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Modelling Interactions Between Fire Regime and Forest Landscape

C. Li, M.T. Ter-Mikaelian, and A.H. Perera

Forest Landscape Ecology Program
Ontario Forest Research Institute
1235 Queen Street East
Sault Ste. Marie, Ontario, Canada
P6A 5N5
Tel :(705) 946-2981
Fax: (705) 946-2030
Internet: ofriin@epo.gov.on.ca

Abstract

The forest stand-replacing wildfire is a natural disturbance that greatly influences the dynamics of the boreal forest landscape. We use a spatial model to investigate the interactions between lightning-caused stand-replacing fires and the forest landscape. A grid of equal sized rectangle cells is superimposed on a forest landscape, and each cell represents a forest unit with a homogenous status (age). Whether a fire ignites at a specific cell depends on the cell's age. The probability of fire spread also depends on the cell's age but differs from the probability of fire ignition. The simulation model can display how a forest landscape's age structure changes over time under fire disturbances and how fire ignition and spread are in turn determined by forest landscape age structures. The results suggest that a spatially explicit approach that considers forest stand age is necessary for modelling natural fire regime.

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Modélisation de la relation entre le régime d'inflammabilité et les terres forestières

C. Li, M. T. Ter-Mikaelian et A. H. Perera

Programme écologique pour les terres forestières
Institut de recherche forestière de l'Ontario
1235 rue Queen E
Sault Ste. Marie (Ontario) Canada
P6A 5N5
Téléphone : (705) 946-2981
Télécopieur : (705) 946-2030
Internet: ofriin@epo.gov.on.ca

Résumé

Les feux de forêt irréprimés nécessitant un repeuplement constitue une des perturbations naturelles qui a une influence sur la dynamique propre à la forêt boréale. Nous faisons appel à un modèle spatial pour examiner l'interaction entre ce genre d'incendie causé par la foudre et les terres forestières. On superpose aux terres forestières une grille formée de cellules rectangulaires de même taille. Chaque cellule représente une unité de forêt au peuplement homogène (même âge). L'apparition d'un feu à l'intérieur d'une cellule précise dépend de l'âge de la forêt de cette cellule. La probabilité de la propagation du feu dépend également de l'âge de la forêt de la cellule, mais elle diffère de la probabilité de l'allumage d'un feu. Le modèle de simulation permet de représenter comment la structure par âge des terres forestières évolue, au fil des ans, à la suite des incendies de forêt, et comment l'allumage et la propagation d'un incendie sont, à leur tour déterminés par la structure par âge des terres forestières. Nos résultats laissent supposer qu'une approche de type spatial, qui tient compte de l'âge du peuplement de forêts, est nécessaire pour la modélisation du régime d'inflammabilité naturel.

Introduction

The forest stand-replacing wildfire is a natural disturbances that greatly influences the dynamics of forest landscape structures. To make wise resource management decisions, for both the short and long term, we must understand the long-term dynamics of forest landscape structure.

Fire models that can simulate the interactions between fire and forest landscape are necessary for investigating the dynamics of fire-adapted forest ecosystems like the Canadian boreal forest. The fire-adapted boreal forest is indicated by the folling facts: most stands in the Canadian boreal forest are even-aged with fire-origin, and the reproductive strategies of some dominant tree species, such as black spruce and jack pine, have adapted to environmental conditions with frequent fire disturbances. These tree species generate seeds yearly; however, their cones need fire to open and disperse the seeds. Using this strategy, these species can accumulate enough seeds to ensure successful regeneration right after a fire disturbance. These characteristics of the Canadian boreal forest suggest that the interaction between fire and forest is indeed important in the studies of forest dynamics.

The relationship between wildfires and forest landscapes is interactive and is an abstracted subsystem from reality. Wildfire occurrence is related to current forest stand-mosaic patterns such as age. The probability of fire occurrence is a function of the age of majority stands in a forest landscape. Wildfires will shape the age-structure of landscape, and the resulting landscape structure will determine the probability of fire occurrence as a feedback. Studying this interaction will enhance the knowledge of dynamics in both wildfires and forest landscape, especially for fire-adapted forest ecosystems.

In most existing fire models, the descriptions of the interaction between fire and forest are inadequate or nonexistent. Much research attention has focused on how fires influence landscape (*e.g.*, Baker *et al.*, 1991; Van Wagner, 1978), without looking at how the resulting landscape influences future fire occurrences. This information gap probably exists because of differing research focuses and modelling approaches.

At the Ontario Forest REsearch Institute (OFRI), the Forest Landscape Ecology Program (FLEP) is developing a landscape model that considers the fire-forest landscape interaction. This model assembles current knowledge of fire processes of ignition and spread into a framework, allowing us to investigate long-term dynamics of the fire-forest interaction system. This paper demonstrates that this model can simulate the interaction between fire and forest and thus provides insight into forest landscape dynamics subject to natural fire disturbances.

Model structure and assumptions

In this section, we briefly describe the fire model for the boreal forests of Northwest Ontario (Li *et al.*, 1995a). In this model, a grid of rectangle cells (300 x 300) is superimposed on a forest landscape. Each cell represents a forest unit with a homogenous status (age). The forest landscape is randomly initialized at the beginning of each simulation.

The model includes 3 major components: growth, fire disturbance, and regeneration. In each of the simulated fire seasons (time steps), the forest in each cell is aged 1 year unless it is destroyed by fire.

A fire disturbance process is considered at 2 stages: ignition and spread (Li and Apps, 1995), and 2 fire probability functions are used at each stage. The probability of fire ignition in a given cell is a function of cell age. Since bimodal fire size distributions, a characteristic of natural fire regime, were generated from both age-dependent and age-independent fire ignition probability functions (Li *et al.*, 1995b), we assume a constant of 0.3277 for the fire ignition probability in the current study.

Once a fire is ignited, it is equally likely to spread to any one of its 8 neighboring cells, those share either a side or a corner with the burning cell. The fire spread probability is to determine which cells will burne due to their adjacency to a burning cell. This process will continue until all the possible cells are checked. A logistic function is used to characterize the relationship between fire spread probability and cell age:

$$P(Spread) = \frac{0.6}{1 + \exp(3.5 - 0.05 \times Age)}$$

The component of regeneration includes seed reproduction and dispersal, for which each tree species has its own temporal pattern. In this model, we assume a complete regeneration of burned cells in one time step. We also assume that the number of lightning strikes per fire season in a particular region is nearly constant, represented by a random number following Poisson distribution (with mean value of 10); that each cell can burne only once within each fire season; that no cells will burne by fires ignited outside landscape boundary; and that fire spread will stop at the landscape boundary. This treatment will generate some edge effect, but it will not be large enough to alter the conclusions (*c.f.* Fig. 1).

Each of the simulation runs uses a total of 1000 time steps. The model output includes final fire sizes, as well as location and age of ignition for each fire. At the end of each time step, the forest age structure is recorded.

Model behavior

Following is a description of how the fire-forest interaction creates landscape spatial patterns over time. The description will use the results of a single simulation run from a series of stochastic simulations.

The 12 landscape age structure images in Fig. 1 are selected from the first 100 time steps of a simulation that shows how fires may interact with the landscape.

At the beginning of the simulation (time step 0), the forest landscape was randomly initialized by assigning an age to each of the cells. The age of a cell is indicated by its grey scale in the image (white = age 0, and black = age not less than 100 years). Since there are many cells were assigned old ages (*e.g.*, greater than 40), a large percentage (almost 70%) burned early on, in Time Sstep 2. The growth process continued until Time Step 38, when most of the cells were old enough for the next big fire (Some small areas, however, burned between time steps 2 and 38).

Time Step 39 was another heavy fire year, during which about 75% of the areas burned. Between this year and Time Step 73, forest aging continued, again with some small fires occurring periodically. At Time Step 73, 45% of the areas burned.

Years with small fires and years with large fires appear alternately throughout the simulation. After about 100 time steps, the percentage of area burned in years with large fires gradually approaches a lower level. This result suggests that the percentage of area burned in years with large fires is overestimated in the transitional period, possibly due to the initialization of landscape structure. To eliminate this effect, we use the results of the last 800 time steps in our analysis. Nevertheless, the results in the first 100 time steps provide a good description of how the model simulates the interaction between fire and forest and how the spatial patterns of the landscape approach a "steady mosaic" status.

The spatial pattern of the landscape is dynamic because of continuous patch transformation. From Fig. 1, we can see that many patches are created by fires. For example, large patches are created in time steps 2 and 39, and small patches are created in time steps 22, 38, 59, 69, and 100. The created patches gradually dissolve through forest aging (*e.g.*, from Time Step 2 to 38 and from 39 to 69). The aged cells provide higher probability of fire and thus provide suitable conditions for new patches.

The current landscape structure influences the final size of a fire. When a fire is ignited on a landscape where most cells are old, the final size is likely to be large. For example, in time steps 2 and 39, large fires ignited on landscapes that contain large proportions of old cells. Small fires, however, may occur in all types of landscape structure. Their occurrence depends mainly on the local conditions (cell age) where fires ignite.

Discussion

The goal of simulating the interaction between fire and forest is to incorporate key processes of fire ignition and spread into the model. In this model, the processes are assumed cell-age-dependent only at this stage. Cell age is used as a state variable indicating forest status. We are now working to incorporate the influences of land cover type and topographical and climatic conditions into the model, and we expect the model will generate more realistic scenarios after we complete these modifications.

This model is unique, because it is designed to connect with real spatial data. This spatial information is needed for a comprehensive geographical information system (GIS) database for Ontario. The GIS database includes: (1) land cover (from LANDSAT TM data) at a ground resolution of 50 meters; (2) terrain at a resolution of 100 meters; (3) soil moisture (from the Ontario Land Inventory) at a resolution of 100 meters; and (4) climate (temperature and precipitation) at a resolution of 1 km. Through spatial data, the model will be coupled with landscape pattern analysis packages, such as LEAP (Landscape Ecology Analysis Package). After the model, the spatial data and spatial pattern analysis packages are linked, an extensive analysis of natural fire regimes in different regions of Ontario can be carried out.

At the current stage, this model has demonstrated great potential and promise as a research tool in both theoretical and practical aspects. In theory, it can enhance our knowledge of how fire disturbances influence the forest landscape, how the resulting landscape may affect future fire probability; and how landscape heterogeneity influences fire-forest interactions. In practice, this kind of model should help resource managers learn to mimic natural disturbance regimes. These models should also predict the general pattern of landscape structure subject to natural disturbances.

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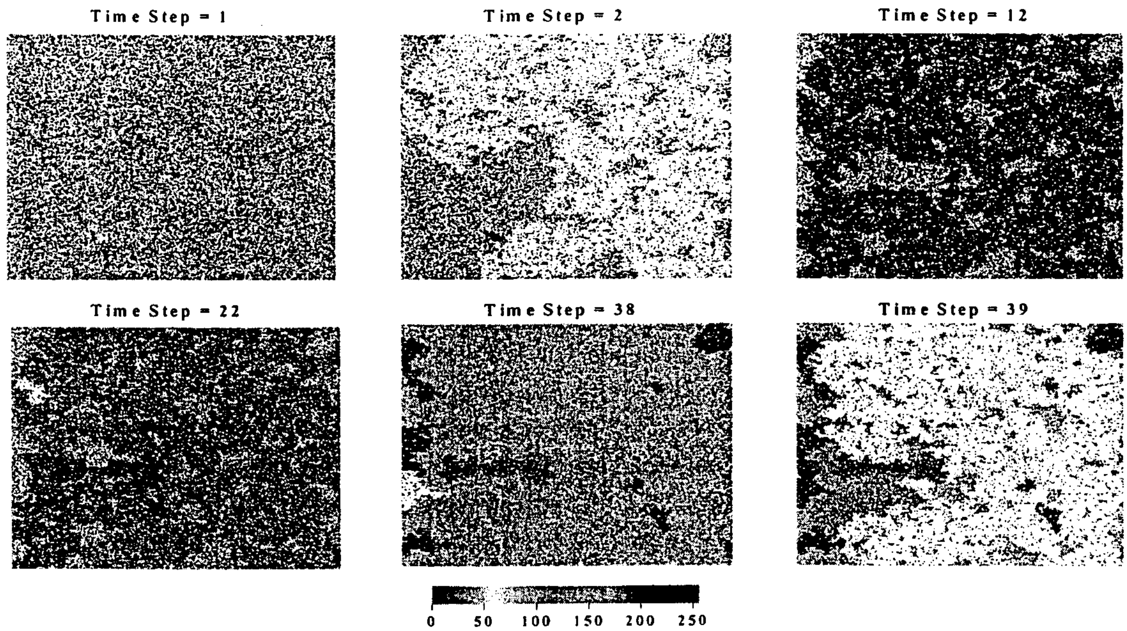

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Fig. 1: The transformation of patch-mosaic of age in a hypothetical forest landscape (300 x 300 cells) results from the interaction between fire and forest. The grey scale in the images indicates cell age: white represents age 0, and black represents age not less than 100 years. See text for detailed explanation.