-spatial models as a general assumption. A look-up table of age-dependent fire probability, for example, was used in EMBYR, and a Weibull distribution function of gap-age is used in FORSKA2, a European forest gap model, for characterizing the frequency of disturbances (Prentice *et al.* 1993). In general, this assumption is associated with studies of forest succession (or long-term ecosystem dynamics), and it is usually not used in any of the studies of short-term ecosystem dynamics.

The base map of fire probability for each time step during the simulations is mainly determined by the age of the forest. The base maps are modified by a number of other factors including weather. The detailed methodology on how these factors affect the base fire probability map will be presented elsewhere. However, the sources of information used in formulating these relationships are largely the results of fire behavior studies.

Weather usually changes at a much faster rate than forest age, and is therefore closely associated with short-term ecosystem dynamics. The current version of ON-FIRE simulates natural fire regimes under a stable climate scenario, which means that lack of rain could be expressed by random events following a normal distribution. The dynamics of moisture content of fuel are assumed to be closely correlated with rainfall. Empirical evidence for the seasonal change patterns of fuel moisture can be found in the Thousand-Hour Timelag Fuel Moisture (THRFM), which is an estimate of the percentage moisture content of dead and downed roundwood fuels larger than 7.6 cm in diameter (Renkin and Despain 1992). A distribution of THRFM compiled by using values of 1,766 days archived for the 1965-1988 fire seasons showed an approximately normal distribution in terms of relative frequency.

In short, we do not simply pre-accept or pre-reject either the fully climate or weather-driven and fully fuel-driven assumptions. Our assumption is that a fire regime is the result of interaction between fire events and forest landscape structures, influenced by weather.

5.2. Model structure

A forest landscape is simulated as a grid of cells. Each cell is considered to be homogeneous in terms of age and vegetation cover type. Cell age is defined as the time since the last severe fire.

There are three main components in ON-FIRE: forest growth, fire disturbance, and regeneration after disturbance. These components are looped for each time step (a year). Figure 8 shows a simple flowchart of the model. The model simulates severe fires only, *i.e.*, stand-replacing fires, where the vegetation is completely burned.

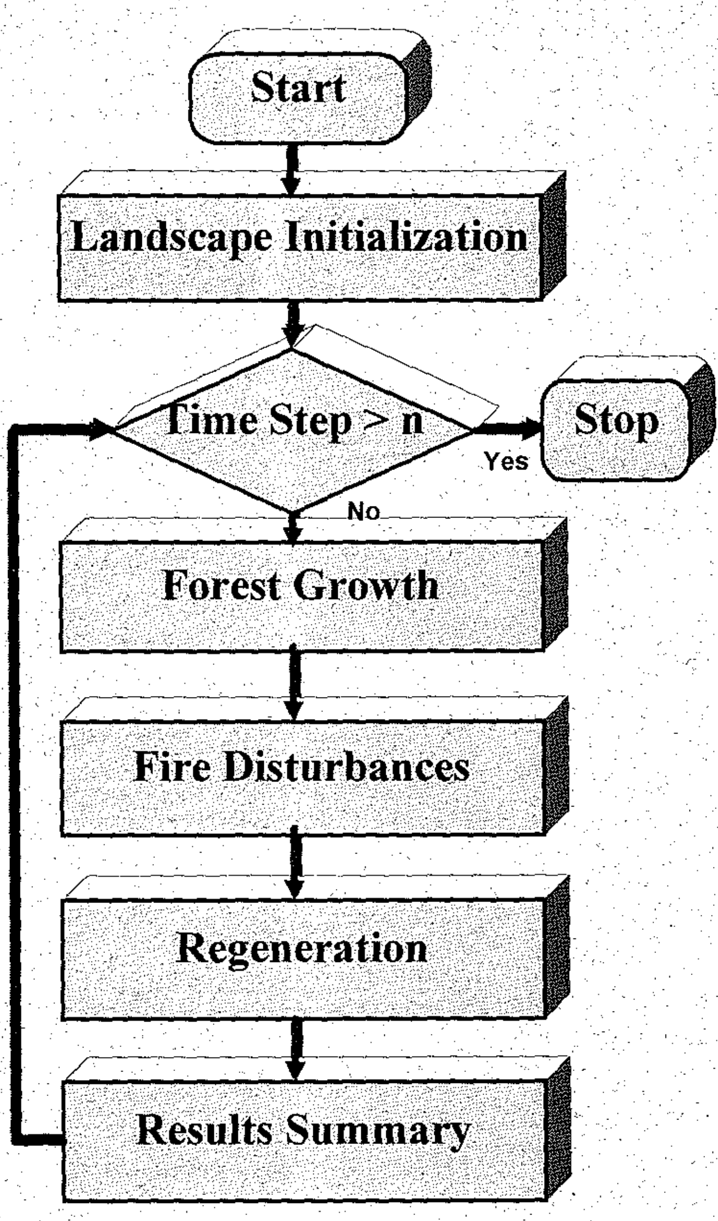

Figure 8. A simple flowchart of the ON-FIRE model.

Forest growth is used to describe changes in the cell's state. This includes increments in age for the current version. However, biomass, fuel load, and species replacement will be included later. The calculation is looped for each of the cells, since these changes occur in the forest at the stand level without fire. Age is the first state variable chosen for the model, because other cell characteristics such as biomass and accumulated fuel can be approximated as functions of age.

Fire disturbance across a landscape is simulated as ignited by a lightning strike in a particular cell. Once a cell is ignited, the fire may spread to the adjacent cells depending on the susceptibilities of these cells. The susceptibility of a cell is determined by its age. Those burned cells again have the potential to spread to adjacent unburned cells. This process continues until susceptibilities drop below a threshold or the fire reaches the boundary of the landscape.

Once an area is burned, the regeneration is assumed to start from the next year and the vegetation cover types will not be changed, *i.e.*, enough seeds will be available after fire disturbance and the outcome of species competition will be the same as that before the disturbance. In later versions, however, detailed seed generation, survival, and dispersal processes will be incorporated.

5.3. Simulation results

The results presented here are samples from a large number of runs to show how realistic fire regimes could be simulated using ON-FIRE and how ON-FIRE can meet all the expectations of the study listed in Section 4. Detailed results and their explanations can be found in Li *et al.* (1995).

The simulated mean fire return intervals are 70 to 80 years. The results are consistent with the summary of Ontario's fire history studies (Ward and Tithecott 1993).

Figure 9a shows a simulated fire size distribution based on a hypothetical landscape. The results indicate that ON-FIRE is able to simulate not only frequent small fires, but also infrequent large fires. The fire regimes simulated by ON-FIRE look closer to observations (Figure 7a) than that simulated by a prescribed negative exponential fire size distribution. This is because the negative exponential fire size distribution may not be able to simulate infrequent large fires very well.

Figure 9b shows a simulated fire size distribution based on a real forest landscape in Northwest Ontario. The study area is 10 by 10 km^2, and located in UTM Zone 15, between 5580900 to 5590900 in northing and between 424000 to 434000 in easting. The results indicate a similar discontinuous pattern as in Figure 7a.

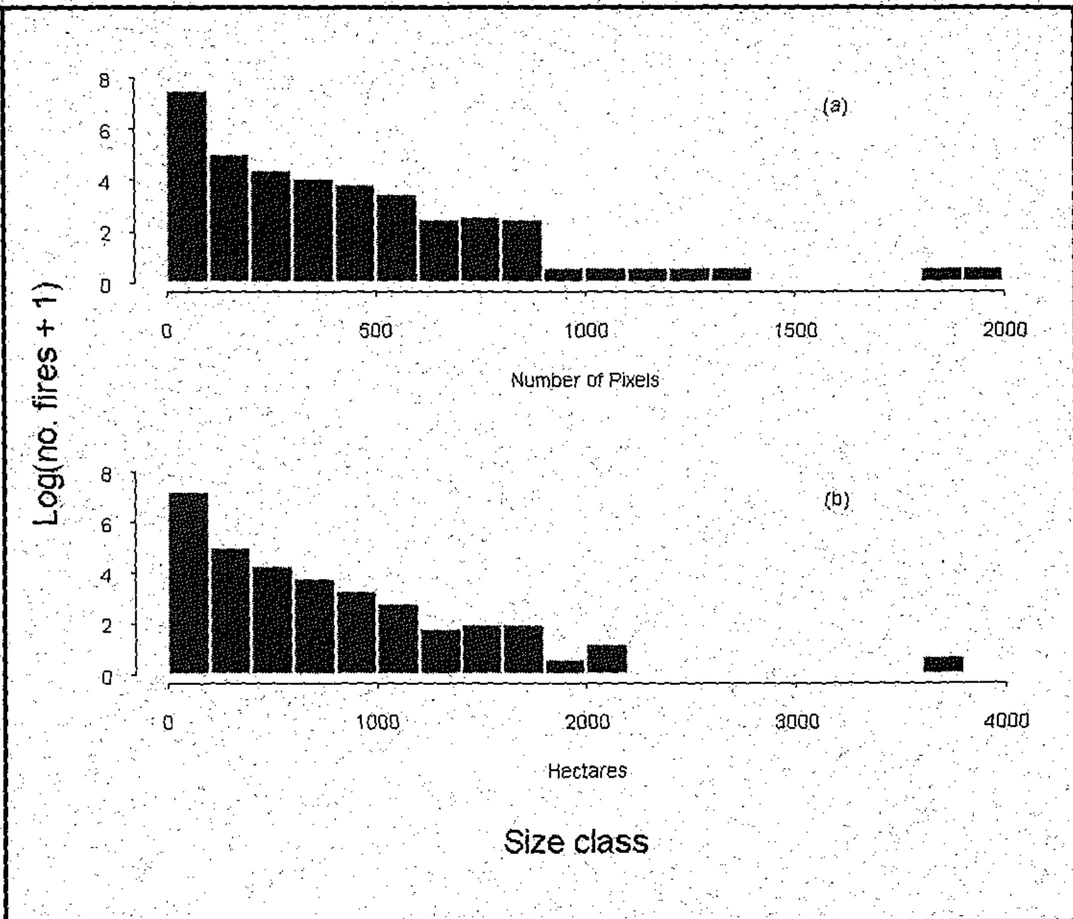

Figure 9. Simulated fire size distributions based on a (a) hypothetical landscape; and (b) real forest landscape in northwestern Ontario.

Figure 10 shows changes in the percentage of area burned over time.

ON-FIRE is also able to output the landscape structure created by fire disturbances at the end of each time step (Figure 11). The results over a certain period can also be summarized as a relative fire hazard map (see Figure 12) which is useful for evaluating the potential impact of fire disturbances for a given study site and assisting forest resource management decisions.

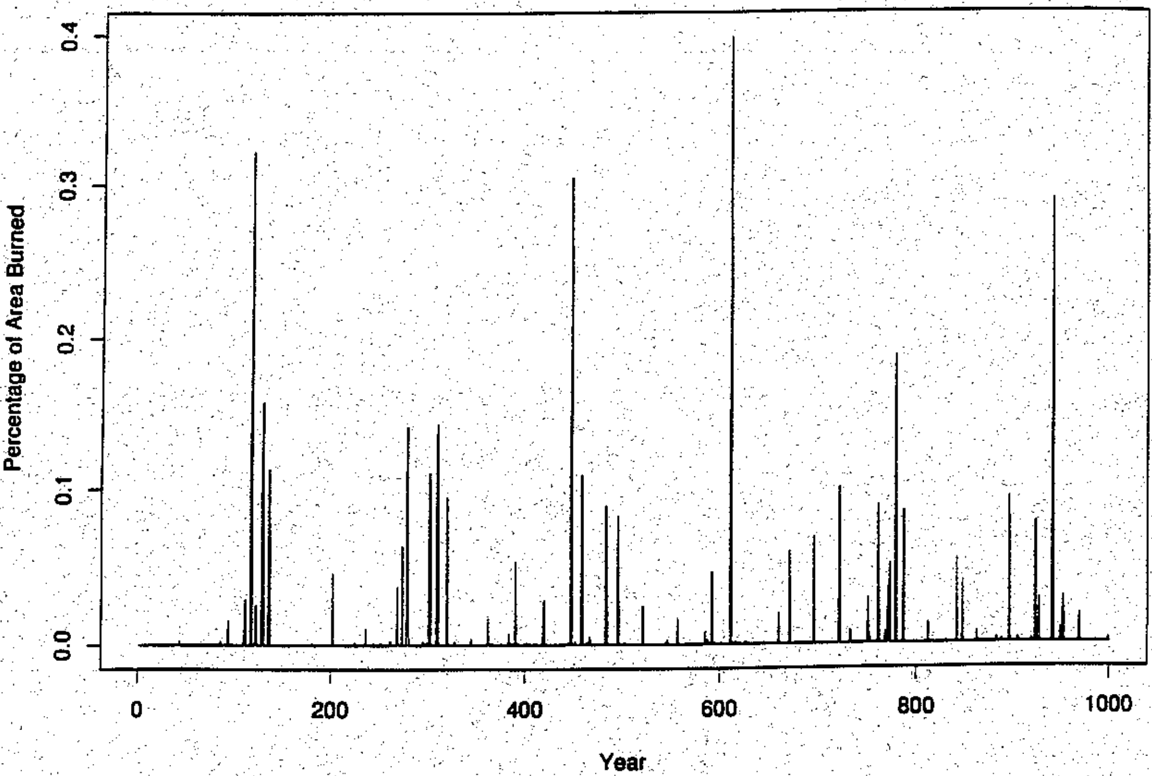

Figure 10. The temporal dynamics in percentage of area burned.

6. USE OF ON-FIRE

ON-FIRE has many potential applications in different fields of forestry. Here we summarize characteristics of ON-FIRE and present some of its applications. An example of how to use the model will be presented in a separate report.

ON-FIRE is able to simulate fire regimes. The fire regimes can be simulated on a hypothetical or real forest landscape. In order to simulate a fire regime on a real forest landscape, users have to input related GIS information about the landscape. The interface between ON-FIRE and a GIS database ensures the simulation results will be realistic. Users will be able to investigate the logical consequences of the dynamics of both landscape and natural fire regime for a given study area, by inputting related GIS information about the study area into the model.

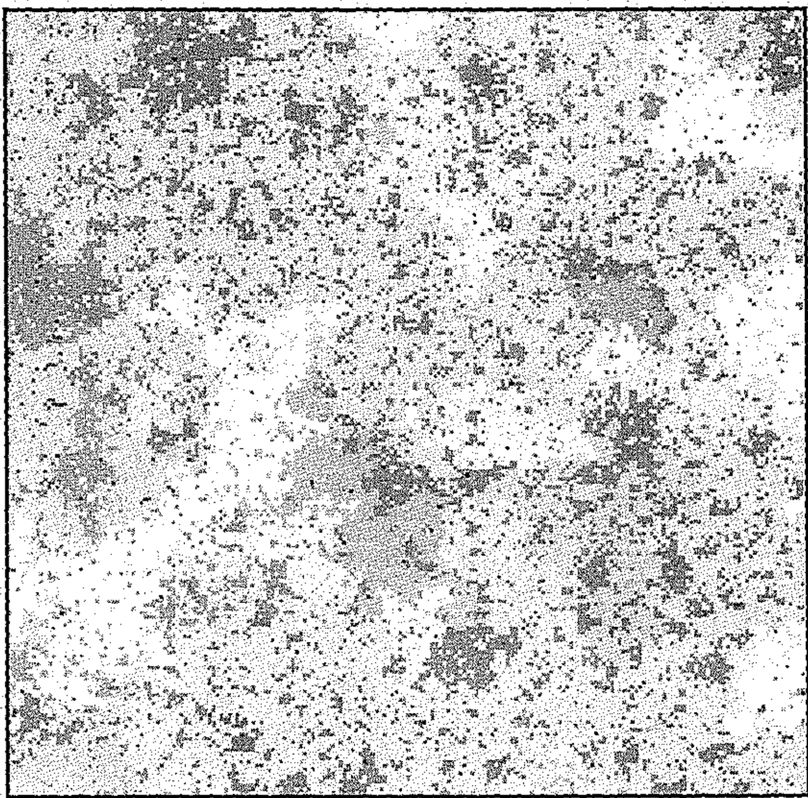

Figure 11. A sample landscape stand-age-mosaic created by forest fires at the 100th time step of a simulation based on a hypothetical forest landscape.

ON-FIRE provides opportunities for examining the influences of different anthropogenic disturbances (in addition to natural fire regimes) on an evolving system -- forest landscape. Ecosystems have been described as evolving systems or moving targets, and thus in the ideal situation the issue of ecosystem management should be discussed within the framework of an evolving system. Management under such circumstance will need new tools for simulating the dynamics of evolving systems. ON-FIRE could serve as one of the new tools.

ON-FIRE can also serve as a framework to incorporate the effects of other natural disturbances, such as insect pests and windstorms. This will be addressed in another study developing an integrated natural disturbance model. The study will consider the interactions among different kinds of natural disturbances such as fire and insect pest.

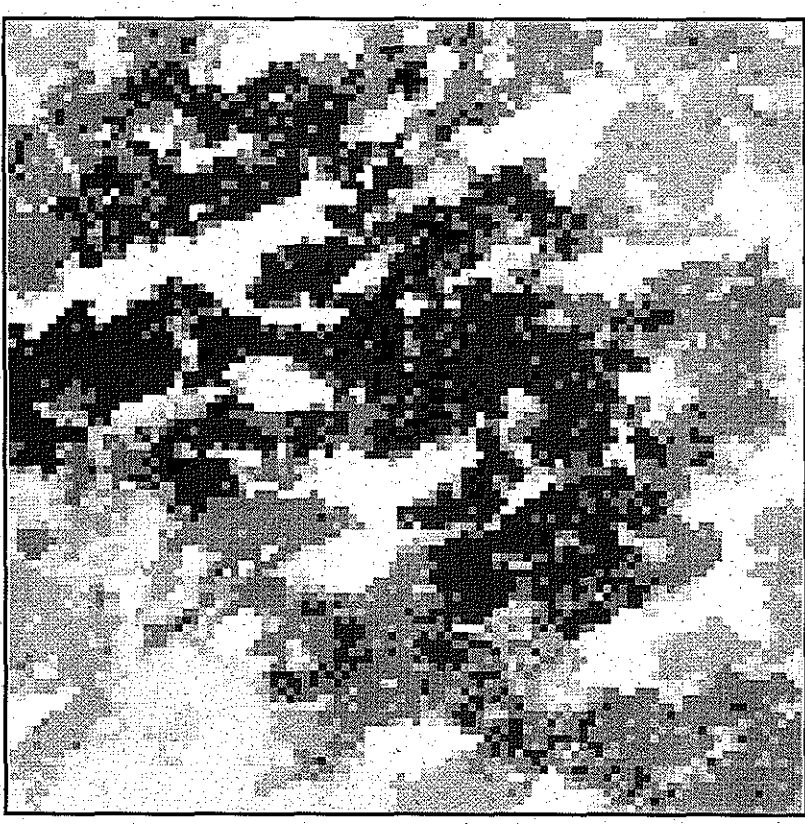

Figure 12. A sample fire hazard map over 500-year's simulation based on a study area in northwestern Ontario. Each pixel represents an area of 1 ha. The darkest color indicates the highest probability of a burn. Most white pixels are the lakes where no fires would occur. The grey scales between white and dark indicate a gradient of fire probability from low to high.

ON-FIRE can be used to examine the impacts of projected climate change on forest landscapes, through the changing dynamics of fire regime. It is generally predicted that the projected global warming in the 21st century will increase fire frequency and severity. This prediction was based on the scenario of increased global surface temperature. This means that fuel would dry out more quickly (assuming precipitation stays constant), and thus the fire probability across a landscape would increase. If this is true, then more fires would be ignited by lightning strikes and the fires would spread more easily. The unique thing about ON-FIRE is that climate change will no longer be seen as the only driving force, but as one component of the system, thus researchers will be able to study system dynamics when one of the system components changes.

In the application of ON-FIRE, forestry policymakers will be able to use the model as a tool to evaluate long-term consequences of different options, based on a landscape of interest. The evaluation will be based on comparisons between two scenarios: under a natural fire regime and under assumed forestry policy on top of the natural fire regime. For example, the influences of fire management on fire regimes in boreal forest landscapes have been investigated using ON-FIRE (Li and Perera, in prep.). Fire managers, forest resource managers, and land use planners will be able to evaluate long-term consequences of different options of management. Wildlife and habitat managers will also be able to link their models to ON-FIRE to evaluate conservation policies and management options.

The algorithm of ON-FIRE could also be adapted into a GIS software package. In this way, users will be able to run ON-FIRE from within the GIS software. The incorporation of ON-FIRE into GIS will also enhance the function of the GIS package by adding the capability to predict the potential stand age-mosaic of forests in the future.

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