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Stand development and fire behavior

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Abstract

Using a fuel model which characterizes stand fuel properties, the paper quantifies and explains the effects of stand development and silvicultural interventions on fire behavior. It also presents and explains that all fire behavior properties are strongly related to fuel characteristics. Results showed that rate of spread (ROS) was relatively high when crown fuels were becoming more involved and the crown base was low. Fuel consumption was related to the quantity of fuel available. Fire behavior in thinned stands followed the same pattern as in the unthinned stands except for sharp changes brought about by the periodic rearrangements in fuel from the thinnings. ROS, fuel consumption and fire intensity all increased abruptly with thinning, but declined rapidly with the decomposition and lower availability of thinned fuels, and the reduced probability of crowning.

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1. Introduction

Fire behavior prediction has been increasingly the focus of much interest and effort in the world throughout the 20th century. Facing with impending economic and ecological consequences of wild fires, forestry organizations have struggled to develop appropriate fire behavior prediction models. Canada, USA and Australia pioneered in this endeavor (e.g., McArthur, 1966; Van Wagner, 1966, 1968; Rothermel, 1972; Lawson, 1973; Stocks, 1987, 1989; Alexander et al., 1991). Many other countries either developed their own systems or adapted one of the pioneer ones.

Fire behavior prediction systems have proven useful for all forestry organizations in fire management planning (i.e., preparedness and presuppression planning). By linking fuel, weather and topography, models permit fire managers to predict potential fire behavior and assess the effects of fire on the environment. While the models now in use differ in formulation, all typically provide rate of spread (ROS[1]), fuel consumption and fire intensity.

Unfortunately, a qualitative fuel description approach that lacks quantitative incorporation of fuel characteristics into fire behavior analyses, inflicts the fire behavior prediction systems currently in use. Lacking a means to incorporate the characteristics of fuel, fire behavior prediction models are limited to fire behavior prediction in a qualitatively described fuel type. While contemporary models have been successfully used in some cases, a severe shortcoming of these efforts has been in their failure to address the dynamics of fuel

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[1] An alphabetical glossary of abbreviations is listed in Appendix A.

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complexes quantitatively, i.e., canopy and forest floor dynamics associated with the growth and development of forest stands, their contribution to each other, and the effects of interventions.

Recently developed state-dependent crown and forest floor dynamics models (Bilgili, 1998; Bilgili and Methven, 1994) quantify crown and forest floor fuel characteristics of even-aged tree stands. The models were constructed in such a way as to generate fuel properties that are considered important in fire behavior. These properties include crown fuel loading (CFL), crown base height (CBH), crown closure (CC), surface fuel loading (SFL) and woody fuel loading (WFL). The models capture the effect of development, and are responsive to silvicultural interventions. Bilgili (1995) demonstrated in detail the characterization and incorporation of fuel characteristics into fire behavior prediction analyses in even-aged stand and slash fuel types. In his study, fuel characteristics were quantified through a set of indices based on readily measurable fuel properties that standardize fuels, and facilitate the incorporation of quantitative fuel characteristics into fire behavior prediction. Indices included fuel depth (FD) (cm), fuel bulk density (BD) (kg/m^3), crown base height index (CBHI), crown volume index (CVI), CC and foliage retention index (FRI), which individually or collectively quantify fuel load and depth, horizontal and vertical fuel continuity, and fuel distribution. A methodology based on these quantitative fuel characteristics was introduced to generate fuel/fire behavior models (Bilgili, 1995). The methodology was based on a comparative analysis of existing fuels, using quantitative properties derived from modeling or measurements. In the process, the dependency of fire behavior on fuel characteristics was established first, and equations compatible with the Fire Behavior Prediction (FBP) System of Canada were developed for managed or even-aged natural stands and slash fuel types. This paper presents and discusses the results of a study application of these efforts.

2. A brief description of the crown and forest floor dynamics models

The models simulate growth of the average conifer tree, emphasizing crown and forest floor development over time and under silvicultural practices such as thinnings. Stand canopy growth is treated as a multiple of the average tree. While it is obvious that a size distribution will exist in stands, mean tree size was used for practical purposes. The models were constructed such that they describe functional relationships quantitatively that would be common to a wide range of situations rather than fitting a trace of growth responses from a small set of measured situations (Baskerville and Kleinschmidt, 1981).

The models mimic the growth response of a crown and dynamics of the forest floor from year to year. Height growth is determined as a function of current height and available net production from the previous year. The growth of a crown is achieved through growing the crown layer whorl by whorl. The capacity to produce new foliage is dependent on the current amount of foliage in the crown and the amount of light the crown receives. The amount of light determines whether branches on any whorl will stay alive. If the light intensity at any whorl is lower than the light compensation point for the species, branches on that whorl are considered dead. This, in turn, moves the crown base up to next live whorl.

Since the model grows the average tree, a function of mortality is used to account for the decrease in the number of trees as they grow in size and exceed the carrying capacity of the site. Mortality is accounted for by Reineke's stand density index (SDI) (Reineke, 1933), which states that there is a predictable relationship between the quadratic mean size and trees per unit area.

As for the forest floor dynamics, litter from the canopy is added to and depleted from the forest floor annually. Decomposition of organic matter is controlled by soil temperature and moisture. Temperature at the forest floor level is determined from open air temperature adjusted for CC. Moisture content of surface fuels is determined from the Duff Moisture Code (DMC) of the Fire Weather Index (FWI) System of Canada. The DMC is a numerical rating of the average moisture content of partially decomposed, loosely compacted organic layers of moderate depth (Forestry Canada, 1993).

The bounding of the models considers both temporal and spatial aspects; the time span of the model is 100 years, with forward steps of 1 year. All calculations are done on a per tree basis for above ground dynamics and per hectare basis for forest floor. There is no chronological time sequence in the model; all variables are determined from internal calculations developed from the driving variable (i.e., stand density), or from functional relationships with other variables (e.g., foliage biomass). The results of the simulations do not depend on stand age. That is, the models are state-dependent rather than time-dependent.

Parameter values specified for model construction were either obtained from the literature (e.g., Stiell, 1969; Linder and Axelson, 1982; Sievänen et al., 1988; Payandeh, 1991) or determined by running the model repeatedly and varying sets of parameters each time. Sets of test data on red pine from Stiell and Berry (1977) and on white spruce from Stiell (1969) were used for calibration. Data from these studies included all or some of the following: total tree height, crown length, crown width, tree diameter, sapwood area, foliage weight and CBH. In the calibration process, parameter values that yielded the best approximation of the measured values were accepted as model parameters. For validation purposes, the models were tested against independent data (e.g., Stiell, 1962, 1966).

2.1. Model input

The stands were assumed to be red pine and white spruce plantations. The sites were assumed to be clear-cut prior to planting, and have a woody and SFL of 5 and 2 kg/m^2, respectively, for the two species. A 2 m × 2 m initial spacing was used in the simulations. Thinnings were performed in years 20, 40 and 60 with 30, 50, and 50% removal of the trees present, respectively. After cutting, stems were assumed to be removed from the site.

The effect of weather was introduced through the initial spread index (ISI), a numerical rating of fire spread in the Canadian FWI System. Three ISI values of 10, 20 and 30 were used. The ISI, in turn is a function of precipitation, relative humidity, wind and temperature.

3. Results and discussion

To explore how fire behavior changes with stand development and thinning and to test the robustness of the models, a series of model runs was carried out with red pine, white spruce at a number of ISI values. Four scenarios have been selected to display the effects of stand development and thinning on fuel dynamics and fire behavior; red pine with and without thinning and white spruce with and without thinning.

3.1. The effect of stand development on fuel characteristics

With the initial values given above, the fuel models were run twice, once with and once without thinning. Fuels were characterized according to Bilgili (1995). Model-generated indices are given in Figs. 1A–4A, for red pine and white spruce without and with thinning, respectively. In the unthinned stands, the SFL and WFL decreased initially, and the CFL and CC increased until crowns closed. With the onset of full CC, CBHI moved steadily up but, as expected, was significantly slower for white spruce than for red pine. This resulted in an increase in the amount of litter deposited to the forest floor, and CFL and CC stabilized for about 30 years, then decreased slightly. The WFL component increased sharply after the onset of natural mortality about 25 years after planting, and stabilized later at 3.3 kg/m^2 (Fig. 1A). There was a pronounced periodicity in WFL, CFL and CC for years over 30. This is brought about by the fact that the model considers the stand as a multiple of the mean tree. Based on and determined by the mortality function in the model, a number of trees are killed when the mean tree reaches a certain size for a given area. Thus, the periodicity in tree mortality results in the observed periodicities in WFL, CFL and CC.

The immediate effects of thinning on stand structure, and the response of the stand to these interventions are shown in Figs. 2A and 4A. A reduction in stand density resulted in an immediate decrease in both CFL and CC, and an increase in WFL and SFL. The CBHI was little affected by the first thinning because of the relatively rapid recovery of CC. However, by the second thinning, recovery was slower and incomplete, and the rate of increase in the CBHI was reduced significantly.

3.2. The effect of stand development on fire behavior

Initially, ROS increased for all ISI values, as crown fuels became more involved, and gradually decreased

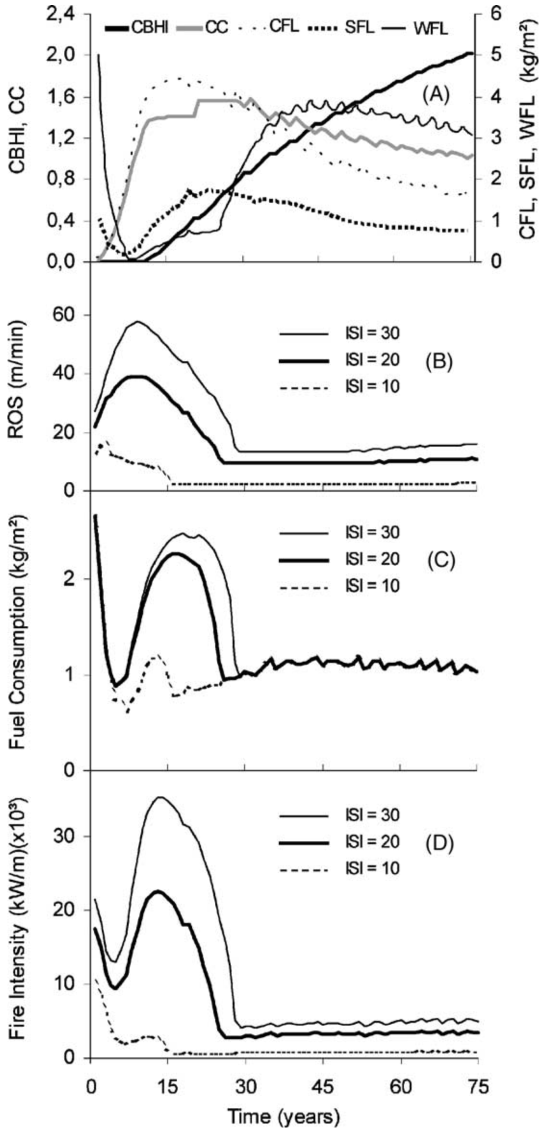

Fig. 1. The relationship between stand development and fuel characteristics (A), the effect of fuel characteristics and weather on fire spread (B), on fuel consumption (C), on fire intensity (D) for red pine. A BUI value of 50 was used in all runs.

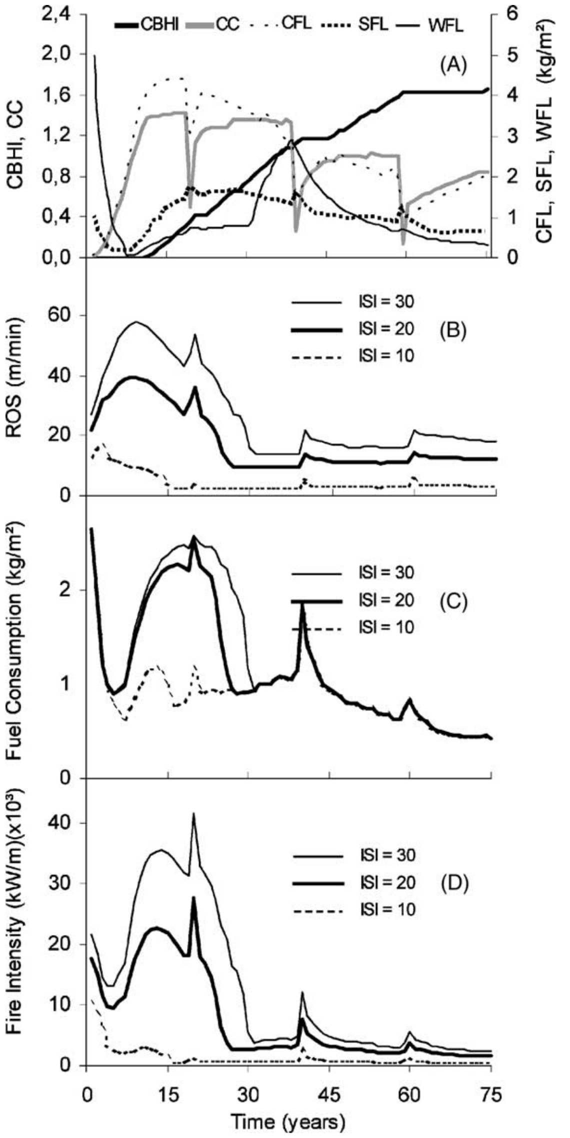

Fig. 2. The relationship between stand development, thinnings and fuel characteristics (A), the effect of fuel characteristics and weather on fire spread (B), on fuel consumption (C), on fire intensity (D) for red pine. A BUI value of 50 was used in all runs.

as the CBHI increased, resulting in an increased vertical discontinuity of fuels. Crown involvement increased significantly with ISI values (Figs. 1B and 3B). At an ISI value of 10, the involvement of crowns ceased immediately after the crown base moved up. At the higher ISI values, however, the surface fire intensity was sufficient to exceed the critical intensity (Van Wagner, 1977) and support crown fire for a longer period of time. When the surface fire intensity or spread rate fell below the critical value required for crown fire initiation, all fires continued as surface fires (Figs. 1B and 3B).

Fuel consumption was related to the quantity of fuel available. After an initial decrease, fuel consumption

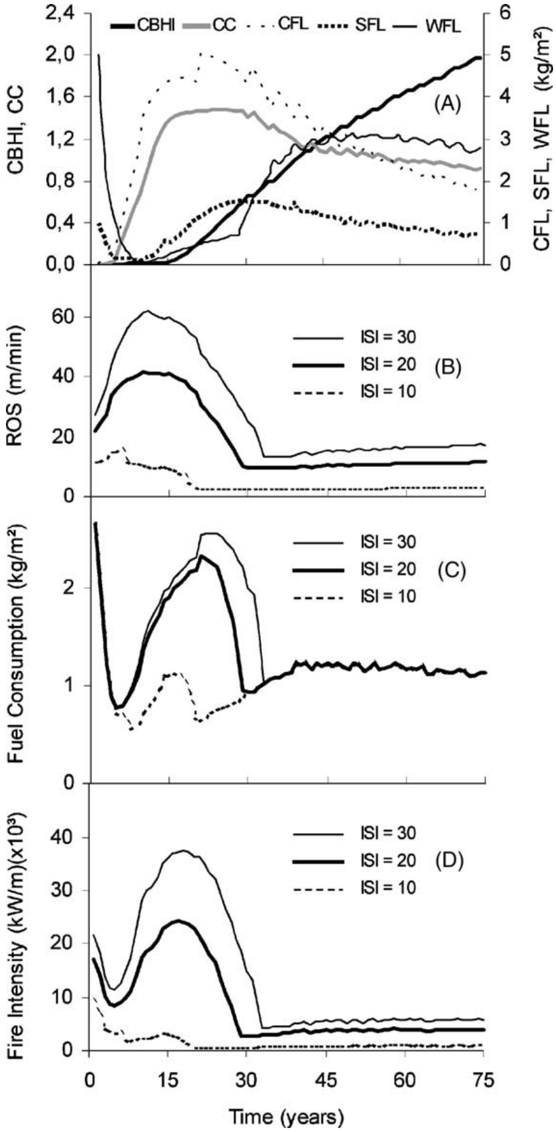

Fig. 3. The relationship between stand development and fuel characteristics (A), the effect of fuel characteristics and weather on fire spread (B), on fuel consumption (C), on fire intensity (D) for white spruce. A BUI value of 50 was used in all runs.

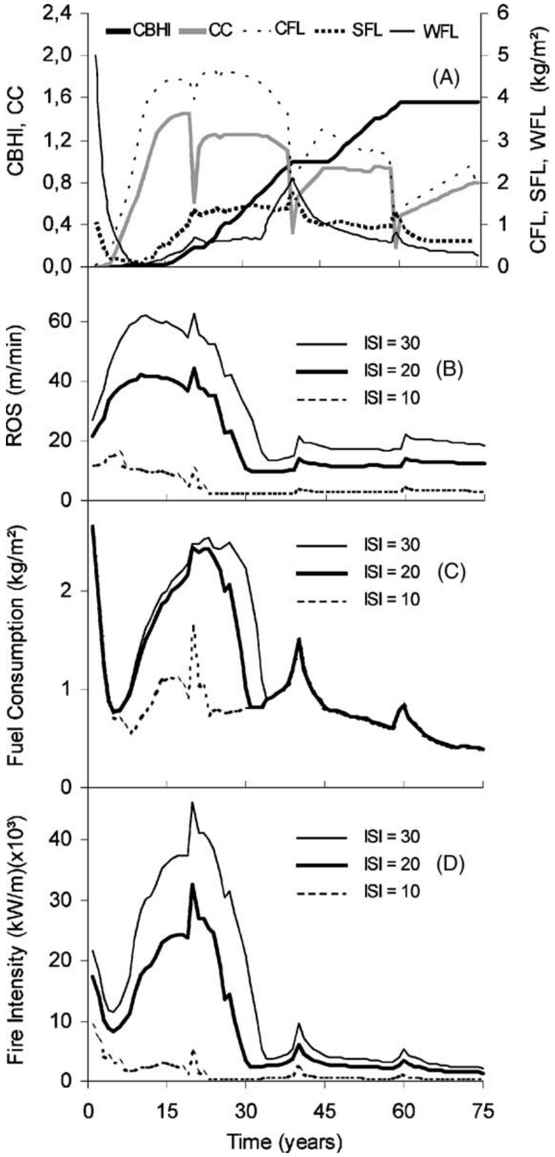

Fig. 4. The relationship between stand development, thinnings and fuel characteristics (A), the effect of fuel characteristics and weather on fire spread (B), on fuel consumption (C), on fire intensity (D) for white spruce. A BUI value of 50 was used in all runs.

increased for all ISI values as crowns became more involved, but at different rates. Maximum fuel consumption occurred when the CFL and the SFL were at their highest, and CBHI was relatively low. When fires spread as surface fires alone, fuel consumption was the same for all ISI values, since the surface fuel consumption was based only on fuel loading, and the BUI was held constant at a value of 50 (Figs. 1C and 3C). The rapid increase in the WFL due to natural mortality at 25 years of age (Fig. 1A) did not significantly affect fuel consumption, as larger fuels were assumed to burn incompletely.

Fire intensity is dependent on total fuel consumption and ROS. Following the initial decrease in fuel loading, fire intensity decreased despite the increasing ROS. As fuels became more available, fire intensity increased. The magnitude of the increase was proportional to the crown involvement (Figs. 1D and 3D). Fire behavior patterns were similar for both species, except the crown involvement was extended for white spruce as a result of delayed increase in CBHI.

3.3. The effect of thinning on fire behavior

Fire behavior in thinned stands followed the same pattern as in the unthinned stands except for sharp changes brought about by the periodic rearrangements in fuel from the thinnings. ROS, fuel consumption and fire intensity all increased abruptly with thinning, but declined rapidly with the decomposition and lower availability of thinned fuels, and the reduced probability of crowning.

The effects of thinnings on fire behavior were sustained for a number of years. Crown involvement, for example, was maintained for four more years at the ISI value of 30. Although the CBHI did not significantly change due to rapid recovery of CC after the first thinning, its rate of increase was reduced significantly after the second thinning.

Of particular interest was the rapid rise and fall of the fire behavior parameters with stand development. This was caused by the early peak in fuels (CFL, SFL and WFL) and a steady increase in CBHI, until a critical level was reached. Low CBHI and the initial rise in fuel loadings resulted in the initial form of fire behavior parameters. In the case of red pine, peak ROS occurred at 8 years, fuel consumption at 17 years and fire intensity, which is a product of ROS and fuel consumption, at 14 years. Equivalent peaks for white spruce occurred at 10, 25, and 16 years, reflecting the delay in such fuel characteristics as SFL, CC and CBHI.

4. Summary and conclusions

The effect of changes in fuel characteristics with stand development and thinnings on fire behavior was illustrated, using red pine and white spruce as examples. Of the fire behavior parameters, ROS increased with the increase in crown fuels and higher involvement thereof so long as the crown base remained close to the ground. Fuel consumption was a function of the quantity of fuel available for combustion. Maximum fuel consumption occurred when the CFL and the SFL were at their highest, and crown base was relatively low. Fire behavior in thinned stands was similar to that in the unthinned stands except for sharp changes in fuels resulted in by the thinnings. ROS, fuel consumption and fire intensity all increased abruptly with thinning, but declined rapidly with the decomposition and lower availability of thinned fuels, and the reduced probability of crowning.

The results of this study will allow fire behavior prediction for a mosaic of forest types and development stages across the landscape based solely on fuel model outputs or relatively simple inventory data. With this ability to predict fire behavior in even-aged stands, it will be possible to incorporate fire management considerations into silvicultural activities, overall forest management planning, and landscape design.

Appendix A. Glossary of abbreviations

BD	bulk density (kg/m^3)
BUI	buildup index: a component of the Canadian Forest FWI System. The BUI is a numerical rating of the total amount of fuel available for combustion that combines the DMC and the DC
CBH	crown base height (height to live crown) (m)
CBHI	crown base height index (CBH/10)
CC	crown closure (%)
CFL	crown fuel loading (kg/m^2)
CVI	crown volume index
DMC	Duff moisture code of the FWI System. The DMC is a numerical rating of the moisture content of the loosely compacted organic layers of moderate depth. This code gives an indication of fuel consumption in moderate duff layers and medium-sized woody material
FBP	fire behavior prediction
FD	fuel depth (cm)
FFC	forest floor consumption (kg/m^2)
FRI	foliage retention index

FWI

fire weather index of the FWI System. The FWI is a numerical rating of fire intensity that combines the ISI and the BUI. It is suitable as a general index of fire danger throughout the forested areas of Canada

ISI

initial spread index of the FWI System. The ISI is a numerical rating of the expected rate of fire spread. It represents the combined effect of wind speed and FFMC on rate of fire spread without the influence of variable quantities of fuel

ROS

rate of spread (m/min)

SFL

surface fuel loading (kg/m^2)

WFL

woody fuel loading (kg/m^2)

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