University of Alberta

Variation in flammability of jack pine/black spruce forests with time since fire

in the Northwest Territories, Canada.

by

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"Fire behavior is not an absolute or a constant, but a highly variable phenomenon both in space and time."

Van Wagner and Methven (1980, pg. 8)

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GLOSSARY

The definitions of the main forest fire management terms used in this document were taken from Merrill and Alexander (1987) unless otherwise specified.

Available Fuel - "The quantity of fuel in a particular fuel type that would actually be consumed under specified burning conditions."

Crown Fire - "A fire that advances through the crown fuel layer, usually in conjunction with the surface fire"

Crown Fuels - "The standing and supported forest combustibles not in direct contact with the ground that are generally only consumed in crown fires (e.g. foliage, twigs, branches, cones)."

Crowning - "A fire ascending into the crowns of trees and spreading from crown to crown."

Duff - "The layer of partially and fully decomposed organic materials lying below the litter and immediately above the mineral soil. It corresponds to the fermentation (F) and humus (H) layers of the forest floor. When moss is present, the top of the duff is just below the green portion of the moss."

Fine Fuels - "Fuels that ignite readily and are consumed rapidly by fire (e.g. cured grass, fallen leaves, needles, small twigs). Dead fine fuels also dry very quickly."

Fire Behaviour - "The manner in which fuel ignites, flame develops, and fire spreads and exhibits other related phenomena as determined by the interaction of fuels, weather, and topography."

Fire Climate - "The composite pattern or integration over time of the fire weather elements that affect fire occurrence and fire behaviour in a given area."

Fire Cycle - "The number of years required to burn over an area equal to the entire area of interest."

Fire Danger - "A general term used to express an assessment of both fixed and variable factors of the fire environment that determine the ease of ignition, rate of spread, difficulty of control, and fire impact."

Fire Environment - "The surrounding conditions, influences, and modifying forces of topography, fuel, and fire weather that determine fire behaviour."

Fire Frequency - "The average number of fires that occur per unit time at a given point."

Fire Interval - "The average number of years between the occurrence of fires at a given point."

Fire Regime - "The kind of fire activity or pattern of fires that generally characterize a given area."

Fire Weather - "Collectively, those weather parameters that influence fire occurrence and subsequent fire behaviour (e.g. dry-bulb temperature, relative humidity, wind speed and direction, precipitation, atmospheric stability, winds aloft)."

Flame Length - "The length of flames measured along their axis at the fire front; the distance between the flame height tip and the midpoint of the flame depth at the ground surface. Flame length is an approximate indicator of frontal fire intensity."

Flammability - "The relative ease with which a substance ignites and sustains combustion." Anderson (1970) defined flammability as consisting of ignitibility, sustainability, and combustibility.

Forest Floor - "The organic surface component of the soil supporting forest vegetation; the combined duff (if present) and litter layers."

Frontal Fire Intensity - "The rate of heat energy release per unit time per unit length of fire front. Flame size is its main visual manifestation. Frontal fire intensity is a major determinant of certain fire effects and difficulty of control. Numerically, it is equal to the product of the net heat of combustion, quantity of fuel consumed in the flaming front, and linear rate of spread."

Fuel Arrangement - "A general term referring to the horizontal and vertical distribution of all combustible materials within a particular fuel type."

Fuel Bulk Density - "The dry weight of combustible materials per unit volume. Numerically, it is equal to fuel load divided by the depth of the particular fuel layer (e.g. duff, tree crown foliage)."

Fuel Load - "The dry weight of combustible materials per unit area."

Fuel Type - "An identifiable association of fuel elements of distinctive species, form, size, arrangement, and continuity that will exhibit characteristic fire behaviour under defined burning conditions."

Fuelbreak - "An existing barrier or change in fuel type (to one that is less flammable than that surrounding it), or a wide strip of land on which the native vegetation has been modified or cleared, that act as a buffer to fire spread so that fires burning into them can be more readily controlled."

Ground Fire - "A fire that burns in the ground fuel layer."

Ground Fuels - "All combustible materials below the litter layer of the forest floor that normally support smouldering or glowing combustion associated with ground fires (e.g. duff, roots, buried punky wood, peat)."

Ladder Fuels - "Fuels that provide vertical continuity between the surface fuels and crown fuels in a forest stand, thus contributing to the ease of torching and crowning (e.g. tall shrubs, small-sized trees, bark flakes, tree lichens)."

Rate of Spread - "The speed at which a fire extends its horizontal dimensions, expressed in terms of distance per unit of time. Generally thought of in terms of a fire's forward movement or head fire rate of spread, but also applicable to backfire and flank fire ROS."

Reburn - "Subsequent burning of an area previously burned."

Smouldering - "A fire burning without flame and barely spreading."

Spot Fire - "(1) A fire ignited by firebrands that are carried outside the main fire perimeter by air currents, gravity, and/or fire whirls. (2) A very small fire that requires little time or effort to extinguish."

Spotting - "A fire producing firebrands carried by the surface wind, a fire whirl, and/or convection column that fall beyond the main fire perimeter and result in spot fires."

Surface Fire - "A fire that burns in the surface fuel layer, excluding the crowns of the trees, as either a head fire, flank fire, or backfire."

Surface Fuels - "All combustible materials lying above the duff layer between the ground and ladder fuels that are responsible for propagating surface fires (e.g. litter, herbaceous vegetation, low and medium shrubs, tree seedlings, stumps, downed-dead roundwood)."

Timelag - "The drying time, under stated conditions of dry-bulb temperature, relative humidity, wind speed, and time of the year, required for dead fuels to lose about two-thirds (2/3) of the difference between their initial moisture content and their equilibrium moisture content. The TL therefore represents the rate of moisture change in a fuel."

Torch or Torching - "A single tree or a small clump of trees is said to "torch" when its foliage ignites and flares up, usually from bottom to top."

Values-at-Risk - "The specific or collective set of natural resources and man-made improvements/ developments that have measurable or intrinsic worth and that could of may be destroyed or otherwise altered by fire in any given area."

CHAPTER 1

Introduction

An understanding of landscapes in terms of their ecosystems' components, processes and interactions, as well as the ability to predict or simulate changes induced by natural or human disturbances, are key elements of sound resource management (Kessell 1979). The task is however rendered relatively complex by the inextricable relation between landscape pattern and disturbance dynamics (Miller and Urban 2000). Looking more specifically at fire, a major disturbance in the boreal landscape, its regime has often been associated with landscape dynamics and ecosystem change in a reciprocal relationship (e.g., Heinselman 1973; Brown 1975; Christensen 1993; Ryan 2002).

Knowledge of the changes that occur in burned stands through time provides insight into the dynamics that lead to the distribution of stands in the landscape, and to their related environmental conditions. Wright and Heinselman (1973) identified various roles of fire in fire-dependant northern conifer forests. They observed that fire influences the physical-chemical environment, it controls plant species and communities, it is a determinant of wildlife habitat patterns and population potential, it is a controller of forest insects, parasites, fungi, etc., it profoundly influences major ecosystem processes and characteristics, and it regulates dry-matter accumulation. Since all fuels necessarily derive from growth of the forest complex (Davis 1959), a knowledge of successional dynamics of stand structure and composition can also provide information about fuel accumulation at various stages of stand development, information which is essential for strategic fire protection planning (McCaw *et al.* 2002).

In the boreal forest of Canada, the typical fire regime is one of long-interval crown fires, or severe surface fires, that kill entire stands and result in their total replacement (Heinselman 1978, 1981a, 1981b; Heathcott and Cornelsen, 1992; Bonan and Shugart, 1989; Epp and Lanoville 1996). The ensuing landscape is composed of a mosaic of stands of different time since the last fire which, given the right conditions, will eventually burn again. Although knowledge of the conditions that determine the likelihood of a stand burning is essential for judicious management of our boreal ecosystems, they are still mostly unknown or undocumented.

What is meant by "conditions" remains obscure until the concept of fire environment (Countryman 1972) is introduced. The fire environment is generally defined as the surrounding conditions, influences, and modifying forces of topography, fuel, and fire weather that determine fire behavior (Merrill and Alexander 1987). Using this definition, we can reformulate the problem in a more tangible way by asking the question: "Is fire a largely random factor, dependent on random human and lightning ignitions and the vagaries of weather, or is the probability of a successful ignition and subsequent development into a major fire controlled by fuel factors that increase systematically with stand age?" (Heinselman 1985, pg. 104).

Over the years, several researchers have attempted to answer this challenging question, directly or indirectly, for several areas and vegetation types (e.g., grasslands (Morgan and Lunt 1999); chaparral (Minnich and Chou 1997); banksia low woodlands (Burrows and McCaw 1990); eucalypts (Raison *et al.* 1983); slash pine-palmetto stands (McNab *et al.* 1978); giant sequoia forests (Parson 1978); lodgepole pine forests (Muraro 1971; Brown 1975); Scots pine forests (Schimmel and Granström 1997); western hemlock/Douglas-fir forest (Agee and Huff 1987); western redcedar (Habeck 1985); mixedwood forests (Hély *et al.* 2000); subalpine forests (Romme 1982)) obtaining various answers. Researchers also have tried to find a definite answer as to which component of the fire behavior triangle is driving the variation in flammability of stands with stand age. Again results differed and Agee (1997) eventually grouped them according to two hypotheses: the "fuel hypothesis" and the "weather hypothesis".

More specific to this project, Van Wagner (1979, 1983) suggested an hypothetical fire behavior cycle, as represented by head fire intensity, in a boreal conifer forest stand as a function of its age (Figure 1-1). In his crown fire section of the model, the fuel complex varies from a relatively fire-proof state immediately after a fire, to one of high hazard early during stand development, followed by a steady state during maturity and finally rising again as the stand becomes overmature. Brown (1975) commented, regarding the concept of fuel accumulation in lodgepole pine stands, that "fuel quantities and fire potential become predictably high as stands become overmature" and "fuel quantities and fire potential cannot be predicted from age in young and immature stands". To illustrate this he presented three curves for fire intensity potential of fuels as a function of time since stand establishment. Two of those curves have a similar shape that the ones suggested by Van Wagner (1978, 1983), although further comparisons are difficult to make since age or time since fire are not specifically identified in any of those graphs (note that Johnson (1992) later suggested some ages to go with Van Wagner's (1978, 1983) curves).

The fire behavior triangle represents the three interacting components of the fire environment that are responsible for fire behavior: fuels, fire weather, and topography. Variation in any one of those components will generally bring observable changes to the fire behavior. This was shown by the studies mentioned above where, depending on the experimental design and the approach taken, an effect of fuels or weather was observed. The complexity of it all was vividly described by Van Wagner (1985, pg. 3):

> *"There can be few natural physical phenomena with the scope and complexity of a forest fire. The fuel that powers it is found in a huge range of sizes, quantities, and arrangements in space. The weather affects the current condition of this fuel array in a bewildering maze of drying and wetting effects, each fuel component responding to a 'different drummer'. The combustion process itself, once under way, responds to a complex blend of fuel variation, moisture status, topography, wind speed, and other atmospheric factors. Its frontal intensity varies over an immense range, from tiny flickers easily stepped over, to dense sheets of flame whose fierce radiation keeps the observer at a distance. Yet, the goal set by the forest fire research community is nothing short of the reasonably accurate explanation and prediction of fire behavior under all possible combinations of fuel, topography, and weather."*

An approach that considers the interaction between the different components of the fire environment mentioned above would be one of overlapping gradients. Fuels, weather and topography vary both spatially and temporally, albeit on different scales. Marked differences in the state of all three components are observed across the landscape. However, changes in time will generally be noticed only for fuels and weather, the topography being usually considered static in the time frame dictated by the question of interest introduced above. Since that question mainly concerns time (with an indirect relation to the spatial aspect presented by the landscape) topography will be ignored in the remaining discussion which will focus on the temporal variation of fuels and weather, and their consequences for fire behavior.

Several studies referred to a gradient approach in landscape studies (e.g., Kessell 1979; Forman and Godron 1981; Romme and Knight 1982; Aber and Melillo 1991; Turner and Romme 1994; Hargrove *et al.* 2000). In the concept of overlapping gradients as it is meant here, an area is subject to the temporal variation of both fuels and weather. From a fire perspective, the resulting effect of those gradients is best described in terms of flammability, the interaction between plant communities and environment over time (Mutch 1970; Habeck and Mutch 1973; Troumbis and Trabaud 1989). Given the dynamic nature of the system, the flammability of the vegetation on an area fluctuates constantly.

Below a certain site-specific flammability threshold, a fire cannot sustain itself without a sustained ignition source. This is due to limitations imposed by the fuels gradient, the weather gradient, or an interaction of both. Eventually, under conditions that increasingly favour combustion, flammability will reach a threshold above which a fire has the potential to start and spread, given an ignition source. As the conditions progress above that limit, the flammability varies and the behavior of the fire is affected accordingly by the fire environment.

The notion of thresholds was mentioned in several fire studies. For example, Hargrove *et al.* (2000) presented a concept of critical densities of combustible fuels where probabilistic results were expressed as risk of area burned under alternative weather scenarios. Minnich and Chou (1997) suggested an age-dependant combustion threshold, in chaparral vegetation, defined as the minimum age for fires to carry easily. Raison *et al.* (1983) observed that weights of fine fuels exceeding 12 t/ha would create control problems in the eucalypt forests they studied. Renkin and Despain (1992) noticed that in the high-elevation lodgepole pine forests of Yellowstone National Park, the fuel moisture of large dead and downed woody fuels must decline to 13% to observe an increase in the proportion of fire starts and in stand-replacing fire activity. Taylor and Fonda (1990) found that the fuels in the subalpine fir forests they studied reached their maximum flammability when the fuel moisture was between 16 and 22 %. In the Los Angeles County, in California, Schoenberg *et al.* (2003) observed nonlinear, threshold-type, relationships between wildfire burn area and several variables (fuel age, temperature, precipitation and fuel moisture). More theoretically, Turner and Romme (1994) suggested that there may be thresholds both in landscape pattern and in meteorological conditions that interact to produce large crown fires.

The overlapping gradients approach has a multi-dimensional character that is difficult to represent and to work with in an applied research context. Fortunately, a hypothetical model presented by Horn (1976) provides a means to overcome that difficulty by bringing back the concept to a two-dimensional representation (Figure 1-2). In this model, the intrinsic flammability of vegetation increases as plant material accumulates after fire. When the flammability reaches a threshold (high in moist periods and low during droughts) common accidents of ignition result in fires. Therefore, the temporal pattern of fires depends as much upon the intrinsic shape of the curve of flammability as on the temporal pattern of droughts that favour fires.

Keeping this model in mind, a way of measuring flammability is needed to be able to build the curve for a given vegetation type. Since flammability in itself is a state and is not readily measurable, an indicator is needed to quantify it. Anderson (1970) suggested that flammability consists of three components: ignitibility, sustainability, and combustibility. He went further and proposed that, in a fuel continuum, ignitibility would be governed by the ignition of fuel elements, sustainability would be more closely associated with the rate of spread, and combustibility would be represented by the intensity of the fire. Although the definition of flammability varies in the literature, several authors have considered the rate of spread (e.g., Brown 1975; Fogarty 2002) and/or the intensity (e.g., Brown 1975; Bond and Midgley 1995; Johnson *et al.* 1998; Fogarty 2002) of a fire as indicators of its state.

Both factors, fire intensity and rate of spread, provide information on the resulting effect of the fuel and weather gradients on an area. Therefore, they supply complementary information on the flammability of a stand. The rate of spread of a fire is the speed at which a fire extends its horizontal dimensions (Merrill and Alexander 1987). On flat terrain, it is a function of the current weather conditions and of the available fuels (the quantity of fuel in a particular fuel type that would actually be consumed under specified burning conditions (Merrill and Alexander 1987)). Fire intensity is the rate of heat energy release per unit time, per unit length of fire front (Merrill and Alexander 1987). This quantity is not directly measurable but it can be calculated using Byram's equation (Byram 1959):

$$I = Hwr \tag{1.1}$$

where I is the frontal fire intensity (kW/m), H is the fuel low heat of combustion (kJ/kg), w is the weight of fuel consumed in the active flaming zone per unit area (kg/m^2), and r is the rate of spread (m/sec). The only element of Anderson's (1970) definition of flammability that is not accounted for by those quantities is the ignitibility. It is however considered in the threshold concept of Horn's (1976) model and does not, therefore, specifically need an extra indicator (although one could be used if available).

Nevertheless, the boreal forest still presents a remarkable challenge for studies dealing with the variation in flammability of coniferous stands with time since fire. The time needed for the first cohort to reach maturity after a stand-replacing fire is considerable compared to other ecosystems in which similar studies were done. Therefore, to follow the progression of the fuels through stand development is a time consuming task. This restriction in itself probably explains why very few studies have been attempted in that forest region. However, the pervasive nature of fire and the resulting mosaic pattern of the landscape are two characteristics that suggest the use of a space-for-time substitution (Pickett 1989) in a study dealing with fuel dynamics in the boreal forest. Further, jack pine (*Pinus banksiana* Lamb.)/black spruce (*Picea mariana* (Mill.) B.S.P.) stands (the type of conifer stand selected for this project) often regenerate to the same tree species after a crown fire (Davis 1959; Heinselman 1973, 1981a, 1981b; Dix and Swan 1971; Carleton and Maycock 1978; Van Wagner 1979; Cogbill 1985); these characteristics facilitate the selection of stands belonging to the same chronosequence.

The main objective of the study was to describe the variation in flammability with time since fire of jack pine stands having a black spruce understory at maturity in a study area located in the Hay River district, Northwest Territories (Canada). This main objective was further divided into three more easily quantifiable sub-objectives:

- To determine the temporal variation in stand structure and fuel characteristics of jack pine/black spruce stands with time since fire;

- To describe the weather-related burning conditions generally experienced in the study area during the peak burning season and define four scenarios representing four different fire weather/fire danger conditions that may occur during that period: "moist", "moderate", "dry", and "extreme";

- To quantify the flammability of forest stands of this type, in terms of potential fire behavior, due to the changes in the fire environment with time since fire through the use of experimental fires, expert opinion, and fire behavior models.

The hypothesis considered in this project was that the flammability of jack pine/black spruce stands in the study area varies according to the hypothetical model (Figure 1-2) presented by Horn (1976).

Accordingly, the first part of the study dealt with the inventory of stands belonging to the same chronosequence and selected using a combination of stem analysis and space-for-time substitution. The information thus obtained provided a characterisation of the vegetation and the fuels in stands of different times since fire (Chapter 2). Although quite valuable in itself, this characterisation of the temporal variation of the fuels in jack pine/black spruce stands needed, for this project, to be interpreted in terms of fire behavior and, ultimately, in terms of flammability (Brown 1978).

In order to do so, the second aspect of the fire environment considered in this project, the fire weather, was analysed. To obtain the information on the weather-related burning conditions in our study area during the peak fire season (mid-June to mid-August), an analysis of the historical fire weather and of the Canadian Forest Fire Weather Index (FWI) System components (Van Wagner 1987) obtained for three weather stations in the general study area was performed (Chapter 3). The results were complemented by outputs from the Canadian Forest Fire Behavior Prediction (FPB) system (Forestry Canada Fire Danger Group 1992) for selected fuel types to better illustrate the influence of the weather on fire behavior in our study area. Although the main goal of that part of the project was to define conditions that could be used in different modelling scenarios to represent moist, moderate, dry, and extreme conditions, the fire weather was also described in a way that could be useful for various research or fire management activities in that part of the Northwest Territories.

With information on the fuels and the weather gradients, it was then possible to make the transition to fire behavior and stand flammability characteristics in order to meet the final goal of this study. Ideally the temporal variation of the flammability would have been determined, for both line and point ignitions, through the use of simultaneous experimental fires that would have been ignited under different drought and weather conditions in stands of different times since fire. Unfortunately, the conditions required for this procedure are rarely met in the boreal forest. Restrictions, whether financial, logistical, or environmental, often preclude it. Moreover, no wildfire of any consequence and burning in the forest type studied was reported in our study area during the years dedicated to the project [1]. For those reason, a multiple approach was adopted for the integration of the data in this project. Anderson (1974) suggested that the following elements should be incorporated into fuel analyses: a) experienced judgement; b) comparison to referenced fuel and vegetation; and c) mathematical models of fire phenomena. Brown (1978) also mentioned the usefulness of mathematical models and experienced judgement in the process of fuel appraisal. Considering their relevance to this project, these approaches were adopted and complemented, whenever possible, with simultaneous experimental fires.

By making simultaneous ignition of point and/or line source fires in the different stands composing the chronosequence, comparisons of the fire behavior in terms of flammability can be more directly related to the fuel types since weather variables are then considered constant. Taking advantage of the unparalleled opportunity provided by the International Crown Fire Modelling Experiment (ICFME)[2] near Fort Providence, Northwest Territories (Stocks *et al.* 2004), investigation into the flammability of recent burns (up to 4 years since fire) following a very detailed (fuels and fire behavior) high-intensity crown fire was performed (Chapter 4). The burnt areas were, before the ICFME experimental fires, sections of a mature (71-year-old) jack pine stand of fire origin having a black spruce understory.

To complement the data collected in the experimental burns (due to the restrictions mentioned above regarding the impossibility to obtain fire behavior information in all the fuel types under all possible burning conditions) an expert opinion survey was done. Through the use of a questionnaire presenting the stands inventoried in the chronosequence, experts were consulted for their opinion on the fire behavior and the flammability of stands of different time since fire under pre-defined weather and drought conditions (Chapter 5).

Fire behavior models were also used in this project to complement and integrate the fire behavior and flammability data obtained from other sources (Chapter 6). The American BEHAVE fire prediction and fuel modelling system (Rothermel 1983; Burgan and Rothermel 1984; Andrews 1986; Burgan 1987; Andrews and Chase 1989), based on Rothermel's (1972) model, was selected for the option it provides of using custom fuel models. However, crown involvement and crown fire behavior are not taken into account in this model since it was developed to predict rate of spread and intensity in a continuous stratum of fuel that is contiguous to the ground (Rothermel, 1972). Since the complex association of aerial and ground fuels and their combined total effect on flammability are difficult to appraise (Davis 1959), this presented a problem for some of the successional stages of this project. As a consequence, other models such as the models presented by Cruz *et al.* (2003; 2004a; 2004b) were used in conjunction with BEHAVE to determine those aspects of fire behavior. The FBP System (Forestry Canada Fire Danger Group, 1992) was also used for comparison purposes. A diagram summarising the methodology used in this project is presented in Figure 1-3.

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[1] The author however had the opportunity to work on the fire behavior prediction and documentation of other wildfires in the Northwest Territories during that period (Lavoie 2000).

[2] The author was a member of the Canadian Forest Service fire research documentation team involved in the ICFME project (Stocks *et al.* 2004, Alexander *et al.* 2004).

Finally, a presentation of the final conclusions, potential fire management[3] implications and future research needs identified through this project are presented in Chapter 7.

[3] Towards this end (during her Ph.D. tenure) the author took the national CIFFC sponsored Advanced Wildland Fire Behavior and Wildland Fire Behavior Specialist courses, the Wildland Fire Behavior Specialist Refresher, as well as the British Columbia's Weather for Fire Operations course and the Alberta's Wildland Firefighter Type I (Helitack Leader/Rapattack Subleader) Training course.

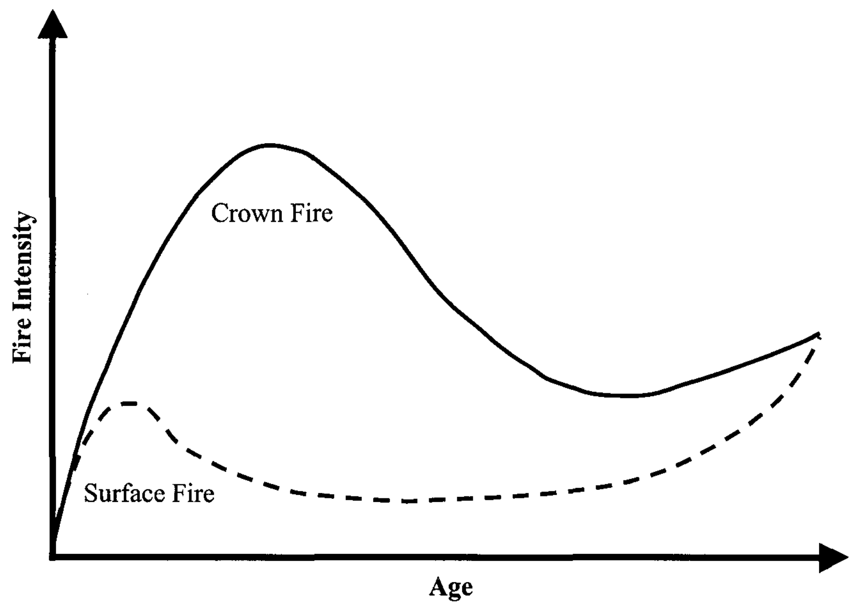

Figure 1-1. Hypothetical fire behavior cycle, as represented by head fire intensity, in a boreal conifer forest stand as a function of its age (modified from Van Wagner (1979, 1983)).

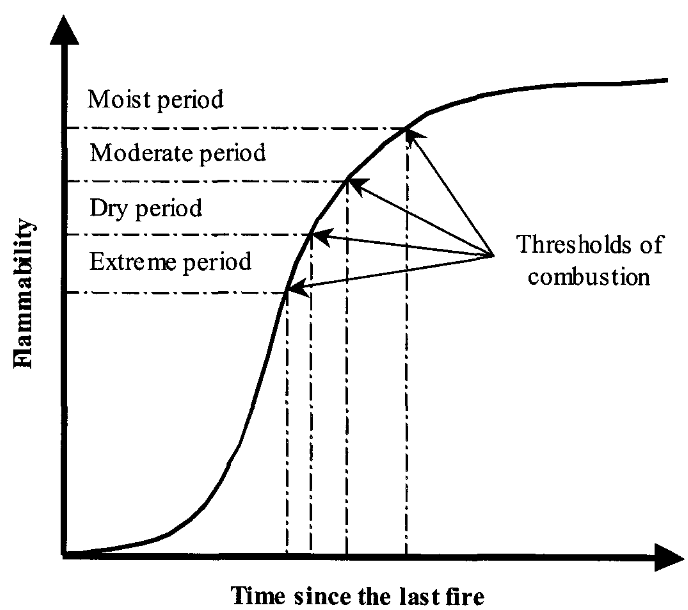

Figure 1-2. Representation of the hypothetical model presented by Horn (adapted from Horn (1976)).

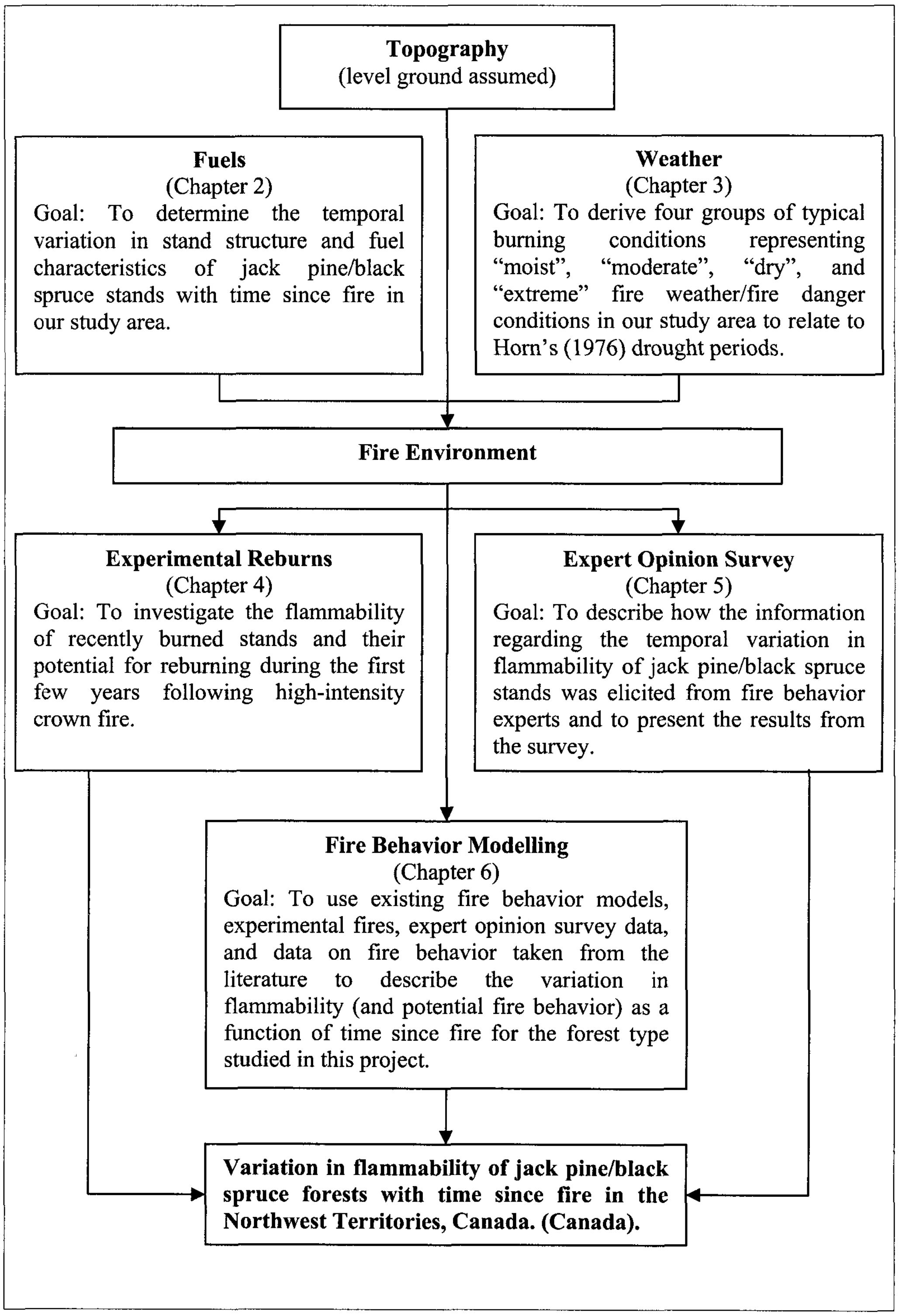

Figure 1-3. Diagram summarising the methodology used in this project to describe the variation in flammability of jack pine/black spruce stands as a function of time since fire in our study area.

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B NO TEXT

CHAPTER 2

Temporal reconstruction of stand structure and fuel loads using stem analysis and chronosequence data

INTRODUCTION

Fire behavior is a product of the environment (fuels, weather, and topography) in which the fire is burning (Countryman 1972). As a consequence, successional patterns of fuel accumulation have a significant influence on the fire regime of an area (Christensen 1993) and the landscape-level forest structure depends strongly on the interaction between disturbances and stand structure (Kuuluvainen 2002). In the boreal forest, the pervasive nature of fire (Van Wagner and Methven 1980; Foster 1985) has shaped the landscape into a mosaic of stands of different times since fire. Each polygon is following a successional pathway after the disturbance. The interval between fires is a regulator of the fuels present in each stand and of their characteristics (Heinselman 1981b) since all fuels necessarily derive from the development of the forest (Davis 1959). It is only a matter of time before these stands are, once again, presented with an ignition source. Whether or not they burn on that occasion, and the manner in which they burn if ignited, will depend on the fire environment.

Considering the resulting effect of past disturbances on the landscape patterns, and how the latter can in turn influence future disturbances (Heinselman 1973, 1996; Brown 1975; White 1979; Oliver and Larson 1996), it is surprising that relatively few vegetation or fuel types are sufficiently documented in terms of their development from a stand-replacing fire to their current state (Mutch 1970; Muraro 1971). In fact, the buildup of fuels after a fire in the boreal forest has received surprisingly little attention (Schimmel and Granström 1997). For this reason, forest managers have little quantitative data relating the time elapsed since the last fire and other stand characteristics to the fuels (McNab *et al.* 1978), despite the fact that knowledge of fuel quantity and distribution in wildland fuel complexes has long been considered a critical requirement for predicting fire behavior (Muraro 1971). One reason for this is that the measurement of forest fuels in consistent relation to their burning behavior is a difficult problem (Davis 1959).

Heinselman (1981b) presented a list of several pertinent key questions related to the problem. The availability of the information on fuel dynamics of a plant community is critical to fire managers and those researching the ecological effects of fire (Raison *et al.* 1983; Burrows and McCaw 1990) at both the community and at the landscape level of organisation (Van Wagner and Methven 1980). Knowledge of the successional pattern of fuel accumulation in the boreal forest is essential, among other things, in the development and the use of various ecology and landscape dynamics models (Heinselman 1981b), in decisions related to fuels management (Raison *et al.* 1983), in the preparation of prescriptions for prescribed or managed fires (Heinselman 1985; Burrows and McCaw 1990), in operational situations to explain or predict fire behavior and its impact on the ecosystem (Raison *et al.* 1983; McNab *et al.* 1978), and at the landscape level to enhance management decisions regarding fire and its relationship to land use (Martin *et al.* 1976). In the specific case of the boreal forest landscape of the Northwest Territories (Canada), where stand age has been reported as a key determinant of fire activity in the landscape (Ward and Mawdsely 2000), that knowledge is essential due to the fact that total fire exclusion is neither economically possible nor ecologically desirable (Ward and Mawdsley 2000; Stocks *et al.* 2003).

It is generally accepted that vegetation biomass accumulates with time after a stand-replacing fire (Brown 1985; Heinselman 1996), an increase that can be attributed to a faster rate of production than of decomposition in the boreal forest. However, not all the biomass of an area can be considered as available fuel (Brown 1975; 1985; Habeck 1985) since only a portion of the combustible material would actually be consumed under specific burning conditions. Consequently it would be erroneous to assume, without further investigation, a successional pattern of fuel accumulation showing a steady increase with time as the correlation of fuels with stand age is not simple due partly to intrinsic cycles of fuel quantities (Brown 1975, 1985; Van Wagner 1979; Heinselman 1996).

Fuel appraisal could be described as viewing forest vegetation from the particular standpoint of its relation to fire behavior (Davis 1959; Brown 1978). Several specific characteristics of the biomass present in a stand at any point in time must be considered when evaluating the fuels such as: fuel quantity, fuel character, and fuel arrangement (Davis 1959; Brown 1978; Pyne *et al.* 1996). Ryan (2002) suggested, as an extension of the fire environment concept, that in ecological studies the fuels be considered in the broader context of the structure of biomass on the site (the quantity, distribution, and horizontal and vertical arrangement of live and dead trees, understory vegetation, woody debris, litter, and humus).

The type of biomass produced is therefore of great importance for fire management applications (Martin *et al.* 1976). A large number of studies found in the literature quantify the biomass of various forest types by separating the material present in the stands into categories that often vary from one study to the other. As useful as the information thus obtained can be for several applications, it is often very difficult to use in fire management since the subdivisions do not consider the properties of the fuels affecting fire behavior.

A few studies have focused specifically on fuel production in various vegetation types and attempted to obtain predictive equations or correlation for fuel properties based mainly on selected stand characteristics, on accumulation and decomposition rates, or on the time elapsed since the last fire. Some obtained relatively good results (e.g., McNab *et al.* 1978; Raison *et al.* 1983; Hély *et al.* 2000; McCaw *et al.* 2002) while others did not (e.g., Muraro 1971; Brown and See 1981) mainly due to the influence of their stands' history on the results, and to the general lack of information on that subject. Other studies presented only a description of the fuels they measured, which constitute nevertheless valuable information considering that in the absence of good correlation, observation and fuel sampling will be used in assessing the fire potential of specific sites (Brown 1975).

To our knowledge, none of these studies considered the fuels dynamics in the jack pine (*Pinus banksiana* Lamb.)/black spruce (*Picea mariana* (Mills.) B.S.P.) forest type. Our goal for this study was to determine the temporal variation in stand structure and fuel characteristics of jack pine/black spruce stands with time since fire in our study area.

METHODOLOGY

Study Area

The study area was located in the Hay River District of the Northwest Territories, Canada. The stands were selected within the rectangular zone delimited by 61° 36' 00" N, 117° 12' 00" W and 61° 03' 06" N, 119° 11' 01" W (Figure 2-1). This area is part of the Upper Mackenzie (B.23a) forest region described by Rowe (1972) and of the Hay River Lowland (64) ecoregion of the Taiga Plains ecozone (Ecological Stratification Working Group 1995). It is classified as having a subhumid mid-boreal ecoclimate and is characterised by short, warm summers and long, cold winters. Its annual temperature varies around -2.5 °C and, on average, the region receives 350-450 mm of precipitation each year (Ecological Stratification Working Group 1995).

High intensity crown fires covering large areas characterise the fire regime of most of the boreal forest (Heinselman 1981a, 1996) and that of our study area. Following the analysis of their Large Fire Data Base (LFDB), Stocks *et al.* (2003) concluded that large fires occurred mostly in the boreal and taiga ecoregions of Canada. More specific to the Taiga Plains ecozone, they reported an average area burned of 366 496 ha, and a percent annual area burned of 0.7%. Their LFDB percent annual area burned for the Hay River Lowland ecoregion fell into the 0.51-1.0 category. Large, high intensity, crown fires were reported by Heathcott and Cornelsen (1992) to be a dominant ecological feature in the jack pine and black spruce forests of Wood Buffalo National Park, located not very far from our region of interest. In fact, large burn areas in given years may be caused by only a few fires in the Northwest Territories (Ward and Mawdsley 2000). An example of this is the Horn Plateau fire, also located in the vicinity of our study area, which covered approximately 1.4 million hectares in 1995.

General Approach

Repeated observations of a same study site over a period of many years can provide a highly specific and unambiguous documentation of ecological succession, but the approach is often limited by the lifetime of the vegetation type studied (Wright and Heinselman 1973; Purchase and La Roi 1983). Thus, the slow growth rate of conifer stands in the boreal forest precluded the use of permanent plots in this study. However, other intrinsic characteristics of the forest type studied made it well suited to a space for time substitution, where a temporal trend is inferred from a study of different aged sites (Pickett 1989).

The technique assumes that spatial vegetational patterns among sites represent temporal vegetation patterns at a fixed site (Jackson *et al.* 1988; Pickett 1989; Wirth *et al.* 1999). The spatial sequence of sites is then assumed to differ only in age and degree of successional development (Jackson *et al.* 1988). In theory, the resulting chronosequence assess the effect of time by holding all other variables constant (Brubaker 1981), but this assumption of environmental and historical constancy is a potential difficulty in such studies (Jackson *et al.* 1988; Pickett 1989). It is however considered valid if the selected stands have developed under comparable climatic and edaphic conditions, and if they share the same disturbance regime (Wirth *et al.* 1999). Although it does not eliminate completely the possibility that other factors could be responsible for some of the variation attributed to time since fire (Burrows and McCaw 1990), a careful selection of sampling areas can minimise it. This approach was selected in several studies that used a chronosequence approach (e.g., Purchase and La Roi 1983; Morneau and Payette 1989; Crowell and Freedman 1994).

Jack pine and black spruce trees have seeds stored in their canopy. After the passage of a fire, those seeds protected by serotinous and semi-serotinous cones are released and usually germinate within a few years of the stand-replacing fire (Heinselman 1973, 1981b, 1996; Rouse 1986). As a consequence, a new even-aged stand is quickly established after the fire and is generally composed of the same dominant species as those present before the disturbance (Davis 1959; Dix and Swan 1971; Methven *et al.* 1975; Heinselman 1973, 1981a, 1981b; Carleton and Maycock 1978; Van Wagner 1979; Payette 1992). The changes observed in the stand as it matures are a reflection of the different growth rates of the species present (Heinselman 1973, 1981b; Methven *et al.* 1975). With careful control of site characteristics to reduce as much as possible influences other than time on the vegetation and the fuels, such even-aged stands of various times-since-fire that share the same disturbance regime can be selected to represent the continuum of temporal stand development. Fuel sampling in those stands will in turn provide valuable information on the temporal variation of the fuels both quantitatively and qualitatively.

For this study we therefore used a chronosequence approach, which we complemented with stem analysis. The integration of those two methods, combined with careful site selection, was chosen to maximise the likelihood of our stands belonging to the same continuum of stand development through the correlation of height with stand age and its use as an indicator of site quality and productivity (Heiberg and White 1956; Carmean 1975; Hägglund 1981).

Stands Selection

Using a map of the soils of the upper Mackenzie River area (Day 1968) and the fire history data available for our study area (fire reports, fire history maps, satellite images, aerial photographs), we made an initial selection of potential sites for the project within most of the Hay River District. This approach was used to compensate for the absence of forest inventory data for the area. We then visited each pre-selected site (the ones with no road access were flown to) and briefly documented it in terms of site characteristics and vegetation.

As a reference point for the chronosequence, we chose the well documented mature jack pine/black spruce stand studied during the International Crown Fire Modelling Experiment (ICFME) (Alexander *et al.* 2004) and also located in the study area. The ICFME forest most closely resembles the jack pine/bearberry lichen (a1.1) plant community type found in the Boreal Highlands Subregion of northern Alberta (Beckingham and Archibald 1996). It is located on beach or glacial lacustrine deposits underlained by lacustrine deposits (Day 1968; Aylsworth *et al.* 2000), in an area generally well drained. The soil has a texture that varies from stony gravelly sandy clay loam to stony gravelly sandy loam.

Our final selection of stands, from among the sites visited, considered the similarity of the selected sites to the characteristics of the ICFME site and was based on the following criteria: (i) strong dominance of jack pine in the overstory, (ii) presence of a spruce component in the understory (investigation at the ICFME site showed that the understory spruce was generally the same age as the overstory pine), (iii) similar growth rates, (iv) no slope, (v) no more than 150m difference in elevation, (vi) similar soils, (vii) charcoal presence in the soil, and (viii) free from obvious disturbance since the last stand-replacing fire. The stands selected (Table 2-1 and Figure 2-1) were located as close together as the fire history of the area permitted and covered the age distribution of postfire stages present in the area for the forest type studied.

Tree Sampling

We used a destructive sampling of jack pine trees to obtain: i) the stem analysis (age/height) data, ii) an approximation of the time elapsed since the last stand-replacing fire in the absence of fire scars, iii) biomass equations for the aboveground tree components and, whenever possible, iv) information about the parent stand. In some stands, black spruce trees were also sampled. To minimise the number of trees harvested and optimise the resources allocated to this very time consuming procedure, we sampled the trees in a way that was compatible with the sampling requirements of each variable. For P10, the raw biomass sampling data collected for the ICFME project by the Canadian Forest Service was used (see Alexander *et al.* 2004), but further tree sampling was nevertheless done in that stand for this project to obtain stem analysis data.

Suitable trees for stem analysis were free-growing, uninjured, dominant jack pine trees showing no major defects or evidence of past suppression of height growth. Those trees were included in our selection covering the range of dbh present in each stand inventoried and were coming from a small portion of each stand having uniform topography and soils. Before being cut, the diameters at the base and at breast height of all the sampled trees were located and measured. Some of the large jack pine trees were also included in the bark flakes (loose pieces of bark present in abundant quantities on the stems of jack pine trees in the area and suspected to contribute to the crown involvement of forest fires) sampling; for these, we also scraped the first section (0-1 m) of each tree with a metal blade and collected the bark on a tarpaulin carefully spread around the base of the tree and sealed to the base of the stem to prevent any loss of bark flakes. The bark thus collected was bagged and brought to the laboratory to be oven-dried and weighed (see below). This extra step on the basal section (section 1) was necessary due to the logging method used on larger trees that could not be cut directly at the base but had to have a notch cut at approximately 0.5 m from the ground before being felled. Once felled, total height and height to the base of the live portion of the crown (live crown base height) of each tree were measured and the stem was sectioned at 0.0 m, 0.1 m, 0.2 m, 0.3 m, 1.0 m, 1.3 m, and 2.0 m above the ground, and at 1 m intervals thereafter up to a minimum stem diameter of 1cm. The height-age data were also obtained for other jack pine and for some black spruce trees in selected stands. Those trees generally covered the height range of the stand. In the case of suppressed trees, the sampling heights were slightly modified to: 0.0 m, 0.1 m, 0.2 m, 0.3 m, 0.5 m, 1.0 m, 1.3 m, 1.5 m, and at 0.5 m intervals thereafter. The diameter of the stem at each of the sampling heights was measured using a diameter tape.

If the tree sampled was used exclusively for stem analysis, a disk was immediately collected from each section and identified on the opposite side from which the rings were to be counted. The disks were brought to the laboratory for further analysis (see below). Otherwise, each section of the tree was limbed and the components were bagged according to the condition of the material collected (live or dead). The bole was either scraped of its bark on site or carefully bagged (to avoid any loss of bark flakes) and brought back to the laboratory for that operation. Care was taken to collect any branch or bark flake that may have fallen from the stem during the careful handling of the tree.

In the laboratory, the bole sections were scraped (when that operation had not been done directly on site) and their loose bark flakes were collected for oven-drying. The intensity of the scraping tried to emulate the effect of a crown fire on the bark flakes of jack pine trees and the samples collected did not constitute the total bark on each section, but the proportion of the bark that had the potential to be involved in a fire due to its nature and position. Although subjective in nature, this procedure was performed by a few people who had had many opportunities to observe crown fires in the study area and the resulting bark on the trees after the disturbance.

The stem sections were then weighed. Disks matching the heights mentioned above were taken from the corresponding section for stem analysis, and one extra disk was taken from each section and weighed to obtain its percent moisture content after oven-drying, an essential procedure to obtain the dry weight of each stem section. The live and dead limbs removed from each section and brought to the laboratory were further sorted into the following categories: needles, cones, live branches 0.0-0.5 cm, live branches 0.6-1.0 cm, live branches 1.1-3.0, live branches 3.1-5.0 cm (when present), dead branches 0-0.5 cm, dead branches 0.6-1.0 cm, dead branches 1.1-3.0, dead branches 3.1-5.0 cm (when present). These diameter classes are the ones adopted by the Canadian Forest Service (McRae *et al.* 1979; Van Wagner 1982). They were also used for the line intersect sampling of the dead and downed woody material (see below) in the stands of our chronosequence. To be sorted in one diameter category, a branch or a portion of a branch had to fit entirely in that category. Since the diameter of a branch often varies along its length, most branches had to be sectioned when their diameter reached the threshold for a given category, and each piece was sorted into its respective category. For each tree section, the different categories were identified, individually oven-dried at 85°C until constant weight was reached, and weighed to obtain their dry weight.

The disks taken along each tree stem were first air dried for several weeks. A belt sander was then used to prepare the samples using sand paper of gradually finer grit, and a disk sander was used to finish the preparation and remove scratches that may have been left in the first stages of the process. The rings on each disk were then counted, along at least three radii, using a binocular microscope. The disk taken at ground level was used for the determination of stand establishment date. The oldest age of the three radii was recorded when the counts differed (Palik and Pregitzer 1995). In the absence of fire scars, we relied on the age structure of the stands to obtain the time since the last fire. The date was established by taking the age of the oldest tree sampled or, in other words, the earliest tree establishment year sampled in the seral age class (Barrett 1994).

For the stem analysis, the true height corresponding to the ring count at a section is almost always located above the cut (Dyer and Bailey 1987). We corrected the heights using the methods suggested by Carmean (1972) by using the following equations (Dyer and Bailey 1987; Newberry 1991):

For the top: $$H_{ij} = h_i + [(h_{i+1} - h_i)/(r_i - r_{i+1} - 0.5)]/2 + (j-1)[(h_{i+1} - h_i)/(r_i - r_{i+1} - 0.5)] \quad (2.1)$$

For all other sections: $$H_{ij} = h_i + [(h_{i+1} - h_i)/(r_i - r_{i+1})]/2 + (j-1)[(h_{i+1} - h_i)/(r_i - r_{i+1})] \quad (2.2)$$

where H_{ij} = estimated total tree height at age t_{ij}, h_i = height at the i^{th} section point, r_i = number of growth rings at the i^{th} section point, and j = growth ring number (assuming the pith as the starting point) $j = 1,\ldots,r_i$.

To confirm our selection of stands for the chronosequence, we used the stem analysis data for three dominant trees on each plot. Those trees had a height and a dbh larger than the 95th percentile, except for P14 where the condition of the snags 5 years after fire was such that only one of the two conditions was met for two of the three trees used in the analyses. Similar to Béland and Bergeron (1996), we did not correct the data through the use of the age at breast height (e.g., Heiberg and White 1956; Schmidt and Carmean 1988) for adverse effects during the establishment period which may result in slow and erratic height growth below breast height, and the age at ground level was used. The average age (from tree ring counts) at each sampled height of the 3 dominant trees in each stand was used to compare the height development of those stands since the last stand-replacing fire. Moreover, a one-way analysis of variance and a Dunnett T3 multiple comparisons test for unequal variances performed on the site index (height at 50 years) obtained from the stem analysis data of the same trees were used to verify that the stands had a same site index. The statistical analyses in this chapter were performed with Minitab 13.0 and Systat 7.0.1 for windows.

Stand Description and Fuel Sampling

We inventoried the ground, surface, ladder, and crown fuels (Figure 2-2) in each of our stands. The sampling methods selected were chosen to be compatible, whenever possible, with the measurements made on the plots of the ICFME project and with the standards of the Canadian Forest Service fire research group (Alexander *et al.* 2004). To ensure the compliance of the fuel inventory work to these restrictions, the data were collected by specially trained personnel having extensive experience of both. Moreover, we collected more information on the fuels of our stands than is currently needed to make predictions using fire behavior models in the hope that (Maxwell and Ward 1981) the extra variables will help in making subjective judgements on fire behavior where formal scientific knowledge is still missing and the information will be useful in linking fire management to other land management activities. Several characteristics of the fuels influence fire behavior. The intrinsic (e.g., chemical composition, heat of combustion, etc.) fuel properties were not specifically sampled for this project since other more variable and less easily quantified properties of the fuel complex have more influence on fire dynamics (Albini 1993). In this project, we focused mainly on the extrinsic fuel properties (e.g., size, live to dead ratio, load, bulk density, arrangement, etc.) and, when needed, relevant approximations for intrinsic fuel properties were obtained from the literature.

In each stand, we located between 23 and 28 sampling points (except for P15 where 8 sampling points were used) systematically, at a fixed 20 m interval, along transects located regularly across, or running diagonally through, the sample area (Figure 2-3). The choice of the layout was determined in each case according to the size and shape of the stand in order to maximise the coverage during the inventory procedure. The starting point of each transect was selected randomly and we used metal pins to mark each sampling point.

One exception was made for the mature stand sampled on the ICFME site where the dead and downed woody material, as well as the overstory and understory tree sampling data collected for plots 4 to 9 (before the fires) and presented in Alexander *et al.* (2004) were combined and used in the description of P10 (below), which explains the larger sample size for some of the data associated with that stand.

Ground Fuels

The ground fuels sampled consisted of the litter (L), fermentation (F), and humus (H) layers of the forest floor present on each site. Three metres left of each sampling point (in the direction of travel), a 10x10 cm square was delimited (Figure 2-3). Using a sharp knife, we sectioned the duff layer into the standard 2-cm depth class intervals (Stocks 1987a, 1987b, 1989; Alexander *et al.* 2004), except for the first two centimetres which were sampled separately (1-cm layers). This method involving a small square surface was used as a compromise between the 30x30 cm sampling frame generally used, and the core sampling method (Woodard and Martin 1980; Nalder and Wein 1998) which was found unsuitable for the ICFME site (Alexander *et al.* 2004). At the four corners of each sampling square, the total depth of the humus layer was measured and those measurements were averaged. Each 1- or 2-cm layer was carefully transferred into a metal tin and sealed. The samples were transported to the laboratory where they were oven-dried at 85°C until constant weight was reached. They were then weighted to obtain their dry weight.

This sampling procedure provided information on the total depth, load (weight per unit area) and bulk density (weight per unit volume) of the whole forest floor, on the bulk density of each layer inventoried, and on the fuel load of the first two centimetres of the forest floor. We used regression analysis to analyse the results of depth, bulk density, and load of the forest floor in response to changing time since fire (individually). A regression was also used between the load of the forest floor as a function of its total average depth. Finally, we used a one-way analysis of variance with contrasts for non-uniform variance to test if there was any significant difference between the values of the total bulk density of the forest floor in recently burned areas and that of the bottom 4-cm layer at the ICFME site (mature stand).

Surface Fuels

The surface fuels measured in each stand were composed of the dead woody material that had accumulated on the forest floor and of the vegetation, other than trees, growing in the understory.

Dead and Downed Woody Material

The dead and downed woody debris were measured using the line intersect method (Van Wagner 1968, 1982; Brown 1974; Brown *et al.* 1982). Sampling lines, 20 m in length, centred on each second sampling point (pin) (Figure 2-3), were located in each stand. Their random orientation was determined using a table of random numbers, insured against a possible orientation bias (Van Wagner 1982) which is likely to be encountered in any stand, but is more probable in young ones due to the windfall of the snags left after a stand-replacing fire. The diameter of each particle at the point of intersection with the 20-m line determined its size class. The classes used were the ones adopted by the Canadian Forest Service (McRae *et al.* 1979; Van Wagner 1982). The measurements were made using a go-no-go gage with openings 0.5, 1.0, 3.0, 5.0, and 7.0 cm. A caliper was used to measure the diameter of any piece of wood with a diameter larger than 7.0 cm that was intersecting the line. The lines were divided into 5-m sections and the depth of the dead and down woody material was measured at the end of each section following Brown (1974).

For consistency, we used the same equations and constants in our calculations as the ones used for calculating the fuel loads in the plots of the ICFME project (Alexander *et al.* 2004). The fuel loads for material with a diameter smaller than 7 cm were therefore calculated with the equation and constants presented in Nalder *et al.* (1999) which were obtained through a sampling performed in the vicinity of our study area. For the larger pieces of wood we used the equation presented by Delisle and Woodard (1988) and the constants were taken form Nalder *et al.* (1999) and Brown (1974). The slope correction factor was not taken into consideration since all the sites were located on flat terrain.

Finally, the percent cover of the dead and down woody material was calculated by summing the diameter of all the pieces crossing the line (the central value of the classes were used for material less than 7.0 cm in diameter), dividing that number by the length of the line, and multiplying the result by 100.

Surface Vegetation

A 1 x 1 m quadrat located 3 m right of each pin (in the direction of travel) was used to inventory the surface vegetation (Figure 2-3). The percent cover, to the nearest 1%, of the species present in each quadrat was first determined through an ocular estimate (facilitated by the 10-cm subdivisions on each side of the square) and their average height was measured with a metric ruler. The surface vegetation was identified in the field using for reference Johnson *et al.* (1995) and Porsild and Cody (1980). Only the most aboundant mosses and lichens were identified. At each second pin, all the vegetation (except for mosses and lichens, which were included in the duff samples) was harvested by clipping it at ground level and sorted into herbs or shrubs. At the end of the day, all the samples were brought to the laboratory and oven dried at 85°C until constant weight was reached. Their dry weight was taken and fuel loads were calculated. In stands less than 5 years since fire, tree seedlings were also inventoried in the 1-m^2 quadrats. They were counted by species to determine their density, and their height was measured. Besides the usual analysis of cover and height, we also calculated the Shannon diversity index and the Equitability (or evenness) in each stand as measures of species diversity, as well as the Czekanowski coefficient which we used as an indication of similarity between our stands. All formulas (2.3 to 2.5) were taken from Kent and Coker (1992).

The Shannon diversity index was obtained by:

$$H' = -\sum p_i \cdot \ln(p_i) \tag{2.3}$$

where the summation is over the number of species (s), p_i is the proportion of individuals or the abundance of the ith species expressed as a proportion to total cover, and ln is the natural logarithm. Averaged covers for each stand were used to calculate this index and only ground vegetation species were used in its calculation (no tree species).

The Equitability (or evenness) was calculated using:

$$J = \frac{\sum p_i \cdot \ln(p_i)}{\ln(s)} \tag{2.4}$$

Finally, the Czekanowski coefficient, which considers both the number of species and their abundance, was calculated between all pairs of stands. That coefficient ranges from 0 (complete dissimilarity) to 1 (total similarity) and was obtained by:

$$S_c = \frac{2 \cdot \sum \min(X_i, Y_i)}{\sum X_i + \sum Y_i} \tag{2.5}$$

where the summation is over the number of species, Xi and Yi are the abundance of species i in each stand, and Σ min (Xi, Yi) is the sum of the lesser scores of species i where it occurs in both stands.

Crown and Ladder Fuels

The overstory trees were inventoried using the point-centered quarter method (Cottam and Curtis 1956). At each pin (Figure 2-3), the area around the point was divided into four quadrants. In each of them, the distance to the nearest tree having a diameter at breast height (dbh) of at least 3 cm was measured. The total height and live crown base height were measured on the four trees using a Suunto clinometer, and the dbh was obtained using a diameter tape. Finally, the species and condition (live or dead) of each tree sampled were noted. The understory trees (dbh smaller than 3 cm) were inventoried at alternate pins using a 2-m radius circular plot (Figure 2-3). The same measurements were taken on those trees, but the diameter at the base of the tree was taken, instead of the dbh, when the total height was less than 1.3 m. The percent canopy cover was measured in each stand by using a convex spherical densiometer (Lemmon 1957) at each pin. Those measurements allowed us to obtain the density, basal area, average height, average live crown base height, and average dbh for the live and dead trees of all species present in our stands, and the summation of those values for the entire stands.

The destructive sampling (see section on tree sampling) of jack pine trees in three stands of different times since fire (P12: 21 years since fire, P11: 57 years since fire, and P10: 71 years since fire) allowed us to treat separately the following six fuel components at strategic times during stand development: needles, bark flakes, live branches (<0.5 and 0.5-1.0 cm in diameter), and dead branches (<0.5 and 0.5-1.0 cm in diameter). For each crown fuel component sampled and some combinations of them (see results section), we used the linear form (Ln (y) = a + b Ln(x), corrected for bias following Baskerville (1972)) of the allometric equation $y = c\, x^d$ to obtain the total dry weight (g) per tree (y) as a function of the diameter at breast height (dbh) of the tree (x) in cm (or its diameter at ground level (dgl) for the black spruce trees with a height less than 1.3 m). That procedure had the advantage of correcting for the increasing variance with diameter size frequently observed in our stands.

Due to limited resources, we assumed that the biomass components of the suppressed spruce trees growing in the understory of all the plots were following the same relations with dbh and dsh as those at P10 (the ICFME site) since they were all growing on similar sites, under comparable environmental conditions, and were included in the range of diameters and height sampled for that stand. Dead jack pine trees were also only sampled for P10 (ICFME site). A look at the data collected indicated that the weight of the fine fuels component of dead trees (the dead branches of 0-0.5 and 0.5-1.0 cm in diameter) were similar to the sum of the live and dead branches of live jack pine trees in each size category (Figure 2-4). We therefore used that relation in the other plots instead of sampling dead jack pine trees. We also used that assumption on black spruce trees. To calculate the weight of the dead stems, a correction factor calculated from the live and the dead jack pine stems at the ICFME site was used.

To obtain the vertical distribution of the crown fuels, we first grouped the range of diameters at breast height present on each plot into 2-cm diameter classes and the central value of each class was used to obtain the total dry weight per tree for each fuel component and combination of fuel components using the regression equations of the total dry weight per tree as a function of dbh (or DGL for black spruce trees with a height less than 1.3 m) obtained previously.

The following step was to distribute that total weight vertically for each fuel component and combination of fuel components. Most of the work published on the vertical distribution of biomass in a forest stand can be classified into three general approaches, which are sometimes combined. The first approach uses an averaging procedure where, for each dbh class, the average dry weight of a component is obtained from the sample trees for each vertical section (e.g., Schreuder and Swank 1974). The second one involves regressions of, for example, the dry weight or a fraction of the total dry weight by crown segment, whorl, or branch as a function of variables such as height or fraction of total crown height (e.g., Kinerson *et al.* 1974; Ek 1979; Snell and Max 1985; Hashimoto 1990, 1991; Gillespie *et al.* 1994; Gilmore and Seymour 1997). In the third method, the dry weight of a fuel component is distributed vertically into a tree or a stand according to an assumed or calculated distribution model (e.g., Stephens 1969; Kinerson and Fritschen 1971; Sando and Wick 1972; Gary 1978; Beadle *et al.* 1982; Hagihara and Hozumi 1986; Maguire and Bennett 1996; Baldwin *et al.* 1997; Xu and Harrington 1998).

The second approach was selected since it suited the study's sampling methodology and the general stand characteristics. Moreover, it allowed for the extrapolations necessary for the few stems present in the plots that had a dbh larger than that of the trees that were destructively sampled for the tree crown biomass estimation. It also had the advantage of requiring a smaller sample size of trees in each diameter class compared to the first approach. Its main advantage over the third approach was to simplify the analysis since the structure of all the stands in the chronosequence was somewhat complex with its two layers consisting of a jack pine overstory and a black spruce understory.

In order to distribute vertically the total dry weight per tree of the individual fuel components, we therefore obtained, for each 1-m section of each sampled tree, the ratio of the cumulative dry weight (from the crown apex) of each component (or combination of fuel components) to its total dry weight for the tree (*RW*). The ratio of the corresponding length along the tree to the total tree height (*RH*) was also obtained. Those two variables, with values between 0 and 1, were fitted to the following curve form:

$$RW = \frac{a}{1 + \exp(b - c(RH))} \tag{2.6}$$

where a, b, and c are parameters. Using equation 2.8, the variable RW of each fuel component was then calculated for each 1-m height section of the diameter classes. This cumulative value was transformed into the fraction of the total dry weight per section and multiplied by the total dry weight of the corresponding fuel component for the tree to obtain the sectional dry weight. Finally, using the tree inventory data for each plot, the stem density per 2-cm diameter class of the live and dead jack pine and black spruce trees was calculated and multiplied by the corresponding dry weight per tree of each fuel component in each section. The results, summed over the diameter classes and converted into kg/m^2, provided the vertical distribution of the fuel load per plot, for each fuel component. Due to the length of each section (1 m) it also conveniently provided the bulk density for each section in kg/m^3.

For the stands where no biomass sampling was done, we used the relations obtained for a sampled stand having a similar time since the last fire. Thus, we used the regression equations derived for stand P11 on P15 and P16, and those obtained for P10 on P13 (see Table 2-1 for general information on each stand). For the stands that had recently burnt (P4-P9, P14), the procedure was slightly different. We used the regression equations obtained for P10 (since the parent stand was mature and approximately the same age as P10 when it burnt) but applied a correction factor for the overstory and understory combustion of the crown fuels during a crown fire. Those were obtained from the results presented in Stocks *et al.* (2004).

The steps used to obtain the vertical distribution of the crown fuels are summarised in Figure 2-5,

Total Fuels and Stand Structure

Our final step was to combine and contrast all the biomass and fine fuel information obtained for individual fuel strata, for which the relation against time since fire was investigated. The ground, surface, and crown fuel loads were added together to obtain the total and the vertical distribution of biomass and fine fuels, and the percentage of fine fuels was also calculated. The process used to derive those quantities is detailed in Figure 2-6. The relationship between the fuels present in each stratum and time since fire was examined in light of that in the other strata and general conclusions were drawn from those results on the structure of the stands with time since fire and on the characteristics of the fine fuels.

Visual Documentation

An important aspect of fuel sampling is a visual documentation of the stands visited. A pictorial catalogue facilitates the visual association of the fuels sampled to other complexes where a fire is expected to burn similarly (Muraro 1971).

For this project, we developed such a catalogue by taking pictures in each plot inventoried. A representative portion of the stand was selected in the area of fuel assessment. Single and stereo photographs were taken using a 35-mm Sony digital camera. The extra time needed to take the three-dimensional image provided by the stereophotos was considered justified by the improvement they provide in the ability to appraise the fuel and the structure of the stands (Ottmar and Vihnanek 1998). A 1.8 m (6 foot) pole, with 30.5-cm (1-foot) sections painted alternately in contrasting (black and white) colors, was located 10 m in front of the camera to serve as a reference and provide scale. General guidelines presented by Maxwell (1980), Fischer (1981), and Ottmar and Vihnanek (1998) were taken into consideration whenever applicable.

RESULTS AND DISCUSSION

Stands Selected

The 13 stands selected for this project (Table 2-1) were between 1 and 108 years since the last stand-replacing fire and covered the age distribution of the post-fire stages present in the area for the forest type studied. Similarly to Visser (1995) in Wood Buffalo National Park, our extended efforts to find stands originating from the 1945-1980 period and belonging to the forest type studied was unsuccessful. We also had a similar limitation with stands being between 6 and 21 years since fire, age range for which only one stand free of post-fire human disturbance was found. Nevertheless, the chronosequence covered the four general physiognomic stages identified by Oliver (1981) and Oliver and Larson (1996): the stand initiation stage, the stem exclusion stage, the stand understory reinitiation stage, and the old growth stage (approximately 0-17, 18-40, 41-85, and 85-110 years since fire or more, respectively). It also covered the post establishment, canopy-development, mature stand, and senescence periods of Heinselman (1996). All the areas sampled on the ICFME site for this project (P4-P10) were considered as individual stands since they were all originating from a different stand-replacing crown fire.

With the exception of the ICFME site, located approximately 40 kilometres north-east of the community of Fort Providence, all the stands selected were located on the south side of the Mackenzie River. The stands were located as close together as the fire history of the area permitted. The maximum difference in elevation between them was approximately 65 m (Table 2-1), based on 1:250 000 scale topographic maps of the area.

The average age (from tree ring counts) at each sampled height of the 3 dominant trees in each stand indicated that all the stands except one had been following a similar height development since the last stand-replacing fire. Stand P15 showed a different (in shape and values) curve (Figure 2-7) which indicated that the data obtained from that area had to be looked at carefully, since it may not have belonged to the same chronosequence as the other ones. The dissimilarity resembled that observed by Béland and Bergeron (1996) between a moderately dry sandy site and their other sites. The former showed a growth delay similar to what we observed in P15 early during stand development.

The one-way analysis of variance performed on the site index (height at 50 years) obtained from the stem analysis data of the same trees showed that at least one of the sites had a site index that was different ($p < 0.001$) than the others (Table 2-2). The Dunnett T3 multiple comparisons test for unequal variances however indicated that only the site index of P15 was different from that of the other stands (from ICFME site (P10) and from P11 (almost the same time since fire)). Although the trees sampled for stem analysis were not randomly selected in the field, their selection was only based on the criteria mentioned in the methodology and we had no way of knowing the height/age curve of each tree before the analysis of the tree rings in the laboratory. We are therefore confident that this semi-random selection had no influence on our results.

Due to the differences observed between P15 and the other stands, the inventory data for that stand were kept for comparison purposes, but were not included in our analyses due to the possibility that P15 may not have been part of the same chronosequence as the other stands inventoried. The curve for P15 in Figure 2-7 indicated that the stand may join the curve for the ICFME within the next 20 years. This stresses the importance of looking at the growth pattern with time and not only at the height of a stand for a given time since fire (or site index) since that information can be misleading when used alone. Polymorphism in height growth of species covering wide ranges is common among areas differing greatly in climate, soil, topography, and site quality (Carmean 1975; Carmean *et al.* 1989) and sites of both similar and different site index can sometimes show different age-related growth trends (Stage 1963; Carmean 1975; Béland and Bergeron 1996).

The mean site index for our plots (excluding P15) was 13.2 m at 50 years. This site index would be in Plonski's site class 3 and in the low productivity class (site index <14 m) used by Béland and Bergeron (1996) in their study area and observed for shallow organic soils, for shallow well-drained tills, and for fluvioglacial sands.

The stand identified as P12, being too young for the calculation of a site index at 50 years (the snags could not be used as for P14 since they had already fallen to the ground and started to rot), was not included in the ANOVA and the subsequent multiple comparisons. However, a graphic representation of the curve (Figure 2-7) showed that the growth rate of that stand was following closely that of the stand at the ICFME site (and therefore that of the other stands) and it was therefore considered in the chronosequence. We also plotted the stem analysis data for all the trees (covering most of the height range observed in each stand) sampled in P10 and P12 (Figure 2-8) and confirmed that the tallest sampled tree at any time in both stands followed a similar curve through stand development. Moreover, the height distribution of the jack pine stems through time was similar for both stands, except for suppressed trees in P12 which did not appear in P10 probably because they died during stand development due to self thinning at a younger age. More variation was however noted for black spruce trees growing in the understory of both stands, but this was to be expected due to the less uniform growth of that species caused by its suppressed position.

Fire history has often been identified as an unknown variable that precludes the derivation of reliable regression equations between time since fire and different fuel characteristics (Muraro 1971; Brown 1975). Information on fire history was available for several of our stands (P4-P9, P12, P14) where a high intensity crown fire in a mature stand was confirmed by on-site observations of fire behavior and/or by the remains of the parent stand after the disturbance. For the other stands, no direct information was available regarding the fire history of the area other than the charcoal in the forest floor and the burnt logs or stumps. However, considering the fire regime in the area and the absence of fire scars on the trees in the stands sampled, it appeared likely that they all originated from a high intensity crown fire.

The structure and composition of the different stands selected for the chronosequence is presented in the following sections, and a photo-series of the chronosequence has been placed in Appendix 1 of this document.

<u>Ground Fuels</u>

Depth

Our sampling method allowed us to obtain information on three characteristics of the forest floor in each stand: depth, bulk density and fuel load. Results on the first one, the average depth of the ground fuels (considered here as the portion from the top of the forest floor down to the mineral soils), are presented in Figure 2-9 as a function of time since fire. The average depth of the forest floor steadily increased with time after a stand-replacing crown fire in our chronosequence. A linear regression showed that 86% of variation in the average depth of the forest floor was explained by time since fire. The slope of the regression line suggested an accumulation rate of 0.098 cm per year (95% confidence interval: 0.071, 0.125) in the forest type studied. The intercept 2.001 (95% confidence interval: 0.789, 3.213) corresponded to the remaining duff generally observed at the ICFME site after the passage of a crown fire (Stocks *et al.* 2004). Accumulation of organic matter on the forest floor in areas with short dry summers and long cold winters has been mentioned in several publications (e.g., Bray and Gorham 1964; Rowe and Scotter 1973). The accumulation rate obtained for our study area is slightly higher than the 1 to 3 inches (2.5 to 7.6 cm) mentioned by Heinselman (1996) for the first 100 years after fire in northeastern Minnesota, located further south.

Table 2-3 provides more details on the average forest floor depth measured in each stand of the chronosequence. Similar to Muraro (1971) and to Barney *et al.* (1981), within stand standard deviation was quite high and, in our case, generally increased with time since fire. Despite the large standard deviation in our forest floor depth data, the ratio of standard error to the mean (Table 2-4) was on average 10% (it varied between 5% and 16%) in all stands. The variation in the average depth of the forest floor among the very young stands was probably more a function of the recent fire behavior and the associated consumption of the forest floor than a consequence of time, since the recent fire history did not allow for much accumulation or decomposition of the forest floor. The average depth measured for P15 was slightly below that of the other two stands of similar time since fire, although the difference does not appear to be significant when looking at the confidence intervals of the average depth of P15 and P11. The difference in depth between P11 and P16 was quite large and may have been the result of a difference in the time of the year or in moisture content of the forest floor at the time of burn (Henselman 1981a) which would have removed less material in P16. That information is unfortunately not available for the stands of our chronosequence that are 56 and 57 years old since the last stand-replacing fire that burnt through each of those areas was not documented, to our knowledge, in a fire report or other similar archive document.

The forest floor depths measured in our chronosequence were much higher than those reported by Visser (1995) in jack pine stands of different ages in Wood Buffalo National Park. However, they were generally similar to those of the stands younger than 60 years old inventoried by Purchase and La Roi (1983) in Alberta, but higher than the depth in their older stands. Similarly, the values we obtained were close to those presented by Stocks (1987b) for an immature (27-33 years) jack pine stand in Ontario but larger than the values he obtained for a mature stand (Stocks 1989). Nevertheless, the depth of 6.9 cm obtained by both Loomis (1977) in jack pine stands 70-105 years in Minnesota, and Miyanishi and Johnson (2002) in jack pine/black spruce stands 90-120 years in Saskatchewan, were in agreement with our data.

Bulk Density

The compaction of the forest floor, generally referred to as its bulk density (unit weight per unit volume), is one of the factors affecting depth of burn and the probability of sustained smouldering (Wade 1986, Hartford 1989). We looked at that variable from two perspectives: the bulk density of the whole forest floor profile, and the individual bulk density of layers of pre-defined thickness (1- or 2-cm) composing the same profile. Figure 2-10 shows the total average bulk density measured in each stand. The data were not corrected for inorganic content but estimates of corrected values can be obtained by using the inorganic content measured for the ICFME project (Alexander *et al.* 2004). The general decrease in total average bulk density with time since fire observed in our data was due in part to the addition of organic matter with time (as shown previously), which provided a larger denominator in the calculation of the bulk density (weight/depth), and to the fact that needles, feathermoss and lichen generally start to be present after some time in that forest type. Those components are generally lighter (smaller numerator) than the decomposing material present in the lower portion of the forest floor in mature stands, which is also are present right at the surface and form the whole profile down to the mineral soil in recently burnt stands.

More within-stand variability in total average bulk density was observed in the young stands, as shown by the confidence interval presented for each data point (average per plot) in Figure 2-10 and the decreasing standard deviation of the total average bulk density with time since fire in Table 2-5. The ratio of standard error to the mean (Table 2-4) remained however between 5% and 14% in our stands. Similar observations on the standard deviation and standard error of the mean were reported by Barney *et al.* (1981) in Alaska. A linear regression indicated that the total average bulk density of the forest floor in those recently burnt stands varied around 201.1 kg/m^3 (95% confidence interval: 174.5, 227.7), a quantity that gradually decreased by approximately 1.1 kg/m^3 (95% confidence interval: -1.7, -0.5) each year thereafter. Time since fire explained 65% the variation in the total average bulk density of the forest floor in our chronosequence. The average bulk density obtained for the stand P15 was significantly lower than that of the other two plots of similar time since fire (P11 and P16) as show by the confidence intervals in Figure 2-10. Values obtained for P11 and P16 were very similar for that variable.

It is worth noting that in the case of the total average bulk density and average depth of the forest floor, an exponential regression model could have well described the relationship between the variables in our chronosequence but its performance was slightly less than that of the linear model when using the standard error and the correlation coefficient as ranking measures. The increased complexity of the exponential model compared to the linear model also made it less attractive to use.

Our data on the average bulk density of individual layers of the forest floor profile (Figure 2-11 and Table 2-5) presented interesting characteristics when the recent burns were compared with the other stands in our chronosequence. During at least the first 5 years after a stand-replacing crown fire (stands P4-P9 and P14), the bulk density generally decreased or remained the same through the profile while later during stand development (P10-P13 and P15-P16) the bulk density increased with depth. Those observations suggested that we should exercise caution when generalising results showing an increase of the bulk density with depth (e.g., Kasischke *et al.* 2000) as they may not apply to stands in their early development after a stand-replacing crown fire. The average bulk density values observed for recently burnt plots are similar to those of the lower layers of mature plots (for example ICFME P10). A one-way ANOVA with contrasts for non-uniform variance actually showed no difference between the values of the total bulk density of the forest floor in the recently burnt areas (1-5 years since fire) and that of the bottom 4-cm layer at the ICFME site (Table 2-6).

This result was not surprising considering that fire generally burned a portion of the forest floor in those stands, leaving exposed what was previously the lower layer of the humus. The latter is therefore the same as the lower layer of the mature stand, with maybe a higher content of inorganic material that may have accumulated there if it was present in the top layer that burnt and did not contribute to the combustion (which could be the topic of a further study). This could also explain the higher bulk density of the top layer in some of the recently burnt areas. In the more mature stands (P11-P13, and P15-P16), the lower bulk density closer to the surface was due to the presence of needles, moss or lichen on the forest floor. Within that group, plots with more needles had a higher bulk density (e.g., P12) at the surface, while plots with a continuous carpet of feather moss had a lower bulk density for that same layer (e.g. P13). The bulk density values we obtained are similar to those obtained in other parts of Canada and Alaska (see Barney *et al.* (1981) for a table presenting comparison of mean bulk densities from several locations and sources).

Load

The last characteristic of the ground fuels that was assessed was the fuel load (Table 2-3). Although a linear regression described satisfactorily the relation between the bulk density or the depth of the forest floor and time since fire, it was not the case for the total fuel load. A nonlinear regression fitted to the allometric equation ($y=ax^b$) or to its equivalent linear form ($\ln(y) = a + b \ln(x)$, corrected for bias (Baskerville 1972) was more appropriate in that case. We used the latter, and the linear regression applied on the natural logarithm of both the dependent and the independent variables (Figure 2-12) showed that 79% of the variation in the average natural logarithm load of the forest floor was explained by the natural logarithm of time since fire ($p < 0.001$). Based on the regression results it appeared that the fuel load gradually increased with time since fire in our chronosequence, albeit at a gradually slower rate when the stands reached maturity where it started to level off after 50 years. P16 had a very high fuel load compared to the other stands with a similar time since fire (in this case P11 and P15 were not significantly different based on their confidence interval) and the inclusion of this stand in the regression resulted in the lack of linearity in the relation. Without P16, a linear equation described well the relation between load and time since fire (with an R^2 of 0.83) with an average increase in the forest floor load of 0.065 kg/m^2 per year.

Most forest floor loads obtained from the literature for jack pine stands of different time since fire (e.g., Van Wagner 1972; Stocks 1987b, 1989) were generally lower than the ones obtained in this study, which is located further north. Surprisingly, Chrosciewicz (1989) had a higher average load under canopy for stands 48-50 years in Alberta, although the values he obtained in openings were similar to the ones in this study. It is possible however that our stands correspond more to spruce stands due to the high density of spruce in the understory, or have characteristics that are somewhere between those of pure spruce and pure pine stands. In fact, the forest floor loads we obtained were slightly lower than those obtained by Barney *et al.* (1981) for spruce in Alaska. As for the average load measured for the first 2 cm of forest floor of the stands composing our chronosequence (Table 2-3), the values were generally similar to the corresponding ones obtained by MacLean and Wein (1977a) for the L-layer in stands 13-57 years and were slightly lower than those obtained by Barney *et al.* (1981) in the L-layer of their spruce stands.

The standard deviation of the average forest floor load generally increased with time and varied between 0.9 and 6.8 kg/m^2. However, the ratio of standard error to the mean (Table 2-4) remained between 8% and 14% in our stands.

Finally, several authors (e.g. Muraro 1971; Woodard and Martin 1980; Barney *et al.* 1981; Harrington 1986) mentioned a relationship between forest floor depth and loading. Having measured both variables at each plot, we were also able to investigate that relation for the forest type studied in this project. Using the natural logarithm form of the allometric equation to homogenise the variance, we performed a linear regression between these two variables. Figure 2-13 shows the results of the analysis and the relation between the average depth and the average fuel load of the forest floor along the chronosequence. The linear regression applied on the natural logarithm of both the dependent and the independent variables showed that 91% of the variation in the fuel load of the forest floor was explained by its depth in the chronosequence. The equation obtained here should however be used with caution (see discussion in Harrington (1986)).

Surface Fuels

Dead and Downed Woody Material

The first surface fuels considered in this project were the dead and downed woody material. Those were the dead twigs, branches, stems, and boles of trees and shrubs that had fallen and were lying on or near the ground (Brown 1974, Brown and Thomas 1981). Their average total fuel load is presented in Figure 2-14 as a function of time since fire. The initial quantity of dead and downed woody material present after a stand-replacing fire appeared to be quite variable, with loads ranging between 0.6 and 1.7 kg/m^2 during the first five years of stand development. Those values covered the range of values for loads in the mature portion of the chronosequence. Considering the very short time elapsed since fire in those very young stands, the variability observed between them was probably a function of the dead and downed woody material in their parent stand, of the fire behavior and the related disturbance-generated debris, and of wind events in the first few years after the fire. Loadings then increased and reached a maximum sometime in the juvenile period (probably around 20 years since fire), when the snags left after the fire had mostly fallen to the ground. Harmon and Sexton (1996) mentioned that the middle stages of succession often have the minimum woody detritus stores. We also observed that the total average loads during the period around 50-60 years were low in our chronosequence, although lower quantities were reached around 110 years when the logs laying on the forest floor were completely covered by moss and were therefore not included in the line intersect sampling. We suspect that a second increase in dead and downed woody material occurs between 70 and 90 years since fire. Evidence for it comes in part from the sampling done in P10 (71 years since fire), where the total average load was slightly higher than that of the stands immediately younger or older, but also from the remarkably high quantity of large woody material buried (and therefore not included in the line intersect sampling) in the thick moss carpet of P13 (109 years since fire). Larsen and Macdonald (1998) found evidence that it took less than 70 years for black spruce to replace jack pine as the local dominant in two stands of the same forest type in Wood Buffalo National Park. Heinselman (1996) observed that the gradual senescence of dominant trees begins at about 100 years when fire fails to return in jack pine/black spruce stands of the Boundary Waters Canoe Area Wilderness ecosystem in northeastern Minnesota, U.S.A. The increase in dead and downed woody material would then come from dying jack pine trees that are being replaced by spruce in the main canopy. The pattern where loadings are high in the juvenile period, drop during the immature and early maturity period, and rise during the late maturity period was characterised by Brown and See (1981) as the one that is most commonly encountered in forest types that begin after a high intensity fire.

The standard deviation was relatively constant through the chronosequence and varied around 0.6 kg/m^2, with the exception of the 5 and 21 year-old stands. There, the standard deviation calculated on the total load of the dead and downed woody material was between two and three times that obtained for the other stands of the chronosequence. This was mainly caused by the large quantity of logs on the forest floor (see discussion on the large woody debris, below) that were distributed unevenly. The ratio of standard error to the mean (Table 2-4) was between 6% and 29% in our stands for the total load of the dead and downed woody debris.

Looking more specifically at some of the size classes sampled, several authors (e.g., Fahnestock 1976; Habeck 1985; Johnson *et al.* 1998) have mentioned that fine fuel loadings among the dead and downed woody material do not show an apparent effect of stand age and are relatively constant through time. We made the same observation for the forest type studied here, where the dead and downed woody material smaller than 1 cm was varying around 0.065 kg/m^2 in all the stands sampled except the very young ones (3 years since fire and less), where that quantity was 10 times less abundant with a fuel load of approximately 0.007 kg/m^2 (Figure 2-15). This can be explained by the fact that the crown fire burnt most of the fine fuels that were available at the time, including those located in the canopy. This removed any source of fine fuels that otherwise could have increased the fine dead and downed fuel load in the immediate years after the disturbance. Nevertheless, after 5 years the fuel load of fine dead and downed woody material was already similar to that encountered in more mature stands.

The temporal distribution pattern of coarse woody debris (our 7.0+ cm class) followed closely that of the total dead and downed fuels mentioned above (Figure 2-16). We did not observe the U-shape curve often mentioned in the literature (Romme 1982; Agee and Huff 1987; Spies *et al.* 1988; Sturtevant *et al.* 1997) for different forest types. This may however have been a consequence of the distribution of "time since fire" in our chronosequence, its temporal resolution. If, for example, 30-year groupings had been used instead of the actual distribution, a high quantity of coarse woody debris would have been observed for the first 0-30 year period following disturbance. The amount of debris would have then declined over time to reach a minimum (between 31 and 60 years) when inputs from the growing stand would have been too small to qualify in that category. Later in the chronosequence (between 61-90 years) the large dead and downed woody material would have started to increase again as a consequence of mortality due to competition and small scale disturbance to eventually peak a second time as the stand started a senescence period with pine being gradually replaced by spruce in the overstory. Another decline may then have appeared as a result of the new stand structure, assuming that those very old stands (fire usually burns a stand before it reaches that age in our study area) would had been considered on their own and not grouped with the senescing stands. This process, described in details by several authors (e.g. Spies and Franklin 1988; Sturtevant *et al.* 1997), would then have described well the dynamics of the coarse woody debris in our stand and would have qualified for the U-shaped curve instead of the M-shaped one we observed.

In the first few years after fire, the between-stand variability in fuel load of the large woody material was quite high in our chronosequence. The loads covered most of the range observed in the mature stage of stand development. This was not unexpected since both the characteristics of the pre-disturbance stand and of the disturbance itself (Harmon *et al.* 1986) are major factors affecting the large woody material on the forest floor at that time. Strong winds generated by the high intensity crown fire can contribute to the fall of some trees. Moreover, the large pieces of wood are not generally consumed much in the flaming zone of the fire front but they can smoulder after its passage and burn partially or completely, thus reducing the load of that size class. After that first period, during the juvenile stage of the chronosequence, the large dead and downed woody material increased sharply to reach a maximum approximately 20 years after fire, when almost all the snags had fallen to the ground. We noted very high within-stand variability at that time due to the distribution of the logs on the forest floor. Those tended to be grouped, probably due to a "domino" effect where one (or more) snags, falling due to wind or decay at their base, led others in their fall. The load of the large woody material then decreased over the next thirty years, the persistence of this class of material being affected by the climate and the species decay rate (Muller and Liu 1991). There then would have been no, or little, input of material at least 7.0 cm in diameter due to the absence of trees of this size in the growing young stand. Only small suppressed trees dying as a consequence of the self-thinning in the dense stand were added to the dead and downed woody material at that time. Later, as the stand matured and grew, large woody material increased again as described previously. Similarly to Muller and Liu (1991), the correlation between stand basal area and load of large woody debris was poor in our chronosequence.

Although they are not generally discussed in the literature, we also looked at the other size classes of dead wood sampled (Table 2-7 and Figure 2-17). The dead and downed woody material between 1.0 and 2.99 cm in diameter gradually increased with time since fire during the first part of the stand development, reached their maximum between 50 and 55 years, probably due to the input from the young self-thinning stand, and later decreased to approximately their initial quantity. A linear regression with time and time^2 explained 81% of the variation observed in the data ($y = -0.00006x^2 + 0.0063x + 0.0997$). Fuels between 3 and 5 cm, and those between 5 and 7 cm did not show any significant trend during stand development, although in the first case the older stand (108 years since fire) had a lower quantity than the other stands considering the 95% confidence intervals. Once again, no relation was observed between the total basal area (nor between the basal area of live or dead trees) and the fuel load in any category. In our mature stands, the loadings we obtained in the different size classes of dead and downed woody material were very similar to those measured by Quintilio *et al.* (1977) in Alberta, except for the diameter class 0-0.5 cm which had a larger load in their study.

The total average percent cover of the dead and downed woody material (Table 2-8, Figure 2-18) generally increased through time until approximately 20 years since the stand-replacing crown fire, following the gradual falling of the snags left after the fire. It then decreased in a more gradual manner during stand development. The average percent cover for P15 was not significantly different than that of the other two plots of the same time since fire. Our data showed that the contribution of each diameter size class to the total average percent cover varied through time similarly to that of the fuel load, although in different proportions. In particular, the fine fuels, considered here as the dead and downed woody material less than 1 cm in diameter, increased by a factor of ten between 3 and 5 years since fire, and remained relatively constant thereafter. Figure 2-19 shows the fraction of the total average percent cover by diameter class.

The average depth of the dead and downed woody material was 10.0 cm in all the plots measured but P14, where it reached 27.1 cm.

Understory Vegetation

The fuel load of the understory vegetation appeared to be closely related to the development and the dynamics of the overstory tree canopy (Figure 2-20). This was probably due to the effects of canopy cover, one of the most important overstory characteristics for understory vegetation (MacLean and Wein 1977b). In our forest type, the vegetation generally started to reappear on the forest floor only a few weeks after fire, an occurrence also observed in Alaska by Dyrness and Norum (1983). The vegetation on the forest floor was however very patchy and in small abundance in the first few years after the fire. The plants gradually reinvaded the sites and increased in their coverage of the area while the new stand was getting established. The maximum average fuel load measured in our clip plots was in P14, five years after fire. However, a gap existed in our data between that time and 21 years since fire indicating that there is a possibility of an increase after five years, even if 21 years after fire the fuel load had diminished considerably. That decrease was most likely due to stand closure and the increase in needle cover on the forest floor caused by the self-thinning and self-pruning of the very dense young pine stand. The average total fuel load of the surface vegetation continued to decrease slightly after crown closure to reach a temporarily constant level around 40 years after fire. The fuel remained around 0.035 kg/m^2 during the remainder of the mature stage, until senescence was reached and the jack pine trees started to die to be replaced by spruce trees in the overstory. The gaps thus created allowed more light to reach the forest floor, changing the microclimate and providing good conditions for understory plants to grow. Their fuel load had actually increased to 0.126 kg/m^2 by 108 years since the last fire in our chronosequence. The shape of the curve was similar for both herbs and shrubs (although the fuel loads were different) except for the oldest stand where the herbs remained constant but the shrubs increased to almost the same levels as in the early stage of the stand development (5 years since fire) (Table 2-9). The shrubs in P15 had a similar fuel load as that of other stands of that age, but the quantity of herbs was significantly higher. The patchiness in the understory vegetation of young and old stands was noted as very high within-stand variability and high standard deviations at those times.

The temporal variation of the fuel load contributed by the understory vegetation (herbs and shrubs) was similar to the one observed in several other studies where high initial loads were recorded a few years after a fire, followed by a rapid decrease at the time of crown closure, stabilisation in the mature stage at lower quantities, and a second increase later during stand development (e.g., Martin *et al.* 1976; MacLean and Wein 1977b; Alaback 1982). Brown and See (1981) however mentioned that cover and biomass of herbaceous vegetation and shrubs can either increase or decrease during stand development depending on site conditions, species present before the fire, and the nature of the disturbance. Depth of burn may be particularly important for understory vegetation (Schimmel and Granström 1996).

After reviewing the literature on the topic, Zavitkovski (1976) noted that in the early part of stand development the biomass of ground vegetation averaged about 0.161 kg/m^2 in coniferous forests of pines and Douglas-fir while it was 0.038 kg/m^2 in late successional coniferous forests of spruce, fir, and redwood. Those values compare well to those measured in the present study, although our maximum value recorded in young stands reached 0.235 kg/m^2. Our values are also similar to values of 0.020 to 0.050 kg/m^2 after one growing season, 0.090 to 0.165 kg/m^2 after two growing seasons, and 0.110 to 0.175 kg/m^2 after three growing seasons obtained by Dyrness and Norum (1983) in lightly and heavily burnt plots (respectively) in Alaska. After consulting the literature, Alaback (1982) mentioned that herb and shrub production generally peaked between 15-25 years. We could not directly rule out the age of 15 years in our study area due to the gap in the chronology of our stands between 5 and 21 years, but our data suggested that this maximum probably occurred a few years before 21 years since fire in our forest type. Looking at the loads obtained by Nalder and Wein (1999) for pure jack pine stands of different ages in the Northwest Territories (their zone 2), we could further assume that the maximum would occur before 16 years, age at which the authors had values slightly lower than the ones we measured in P14 five years after fire. The loads obtained by Nalder and Wein (1999) for shrubs and ground vegetation were similar to those measured in this study when confidence intervals were taken into consideration, with the exception of their 30 year old stand which showed very high values compared to ours. The proportion of shrubs/herbs was also different in several stands of similar age. This might however be due to the presence of black spruce in the understory of our stands.

The total percent cover per category of understory vegetation is presented in Table 2-10. Of the species encountered in our stands, several were present throughout the chronosequence while others were specific to early or late stages of stand development. Focusing on the species covering an average of one percent or more in at least one of the stands inventoried (Table 2-11), we observed that *Arctostaphylos uva-ursi, Carex spp., Cornus canadensis, Galium trifidum,* Grass (undifferentiated), and *Linnaea borealis* were the main herbs present at each stage of stand development, while for the shrubs it was *Potentilla fruticosa, Rosa acicularis, Salix spp.*, and *Shepherdia canadensis*. Those species that were encountered only at the beginning of stand development were *Aster puniceus, Epilobium angustifolium* (although its presence was noted in stand P15 which was not considered as part of the chronosequence), *Geranium bicknellii*, and

Ceratodon purpereus. Species that only appeared later in the chronosequence were mainly lichen and moss species such as *Cladina rangiferina, Peltigera aphthosa, Aulacomnium palustre, Dicranum spp., Hylocomium splendens*, and *Pleurozium schreberi*. A few shrubs also appeared in later stages of stand development such as *Alnus crispa, Juniperus communis and Viburnum edule*. Very similar observations were made by Purchase and La Roi (1983) and Visser (1995) in northern Alberta and many of those species were recorded as having very high presence values in other boreal conifer ecosystems across Canada and Alaska (e.g., La Roi 1967; Foote 1983).

The Shannon diversity index, which considers both the number of species and their proportion of total cover, was similar throughout the chronosequence with values varying generally between 2 and 2.5 (Table 2-12). One exception was however noted in the oldest stand where the index abruptly decreased to 1.5. The equitability or evenness calculated showed a similar trend with values generally oscillating between 0.6 and 0.8 throughout stand development but becoming 0.43 in the oldest stand (Table 2-12). This was probably due to the deep carpet of feathermoss present in P13 and its interference with the growth of many other species generally encountered earlier during stand development. Those values (Shannon diversity index and evenness) are in general slightly higher than those obtained by Purchase and La Roi (1983) in northern Alberta but are similar to the ones reported by Légaré *et al.* (2001) for their boreal jack pine cover type in north-western Quebec. The Czekanowski coefficient of percent similarity between stands (Table 2-13) was, as expected, generally higher between those stands that were closer together in terms of time since fire.

Finally, the average and maximum height of the different vegetation categories observed in the stands of our chronosequence are presented in Table 2-14. Moss and lichen generally increased in average height, while the herbs decreased with time since fire. The shrubs were more variable with an increase at the beginning of the chronosequence, a decrease in its mature stage, and another increase when the stand became old and started to have openings due to the death of jack pine trees.

Crown and Ladder Fuels

In order to adequately describe the crown and ladder fuels of the stands inventoried, we first obtained their basic characteristics, summarised in Tables 2-15 to 2-18, and then used them in combination with the data from the destructive sampling of trees to obtain the total average biomass and fine fuel load, density, and vertical distribution.

General Dendrometric Data

Tree density, obtained from a combination of three different sampling methods (PCQ for trees with a dbh of at least 3.0 cm, 2-m radius plot for trees with a dbh smaller than 3.0 cm, and $1 m^2$ plot for seedlings), is presented in Table 2-15 for the stands of our chronosequence. Overall, tree density decreased with time since fire. The more pronounced changes happened at the beginning of stand development, during that period between stand establishment and crown closure. A similar observation was made by Visser (1995). During the first two years after the fire, seedling densities were quite high and varied between 88,800 and 790,870 seedlings per hectare. Massive seedling establishment in the first years after a fire usually occurs in species with serotinous and semi-serotinous cones such as jack pine and black spruce (Payette 1992). Initial densities of 30,000 to over 50,000 seedlings per hectare were reported by Weber *et al.* (1987) while Brown (1975) mentioned a high density of 121,406 seedlings per hectare (300,000 seedlings per acre) in stands described by Mason (1915). A high initial density of seedlings can result in 16,000 jack pine stems per hectare by age 20, and 1000 stems per hectare 65 years after a high intensity fire (Weber 1988). Those are lower densities than the ones measured in the present project but they nevertheless follow the general trend we observed for the jack pine component of our stands. Methven *et al.* (1975) looked at the regeneration on four different fires and obtained total densities between 158,000 and 352,000 stems/ha after one year, between 13,000 and 88,000 stems/ha after 4 years (no jack pine), between 25,750 and 33,350 stems/ha after 14 years, and a density of 20,880 stems/ha after 45 years in what was mainly jack pine/black spruce stands (other species such as *Populus tremuloides*, *Betula papyrifera* and *Abies blasamea* were sometime present and were included in those numbers). Those values are similar to the densities obtained in the present study. Our plots in the two 1-year-old stands did not show the presence of black spruce seedlings but that species was present in all the other stands of the chronosequence.

The snags left after the stand-replacing fire remained standing for approximately two decades, after which only a few very large stems were still present and widely spaced in the stand. Similarly to Keen (1955), rate of fall was slow at least for the first three to five years in our chronosequence. Weaknesses in the structural integrity of the snags had however started to appear by that time, mostly within the first metre from the ground, and could be observed on several stems (Figure 2-21). Snag fall rates are a function of size (diameter and height), species, cause of mortality, season of mortality, and microenvironment (Morrison and Raphael 1993; Everett *et al.* 1999). Nalder and Wein (1999) mentioned that jack pine snags often do not fall for 10-20 years after fire, while Heinselman (1981b) reported that snags last 20-50 years in the north and will fall within 15-20 years in the Lake Superior Region (Heinselman 1978; 1996). In Montana, Lyon (1977) observed that nearly all snags less than 7.6 cm (3 inches) dbh fell at a rate of 27.9 % and were down in 15 years while those larger than 8 cm dbh fell at an annual rate of 8.4% in the Sleeping Child Burn where the dominant species was lodgepole pine. Average fall rates can however be misleading since the relationship is not linear and snags can fall faster when critical decay levels are reached (Everett *et al.* 1999).

At the time of stand closure, the high density of jack pine trees in the overstory lead to an increase in dead stems that were not originating from the fire. Stand P12 appeared to be in the process of self thinning and had a high proportion of dead saplings, likely due to the intensification of competition (density-induced mortality). Yarranton and Yarranton (1975) observed a similar increase in the mortality rate of jack pine trees from 18 to 47 years after fire, while in Carleton's (1982) study self-thinning did not occur until the stand was approximately 30 years old.

In terms of basal area (Table 2-15), the live component of the stands increased linearly with time, time since fire explaining 95% of the variation observed in our chronosequence. Immediately after the stand-replacing crown fire, the dead fraction of the total basal area was 100%. It then decreased sharply until approximately 20 years since fire, when it reached a minimum. That period coincided with the time where all the snags resulting from the fire had fallen to the ground and when the only dead trees left standing were those that died due to self-thinning. The dead portion of the total basal area later increased gradually to about 20% of the total basal area when the stand reached maturity and began to decline.

Other stand characteristics such as height, live crown base height, and diameter at breast height generally increased with time following the pattern of growth of the trees during stand development (Tables 2-16 and 2-17). The temporal variation in the average stand height in our chronosequence indicated that a height of 3.7 to 4.1 m should be expected in that forest type between 13 and 15 years since fire, a height associated by Weber *et al.* (1987) to high intensity crown fires of at least 17 000 kW/m. Percent canopy cover being a function of the number of trees and their size, it increased in the first stage of stand development until crown closure and decreased thereafter probably due to self-thinning. It however started to increase again as the spruce started to replace the trees in the overstory (Table 2-18). This pattern was quite different than that reported by MacLean and Wein (1977b) where young stands (13 and 16 years old) had low crown covers while their 10 stands older than 29 years had a relatively constant crown cover. It was however similar to the crown cover values reported by Purchase and La Roi (1983) in their jack pine stands of northern Alberta. Percent canopy cover was, on average, 18% in the first five years after a stand-replacing fire. This value was due to the cover created by the standing snags. It seems reasonable to assume that percent canopy cover generally decreases sometime between 5 and 21 years since fire as the snags gradually fall down to the ground and before tree height has increased enough to be included in the canopy and considered in the measurement of that variable.

This would however have to be verified as no stands between 5 and 21 years since fire were included in our chronosequence.

Loads of Fine and Total Crown Components

Our selection of stands P11, P12, and P10 for the destructive sampling was supported by our need to obtain information on the biomass and the fuels during the entire period covered by our chronosequence. Using the data collected on those three stands, we were able to do so, with the exception of the oldest stand (P13, 108 years since fire) for which the equations derived for P10 were used to avoid any unnecessary disturbance to the site since stands of that age are not often found in that area. The regression equations (and related information) obtained for the biomass of the different tree components in each stand are presented in Tables 2-19 to 2-22, while those for the vertical distribution of the tree components are presented in Tables 2-23 to 2-26. Similar to Alban and Laidly (1982), the equations we obtained for branches were generally not as good as those for the other tree components, especially in the case of larger or dead branches. The equations for P10 are a variant of those obtained by Alexander *et al.* (2004) using nonlinear regression, and are based on the data collected for the ICFME project by the Canadian Forest Service.

Most of our equations are difficult to compare with others found in the literature due to the different categories of tree components selected. However, the biomass equation for total aboveground tree biomass as a function of dbh (or dbh and height) is usually provided in most papers on the topic. We therefore selected it and compared, in Figure 2-22, the equation we obtained for P10 and P11 to several others found in the literature. Although the equation for P11 is similar to (but provides slightly lower values than) several others, the one for P10 is quite distinct and could not have been replaced by any equation found in the literature, even the one obtained by Singh (1984) in the Northwest Territories. Age and density may be a factor in the differences between the curves, but in most of the other studies the equations were derived for pure jack pine stands. It is therefore possible that the presence of black spruce in our stands had an influence on the biomass of the jack pine trees. Effects of companion species on the growth of jack pine trees have been reported in the literature (e.g., Longpré *et al.* 1994).

The loads (mass per surface area) of fine and total tree components per species are presented in Table 2-27 for all the stands of the chronosequence. Total average load varied between 3.8 and 28.4 kg/m^2 while that of the fine tree components was between 0.1 and 3.7 kg/m^2. The total average load contributed by the trees first decreased after the stand-replacing crown fire. That trend lasted approximately until the period where canopy closure occurred and was then replaced by an increase in the quantity with time. A linear relation was noted between the total tree load and the basal area of the stands (Figure 2-23). Basal area explained 94% of the variance observed in the total load of the trees in the stands of our chronosequence and an increase of 1 m^2/ha in basal area showed an increase of 0.876 kg/m^2 in tree load. The linear relation with basal area instead of time since fire was mainly caused by the presence of a high density of snags in the early years after fire and the fact that the bole and large branches contribute a high percentage to the weight of a tree. Trees killed in a crown fire are seldom entirely consumed (Heinselman 1981b; Kasischke *et al.* 1995; Heinselman 1996). While the needles, twigs, small branches and bark flakes burn, the larger branches and the standing stem remain on site for some time. Another factor explaining the good relation between basal area and tree load is that they are both related to the dbh of the trees. When we only considered the portion of the chronosequence between 21 and 108 years (after the total attrition of the snags) a linear relation was present between total tree load and time since fire. Time since fire then explained 90% of the variation observed in total tree load with average increments of 0.298 kg/m^2 per year.

The fine tree components (needles, bark, live and dead branches 0-1 cm in diameter) increased steadily with time since fire (Figure 2-24). Time explained 95 % of the variance in that linear relation and the load of the fine tree components increased, on average, by 0.035 kg/m^2 each year along our chronosequence. Since the total load of the trees and that of their fine components did not vary similarly with time, it followed that the proportion of fine tree components in the canopy also varied with time since fire. It was very low in the first years after fire, with values between 0.8 to 1.6 %. It then increased at the time of crown closure and for at least 30 years varied between 23 and 29% in the immature stand to finally reach a value of 13% at maturity.

In the jack pine portion of the stands the fine fuels varied between 0.1 and 1.5 kg/m^2. The loads of the mature stands were similar, although slightly higher when the exact age of each stand and the limits of size classes were considered, to the fine fuels measured by Quintilio *et al.* (1977) in the jack pine stand of the Darwin Lake project, in northeastern Alberta. The difference may be due to the lower density and basal area in their stands.

The needles unsurprisingly occupied an important portion of the total load of the fine tree components in jack pine trees. We however observed that bark flakes grew in importance with time to reach quantities higher than those of the needles when the stand reached maturity. The ratio of bark flake to needle loads increased with time in our chronosequence following a sigmoidal (S-shaped) curve (Figure 2-25). After approximately 65 years, the load of the bark flakes became more important than that of the needles. The increase in quantity and flakiness of the bark with time can also be noted in Figure 2-26. Interestingly, needle and bark flake loads appeared to complement each other in the vertical distribution of the fine fuels (Figure 2-27). Larger loads of needles were generally present in the top portion of the trees while bark flakes took over lower along the stem, when the needles started to be less abundant (at the general level of the live crown base height). Overall, those two tree components were responsible for a relatively constant load of fine fuels with height as the stands of our chronosequence became more mature.

Considering those results and even factoring in for the possibility that the bark flake quantity removed from the boles during the sampling may have been slightly higher than what is usually consumed by fire in that forest type (further research is needed on that topic), it appeared that bark flakes may be more important then previously thought in those forests. Although bark flakes were reported among the fine fuels generally consumed in a crown fire or were noted as effective ladder fuels (Figure 2-28) on several occasions (e.g., Quintilio *et al.* 1977; Heinselman 1981b; Taylor *et al.* 2004; ICFME project, personal observation), they are never considered in the calculation of the fuels consumed in a fire or that of the fire intensity. Moreover, they are seldom explicitly considered in the evaluation of spotting potential and their contribution to the onset of crowning and the ensuing crown fire behavior is unknown in Canada. In Australia crowning, spotting, and suppression difficulty have been related to bark hazard (McCaw *et al.* 1992; Burrows *et al.* 2001; Catchpole 2002) in some forests. Guides were produced to help with the assessment of that hazard (e.g., Wilson 1992; McCarthy *et al.* 1998). Values of bark loads between 0.3 and 0.5 kg/m^2 were reported in some Australian forests as being available to, or consumed by, fires (McCaw *et al.* 1992; Burrows *et al.* 2001). Although those examples do not cover the extent of the Australian literature on the topic, they provide an interesting comparison basis with the 0.2 to 0.5 kg/m2 obtained for bark flakes in this study.

The occurrence of black spruce in the understory of jack pine or lodgepole pine stands has been reported across Canada (e.g., Hamilton and Krause 1985; St-Pierre *et al.* 1992; Methven *et al.* 1975; Stocks 1989; Kenkel 1986; Sims *et al.* 1990; Scotter 1963; Chrosciewicz 1983; Alexander *et al.* 2004). Three patterns of black spruce influx into the subcanopy of jack pine were identified by Carleton (1982): a gradual influx over a long time span in the oldest stands, an invasion of black spruce cohorts following surface fire activity, and a contemporaneous post-fire reestablishment of both species similar to what we observed in our chronosequence. It has long been recognised (e.g., Brown 1975; Van Wagner 1977; Brown and See 1981; Heinselman 1978, 1996) that the presence of black spruce growing below the jack pine crown may provide vertical continuity and increase crown fire potential.

The added fine fuel load contributed by the black spruce to the stand can be seen by comparing Figures 2-27 and 2-29. The first of those graphs show the vertical distribution of the fine fuels contributed by the jack pine only, while both jack pine and black spruce are included in the data presented in the second graph (note the different scale for load and bulk density in the two graphs). Sando and Wick (1972) assumed that a value of 0.037 kg/m^3 (100 pounds per acre per foot) was the amount of fuel required to support combustion vertically. A more detailed discussion on crown fire potential will be presented in Chapter 6, but we can say at the moment that the bulk density of the fine components in the crowns of our stands was higher than that value in most of the crown profile before the stands reached 21 years since fire in our chronosequence. Most biomass studies do not refer to understory trees and cannot be directly compared to our results. Agee (1983) however presented interesting results on the fuel weights of understory-grown conifers in Oregon. Unfortunately, his results are not directly comparable with the ones presented here due in part to a different sampling strategy and to very different stand compositions. The fine fuel load contributed by black spruce varied between 0.0 to 2.2 kg/m^2 in our chronosequence.

Total Fuels and Stand Structure

Combining the results of our analyses for the different fuel layers, we were able to summarise the biomass information in terms of quantity and distribution through the stands of the chronosequence (Figure 2-30). From a load of approximately 20 kg/m^2 immediately after a stand-replacing crown fire, the load of the total biomass (excluding roots) decreased during the first stage of stand development. This is in accordance with the hypothesis of Bormann and Likens (1979) that stand biomass increments should be negative for a short period following major disturbances. The decrease in biomass lasted past the crown closure stage (approximately 17 years since fire), well into the stem exclusion stage (between approximately 18 and 40 years since fire). The decay of the snags that had gradually fallen to the ground, combined with the decrease in the understory vegetation and the presence of a relatively high density of small trees were most likely accountable for that decrease in total biomass load and for the low value of 11 kg/m^2 it reached at 21 years since fire. After that period, the quantity steadily increased with time to reach almost 40 kg/m^2 by the age of 108 years. Pearson *et al.* (1987) observed maximum total biomass accumulation rates between 40 and 60 years in even-aged lodgepole pine forests of Wyoming; this corresponds with the period when the same was observed in our chronosequence.

Fuel is the only portion of the biomass that will burn and contribute to combustion (Brown 1975; Brown 1985), and the quantity of forest biomass is not necessarily the same as that of the forest fuels (Brown and Thomas 1981). That is why we also identified that portion of the total biomass that is generally considered to be fine fuels and quantified it in our chronosequence. Due to their size, these fuels have a high potential for burning although the amount of biomass that is available for combustion (the available fuels) also depends on other factors such as their arrangement, moisture content, and intrinsic characteristics, as well as on the prevailing environmental conditions.

Since the temporal variation of the fine fuels does not necessarily follow that of the total forest biomass and because each fuel component may change differently (Brown 1975; Brown and Thomas 1981), we were not surprised to observe that the fine fuels did not follow the same trend (Figure 2-30) as the one depicted for the total forest biomass in our chronosequence. After an initial period where their fuel load was very low (on average 0.2 kg/m^2) due to the recent passage of the fire and the still patchy vegetation reinvading the site, it then gradually increased to reach a relatively constant level oscillating around 4.3 kg/m^2 after approximately 50 years. However, the contribution of each fuel layer to the total fine fuel load varied with time, as seen in Figure 2-31.

By definition, a fire burns all material combustible under the prevailing conditions and reduces them to ash (Heinselman 1978). Consequently the fine fuel load contributed by each fuel layer (ground, surface, crown) was relatively low in our young stands (after a high intensity, stand-replacing, crown fire). Those quantities later diverged and followed their own temporal course. Thus the surface fuels, as represented by the understory vegetation and the dead and downed woody material, contributed only a very small amount to the total load of the fine fuels during most of the stand development. The distinction of those two fractions, dead and living fuels, is important as their moisture regimes are different. The live component of the surface fuels was higher than the dead one during the first 20 years of stand development, a situation also observed later in the senescing stand (approximately 85 to 110 years after fire). Between those two periods the dead and downed woody material fine fuel load was higher than that of the surface vegetation except 21 years after fire, when both quantities were equal. The load of the top portion of the ground fuels generally involved in a fire (composed of live and dead components such as needles, moss, lichen, and duff) increased early during stand development, reached a maximum between 20 and 60 years and decreased slowly after that. The top portion of the ground fuels and the surface fuels are important determinants of the fire behavior and the intensity of the fire in those fuels will partly determine if crown involvement is likely. Another important factor is the quantity of the fine fuels in the tree canopy, which steadily increased with time since fire in our chronosequence. When the crown and ladder fine fuels are not included in the total fine fuels, the curve does not remain constant after 50 years but starts to decrease from approximately 2.0 kg/m^2 (the maximum fine fuel load reached when the crown fuels are not included) to 0.9 kg/m^2 at 108 years (Figure 2-32). It is important to note at this point that the burning conditions will determine what portion of the fine fuel loads described above will burn, as well as the reduction that will occur in larger fuels not quantified here but included in the total stand biomass.

The difference between the dynamics of the total biomass *versus* that of the fine fuels resulted in the percentage of fine fuels on a square-metre basis fluctuating through stand development (Figure 2-33). Being very close to zero immediately after a stand-replacing fire, it increased sharply to reach a maximum probably between 25 and 30% approximately 30 years after the disturbance. The percentage of fine fuels then gradually decreased with time since fire to reach what appears to be a plateau varying around 12% at maturity (after approximately 65 to 70 years).

Knowing the quantity of fuels is not sufficient to understand the potential differences in fire behavior with time since fire. It is also important to look at the structure of those fuels as well (Mutch 1970). The vertical distribution (1-m sections) of the load and bulk density of the fine fuels and total stand biomass (excluding roots) is presented Table 2-28. That representation provided insight into the importance of the interacting fuel layers often mentioned in the literature (e.g., Davis 1959; Muraro 1971; Van Wagner 1979), although it only considers the quantity of biomass and fine fuels and not all the important fuel properties for predicting fire behavior (Davis 1959; Brown 1975, 1978; Van Wagner 1979; Christensen 1993): moisture content, particle size, quantity, compactness, arrangement, continuity, inorganic content, and organic chemical characteristics.

Overall, a vertical continuity of the fine fuels from the ground layer to the crown of the trees could already be observed 21 years after fire and remained present through stand development. The bridge (ladder fuels) between the surface and crown fuels may have followed the development of the trees but we were not able to confirm this due to the absence of stands between 5 and 21 years since fire in our chronosequence. The total forest biomass load generally decreased with increasing height in the canopy anywhere along the chronosequence.

Summary of Stand and Fuel Dynamics in the Chronosequence

A qualitative description of the chronosequence appears to be an ideal way to wrap up the information obtained in this part of the project aiming at describing the temporal development of the vegetation and the fuels in the jack pine/black spruce forest type of our study area. Immediately after a stand-replacing crown fire in a jack pine/black spruce stand, only snags and some duff remain in our study area. All the available fuels have been consumed. Some vegetation then begins to appear, sometimes only a few weeks after the disturbance. The herbs and shrubs are nevertheless very patchy and remain so for at least the first 3 years following fire. The discontinuities in surface vegetation are, at that time, bridged by the compact duff remaining after the fire. High densities of tree seedlings also start to appear in the first few years after the fire. Their species are the same as the ones observed before the disturbance due to the presence of serotinous and semi-serotinous cones. Although the live fuels gradually increase at that time, most of the dead fuels not consumed in the fire are large logs on the ground and standing snags holding medium to large branches. With time, the trees grow and a new canopy is formed. This period also coincides with the gradual falling of the snags. After 20 years all the snags are on the ground and the tree density has declined considerably due to high mortality rates early during stand development. The dead trees standing are now much smaller and originate from the new stand. They still hold small branches and, sometimes, dead needles. After crown closure, the surface vegetation decreases considerably and most of the forest floor is now covered by pine needles. Small spruce trees grow slowly in the understory. That situation remains for a few years, although mortality decreases with time as conditions change in the stands. The large woody debris then gradually decay and the lower density stand grows in height. Feather mosses and lichens gradually become more abundant on the forest floor. The spruce trees grow at different rates below the pine, depending on local conditions, and contribute to the vertical continuity of the fuels in the canopy. The stand then reaches maturity and from approximately 40 to 70 years keeps relatively constant conditions in terms of surface fuels. The ground and crown biomass nevertheless continues to increase with the thickening of the forest floor and the continual increase in tree biomass. Towards the end of that period a gradual senescence appears in the stand. Jack pine trees start to die if fire has not returned by then, and the stand starts to break up. This creates an increase in the load of dead and downed woody material. With time the gradual decline in pine abundance continues and the spruce starts to dominate in the stand. The surface vegetation takes advantage of the conditions created by the openings in the canopy and its biomass (load) increases, especially that of the shrubs. Eventually the fallen jack pine trees are integrated into the deep moss and are only apparent as mounds on the forest floor. Although site quality and latitude may influence forest biomass and fuel accumulation (Mutch 1970; Heinselman 1978), this description is very similar to the one presented by Heinselman (1996) for the jack pine/black spruce stands in the more southerly near-boreal upland conifer forest of the Boundary Waters Canoe Area Wilderness ecosystem in northeastern Minnesota, U.S.A.

SUMMARY AND CONCLUSION

Through the sampling done in this project, we defined one of the first chronosequence focusing on fuel development in the northern boreal forest. Extended work was done on the biomass and fine fuel quantification in all the stands' fuel strata, leading to unique vertical fine fuel and total biomass profiles. The sampling even included some fuels, such as bark flakes, that are generally ignored in fuel quantification although they are suspected to contribute significantly to fire behavior. The detailed description of the fuels in each stand provided, by itself, valuable information for fire management purposes. Because the data collection was performed to be compatible with several fire behavior models currently available, it also had the potential of being valuable in near real time fire behavior forecasting and simulation modelling. The description of the "fuels" portion of the fire environement as a function of time since fire was the first step in the appraisal of the forest type studied in terms of potential fire behavior and flammability.

More specifically, the goal of this study was to determine the temporal variation in stand structure and fuel characteristics of a jack pine stand having a black spruce understory. The 12 stands of our chronosequence were inventoried by fuel strata and the results were first presented as such. They were later combined and their vertical arrangement was presented to provide a more encompassing view of the fuel situation as it varied with time since fire.

Our main results for the ground fuels indicated an increase in average depth and average load of the forest floor with time since fire in our chronosequence. The average bulk density showed a different relation with time and decreased during stand development. Interestingly, the bulk density of recently burnt stands was not significantly different than that of the lower duff layer in mature stands. Our data on the average bulk density of individual layers of the forest floor profile also indicated that for at least the first 5 years after a stand-replacing crown fire the bulk density generally decreased or remained the same through the profile, while later during stand development the bulk density increased with depth. Those observations suggested that we should exercise caution when generalising results showing an increase of the bulk density with depth. Finally, a linear regression applied on the natural logarithm of both the dependent and the independent variables showed that 91% of the variation in the fuel load of the forest floor was explained by its depth in the chronosequence.

Two categories of surface fuels were considered in our analyses: the dead and downed woody material and the surface vegetation. In both cases, the relation with time since fire was not as straightforward as the one observed for the ground fuels. We first looked at the dead and downed woody material. The initial average load of dead and downed woody material present after a stand-replacing fire appeared to be quite variable and covered most of the loads observed in the mature portion of the chronosequence. That quantity started to increase with time after a few years and was relatively high after 20 years, when the snags left after the fire had mostly fallen on the ground. A decrease in the total average load of the woody debris was then observed, with the lowest quantities occurring during the period around 50-60 years. A second increase in dead and downed woody material was noted between 70 and 90 years since fire but the pieces of wood were later incorporated into the deep moss layer and our sampling indicated that biomass of coarse downed wood was considerably lower 108 years after fire.

The portion of the total load contributed by the fine fuels (dead and downed woody material with a diameter less than 1.0 cm) remained relatively constant with time, except in the early years following a stand-replacing crown fire. The dynamics of the surface vegetation were different than for the dead surface fuels. Vegetation started to reappear on the forest floor only a few weeks after fire but was very patchy and in small abundance in the first few years after the fire. The plants gradually reinvaded the sites and increased in their coverage of the area, while the new stand was getting established. The maximum average fuel load measured in our clip plots was at five years after fire. However, a gap existed in our data between that time and 21 years since fire such that we cannot know whether there is a possibility of an increase after five years, even if 21 years after fire the fuel load had diminished considerably. The average total fuel load of the surface vegetation continued to decrease slightly after crown closure to reach a temporarily constant level around 40 years after fire. When the stand reached senescence, the jack pine trees started to die and were replaced by spruce trees in the overstory. The gaps thus created would have changed the microclimate and provided good conditions for understory plants to grow, and their biomass increased. Of the species encountered in our stands, several were present throughout the chronosequence while others were specific to early or late stages of stand development.

Finally, the crown fuels were assessed. This was first done through a general description of the stands as a function of time since fire. Overall, tree density decreased with time since fire. The more pronounced changes happened at the beginning of stand development, during that period between stand establishment and crown closure (approximately 17 years since fire). The snags left after the stand-replacing fire remained standing for approximately two decades, after which only a few very large stems were still present and widely spaced in the stand. The rate of fall was slow at least for the first three to five years in our chronosequence but weaknesses in the structural integrity of the snags started to appear at that time. In terms of basal area, the live component of the stands increased linearly with time while the dead fraction decreased sharply until approximately 20 years since fire, when it reached a minimum, and later increased gradually to about 20% of the total basal area; when the stand reached maturity it began to decline. Other stand characteristics such as height, live crown base height, and diameter at breast height generally increased with time following the growth of the trees during stand development.

Biomass equations as a function of diameter at breast height were developed for several tree components in stands of three different times since fire. The total average load contributed by the trees first decreased after the stand-replacing crown fire. That trend lasted approximately until the period where canopy closure occurred and was then replaced by an increase in the quantity with time. A linear relation was noted between the total tree load and the basal area of the stands for the whole chronosequence, and between total tree load and time since fire when only the period between 21 (after all the snags had fallen to the ground) and 108 years was considered. The fine tree components (needles, bark flakes, live and dead branches 0-1 cm in diameter) increased steadily with time since fire in our chronosequence. The ratio of bark flake to needle loads increased with time, following a sigmoidal (S-shaped) curve. After approximately 65 years, the load of the bark became more important than that of the needles. Both tree components complemented each other in the vertical distribution of the fine fuels. Larger loads of needles were generally present in the top portion of the trees while bark flakes took over lower along the stem, when the needles started to be less abundant (at the general level of the live crown base height). Overall, those two tree components were responsible for a relatively constant load of fine fuels with height as the stands of our chronosequence became more mature. This brought to our attention the fact that the contribution of bark flakes may be underestimated in fires occurring in jack pine stands. Black spruce growing in the understory of the stands inventoried had high fine fuel loads and also contributed to the vertical continuity of the fuels through time in our chronosequence.

Combining the information collected for each fuel layer, we were able to describe how the total stand biomass (excluding roots) varied with time in our chronosequence. From a load of approximately 20 kg/m^2 immediately after a stand-replacing crown fire, it decreased during the first stage of stand development and reached the low value of 11 kg/m^2 at 21 years since fire. After that period, the quantity steadily increased with time to reach approximately 29 kg/m^2 by 71 years since fire, and almost 40 kg/m^2 by the age of 108 years (although in general few stands reach that age in our study area). The fine fuels did not, however, follow the same trend. After an initial period where their fuel load was very low (on average 0.2 kg/m^2) due to the recent passage of the fire and the still patchy vegetation reinvading the site, it gradually increased to reach a relatively constant level oscillating around 4.3 kg/m^2 after approximately 50 years. The contribution of each fuel layer to the total fine fuel load varied with time. The live component of the surface fuels was higher than the dead one during the first 20 years of stand development, a situation also observed later in the senescing stand (approximately 90 to 100 years after fire). Between those two periods the dead and downed woody material fine fuel load was higher than that of the surface vegetation except 21 years after fire, when both quantities were equal. The load of the top portion of the ground fuels generally involved in a fire (composed of live and dead components such as needles, moss, lichen, and duff) increased early during stand development, reached a maximum between 20 and 60 years and decreased slowly after that. The fine fuels in the tree canopy steadily increased with time since fire in our chronosequence. When the crown fine fuels were not included in the total fine fuels, the curve did not remain constant after 50 years but decreased from approximately 2.0 kg/m^2 to 0.9 kg/m^2 at 108 years. The difference between the dynamics of the total biomass versus that of the fine fuels resulted in the percentage of fine fuels on a square-metre basis fluctuating through stand development. Being very close to zero immediately after a stand-replacing fire, it increased sharply to reach a maximum approximately 30 years after the disturbance. The percentage of fine fuels then gradually decreased with time since fire to reach what appears to be a plateau at maturity, after approximately 65 to 70 years. Overall, vertical continuity of the fine fuels from the ground layer to the crown of the trees could already be observed 21 years after fire and remained present through stand development. The total forest biomass load generally decreased with increasing height anywhere along the chronosequence.

Fuel appraisal is more than only a fuel characterisation process; it also involves an interpretation of the fuel description in terms of fire behavior (Anderson 1974; Brown *et al.* 1977; Brown 1978). The first part of the fuel appraisal process was performed in this chapter. The second will be carried out in the remaining chapters where a description of the fire weather, the fire danger and the general fire potential conditions of the study area will first be done. That description will then be combined with the fuel information to make assessments of potential fire behavior and flammability through stand development using experimental fires, expert opinion, and fire behavior models.

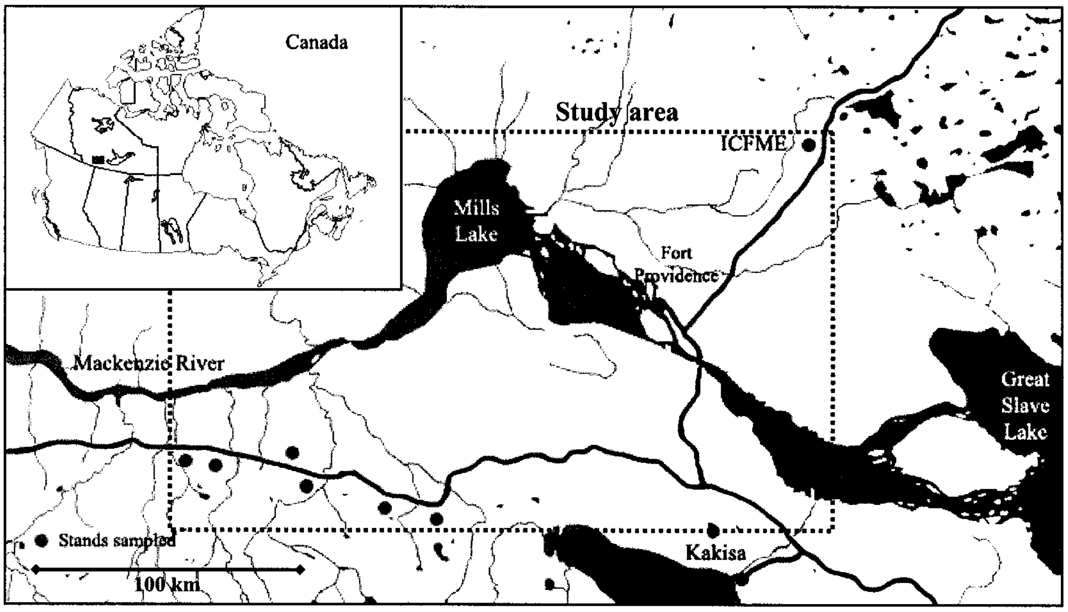


Figure 2-1. Map of the study area located in the Northwest Territories, Canada. The red dots show the approximate location of the stands sampled.

Table 2-1. General characteristics of the stands composing the chronosequence.

Stand #	TSF	Location		Elevation
		Latitude	Longitude	(m)
P4	1	61° 36' N	117° 12' W	195
P9	1	61° 36' N	117° 12' W	195
P7	2	61° 36' N	117° 12' W	195
P8	2	61° 36' N	117° 12' W	195
P5	3	61° 36' N	117° 12' W	195
P6	3	61° 36' N	117° 12' W	195
P14	5	61° 09' N	119° 05' W	260
P12	21	61° 06' N	118° 50' W	250
P16	56	61° 03' N	118° 23' W	260
P11	57	61° 05' N	118° 44' W	240
P15	57	61° 04' N	118° 32' W	255
P10	71	61° 36' N	117° 12' W	195
P13	108	61° 08' N	119° 11' W	245

Note: TSF = time since fire

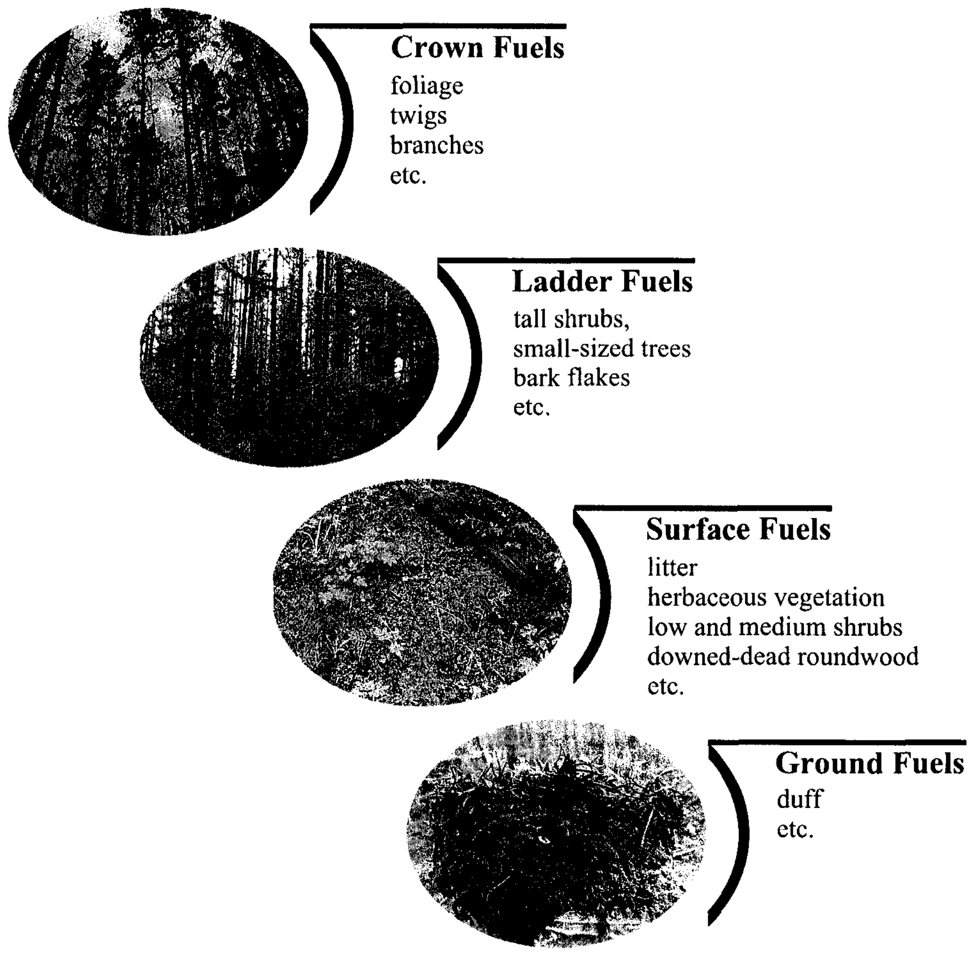


Figure 2-2. Representation of the fuel strata inventoried in each stand of the chronosequence.

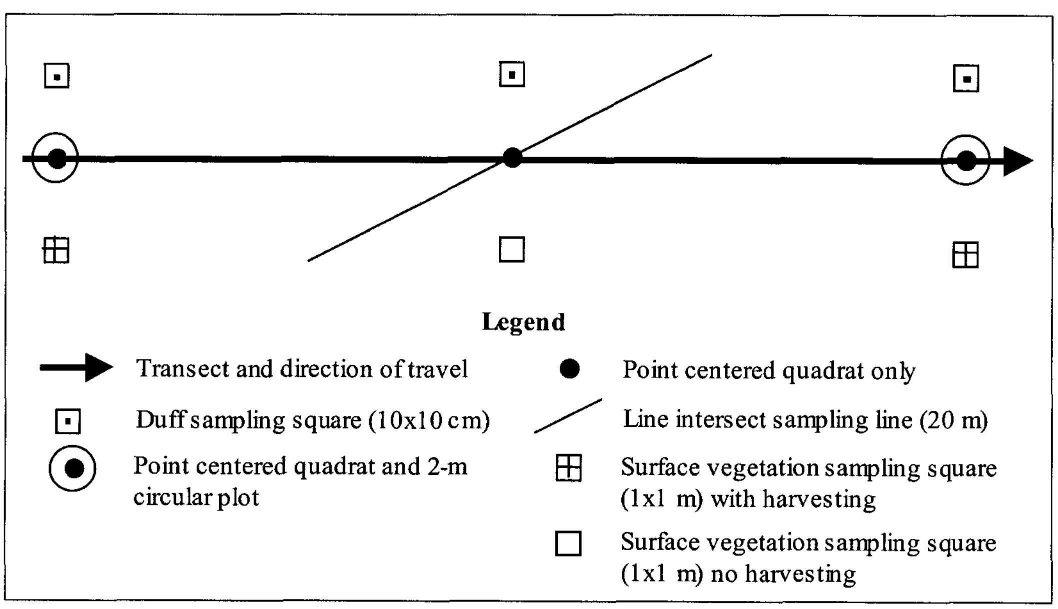
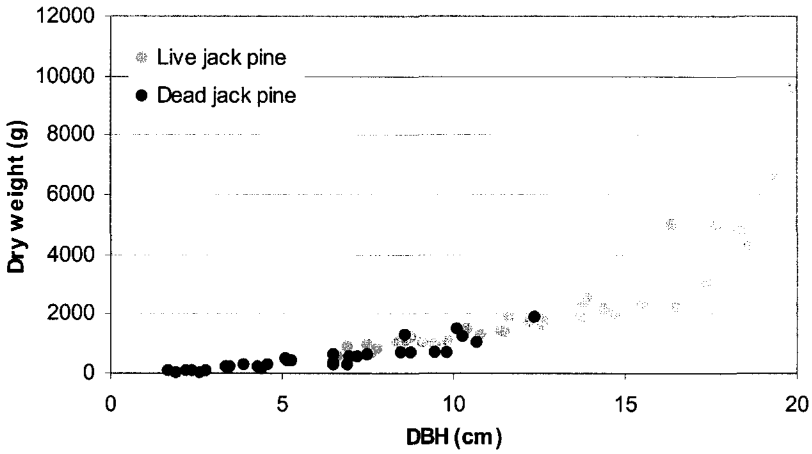
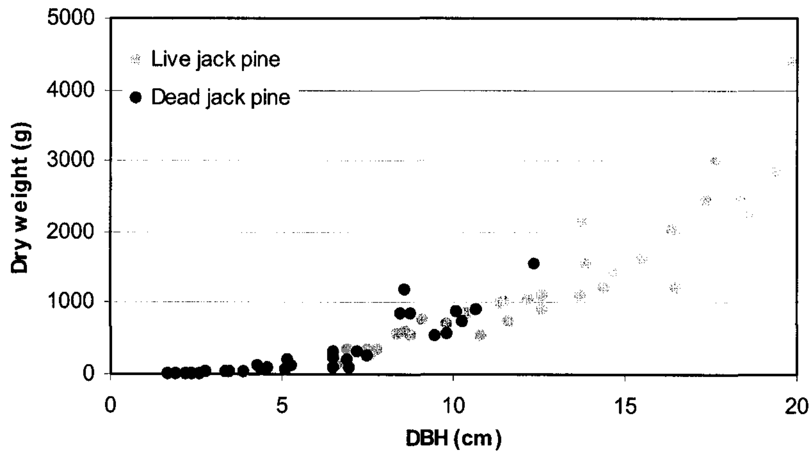


Figure 2-3. Illustration of a representative portion of a transect used to sample the fuels in each plot of the chronosequence.



(a)



(b)

Figure 2-4. Dry weight of all branches (a) 0.00-0.49 cm in diameter and (b) 0.50-0.99 cm in diameter as a function of dbh for live and dead jack pine trees.

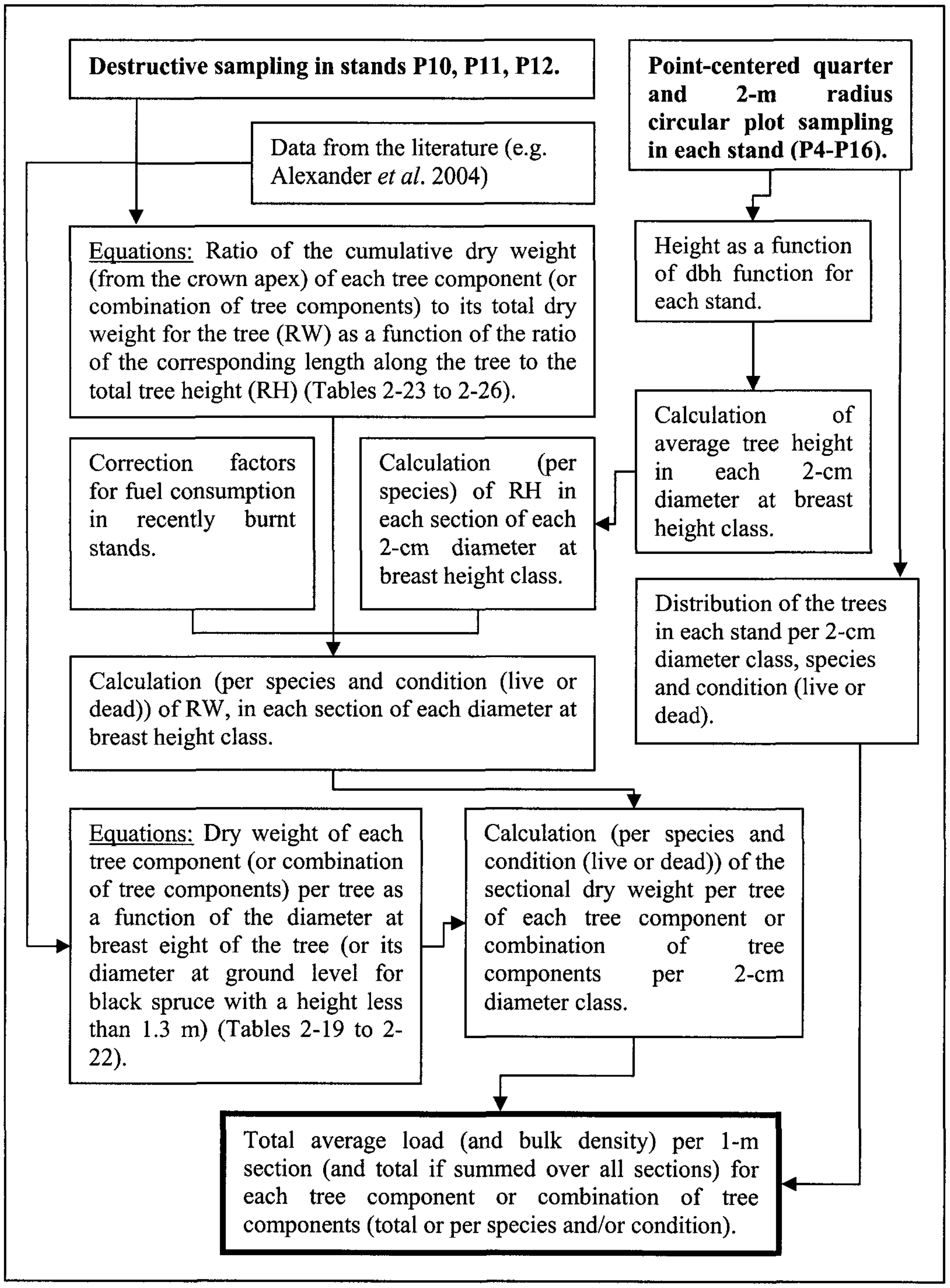


Figure 2-5. Flowchart showing the procedure used to obtain the vertical distribution of the fine and total tree and stand biomass loads (and bulk density) per 1-m section.

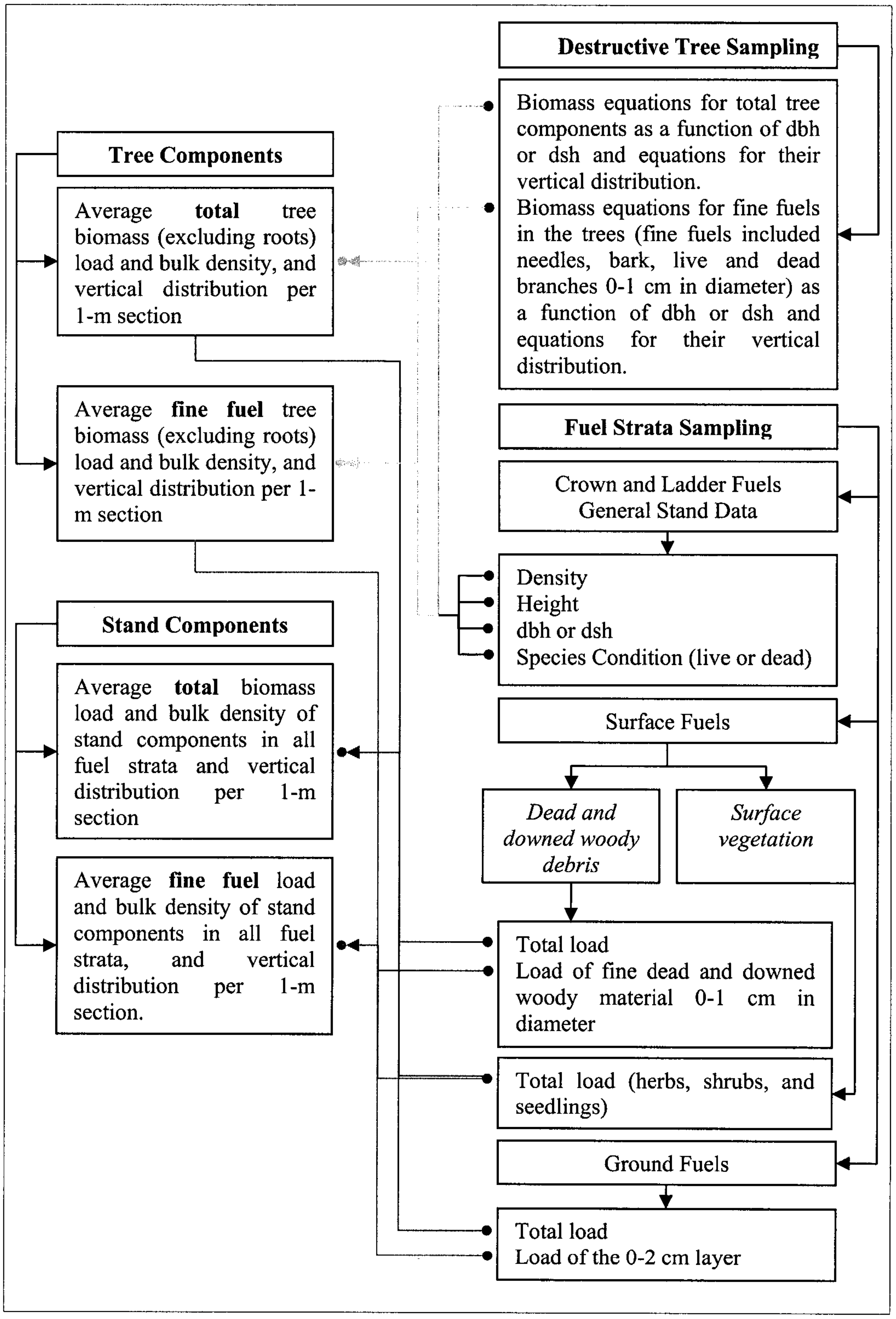


Figure 2-6. Data from the destructive and non-destructive sampling used in the calculation of the average fine fuel tree load and total biomass (excluding roots), the average fine fuel load and total biomass of stand components in all fuel strata, and their vertical distribution per 1-m section.

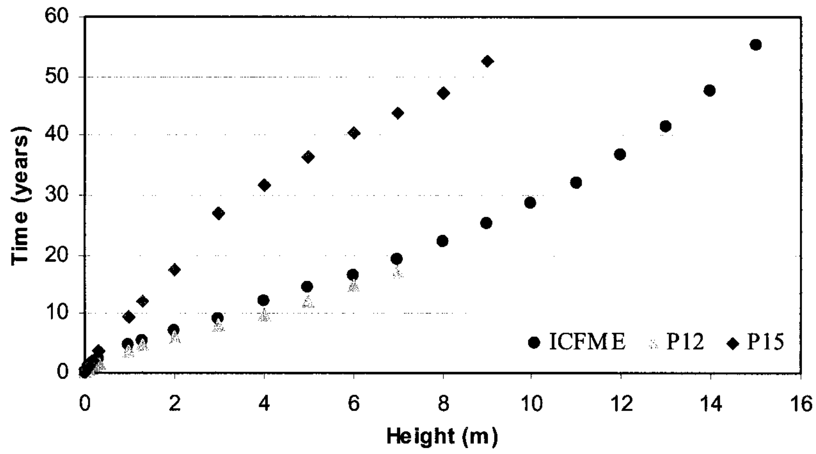


Figure 2-7. Average age at each sampling height for three dominant jack pine trees (above 95th percentile of height and dbh) in stands P12, P15, and P10 (the ICFME site).

Table 2-2. Results of the one-way ANOVA performed on the site index (height at 50 years) of the dominant trees selected.

Model	Sum of squares	df	Mean square	F	Sig.
Betw een groups	81.975	5	16.395	10.193	0.001
Within groups	19.301	12	1.608		
Total	101.276	17			

Note: df = degrees of freedom, F = F statistic, Sig. = significance

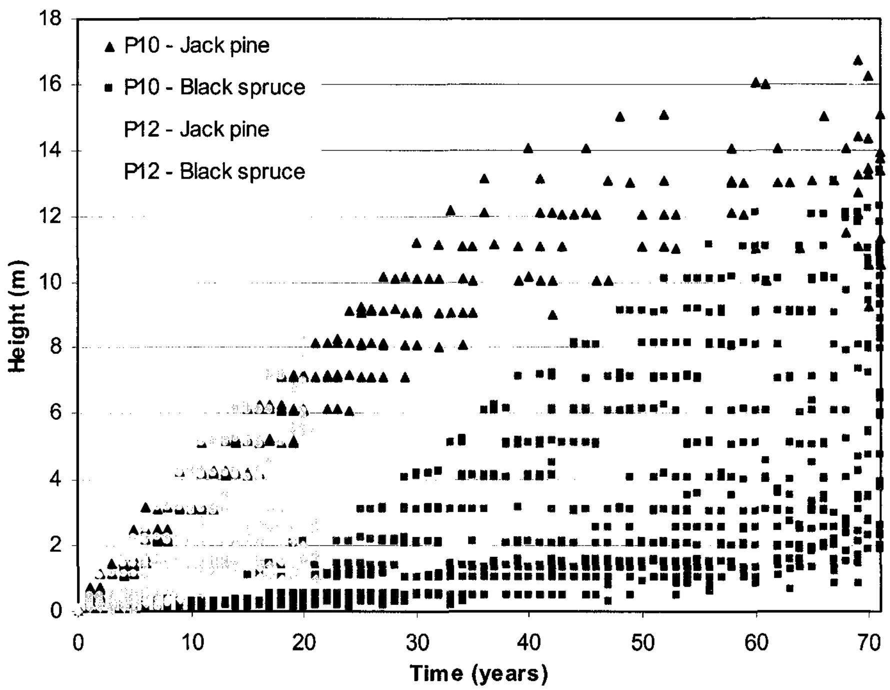


Figure 2-8. Stem analysis data for jack pine and black spruce trees covering most of the height range in stands P12 and P10.

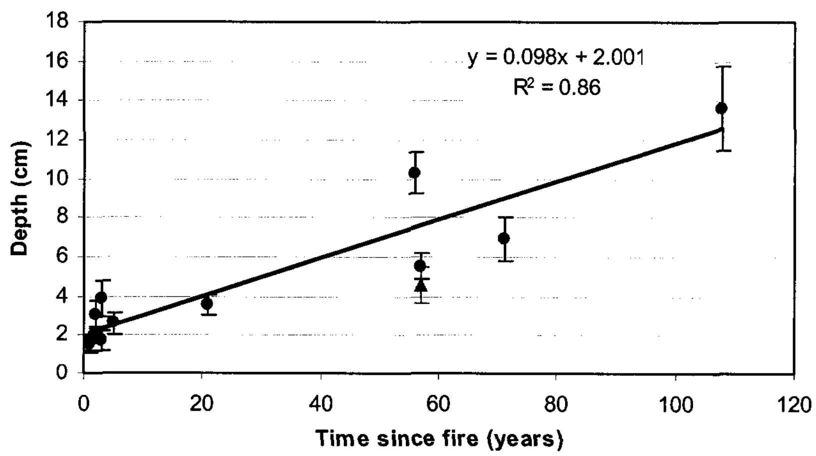


Figure 2-9. Average depth (cm) (and 95% confidence interval) of the forest floor as a function of time since fire (P15 is in red - not included in the regression).

Table 2-3. Average depth (cm) and load (kg/m^2) of the total forest floor and average load of its first 2 centimetres for each stand of the chronosequence.

Stand #	TSF (years)	n	Average total depth			Average total load			Average load 0-2 cm		
			Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
4	1	25	1.5	1.0	0.3 - 3.6	2.4	0.9	0.9 - 4.3	2.1	0.7	0.9 - 3.4
9	1	24	1.6	1.0	0.2 - 3.6	2.6	1.4	0.8 - 5.2	2.3	1.1	0.8 - 4.7
7	2	25	2.0	1.0	0.5 - 4.6	3.7	2.0	0.9 - 8.3	3.0	1.2	0.9 - 5.3
8	2	25	3.1	1.8	0.3 - 6.3	4.4	2.3	1.0 - 9.1	2.7	0.8	1.0 - 4.6
5	3	25	1.7	1.4	0.4 - 5.8	3.3	1.7	1.3 - 7.7	2.7	1.0	1.3 - 5.4
6	3	25	3.9	2.3	0.8 - 9.7	6.0	3.5	0.9 - 14.4	2.8	1.0	0.9 - 4.9
14	5	28	2.6	1.6	1.0 - 7.5	5.0	2.1	2.1 - 9.1	3.2	1.4	1.6 - 7.0
12	21	25	3.6	1.4	1.2 - 7.6	4.8	2.9	1.6 - 13.1	1.7	0.5	1.0 - 3.1
16	56	19	10.3	2.4	6.1 - 14.0	15.4	6.1	6.5 - 27.3	1.7	0.5	0.8 - 3.4
11	57	25	5.5	1.8	2.5 - 9.9	7.9	3.7	2.1 - 14.4	2.0	0.5	0.6 - 2.8
15*	57	8	4.6	1.3	3.5 - 7.5	4.6	2.9	1.5 - 9.6	1.1	0.3	0.5 - 1.6
10	71	24	6.9	2.9	3.0 - 12.0	9.4	6.0	2.0 - 23.7	1.3	0.4	0.3 - 2.2
13	108	23	13.6	5.2	5.3 - 24.0	9.9	6.8	0.7 - 35.2	0.7	0.7	0.2 - 2.7

* Stand not considered as part of the chronosequence for this project (refer to text for details)

Note: TSF = time since fire, n = sample size, SD = standard deviation

Table 2-4. Standard error over mean of the forest floor total depth, total load, and total bulk density, and of the dead and downed woody debris total load.

Stand #	TSF	Forest floor Total depth	Forest floor Total load	Forest floor Total bulk density	Woody debris Total load
P4	1	0.14	0.08	0.11	0.15
P9	1	0.13	0.11	0.10	0.14
P7	2	0.10	0.11	0.06	0.14
P8	2	0.12	0.10	0.14	0.10
P5	3	0.16	0.10	0.13	0.11
P6	3	0.12	0.12	0.05	0.18
P14	5	0.11	0.08	0.11	0.29
P12	21	0.08	0.12	0.07	0.21
P16	56	0.05	0.09	0.05	0.15
P11	57	0.06	0.09	0.06	0.13
P15*	57	0.10	0.22	0.15	0.20
P10	71	0.08	0.13	0.07	0.06
P13	108	0.08	0.14	0.08	0.20

* The stand was not considered as part of the chronosequence for this project (refer to text for details)

Note: TSF = time since fire

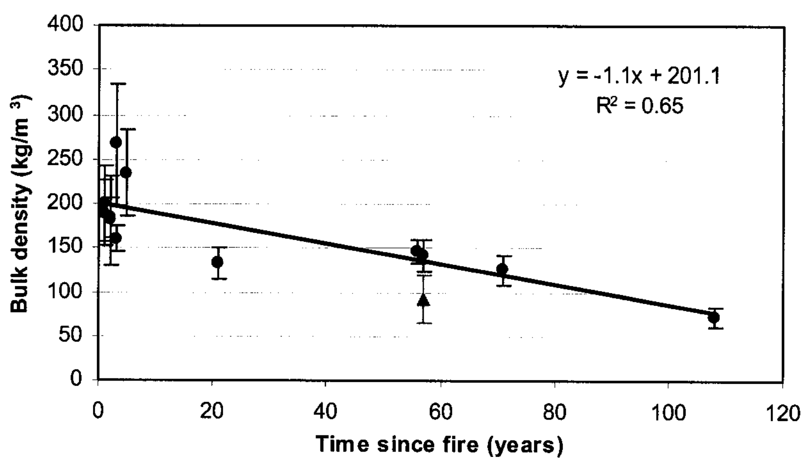


Figure 2-10. Total average bulk density (kg/m^3) (and 95% confidence interval) of the whole forest floor as a function of time since fire (P15 is in red - not included in the regression).

Table 2-5. Average bulk density (kg/m^3) of the total forest floor and of individual sections of pre-determined depth covering the average depth per plot.

Stand	TSF	Total			0-2 cm			2-4 cm			4-6 cm		
#	(years)	Mean (n)	SD	Range	Mean (n)	SD	Range	Mean (n)	SD	Range	Mean (n)	SD	Range
4	1	200.3 (25)	109.0	94.7 - 495.4	201.5 (25)	109.0	81.5 - 495.4	--	--	--	--	--	--
9	1	189.8 (24)	90.3	94.6 - 553.3	193.2 (24)	88.1	97.5 - 553.3	--	--	--	--	--	--
7	2	184.7 (24)	56.2	95.1 - 295.7	186.2 (24)	54.0	96.5 - 295.7	173.3 (08)	91.3	90.8 - 389.7	--	--	--
8	2	181.1 (25)	126.5	82.5 - 636.4	185.7 (25)	124.2	86.0 - 636.4	163.9 (15)	102.6	61.0 - 473.8	--	--	--
5	3	266.8 (25)	173.2	95.1 - 650.0	268.7 (25)	171.9	98.0 - 650.0	149.3 (05)	109.2	78.5 - 338.0	--	--	--
6	3	159.9 (25)	37.3	88.1 - 242.9	156.0 (25)	40.7	81.5 - 245.5	134.1 (16)	66.3	53.5 - 333.3	224.8 (11)	77.2	85.0 - 334.5
14	5	234.1 (28)	131.1	102.3 - 682.0	210.1 (28)	136.8	78.0 - 682.0	209.2 (11)	127.3	60.0 - 460.0	--	--	--
12	21	132.4 (25)	45.3	59.4 - 239.2	90.7 (25)	31.7	52.0 - 171.1	181.1 (21)	100.3	52.0 - 421.5	332.0 (05)	145.7	167.4 - 550.8
16	56	145.4 (19)	29.5	105.6 - 194.7	83.6 (19)	26.5	38.0 - 170.5	94.8 (19)	24.9	59.0 - 136.0	143.8 (19)	38.3	93.0 - 245.0
11	57	142.4 (25)	45.8	26.2 - 252.1	100.7 (25)	24.1	30.5 - 140.0	115.0 (25)	39.4	19.5 - 196.5	249.3 (19)	121.1	52.5 - 487.3
15*	57	92.3 (08)	39.7	40.6 - 141.2	55.1 (08)	17.4	24.0 - 77.5	90.3 (08)	31.0	47.6 - 132.5	250.6 (04)	95.2	141.0 - 361.3
10	71	125.8 (24)	42.3	54.1 - 200.9	65.6 (24)	21.3	16.5 - 110.0	108.9 (24)	50.1	26.0 - 229.0	160.6 (20)	82.0	49.5 - 428.9
13	108	71.6 (23)	28.2	11.5 - 146.7	35.9 (23)	36.6	8.0 - 133.5	37.0 (23)	31.3	8.5 - 126.0	55.9 (23)	39.0	11.0 - 143.0

Table 2-5. (continued)

Stand	TSF	6-8 cm			8-10 cm			10-12 cm			12-14 cm		
#	(years)	Mean (n)	SD	Range	Mean (n)	SD	Range	Mean (n)	SD	Range	Mean (n)	SD	Range
16	56	192.8 (18)	80.6	101.0 - 467.0	203.1 (14)	43.1	118.0 - 288.0	227.4 (07)	48.6	164.3 - 300.0	--	--	--
11	57	249.5 (07)	123.8	98.3 - 463.2	--	--	--	--	--	--	--	--	--
10	71	236.5 (11)	81.9	98.0 - 403.9	253.2 (09)	83.1	174.0 - 399.5	--	--	--	--	--	--
13	108	75.6 (21)	56.5	15.0 - 202.1	88.8 (17)	57.7	25.0 - 231.2	100.4 (16)	51.6	38.5 - 215.5	103.2 (12)	43.4	56.5 - 168.5

Table 2-5. (continued)

Stand	TSF	14-16 cm			16-18 cm			18-20 cm			20-22 cm		
#	(years)	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
13	108	126.8 (10)	37.9	69.0 - 191.0	--	--	--	--	--	--	--	--	--

* The stand was not considered as part of the chronosequence for this project (refer to text for details)

Note: TSF = time since fire. SD = standard deviation. n = sample size

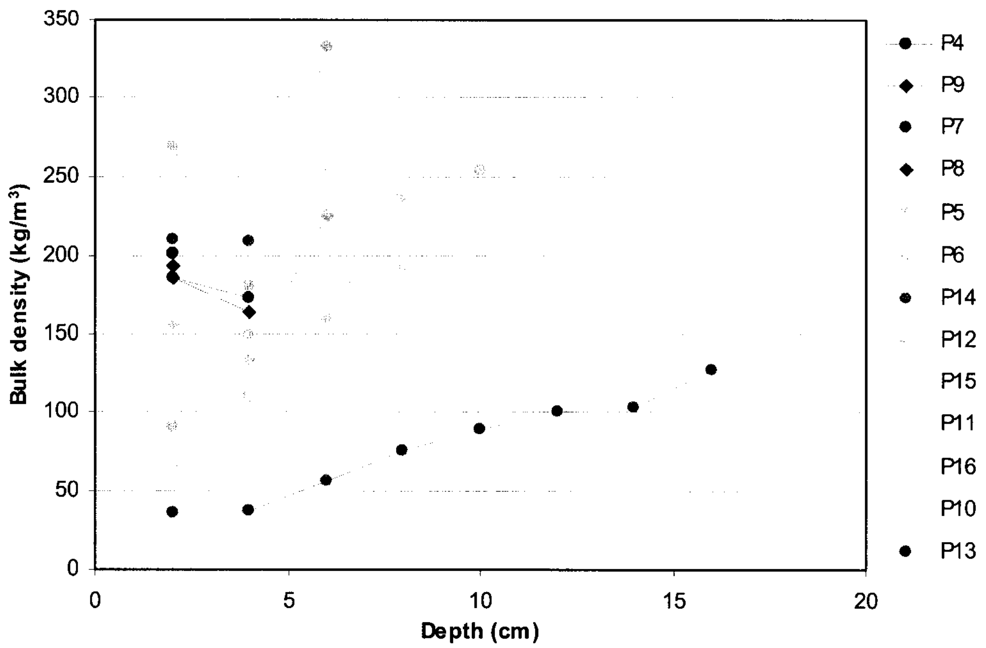


Figure 2-11. Average bulk density of the forest floor for each 2-cm layer (the maximum depth of each layer was used on the graph) covering the average depth per plot. Plots of similar time since fire have the same colour code, which varies from dark blue for younger plots to bright red for older plots.

Table 2-6. ANOVA and contrast results for the differences between the total bulk density of the forest floor in recently burnt areas (1-5 years since fire) and the lower 4-cm layer in the ICFME mature stand.

Model	Sum of squares	df	Mean square	F	Sig.
Between groups	0.215	7	0.031	2.507	0.017
Within groups	2.353	192	0.012		
Total	2.568	199			

Contrast	Value of contrast	Standard error	t	df	Sig. (2-tailed)
Assume:					
Equal variance	-0.184	0.169	-1.092	192	0.276
Unequal variance	-0.184	0.147	-1.252	32	0.220

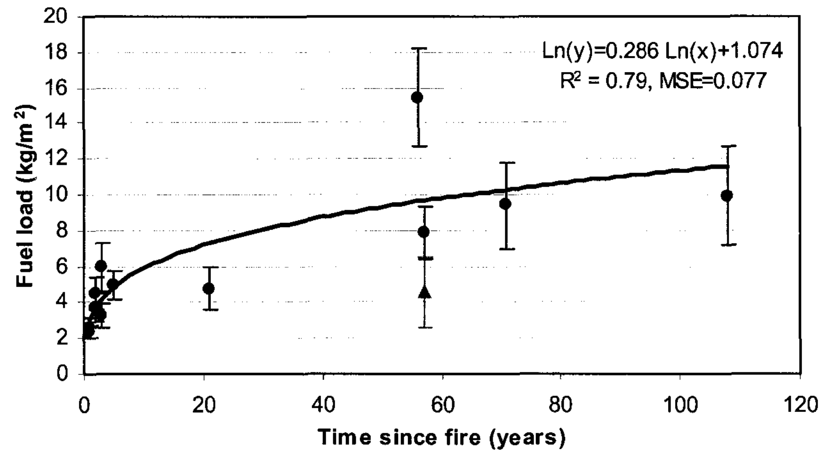


Figure 2-12. Average fuel load (kg/m^2) (and 95% confidence interval) of the forest floor as a function of time since fire (P15 is in red - not included in the regression).

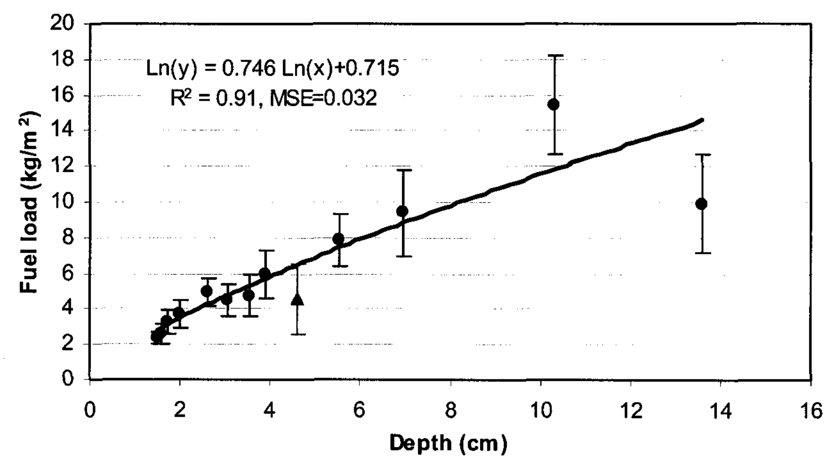


Figure 2-13. Average fuel load (kg/m^2) (and 95% confidence interval) of the forest floor as a function of its average depth for each plot sampled (P15 is in red - not included in the regression).

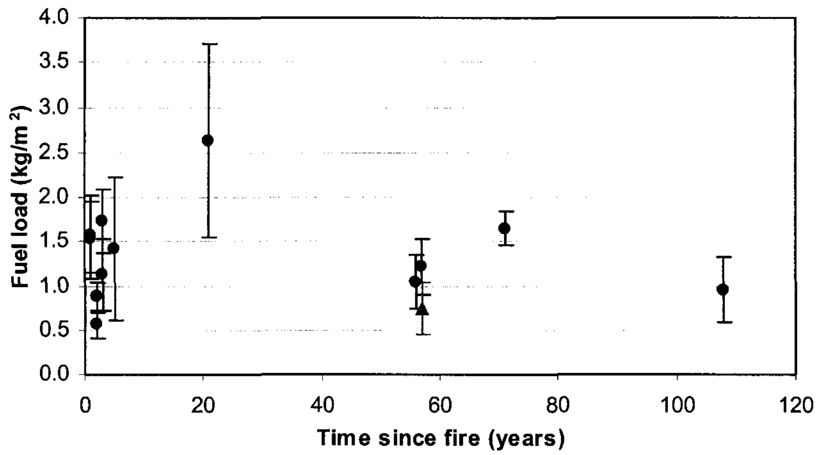


Figure 2-14. Average total fuel load (kg/m^2) (and 95% confidence interval) of the dead and downed woody material as a function of time since fire (P15 is in red).

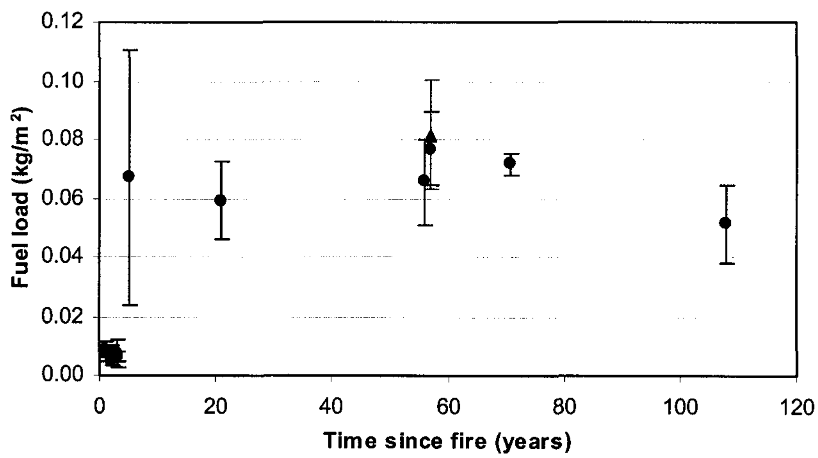


Figure 2-15. Average fuel load (kg/m^2) (and 95% confidence interval) of the fine (0-1 cm in diameter) dead and downed woody material as a function of time since fire (P15 is in red).

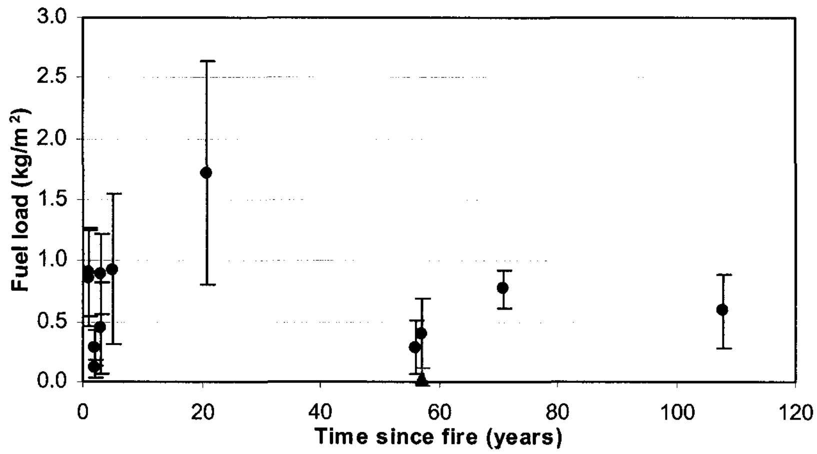


Figure 2-16. Average fuel load (kg/m^2) (and 95% confidence interval) of the coarse (7.0+ cm in diameter) dead and downed woody material as a function of time since fire (P15 is in red).

Table 2-7. Average load (kg/m^2) of the dead and downed woody material per roundwood diameter class.

Stand	TSF	n	0.00-0.50 cm			0.51-1.00 cm			1.01-3.00 cm			3.01-5.00 cm		
#	(years)		Mean	SD	Range	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
4	1	12	0.002	0.001	0.000 - 0.003	0.006	0.004	0.002 - 0.012	0.136	0.052	0.065 - 0.229	0.269	0.138	0.085 - 0.551
9	1	11	0.002	0.002	0.000 - 0.006	0.006	0.004	0.000 - 0.014	0.113	0.048	0.055 - 0.197	0.213	0.099	0.085 - 0.383
7	2	12	0.001	0.001	0.000 - 0.003	0.003	0.002	0.000 - 0.006	0.071	0.047	0.000 - 0.178	0.184	0.090	0.000 - 0.346
8	2	12	0.002	0.002	0.000 - 0.007	0.005	0.004	0.002 - 0.016	0.126	0.060	0.034 - 0.227	0.247	0.115	0.044 - 0.442
5	3	12	0.002	0.004	0.000 - 0.014	0.005	0.005	0.000 - 0.014	0.100	0.047	0.011 - 0.186	0.301	0.173	0.085 - 0.724
6	3	12	0.001	0.001	0.000 - 0.002	0.006	0.003	0.000 - 0.011	0.113	0.061	0.044 - 0.210	0.208	0.114	0.000 - 0.387
14	5	14	0.035	0.050	0.000 - 0.173	0.032	0.033	0.005 - 0.116	0.133	0.078	0.023 - 0.323	0.131	0.132	0.000 - 0.448
12	21	12	0.022	0.012	0.005 - 0.050	0.037	0.014	0.022 - 0.060	0.225	0.118	0.055 - 0.504	0.263	0.161	0.043 - 0.596
16	56	8	0.034	0.011	0.021 - 0.051	0.032	0.014	0.013 - 0.050	0.237	0.150	0.049 - 0.485	0.230	0.168	0.047 - 0.520
11	57	12	0.020	0.006	0.012 - 0.034	0.057	0.021	0.027 - 0.094	0.343	0.113	0.218 - 0.540	0.238	0.244	0.000 - 0.759
15*	57	4	0.025	0.005	0.018 - 0.031	0.056	0.015	0.039 - 0.073	0.319	0.141	0.174 - 0.512	0.116	0.126	0.000 - 0.297
10	71	89	0.040	0.009	0.019 - 0.061	0.031	0.013	0.010 - 0.062	0.202	0.085	0.023 - 0.476	0.269	0.132	0.000 - 0.678
13	108	11	0.016	0.007	0.008 - 0.031	0.036	0.018	0.011 - 0.074	0.111	0.086	0.000 - 0.306	0.067	0.066	0.000 - 0.229

Table 2-7. (continued)

Stand	TSF	n	5.01-7.00 cm			0.0-7.00 cm			7.0+ cm			Total		
#	(years)		Mean	SD	Range	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
4	1	12	0.256	0.150	0.096 - 0.673	0.668	0.172	0.430 - 0.965	0.851	0.700	0.178 - 2.047	1.518	0.780	0.665 - 3.012
9	1	11	0.333	0.151	0.096 - 0.578	0.667	0.190	0.278 - 0.886	0.912	0.609	0.210 - 1.918	1.579	0.740	0.488 - 2.797
7	2	12	0.195	0.161	0.000 - 0.584	0.454	0.174	0.106 - 0.809	0.107	0.125	0.000 - 0.367	0.562	0.275	0.106 - 1.177
8	2	12	0.206	0.155	0.000 - 0.495	0.587	0.271	0.085 - 1.058	0.282	0.256	0.000 - 0.862	0.869	0.301	0.540 - 1.368
5	3	12	0.442	0.223	0.096 - 0.867	0.851	0.314	0.437 - 1.715	0.884	0.583	0.173 - 1.843	1.735	0.632	0.746 - 2.823
6	3	12	0.356	0.200	0.097 - 0.680	0.683	0.259	0.395 - 1.201	0.441	0.673	0.000 - 1.947	1.124	0.704	0.395 - 2.618
14	5	14	0.157	0.174	0.000 - 0.600	0.488	0.404	0.088 - 1.327	0.928	1.188	0.000 - 4.402	1.416	1.528	0.088 - 5.503
12	21	12	0.370	0.363	0.000 - 0.964	0.916	0.480	0.491 - 1.773	1.718	1.618	0.107 - 4.816	2.635	1.904	0.805 - 6.098
16	56	8	0.221	0.151	0.000 - 0.416	0.753	0.314	0.330 - 1.175	0.285	0.327	0.000 - 0.899	1.039	0.444	0.330 - 1.688
11	57	12	0.150	0.173	0.000 - 0.598	0.808	0.306	0.331 - 1.287	0.403	0.506	0.000 - 1.354	1.211	0.542	0.331 - 2.041
15*	57	4	0.192	0.078	0.096 - 0.288	0.709	0.261	0.328 - 0.883	0.039	0.078	0.000 - 0.157	0.748	0.302	0.328 - 1.028
10	71	89	0.334	0.230	0.000 - 1.440	0.877	0.325	0.188 - 2.431	0.768	0.754	0.000 - 3.283	1.645	0.930	0.344 - 4.469
13	108	11	0.129	0.112	0.000 - 0.305	0.358	0.205	0.077 - 0.696	0.587	0.523	0.000 - 1.534	0.946	0.628	0.077 - 2.183

* The stand was not considered as part of the chronosequence for this project (refer to text for details)

Note: TSF = time since fire, SD = standard deviation, n = sample size, N/A = not available

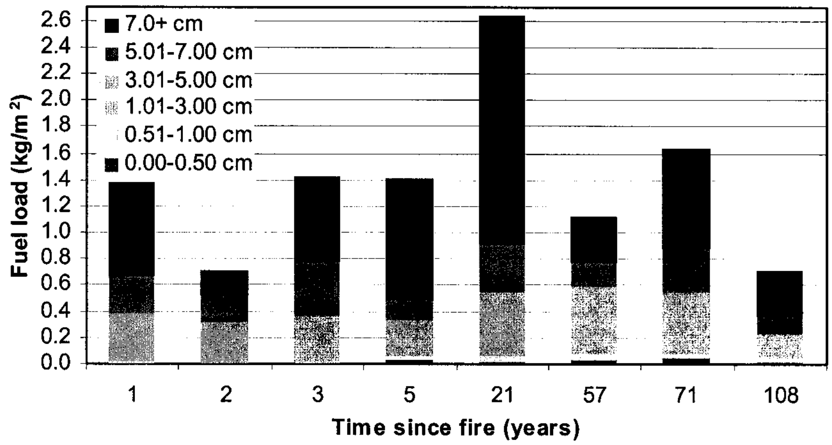


Figure 2-17. Average fuel load (kg/m^2) per size class for the different periods sampled in the chronosequence (when more than one stand had been inventoried for a given time, the average was taken).

Table 2-8. Average percent cover (%) for the dead and downed woody material per roundwood diameter class.

Stand	TSF	n	0.00-0.50 cm			0.51-1.00 cm			1.01-3.00 cm			3.01-5.00 cm		
#	(years)		Mean	SD	Range	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
4	1	12	0.1	0.0	0.0 - 0.2	0.1	0.1	0.0 - 0.3	1.2	0.5	0.6 - 2.1	1.3	0.7	0.4 - 2.6
9	1	11	0.1	0.1	0.0 - 0.3	0.2	0.1	0.0 - 0.3	1.0	0.4	0.5 - 1.8	1.0	0.5	0.4 - 1.8
7	2	12	0.1	0.0	0.0 - 0.2	0.1	0.1	0.0 - 0.2	0.6	0.4	0.0 - 1.6	0.9	0.4	0.0 - 1.6
8	2	12	0.1	0.1	0.0 - 0.3	0.1	0.1	0.0 - 0.3	1.1	0.5	0.3 - 2.0	1.1	0.5	0.2 - 2.0
5	3	12	0.1	0.2	0.0 - 0.6	0.1	0.1	0.0 - 0.3	0.9	0.4	0.1 - 1.7	1.4	0.8	0.4 - 3.4
6	3	12	0.0	0.0	0.0 - 0.1	0.1	0.1	0.0 - 0.3	1.0	0.6	0.4 - 1.9	1.0	0.5	0.0 - 1.8
14	5	14	1.7	2.4	0.0 - 8.3	0.7	0.8	0.1 - 2.7	1.2	0.7	0.2 - 2.8	0.6	0.6	0.0 - 2.0
12	21	12	1.0	0.5	0.2 - 2.3	0.9	0.3	0.5 - 1.5	2.1	1.1	0.5 - 4.6	1.2	0.8	0.2 - 2.8
16	56	8	1.7	0.5	1.1 - 2.5	0.6	0.3	0.3 - 1.0	2.0	1.2	0.4 - 4.0	1.0	0.7	0.2 - 2.2
11	57	12	1.0	0.3	0.6 - 1.7	1.2	0.5	0.6 - 2.0	3.0	1.0	1.9 - 4.7	1.1	1.1	0.0 - 3.4
15	57	4	1.1	0.2	0.8 - 1.4	1.4	0.4	1.0 - 1.8	2.9	1.3	1.6 - 4.7	0.6	0.6	0.0 - 1.4
10	71	89	1.9	0.4	0.9 - 2.8	0.7	0.3	0.2 - 1.5	1.8	0.8	0.2 - 4.3	1.3	0.6	0.0 - 3.2
13	108	11	0.8	0.3	0.4 - 1.5	0.7	0.4	0.2 - 1.5	0.9	0.7	0.0 - 2.6	0.3	0.3	0.0 - 1.0

Table 2-8. (continued)

Stand	TSF	n	5.01-7.00 cm			0.0-7.00 cm			7.0+ cm			Total		
#	(years)		Mean	SD	Range	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
4	1	12	0.8	0.5	0.3 - 2.1	3.5	0.8	2.5 - 5.3	1.2	0.9	0.4 - 3.0	4.7	1.3	2.9 - 7.6
9	1	11	1.0	0.5	0.3 - 1.8	3.3	0.8	1.8 - 4.4	1.6	1.0	0.4 - 3.4	5.0	1.5	2.2 - 7.2
7	2	12	0.6	0.5	0.0 - 1.8	2.2	0.7	1.1 - 3.4	0.2	0.2	0.0 - 0.6	2.5	0.8	1.1 - 4.0
8	2	12	0.6	0.5	0.0 - 1.5	3.1	1.3	0.7 - 5.2	0.5	0.4	0.0 - 1.5	3.6	1.2	1.3 - 5.4
5	3	12	1.4	0.7	0.3 - 2.7	3.9	1.2	2.6 - 7.3	1.6	0.9	0.4 - 3.1	5.5	1.3	3.6 - 7.8
6	3	12	1.1	0.6	0.3 - 2.1	3.2	0.9	2.0 - 5.1	0.7	1.0	0.0 - 2.9	4.0	1.5	2.0 - 6.8
14	5	14	0.5	0.5	0.0 - 1.8	4.6	4.4	0.9 - 15.1	1.5	1.8	0.0 - 6.7	6.1	5.6	0.9 - 17.7
12	21	12	1.2	1.1	0.0 - 3.0	6.3	1.9	3.2 - 9.0	3.8	3.3	0.4 - 11.0	10.1	4.4	4.1 - 18.7
16	56	8	0.6	0.4	0.0 - 1.2	5.9	2.2	2.9 - 8.3	0.7	0.7	0.0 - 2.0	6.6	2.1	2.9 - 8.9
11	57	12	0.5	0.5	0.0 - 1.8	6.7	1.3	4.1 - 8.6	0.8	1.0	0.0 - 2.7	7.5	1.7	4.1 - 9.8
15	57	4	0.6	0.2	0.3 - 0.9	6.6	2.1	3.7 - 8.7	0.1	0.2	0.0 - 0.5	6.7	2.2	3.7 - 8.7
10	71	89	1.0	0.7	0.0 - 4.5	6.7	1.6	2.4 - 13.3	1.6	1.4	0.0 - 6.3	8.3	2.5	2.8 - 17.3
13	108	11	0.4	0.3	0.0 - 0.9	3.1	1.5	1.1 - 6.4	1.5	1.2	0.0 - 3.7	4.6	2.2	1.1 - 7.9

* The stand was not considered as part of the chronosequence for this project (refer to text for details)

Note: TSF = time since fire. SD = standard deviation. n = sample size

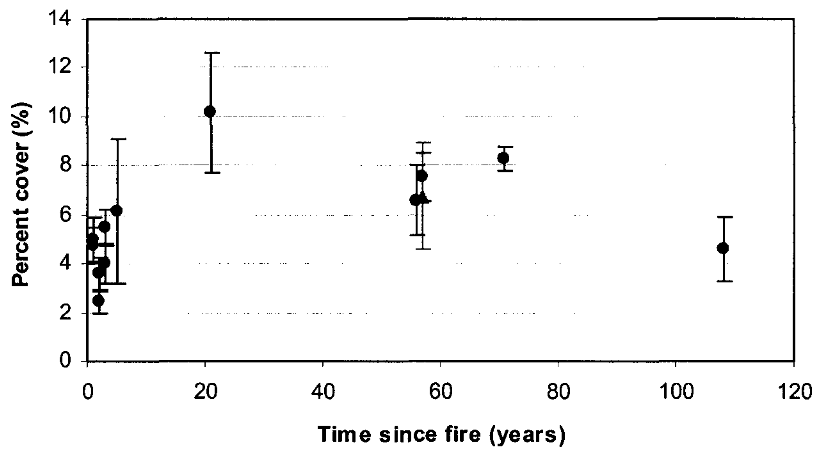


Figure 2-18. Average percent cover (and 95% confidence interval) of the total dead and downed woody material (and confidence interval per plot) as a function of time since fire (P15 is in red).

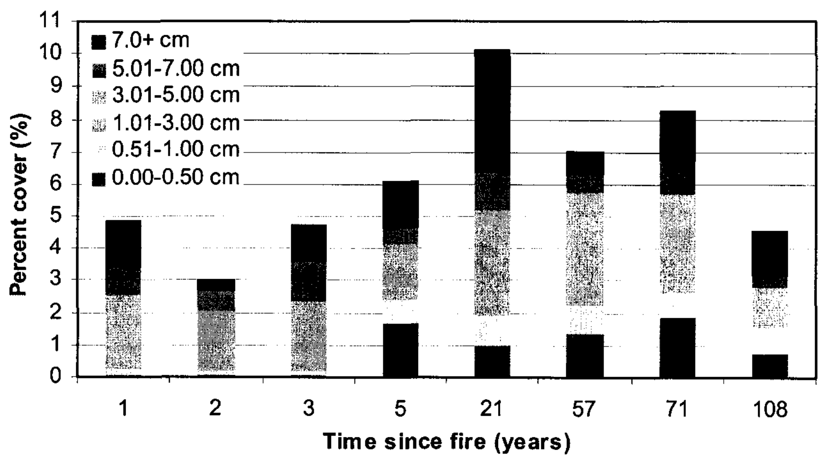


Figure 2-19. Average percent cover in each diameter class for the different periods sampled in the chronosequence (when more than one stand had been inventoried for a given time, the average was taken).

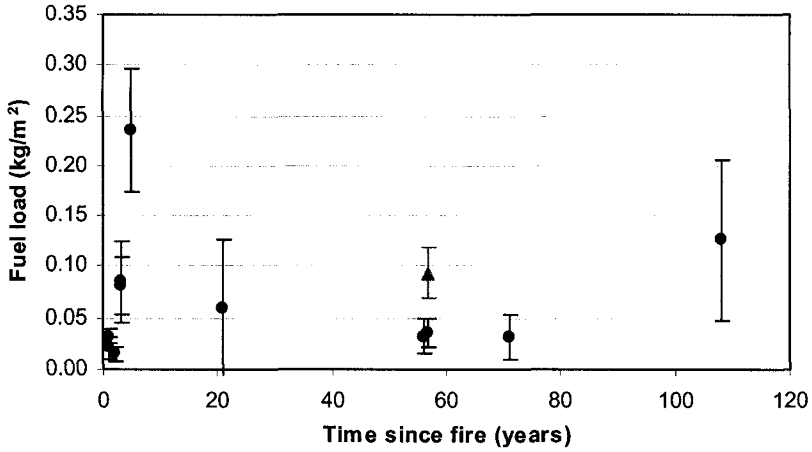


Figure 2-20. Average total fuel load (kg/m^2) (and 95% confidence interval) of the understory vegetation as a function of time since fire (P15 is in red).

Table 2-9. Average load (kg/m²) of the understory vegetation.

Stand #	TSF (years)	n	Herbs			Shrubs			Total		
			Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
4	1	12	0.011	0.007	0.002 - 0.026	0.021	0.011	0.010 - 0.040	0.033	0.012	0.017 - 0.053
9	1	11	0.006	0.006	0.001 - 0.018	0.015	0.015	0.000 - 0.042	0.021	0.019	0.003 - 0.057
7	2	--	--	--	--	--	--	--	--	--	--
8	2	13	0.005	0.007	0.001 - 0.025	0.010	0.009	0.001 - 0.030	0.015	0.014	0.002 - 0.055
5	3	12	0.040	0.056	0.010 - 0.216	0.042	0.029	0.000 - 0.083	0.085	0.071	0.013 - 0.284
6	3	13	0.035	0.019	0.003 - 0.068	0.047	0.058	0.000 - 0.201	0.081	0.051	0.017 - 0.203
14	5	14	0.070	0.059	0.012 - 0.247	0.121	0.079	0.010 - 0.279	0.235	0.117	0.072 - 0.493
12	21	12	0.008	0.006	0.001 - 0.019	0.052	0.115	0.000 - 0.400	0.059	0.118	0.003 - 0.419
16	56	10	0.021	0.012	0.007 - 0.044	0.011	0.017	0.000 - 0.058	0.032	0.027	0.007 - 0.101
11	57	12	0.023	0.019	0.007 - 0.073	0.011	0.010	0.001 - 0.033	0.035	0.025	0.011 - 0.087
15*	57	6	0.073	0.034	0.035 - 0.116	0.020	0.010	0.013 - 0.040	0.093	0.031	0.048 - 0.131
10	71	8	0.018	0.024	0.004 - 0.075	0.014	0.028	0.000 - 0.083	0.032	0.031	0.006 - 0.086
13	108	11	0.018	0.030	0.001 - 0.084	0.108	0.136	0.000 - 0.416	0.126	0.133	0.001 - 0.417

* The stand was not considered as part of the chronosequence for this project (refer to text for details)

Note: TSF = time since fire, SD = standard deviation, n = sample size

Table 2-10. Average percent cover of the different understory components in each stand.

Stand #	TSF (years)	Lichen	Moss	Herbs	Shrubs	Total
4	1		0.6	11.8	14.6	26.9
9	1		0.0	4.7	6.6	11.3
7	2		1.5	14.0	7.2	22.8
8	2		8.5	3.0	6.1	17.8
5	3		7.4	18.3	16.3	42.6
6	3		8.7	15.3	14.2	38.2
14	5	0.9	28.9	35.3	20.0	85.1
12	21	0.2	1.6	9.3	13.3	24.3
16	56	0.6	18.7	20.2	10.7	50.2
11	57	1.1	23.8	17.7	8.2	50.9
15*	57	3.0	17.8	41.8	21.2	83.8
10	71	4.4	16.1	11.9	7.8	40.2
13	108	1.7	66.7	9.3	17.7	95.3

* Stand not considered as part of the chronosequence for this project (refer to text for details)
Note: TSF = time since fire

Table 2-11. Average percent cover of the main species (defined as species with at least 1% cover in one of the stands of the chronosequence) in each stand.

Species	Category	Stand (TSF)												
		4 (1)	9 (1)	7 (2)	8 (2)	5 (3)	6 (3)	14 (5)	12 (21)	16 (56)	11 (57)	15* (57)	10 (71)	13 (108)
Arctostaphylos rubra	Herbs	0.1				0.1				4.3	0.5			1.0
Arctostaphylos uva-ursi	Herbs	0.3	0.0	0.5	0.3	1.7	1.3	7.7	0.1	0.4	3.8	8.1	5.9	2.2
Aster puniceus	Herbs	0.2		0.4		1.0		3.4						
Carex spp.	Herbs	0.1	0.0	4.0	0.4	0.9	3.9	0.2	0.0	1.9	0.4		0.9	0.0
Cornus canadensis	Herbs	1.4	0.0	0.6		0.4		2.1	1.8	3.1	3.1	5.8	0.3	0.9
Epilobium angustifolium	Herbs			0.6	0.5	1.2	1.9	4.4	1.1			0.1		
Fragaria virginiana	Herbs	0.0			0.0			1.1	2.4		0.3			0.0
Galium trifidum	Herbs	0.4	0.3	0.6	0.1	1.9	0.6	1.8	0.0	0.7	0.2			0.1
Geranium bicknellii	Herbs	3.1	2.0	0.2	0.1	0.1		0.0						
Grass	Herbs	0.0	0.0	0.4	0.2	1.3	1.5	0.4	1.5	3.2	1.3	0.4	0.1	2.3
Linnaea borealis	Herbs	4.4	1.2	4.4	0.2	7.7	3.8	2.4	1.3	3.0	6.8	26.4	3.5	1.6
Oryzopsis asperifolia	Herbs							6.9						
Rubus pubescens	Herbs			0.0				2.2						
Cladina rangiferina	Lichen										0.1	2.4	0.6	1.2
Cladonia gracilis	Lichen												1.6	
Peltigera aphthosa	Lichen							0.8	0.2	0.4	0.7	0.6	1.9	0.4
Aulacomnium palustre	Moss							0.0		4.2				0.2
Ceratodon purpureus	Moss	0.6	0.0	1.5	8.5	7.4	8.7	28.5	1.6					
Dicranum spp.	Moss									0.5	2.3			0.4
Hylocomium splendens	Moss									11.9	19.4	17.7	15.4	64.3
Pleurozium schreberi	Moss									1.9	2.1		0.4	1.6
Alnus crispa	Shrubs							0.4	1.5		0.2			7.1
Juniperus communis	Shrubs							0.5	0.0		0.8			1.3
Potentilla fruticosa	Shrubs	0.8	0.4	0.5	0.1	2.3	0.9		0.4	1.1	1.2		2.6	0.7
Rosa acicularis	Shrubs	11.7	3.1	4.3	3.3	6.9	3.2	12.7	5.5	4.6	4.8	14.5	4.3	6.1
Salix spp.	Shrubs	2.0	3.1	2.1	2.6	6.9	10.1	4.6	4.4	4.5	0.7	0.4	0.9	0.7
Shepherdia canadensis	Shrubs	0.0		0.3		0.0	0.1	0.3	1.1	0.2	0.4	5.1		1.9
Viburnum edule	Shrubs							1.3			0.2	1.1		0.0

* The stand was not considered as part of the chronosequence for this project (refer to text for details)

Note: TSF = time since fire, 0.0 = presence but less than 0.25% cover

Table 2-12. Shannon diversity index and equitability for the sampled stands.

Stand #	TSF (years)	Shannon diversity index	Equitability
4	1	2.0	0.60
9	1	1.9	0.67
7	2	2.5	0.76
8	2	1.8	0.57
5	3	2.4	0.71
6	3	2.2	0.69
14	5	2.4	0.68
12	21	2.4	0.74
16	56	2.7	0.78
11	57	2.3	0.67
15*	57	1.9	0.69
10	71	2.1	0.71
13	108	1.5	0.43

* The stand was not considered as part of the chronosequence for this project (refer to text for details)

Note: TSF = time since fire

Table 2-13. Czekanowski coefficient showing percent similarity in species composition between the stands inventoried.

Stand	(TSF)	4 (1)	9 (1)	7 (2)	8 (2)	5 (3)	6 (3)	14 (5)	12 (21)	16 (56)	11 (57)	15* (57)	10 (71)	13 (108)
4	(1)		51	58	32	48	36	35	45	34	33	33	30	18
9	(1)			48	46	32	35	17	44	27	18	10	22	10
7	(2)				46	52	58	26	49	39	34	21	35	15
8	(2)					52	59	31	42	23	16	9	18	9
5	(3)						69	45	48	37	38	28	33	19
6	(3)							38	44	37	27	15	27	14
14	(5)								33	24	25	33	23	15
12	(21)									41	32	20	23	23
16	(56)										62	37	53	38
11	(57)											58	68	50
15*	(57)												51	37
10	(71)													39
13	(108)													

* The stand was not considered as part of the chronosequence for this project (refer to text for details)

Note: TSF = time since fire (years)

Table 2-14. Average (considering height and cover of individual species in each category) and maximum height (cm) for understory components.

Stand #	TSF (years)	Lichen		Moss		Herbs		Shrubs		Coniferous seedlings		Deciduous seedlings		Total	
		Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max
4	1	--	--	1.0	4.0	12.5	50.0	22.6	40.0	4.6	8.0	--	--	5.5	50.0
9	1	--	--	0.2	0.2	8.7	40.0	18.4	35.0	1.7	3.8	--	--	10.2	40.0
7	2	--	--	0.4	0.5	18.5	80.0	22.1	45.0	9.9	15.0	10.0	10.0	17.4	80.0
8	2	--	--	0.2	0.2	12.7	50.0	21.9	35.0	2.9	6.6	--	--	11.8	50.0
5	3	--	--	0.3	0.5	13.7	55.0	22.8	60.0	12.1	20.0	10.0	10.0	14.5	60.0
6	3	--	--	0.6	4.0	10.0	60.0	25.2	45.0	4.9	14.8	10.0	10.0	12.5	60.0
14	5	3.4	4.0	0.8	3.0	13.6	100.0	58.4	140.0	29.0	60.0	95.3	170.0	28.8	170.0
12	21	1.7	2.0	0.2	0.2	11.3	35.0	64.1	200.0	--	--	--	--	14.3	200.0
16	56	2.5	5.0	5.4	30.0	7.6	30.0	13.5	40.0	--	--	--	--	5.0	40.0
11	57	3.3	5.0	2.9	15.0	7.4	50.0	40.8	106.0	--	--	10.0	10.0	9.6	106.0
15*	57	3.4	5.5	4.0	6.0	5.6	28.0	28.5	60.0	--	--	--	--	9.7	60.0
10	71	3.0	6.0	4.7	9.0	5.1	15.0	29.1	50.0	--	--	--	--	6.7	50.0
13	108	4.2	7.0	9.5	15.0	6.5	35.0	80.6	220.0	10.0	10.0	--	--	24.2	220.0

* The stand was not considered as part of the chronosequence for this project (refer to text for details)

Note: TSF = time since fire, Max = maximum height

Table 2-15. Total average density (stems/ha) and basal area (m^2/ha) of the stands inventoried.

Stand #	TSF (years)	Total average density (stems/ha)											
		Jack pine			Black spruce			*Populus spp.*			Total		Total
		Live	Dead	Total	Live	Dead	Total	Live	Dead	Total	Live	Dead	
4	1	790870	7132	798002	0	2662	2662	0	0	0	790870	9794	800663
9	1	149565	7032	156598	0	4903	4903	0	0	0	149565	11936	161501
7	2	500800	3825	504625	3600	4720	8320	0	0	0	504400	8546	512946
8	2	84800	4059	88859	4000	12600	16600	0	0	0	88800	16659	105459
5	3	48696	5557	54252	4348	6517	10865	0	0	0	53043	12074	65117
6	3	24400	7413	31813	8800	8776	17576	0	0	0	33200	16188	49388
14	5	57637	1442	59079	2501	865	3366	23873	415	24288	84011	2722	86733
12	21	23242	11405	34647	6508	367	6876	6058	2999	9058	35809	14772	50581
16	56	1925	1431	3357	29762	1157	30920	72	0	72	31760	2589	34349
11	57	4841	2923	7764	33704	490	34193	66	188	254	38610	3601	42211
15*	57	13194	2983	16177	1293	0	1293	0	0	0	14487	2983	17470
10	71	3061	2595	5655	6635	995	7629	0	0	0	9696	3589	13285
13	108	1066	519	1585	18235	925	19160	199	464	663	19500	1908	21408

Stand #	TSF (years)	Total average basal area (m^2/ha)											
		Jack pine			Black spruce			*Populus spp.*			Total		Total
		Live	Dead	Total	Live	Dead	Total	Live	Dead	Total	Live	Dead	
4	1	0.0	30.6	30.6	0.0	0.3	0.3	0.0	0.0	0.0	0.0	31.0	31.0
9	1	0.0	28.2	28.2	0.0	1.2	1.2	0.0	0.0	0.0	0.0	29.3	29.3
7	2	0.0	21.5	21.5	0.0	3.7	3.7	0.0	0.0	0.0	0.0	25.3	25.3
8	2	0.0	22.1	22.1	0.0	9.4	9.4	0.0	0.0	0.0	0.0	31.5	31.5
5	3	0.0	22.0	22.0	0.0	1.0	1.0	0.0	0.0	0.0	0.0	23.0	23.0
6	3	0.0	29.7	29.7	0.0	4.1	4.1	0.0	0.0	0.0	0.0	33.8	33.8
14	5	0.0	14.9	14.9	0.0	8.0	8.0	0.4	3.5	3.9	0.4	26.5	26.9
12	21	15.9	0.4	16.3	0.2	0.0	0.2	1.3	0.0	1.3	17.4	0.4	17.8
16	56	14.3	1.6	15.9	9.3	0.1	9.4	0.0	0.0	0.0	23.7	1.7	25.3
11	57	16.5	1.5	18.0	3.7	0.1	3.8	0.1	0.1	0.2	20.4	1.7	22.0
15*	57	20.9	0.9	21.8	0.0	0.0	0.0	0.0	0.0	0.0	20.9	0.9	21.9
10	71	21.9	4.9	26.8	4.1	0.8	4.9	0.0	0.0	0.0	26.0	5.7	31.7
13	108	22.6	3.9	26.5	16.9	0.5	17.4	0.1	0.0	0.1	39.5	4.4	44.0

* The stand was not considered as part of the chronosequence for this project (refer to text for details)

Note: TSF = time since fire

Table 2-16. Overstory and understory average tree height and live crown base height (m).

Stand #	TSF	Overstory (diameter at breast height of at least 3.0 cm)																											
		Jack pine								Black spruce								Deciduous								Total			
		Live					Dead			Live					Dead			Live					Dead						
		Height		LCBH		n	Height		n	Height		LCBH		n	Height		n	Height		LCBH		n	Height		n	Height		LCBH	
		Mean	SD	Mean	SD		Mean	SD		Mean	SD	Mean	SD		Mean	SD		Mean	SD	Mean	SD		Mean	SD		Mean	SD	Mean	SD
4	1	--	--	--	--	--	10.3	2.2	100	--	--	--	--	--	-	-	-	--	--	--	--	--	--	--	--	10.3	2.2	--	--
9	1	--	--	--	--	--	10.5	2.8	55	--	--	--	--	--	5.8	2.1	9	--	--	--	--	--	--	--	--	9.8	3.1	--	--
7	2	--	--	--	--	--	11.3	3.0	70	--	--	--	--	--	5.4	1.6	30	--	--	--	--	--	--	--	--	9.6	3.8	--	--
8	2	--	--	--	--	--	10.0	2.5	44	--	--	--	--	--	5.8	2.2	56	--	--	--	--	--	--	--	--	7.6	3.1	--	--
5	3	--	--	--	--	--	9.6	2.9	88	--	--	--	--	--	4.9	1.3	12	--	--	--	--	--	--	--	--	9.1	3.2	--	--
6	3	--	--	--	--	--	10.3	3.4	56	--	--	--	--	--	5.7	1.8	44	--	--	--	--	--	--	--	--	8.3	3.6	--	--
14	5	--	--	--	--	--	10.4	2.8	74	--	--	--	--	--	9.9	5.4	28	--	--	--	--	--	10.6	2.6	10	10.3	3.6	--	--
12	21	5.1	0.7	2.6	0.6	95	1.7	--	1	3.6	-	0.0	-	1	--	--	--	5.2	0.2	3.2	0.3	3	--	--	--	5.1	0.8	2.6	0.6
16	56	9.7	1.9	6.7	1.9	27	5.7	2.2	15	5.2	1.7	2.1	1.3	41	--	--	--	--	--	--	--	--	--	--	--	6.7	2.8	3.9	2.7
11	57	8.0	2.0	4.8	1.1	67	5.3	0.6	10	4.5	0.4	1.7	0.6	21	--	--	--	5.0	--	2.5	--	1	4.1	--	--	7.0	2.3	4.1	1.7
15*	57	6.6	1.4	3.6	0.9	31	4.4	--	1	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	6.5	1.4	3.6	0.9
10	71	11.6	2.4	7.9	2.7	465	8.1	2.1	284	5.7	1.9	1.6	1.1	223	5.1	1.7	39	--	--	--	--	--	--	--	--	9.1	3.3	5.9	3.8
13	108	13.8	2.0	9.6	1.9	33	10.7	3.1	14	9.6	4.7	4.4	3.4	41	5.9	2.3	4	--	--	--	--	--	--	--	--	11.1	4.2	6.7	3.8

Stand #	TSF	Understory (diameter at breast height smaller than 3.0 cm)																											
		Jack pine								Black spruce								Deciduous								Total			
		Live					Dead			Live					Dead			Live					Dead						
		Height		LCBH		n	Height		n	Height		LCBH		n	Height		n	Height		LCBH		n	Height		n	Height		LCBH	
		Mean	SD	Mean	SD		Mean	SD		Mean	SD	Mean	SD		Mean	SD		Mean	SD	Mean	SD		Mean	SD		Mean	SD	Mean	SD
4**	1	--	--	--	--	--	0.9	0.9	20	--	--	--	--	--	1.1	0.5	36	--	--	--	--	--	--	--	--	1.0	0.7	--	--
9**	1	--	--	--	--	--	0.6	0.4	17	--	--	--	--	--	1.4	0.8	68	--	--	--	--	--	--	--	--	1.2	0.8	--	--
7**	2	--	--	--	--	--	0.5	0.5	7	--	--	--	--	--	2.0	1.2	51	--	--	--	--	--	--	--	--	1.8	1.3	--	--
8**	2	--	--	--	--	--	1.1	-	1	--	--	--	--	--	2.2	1.1	126	--	--	--	--	--	--	--	--	2.1	1.1	--	--
5**	3	--	--	--	--	--	0.4	0.2	6	--	--	--	--	--	1.5	0.8	102	--	--	--	--	--	--	--	--	1.4	0.8	--	--
6**	3	--	--	--	--	--	1.5	1.4	17	--	--	--	--	--	1.8	1.0	114	--	--	--	--	--	--	--	--	1.8	1.0	--	--
14	5	0.2	0.1	0.0	0.0	1014	3.4	-	1	0.2	0.2	0.0	0.0	44	1.2	0.6	6	0.8	0.6	0.5	0.3	420	1.9	1.1	4	0.4	0.4	0.1	0.2
12	21	2.9	1.3	2.0	0.9	254	0.8	0.4	185	0.5	0.5	0.0	0.1	105	0.5	0.4	6	2.9	1.3	1.8	0.8	95	1.0	0.7	49	1.8	1.5	1.5	1.1
16	56	--	--	--	--	--	2.7	1.0	5	1.4	0.7	0.8	0.4	370	1.4	0.9	16	2.3	--	1.0	--	1	--	--	--	1.4	0.7	0.8	0.4
11	57	4.7	0.5	3.0	1.0	7	3.3	1.1	37	1.3	0.8	0.7	0.4	528	1.4	1.4	8	--	--	--	--	--	3.6	0.6	2	1.5	1.0	0.7	0.5
15*	57	3.7	1.0	1.8	0.4	40	2.5	0.9	27	1.1	0.4	0.0	0.1	13	--	--	--	--	--	--	--	--	--	--	--	2.9	1.3	1.4	0.8
10	71	4.6	0.6	1.9	0.6	2	3.2	1.9	127	1.6	0.8	0.6	0.5	896	1.1	0.7	127	--	--	--	--	--	--	--	--	1.7	1.1	0.6	0.5
13	108	--	--	--	--	--	0.5	--	1	0.5	0.4	0.1	0.2	255	0.9	0.6	12	2.7	1.1	2.1	0.5	3	0.8	0.5	7	0.5	0.5	0.1	0.3

* Stand was not considered as part of the chronosequence ** Does not include seedlings (stands 4-9)

Note: TSF = time since fire, LCBH = live crown base height, SD = standard deviation, n = sample size

Table 2-17. Overstory (diameter at breast height of at least 3.0 cm) average diameter at breast height (cm).

Stand #	TSF	Jack pine									Black spruce									Deciduous									All species					
		Live			Dead			Total			Live			Dead			Total			Live			Dead			Total			Live		Dead		Total	
		Mean	SD	n	Mean	SD	n	Mean	SD		Mean	SD	n	Mean	SD	n	Mean	SD		Mean	SD	n	Mean	SD	n	Mean	SD		Mean	SD	Mean	SD	Mean	SD
4	1	--	--	--	7.8	2.8	99	7.8	2.8		--	--	--	6.3	--	1	6.3	--		--	--	--	--	--	--	--	--		--	--	7.8	2.8	7.8	2.8
9	1	--	--	--	7.4	2.5	90	7.4	2.5		--	--	--	4.2	0.5	6	4.2	0.5		--	--	--	--	--	--	--	--		--	--	7.2	2.5	7.2	2.5
7	2	--	--	--	8.4	3.4	68	8.4	3.4		--	--	--	4.7	1.4	32	4.7	1.4		--	--	--	--	--	--	--	--		--	--	7.2	3.4	7.2	3.4
8	2	--	--	--	8.1	2.8	45	8.1	2.8		--	--	--	4.4	1.1	55	4.4	1.1		--	--	--	--	--	--	--	--		--	--	6.0	2.7	6.0	2.7
5	3	--	--	--	7.0	2.3	95	7.0	2.3		--	--	--	3.6	0.5	5	3.6	0.5		--	--	--	--	--	--	--	--		--	--	6.9	2.3	6.9	2.3
6	3	--	--	--	7.3	2.7	78	7.3	2.7		--	--	--	4.5	1.0	22	4.5	1.0		--	--	--	--	--	--	--	--		--	--	6.7	2.7	6.7	2.7
14	5	--	--	--	10.9	4.3	74	10.9	4.3		--	--	--	11.4	8.3	28	11.4	8.3		--	--	--	13.3	8.1	10	--	--		--	--	11.2	5.9	11.2	5.9
12	21	4.3	1.2	95	7.0	--	1	4.3	1.2		4.5	--	1	--	--	--	4.5	--		3.9	0.8	3	--	--	--	3.9	0.8		4.3	1.2	7.0	--	4.3	1.2
16	56	9.2	2.5	27	4.5	1.5	15	7.5	3.2		5.0	1.8	42	--	--	--	5.0	1.8		--	--	--	--	--	--	--	--		6.6	3.0	4.5	1.5	6.3	2.9
11	57	6.5	2.1	67	4.2	0.9	10	6.2	2.1		3.8	0.7	21	--	--	--	3.8	0.7		5.4	--	1	3.7	--	1	4.6	1.2		5.9	2.2	4.1	0.9	5.7	2.2
15*	57	5.0	1.5	31	5.5	--	1	5.0	1.5		--	--	--	--	--	--	--	--		--	--	--	--	--	--	--	--		5.0	1.5	5.5	--	5.0	1.5
10	71	9.6	7.0	465	5.3	2.1	284	8.0	6.1		5.2	1.8	223	5.5	2.6	40	5.2	1.9		--	--	--	--	--	--	--	--		8.2	6.2	5.3	2.2	7.2	5.4
13	108	16.1	3.4	33	10.2	3.7	14	14.3	4.4		11.1	6.2	41	6.4	3.0	4	10.7	6.1		--	--	--	--	--	--	--	--		13.3	5.7	9.4	3.8	12.5	5.6

* Stand was not considered as part of the chronosequence

Note: TSF = time since fire, SD = standard deviation, n = sample size

Table 2-18. Percent canopy cover in each stand.

Stand #	TSF (years)	Cover		
		Mean (n)	SD	Range
4	1	20 (25)	3	15 - 25
9	1	15 (24)	4	8 - 22
7	2	23 (25)	4	16 - 34
8	2	19 (25)	5	13 - 32
5	3	15 (24)	4	8 - 23
6	3	16 (25)	4	8 - 28
14	5	18 (28)	4	9 - 29
12	21	55 (25)	14	17 - 75
16	56	40 (20)	10	22 - 55
11	57	47 (25)	11	27 - 67
15*	57	24 (8)	2	19 - 26
10	71	29 (25)	7	20 - 48
13	108	52 (23)	11	31 - 70

* The stand was not considered as part of the chronosequence for this project (refer to text for details)

Note: TSF = time since fire, SD = standard deviation, n = sample size

Figure 2-21. Weaknesses in the structural integrity of some snags appearing during the first 3 years after a stand-replacing crown fire (photos taken at ICFME site).

Table 2-19. Linear regression of P10 (ICFME site) tree components (g) as a function of the diameter at breast height (cm) of live and dead jack pine trees.

Tree Component	Live jack pine[a] R^2	Live MSE	Live Parameter[c]		Live SE	Live 95% C. I. Lower bound	Live 95% C. I. Upper bound	Dead jack pine[b] R^2	Dead MSE	Dead Parameter[c]		Dead SE	Dead 95% C. I. Lower bound	Dead 95% C. I. Upper bound
Needles	0.884	0.073	a	1.905	0.367	1.156	2.654							
			b	2.257	0.147	1.957	2.557							
Bark flakes	0.928	0.034	a	1.425	0.461	0.437	2.412							
			b	2.441	0.181	2.051	2.830							
Live branches 0.0-0.5 cm	0.885	0.061	a	1.624	0.336	0.938	2.310							
			b	2.076	0.135	1.802	2.350							
Dead branches 0.0-0.5 cm	0.771	0.091	a	2.482	0.426	1.612	3.351	0.871	0.174	a	2.518	0.243	2.021	3.015
			b	1.725	0.172	1.375	2.075			b	1.922	0.138	1.641	2.203
All branches 0.0-0.5 cm	0.880	0.058	a	2.581	0.329	1.911	3.251							
			b	1.980	0.132	1.712	2.248							
Live branches 0.5-1.0 cm	0.802	0.157	a	0.098	0.539	-1.001	1.197							
			b	2.419	0.216	1.980	2.859							
Dead branches 0.5-1.0 cm	0.818	0.128	a	0.477	0.488	-0.518	1.472	0.895	0.247	a	-0.812	0.418	-1.672	0.048
			b	2.306	0.195	1.908	2.704			b	3.257	0.223	2.797	3.717
All branches 0.5-1.0 cm	0.907	0.058	a	1.204	0.329	0.534	1.874							
			b	2.287	0.132	2.019	2.555							
All branches 0.0-1.0 cm	0.914	0.044	a	2.779	0.286	2.194	3.363	0.965	0.062	a	2.663	0.146	2.365	2.960
			b	2.078	0.115	1.844	2.311			b	2.321	0.082	2.153	2.489
Total fine fuels	0.970	0.016	a	3.254	0.175	2.898	3.611							
			b	2.225	0.070	2.082	2.368							
Total tree[d] (no needles)	0.962	0.023	a	5.417	0.206	4.997	5.837	0.983	0.032	a	4.722	0.105	4.509	4.936
			b	2.299	0.082	2.131	2.467			b	2.457	0.059	2.336	2.578
Total tree	0.963	0.022	a	5.463	0.201	5.053	5.874							
			b	2.302	0.081	2.138	2.466							

a. Based on the data collected on 33 live jack pine trees

b. Based on the data collected on 31 dead jack pine trees.

c. Equation Ln(y) = a + b Ln(x), where y is the tree component (g) and x is diameter at breast height (cm)

d. Exceptionally with no needles and no bark for live jack pine, for calculations in burnt stands (P4-P9, and P14) along with a combustion factor

Table 2-20. Linear regression of P10 (ICFME site) tree components (g) as a function of the diameter at breast height or at ground level (cm) of live black spruce trees.

Tree Component	Live black spruce[a] (DBH)							Live black spruce[b] (DGL)						
	R^2	MSE	Parameter[c]		SE	95% C. I. Lower bound	95% C. I. Upper bound	R^2	MSE	Parameter[c]		SE	95% C. I. Lower bound	95% C. I. Upper bound
Needles	0.837	0.256	a	5.001	0.189	4.614	5.388	0.948	0.170	a	2.827	0.131	2.562	3.092
			b	1.565	0.133	1.293	1.837			b	2.315	0.085	2.144	2.486
Live branches 0.0-0.5 cm	0.890	0.127	a	4.468	0.133	4.195	4.741	0.949	0.130	a	2.590	0.114	2.359	2.821
			b	1.388	0.094	1.196	1.580			b	2.032	0.074	1.883	2.181
Dead branches 0.0-0.5 cm	0.806	0.223	a	3.723	0.176	3.362	4.085	0.868	0.344	a	1.840	0.185	1.467	2.212
			b	1.315	0.124	1.061	1.570			b	1.953	0.119	1.713	2.194
All branches 0.0-0.5 cm	0.938	0.063	a	4.941	0.094	4.749	5.134	0.953	0.116	a	3.034	0.107	2.817	3.251
			b	1.332	0.066	1.196	1.467			b	1.996	0.069	1.856	2.135
Live branches 0.5-1.0 cm	0.702	0.554	a	3.501	0.278	2.931	4.071	0.779	0.660	a	1.866	0.256	1.350	2.383
			b	1.558	0.195	1.157	1.959			b	1.986	0.165	1.652	2.319
Dead branches 0.5-1.0 cm	0.754	0.648	a	1.353	0.356	0.619	2.087	0.735	0.825	a	-0.806	0.593	-2.026	0.415
			b	2.046	0.238	1.554	2.538			b	2.662	0.320	2.004	3.321
All branches 0.5-1.0 cm	0.818	0.316	a	3.693	0.210	3.263	4.123	0.828	0.560	a	1.855	0.235	1.380	2.330
			b	1.624	0.148	1.321	1.926			b	2.132	0.152	1.825	2.438
All branches 0.0-1.0 cm	0.922	0.090	a	5.216	0.112	4.985	5.446	0.960	0.096	a	3.430	0.098	3.233	3.628
			b	1.406	0.079	1.244	1.568			b	1.974	0.063	1.847	2.101
Total fine fuels	0.901	0.127	a	5.844	0.133	5.720	6.117	0.965	0.100	a	3.889	0.097	3.692	4.086
			b	1.467	0.093	1.275	1.659			b	2.115	0.063	1.988	2.242
Total tree (no needles)	0.963	0.084	a	5.381	0.108	5.158	5.603	0.977	0.090	a	3.280	0.097	3.084	3.476
			b	2.019	0.076	1.863	2.176			b	2.597	0.063	2.471	2.723
Total tree	0.955	0.102	a	6.090	0.119	5.485	6.334	0.981	0.080	a	3.823	0.091	3.640	4.007
			b	2.012	0.084	1.840	2.184			b	2.682	0.059	2.563	2.800

a. Based on the data collected on 29 live black spruce trees for equations with DBH

b. Based on the data collected on 44 live black spruce trees for equations with DGL

c. Equation Ln(y) = a + b Ln(x), where y is the tree component (g) and x is diameter at breast height or at ground level (DGL) (cm)

Table 2-21. Linear regression of P11 tree components (g) as a function of the diameter at breast height (cm) of live jack pine trees.

Tree Component	Live jack pine[a]						
	R^2	MSE	Parameter[b]		SE	95% C. I. Lower bound	95% C. I. Upper bound
Needles	0.973	0.059	a	1.304	0.260	0.732	1.877
			b	2.561	0.128	2.280	2.842
Bark flakes	0.980	0.038	a	1.421	0.208	0.962	1.879
			b	2.395	0.102	2.170	2.620
Live branches 0.0-0.5 cm	0.951	0.056	a	2.211	0.255	1.651	2.772
			b	1.823	0.125	1.547	2.098
Dead branches 0.0-0.5 cm	0.879	0.131	a	2.455	0.388	1.601	3.310
			b	1.703	0.191	1.284	2.123
All branches 0.0-0.5 cm	0.953	0.049	a	3.079	0.238	2.555	3.603
			b	1.746	0.117	1.489	2.004
Live branches 0.5-1.0 cm	0.832	0.467	a	-0.302	0.733	-1.915	1.311
			b	2.658	0.360	1.866	3.451
Dead branches 0.5-1.0 cm	0.831	0.190	a	-0.520	0.881	-2.552	1.512
			b	2.555	0.407	1.616	3.494
All branches 0.5-1.0 cm	0.944	0.144	a	0.026	0.407	-0.869	0.921
			b	2.730	0.200	2.291	3.170
Total fine fuels (no needles)	0.984	0.024	a	3.105	0.165	2.742	3.469
			b	2.106	0.081	1.927	2.285
Total fine fuels	0.987	0.022	a	3.230	0.158	2.882	3.578
			b	2.220	0.078	2.050	2.391
Total tree (no needles)	0.995	0.009	a	4.043	0.104	3.815	4.271
			b	2.439	0.051	2.327	2.551
Total tree	0.996	0.007	a	4.732	0.089	4.537	4.928
			b	2.305	0.044	2.208	2.401

a. Based on the data collected on 13 live trees jack pine trees

b. Equation Ln(y) = a + b Ln(x), where y is the tree component (g) and x is diameter at breast height (cm)

Table 2-22. Linear regression of P12 tree components (g) as a function of the diameter at breast height (cm) of live jack pine trees.

Tree Component	Live jack pine[a]						
	R^2	MSE	Parameter[b]		SE	95% C. I. Lower bound	Upper bound
Needles	0.918	0.197	a	2.324	0.183	1.953	2.695
			b	2.339	0.120	2.095	2.583
Bark flakes	0.945	0.123	a	-0.346	0.165	-0.682	-0.011
			b	2.412	0.104	2.200	2.624
Live branches 0.0-0.5 cm	0.927	0.123	a	1.993	0.144	1.700	2.285
			b	1.971	0.095	1.779	2.163
Dead branches 0.0-0.5 cm	0.921	0.091	a	2.278	0.124	2.026	2.530
			b	1.618	0.082	1.453	1.784
All branches 0.0-0.5 cm	0.972	0.038	a	2.866	0.080	2.703	3.029
			b	1.798	0.053	1.691	1.906
Live branches 0.5-1.0 cm	0.899	0.361	a	-1.604	0.396	-2.414	-0.794
			b	3.765	0.239	3.275	4.255
Dead branches 0.5-1.0 cm	0.768	0.311	a	-3.046	1.059	-5.279	-0.812
			b	4.177	0.557	3.002	5.352
All branches 0.5-1.0 cm	0.894	0.440	a	-1.695	0.435	-2.585	-0.805
			b	4.028	0.263	3.490	4.566
Total fine fuels (no needles)	0.961	0.080	a	2.719	0.116	2.482	2.955
			b	2.211	0.076	2.055	2.366
Total fine fuels	0.960	0.086	a	3.261	0.120	3.017	3.505
			b	2.261	0.079	2.100	2.421
Total tree (no needles)	0.993	0.015	a	4.193	0.050	4.091	4.294
			b	2.265	0.033	2.199	2.332
Total tree	0.991	0.016	a	4.927	0.052	4.821	5.032
			b	2.131	0.034	2.062	2.201

a. Based on the data collected on 38 live trees jack pine trees

b. Equation Ln(y) = a + b Ln(x), where y is the tree component (g) and x is diameter at breast height (cm)

Table 2-23. Regression of the cumulative fraction of fuel component (y) as a function of cumulative fraction of height (x) from the tree top for jack pine in stand P10 (ICFME site).

Tree Component	Live jack pine[a]							Dead jack pine[b]						
	R^2	MSE	Parameter[c]		ASE	95% C. I. Lower	Upper	R^2	MSE	Parameter[c]		ASE	95% C. I. Lower	Upper
Needles	0.886	0.008	a	0.996	0.006	0.985	1.008			a				
			b	2.403	0.110	2.186	2.620			b				
			c	13.086	0.558	11.989	14.183			c				
Bark flakes	0.989	0.001	a	1.243	0.029	1.187	1.300			a				
			b	3.935	0.057	3.824	4.047			b				
			c	5.328	0.135	5.062	5.595			c				
Live branches 0.0-0.5 cm	0.893	0.009	a	0.996	0.006	0.984	1.008			a				
			b	2.936	0.135	2.671	3.200			b				
			c	14.112	0.623	12.887	15.336			c				
Dead branches 0.0-0.5 cm	0.940	0.008	a	1.025	0.016	0.993	1.057	0.914	0.009	a	1.053	0.024	1.004	1.101
			b	3.840	0.118	3.608	4.071			b	2.625	0.100	2.428	2.823
			c	6.945	0.263	6.429	7.462			c	5.358	0.280	4.807	5.910
All branches 0.0-0.5 cm	0.924	0.008	a	0.970	0.009	0.951	0.988			a				
			b	2.438	0.081	2.279	2.596			b				
			c	7.077	0.256	6.574	7.580			c				
Live branches 0.5-1.0 cm	0.879	0.009	a	0.997	0.006	0.985	1.009			a				
			b	2.538	0.121	2.300	2.776			b				
			c	13.46	0.603	12.275	14.646			c				
Dead branches 0.5-1.0 cm	0.903	0.014	a	1.059	0.027	1.006	1.112	0.825	0.019	a	1.090	0.042	1.007	1.172
			b	4.079	0.160	3.765	4.393			b	2.282	0.124	2.038	2.525
			c	6.706	0.340	6.037	7.374			c	4.769	0.386	4.010	5.529
All branches 0.5-1.0 cm	0.888	0.011	a	0.994	0.015	0.965	1.024			a				
			b	2.150	0.080	1.993	2.308			b				
			c	5.722	0.259	5.213	6.230			c				
All branches 0.0-1.0 cm	0.894	0.010	a	0.974	0.011	0.952	0.996			a				
			b	2.290	0.089	2.115	2.464			b				
			c	6.786	0.290	6.217	7.356			c				
Total fine fuels (no needles)	0.921	0.008	a	0.977	0.010	0.956	0.997	0.963	0.004	a	1.144	0.027	1.092	1.196
			b	2.325	0.076	2.175	2.474			b	2.813	0.060	2.695	2.932
			c	6.545	0.242	6.071	7.020			c	4.715	0.170	4.381	5.050
Total fine fuels	0.940	0.005	a	0.996	0.011	0.974	1.019			a				
			b	1.973	0.051	1.874	2.073			b				
			c	5.274	0.171	4.937	5.610			c				
Total tree[d] (no needles)	0.994	0.001	a	1.372	0.024	1.325	1.419	0.989	0.001	a	1.526	0.052	1.424	1.629
			b	3.906	0.025	3.857	3.954			b	4.013	0.038	3.938	4.087
			c	4.814	0.068	4.681	4.947			c	4.623	0.109	4.408	4.837
Total tree	0.994	0.001	a	1.391	0.025	1.342	1.441			a				
			b	3.716	0.022	3.672	3.760			b				
			c	4.581	0.065	4.453	4.709			c				

a. Based on the data collected on 33 live jack pine trees

b. Based on the data collected on 31 dead jack pine trees.

c. Equation y = a/(1+exp(b-(cx))), where the cumulative fraction of tree component (y) is a function of cumulative fraction of height (x) from tree top

d. Exceptionally with no needles and no bark for live jack pine, for calculations in burnt stands (P4-P9, and P14) along with a combustion factor

Table 2-24. Regression of the cumulative fraction of fuel component (y) as a function of cumulative fraction of height (x) from the tree top for black spruce in stand P10 (ICFME site).

Tree Component	Live black spruce[a]						
	R^2	MSE	Parameter[b]		ASE	95% C. I.	
						Lower	Upper
Needles	0.872	0.015	a	1.015	0.019	0.977	1.054
			b	2.755	0.200	2.361	3.149
			c	6.923	0.545	5.846	7.999
Live branches 0.0-0.5 cm	0.830	0.020	a	1.032	0.028	0.976	1.087
			b	2.654	0.219	2.221	3.086
			c	6.113	0.584	4.958	7.267
Dead branches 0.0-0.5 cm	0.902	0.019	a	2.932	2.037	-1.091	6.954
			b	6.300	0.299	5.710	6.891
			c	5.645	1.000	3.670	7.619
All branches 0.0-0.5 cm	0.914	0.011	a	1.152	0.052	1.051	1.254
			b	2.869	0.141	2.591	3.147
			c	4.703	0.377	3.958	5.448
Live branches 0.5-1.0 cm	0.802	0.032	a	1.144	0.079	0.988	1.301
			b	3.386	0.302	2.791	3.982
			c	5.351	0.704	3.961	6.742
Dead branches 0.5-1.0 cm	0.891	0.019	a	2.314	1.469	-0.592	5.220
			b	9.000	0.971	7.079	10.920
			c	8.731	1.991	4.794	12.668
All branches 0.5-1.0 cm	0.869	0.021	a	1.429	0.199	1.036	1.821
			b	3.733	0.208	3.323	4.143
			c	4.584	0.586	3.426	5.742
All branches 0.0-1.0 cm	0.916	0.011	a	1.228	0.074	1.081	1.375
			b	3.096	0.143	2.814	3.378
			c	4.548	0.390	3.777	5.319
Total fine fuels	0.908	0.011	a	1.064	0.029	1.006	1.121
			b	2.772	0.156	2.464	3.079
			c	5.435	0.399	4.648	6.223
Total tree (no needles)	0.989	0.002	a	1.501	0.070	1.362	1.639
			b	3.960	0.061	3.840	4.080
			c	4.642	0.175	4.297	4.987
Total tree	0.988	0.002	a	1.407	0.054	1.300	1.513
			b	3.597	0.056	3.486	3.707
			c	4.479	0.162	4.159	4.799

a. Based on the data collected on 44 live black spruce trees

b. Equation y = a/(1+exp(b-(cx))), where the cumulative fraction of tree component (y) is a function of cumulative fraction of height (x) from tree top

Table 2-25. Regression of the cumulative fraction of fuel component (y) as a function of cumulative fraction of height (x) from the tree top for jack pine in stand P11.

Tree Component	Live jack pine[a]						
	R^2	MSE	Parameter[b]		ASE	95% C. I. Lower	Upper
Needles	0.939	0.005	a	0.994	0.008	0.977	1.011
			b	2.677	0.177	2.327	3.026
			c	14.826	0.939	12.965	16.686
Bark flakes	0.986	0.002	a	1.160	0.032	1.095	1.224
			b	4.077	0.105	3.868	4.285
			c	5.814	0.227	5.365	6.264
Live branches 0.0-0.5 cm	0.965	0.004	a	0.998	0.008	0.983	1.013
			b	3.343	0.176	2.994	3.692
			c	14.783	0.767	13.264	16.302
Dead branches 0.0-0.5 cm	0.969	0.005	a	1.005	0.016	0.973	1.037
			b	5.111	0.266	4.585	5.638
			c	9.648	0.544	8.571	10.726
All branches 0.0-0.5 cm	0.984	0.002	a	0.994	0.008	0.978	1.011
			b	2.857	0.087	2.686	3.029
			c	7.851	0.256	7.344	8.359
Live branches 0.5-1.0 cm	0.856	0.014	a	1.010	0.016	0.979	1.042
			b	2.373	0.236	1.906	2.840
			c	11.043	1.056	8.952	13.134
Dead branches 0.5-1.0 cm	0.942	0.011	a	1.002	0.021	0.961	1.044
			b	5.834	0.481	4.882	6.787
			c	11.423	0.988	9.464	13.382
All branches 0.5-1.0 cm	0.856	0.016	a	1.007	0.023	0.961	1.052
			b	2.268	0.208	1.857	2.679
			c	7.458	0.714	6.043	8.873
All branches 0.0-1.0 cm	0.980	0.002	a	0.993	0.009	0.976	1.010
			b	2.746	0.095	2.558	2.934
			c	8.164	0.298	7.575	8.754
Total fine fuels (no needles)	0.984	0.002	a	1.008	0.013	0.982	1.033
			b	2.773	0.077	2.620	2.926
			c	6.147	0.211	5.729	6.566
Total fine fuels	0.978	0.002	a	0.976	0.010	0.956	0.996
			b	2.240	0.076	2.090	2.389
			c	6.600	0.246	6.112	7.087
Total tree (no needles)	0.993	0.001	a	1.385	0.046	1.294	1.476
			b	3.404	0.040	3.325	3.482
			c	4.299	0.120	4.061	4.537
Total tree	0.993	0.001	a	1.433	0.052	1.330	1.537
			b	3.280	0.036	3.209	3.351
			c	4.063	0.116	3.833	4.293

a. Based on the data collected on 13 live jack pine trees

b. Equation y = a/(1+exp(b-(cx))), where the cumulative fraction of tree component (y) is a function of cumulative fraction of height (x) from tree top

Table 2-26. Regression of the cumulative fraction of fuel component (y) as a function of cumulative fraction of height (x) from the tree top for jack pine in stand P12.

Tree Component	Live jack pine[a]					
	R^2	MSE	Parameter[b]	ASE	95% C. I. Lower	95% C. I. Upper
Needles	0.901	0.010	a 0.998	0.010	0.978	1.019
			b 2.621	0.166	2.293	2.949
			c 10.658	0.653	9.369	11.946
Bark flakes	0.970	0.004	a 1.238	0.047	1.145	1.332
			b 4.346	0.132	4.085	4.607
			c 5.745	0.275	5.202	6.287
Live branches 0.0-0.5 cm	0.910	0.011	a 1.008	0.012	0.984	1.032
			b 3.002	0.182	2.642	3.361
			c 9.669	0.593	8.500	10.838
Dead branches 0.0-0.5 cm	0.961	0.006	a 1.084	0.028	1.029	1.139
			b 7.521	0.388	6.755	8.287
			c 9.933	0.584	8.782	11.085
All branches 0.0-0.5 cm	0.977	0.003	a 1.064	0.016	1.034	1.095
			b 2.862	0.068	2.727	2.997
			c 5.449	0.176	5.102	5.796
Live branches 0.5-1.0 cm	0.696	0.036	a 1.034	0.030	0.974	1.094
			b 1.930	0.219	1.498	2.362
			c 6.476	0.776	4.945	8.006
Dead branches 0.5-1.0 cm	0.901	0.018	a 1.020	0.034	0.954	1.087
			b 10.050	1.046	7.985	12.116
			c 13.862	1.524	10.852	16.873
All branches 0.5-1.0 cm	0.669	0.043	a 1.107	0.074	0.961	1.253
			b 1.998	0.191	1.621	2.375
			c 4.403	0.637	3.147	5.659
All branches 0.0-1.0 cm	0.968	0.004	a 1.065	0.017	1.031	1.099
			b 2.792	0.078	2.638	2.946
			c 5.471	0.204	5.069	5.873
Total fine fuels (no needles)	0.972	0.003	a 1.075	0.018	1.040	1.110
			b 2.856	0.073	2.711	3.001
			c 5.361	0.190	4.987	5.735
Total fine fuels	0.950	0.005	a 0.992	0.012	0.968	1.016
			b 2.371	0.093	2.188	2.554
			c 6.459	0.282	5.903	7.014
Total tree (no needles)	0.993	0.001	a 1.363	0.032	1.300	1.427
			b 3.816	0.043	3.732	3.901
			c 4.805	0.109	4.590	5.020
Total tree	0.989	0.001	a 1.379	0.040	1.299	1.458
			b 3.436	0.041	3.354	3.517
			c 4.377	0.119	4.142	4.611

a. Based on the data collected on 38 live jack pine trees

b. Equation y = a/(1+exp(b-(cx))), where the cumulative fraction of tree component (y) is a function of cumulative fraction of height (x) from tree top

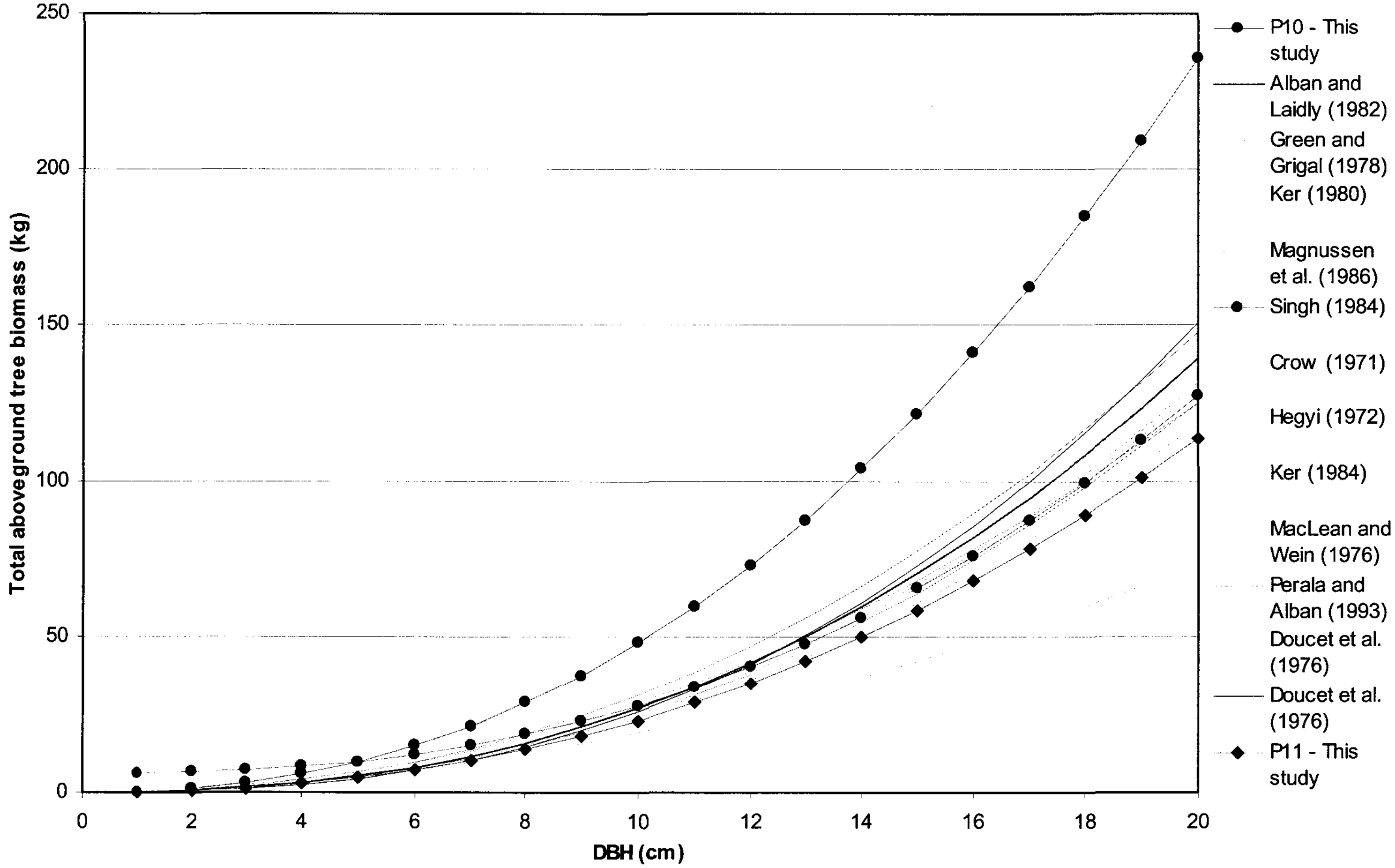


Figure 2-22. Total aboveground tree biomass as a function of dbh for different studies found in the literature.

Table 2-27. Estimated load (kg/m^2) of the different tree components sampled in each stand.

Plot	TSF	Jack pine								Black spruce							Decidous**		Total fine	Total
		Needles	Bark flakes	Live branches		Dead branches		Total fine	Total	Needles	Live branches		Dead branches		Total fine	Total	Total fine	Total		
				0.0-0.5	0,51-1.0	0.0-0.5	0,51-1.0				0.0-0.5	0,51-1.0	0.0-0.5	0,51-1.0						
4	1	0.000	0.000	0.000	0.000	0.057	0.073	0.129	16.275	0.000	0.000	0.000	0.004	0.004	0.007	0.072	0.000	0.000	0.136	16.347
9	1	0.000	0.000	0.000	0.000	0.052	0.066	0.118	14.709	0.000	0.000	0.000	0.011	0.010	0.021	0.222	0.000	0.000	0.139	14.931
7	2	0.000	0.000	0.000	0.000	0.040	0.053	0.093	11.907	0.000	0.000	0.000	0.024	0.026	0.050	0.788	0.000	0.000	0.143	12.695
8	2	0.000	0.000	0.000	0.000	0.041	0.053	0.093	11.834	0.000	0.000	0.000	0.065	0.068	0.133	1.898	0.000	0.000	0.227	13.732
5	3	0.000	0.000	0.000	0.000	0.041	0.050	0.091	11.275	0.000	0.000	0.000	0.012	0.011	0.022	0.179	0.000	0.000	0.113	11.454
6	3	0.000	0.000	0.000	0.000	0.055	0.069	0.124	15.540	0.000	0.000	0.000	0.031	0.031	0.062	0.813	0.000	0.000	0.186	16.353
14	5	0.000	0.000	0.000	0.000	0.027	0.040	0.067	8.976	0.000	0.000	0.000	0.020	0.032	0.052	2.145	0.011	1.385	0.130	12.505
12	21	0.373	0.028	0.152	0.078	0.128	0.042	0.795	3.420	0.029	0.015	0.008	0.007	0.002	0.061	0.128	0.017	0.261	0.873	3.809
16	56	0.259	0.208	0.113	0.081	0.143	0.051	0.806	4.415	1.107	0.493	0.288	0.238	0.073	2.147	5.666	0.000	0.001	2.953	10.083
11	57	0.249	0.209	0.138	0.075	0.174	0.048	0.856	4.563	0.572	0.282	0.154	0.140	0.030	1.177	2.298	0.003	0.052	2.036	6.914
15*	57	0.265	0.227	0.185	0.078	0.219	0.049	0.986	5.154	0.011	0.006	0.003	0.003	0.000	0.024	0.030	0.000	0.000	1.010	5.183
10	71	0.355	0.394	0.174	0.089	0.253	0.135	1.357	14.962	0.460	0.199	0.120	0.137	0.056	0.943	2.756	0.000	0.000	2.300	17.718
13	108	0.415	0.488	0.186	0.113	0.217	0.174	1.529	17.591	1.232	0.463	0.331	0.228	0.152	2.202	10.787	0.001	0.021	3.733	28.400

* The stand was not considered as part of the chronosequence for this project (refer to text for details)

** Populus spp.

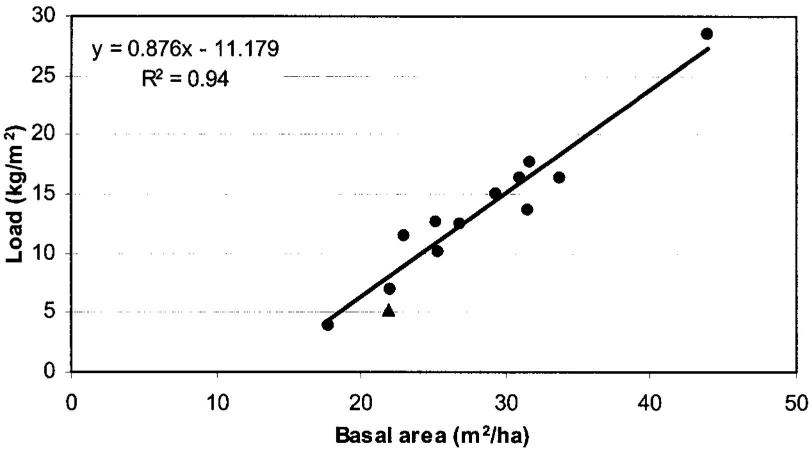


Figure 2-23. Total tree load (kg/m^2) as a function of basal area for the stands in the chronosequence (P15 is in red).

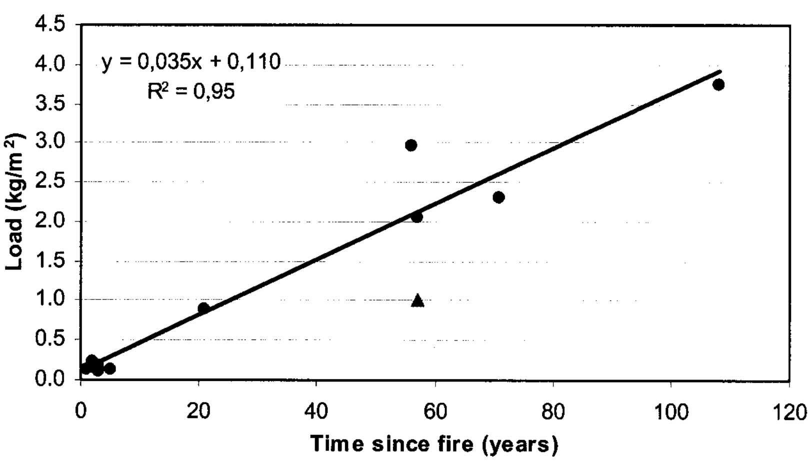


Figure 2-24. Total load (kg/m2) of the fine tree components (needles, bark flakes, live and dead branches 0-1 cm in diameter) as a function of time since fire.

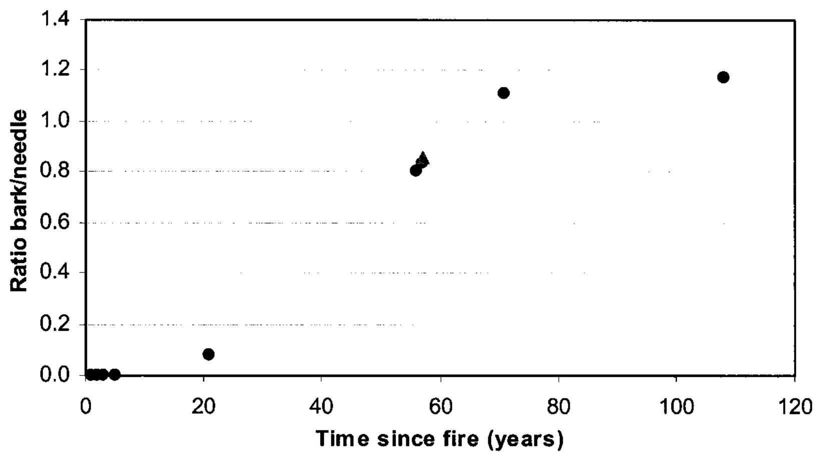
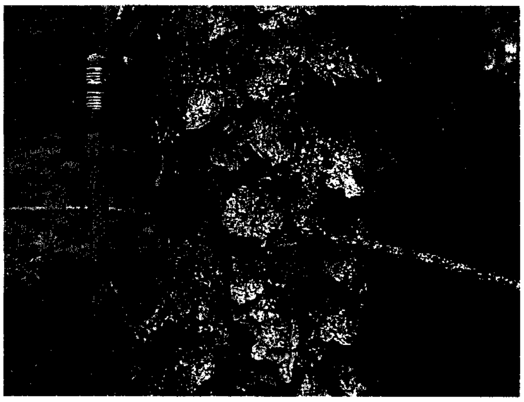


Figure 2-25. Ratio of bark flake to needle loads as a function of time since fire for the jack pine component of the stands (P15 is in red).

(a) 12 years since fire (P12)



(b) 57 years since fire (P11)

(c) 108 years since fire (P13)

(d) after the fire (P9)

Figure 2-26. Bark flakes along the stem of jack pine trees at different times since fire.

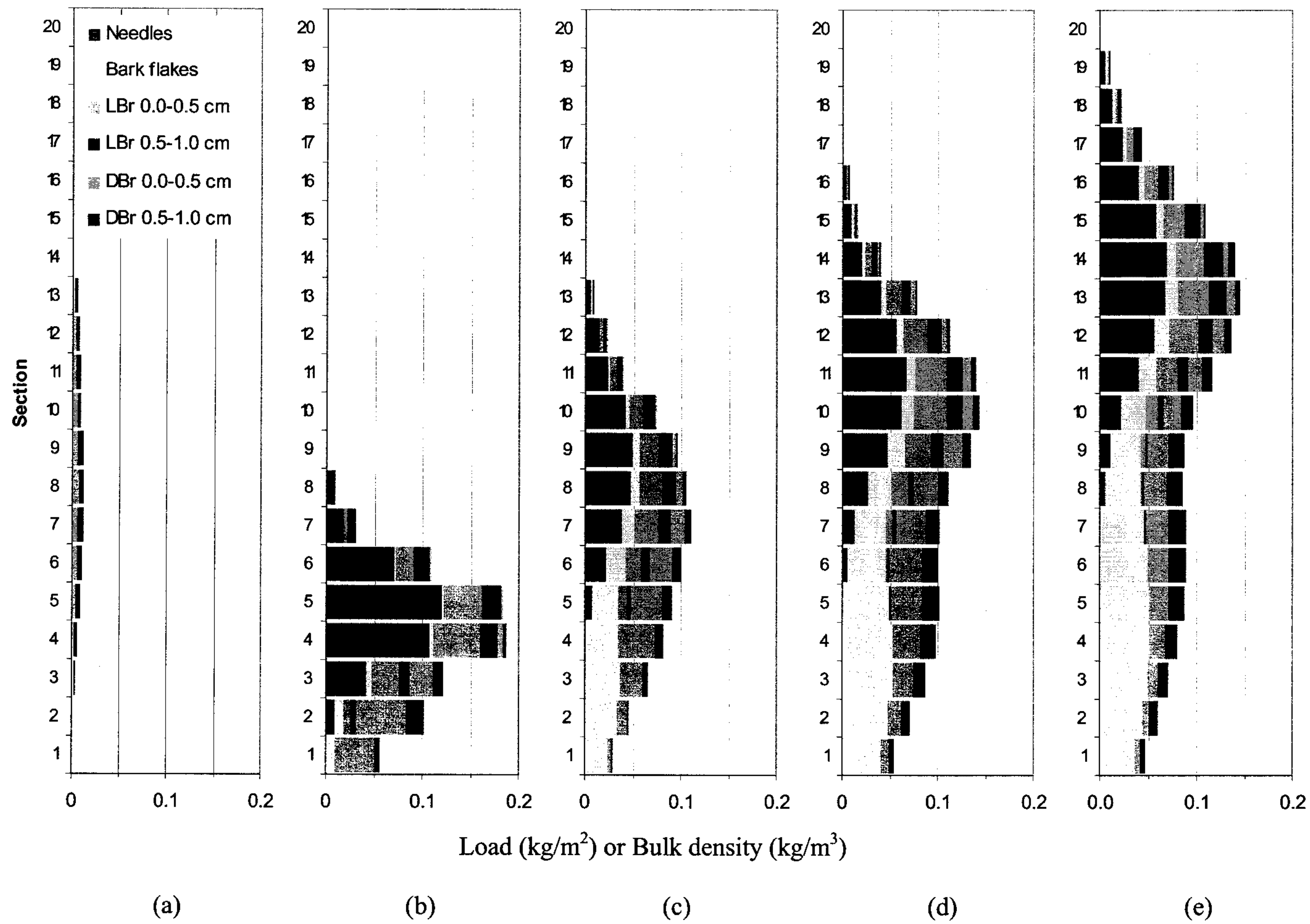
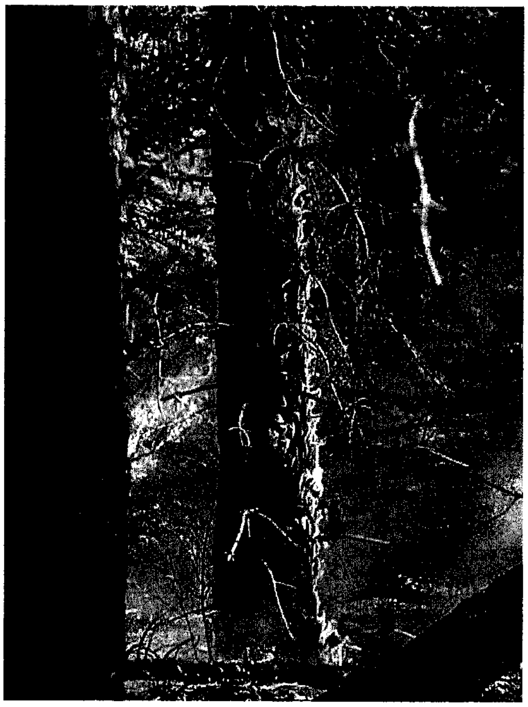


Figure 2-27. Vertical distribution (per 1-m sections) of the load (kg/m^2) and bulk density (kg/m^3) of the jack pine fine crown components at a) 0-5, b) 21, c) 57, d) 71, and e) 108 years since fire.



(a) (b)

(c) (d)

Figure 2-28. Fire being carried into the crown along the bark of trees.

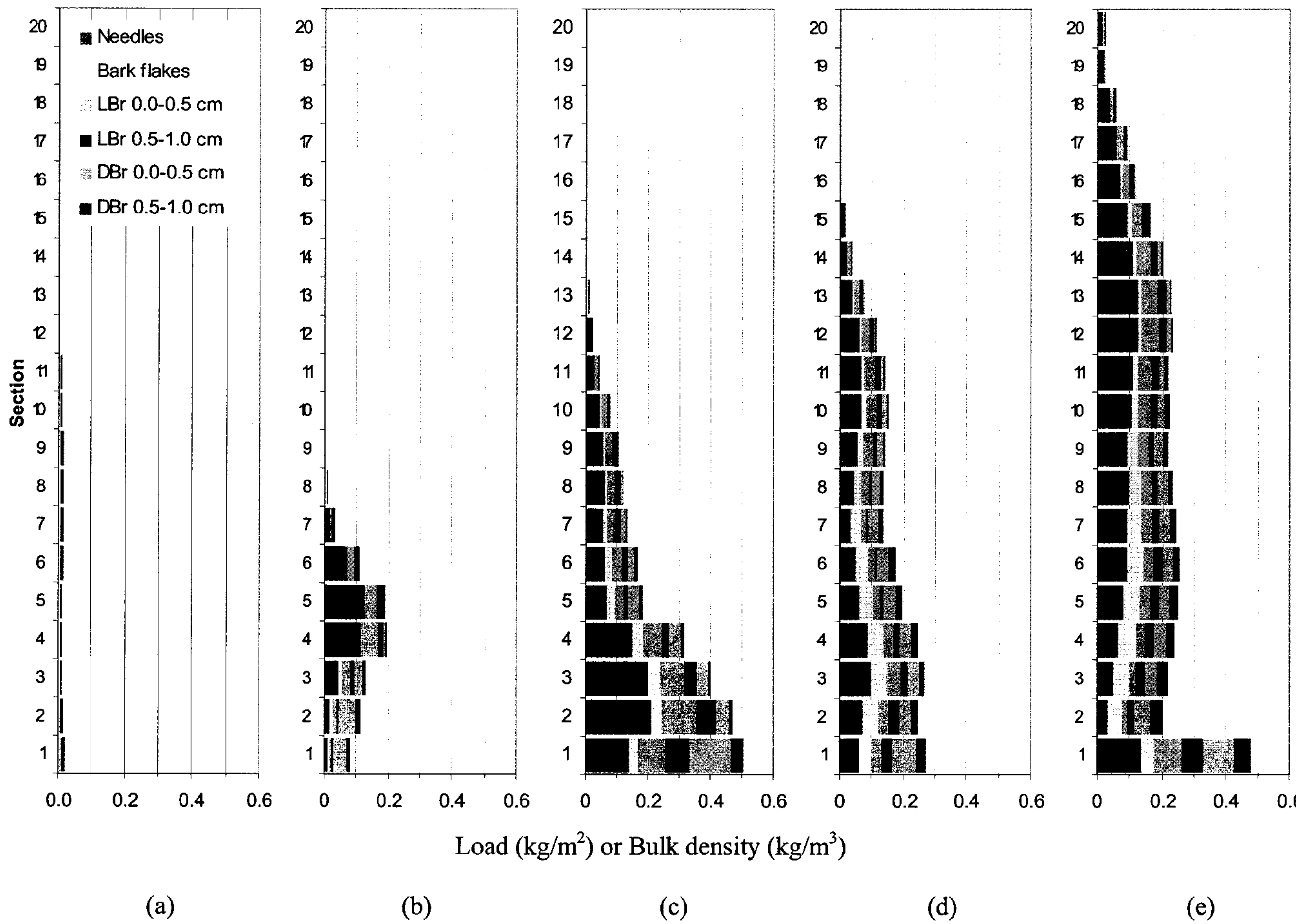


Figure 2-29. Vertical distribution (per 1-m sections) of the load (kg/m^2) and bulk density (kg/m^3) of the total fine crown components at a) 0-5, b) 21, c) 57, d) 71, and e) 108 years since fire.

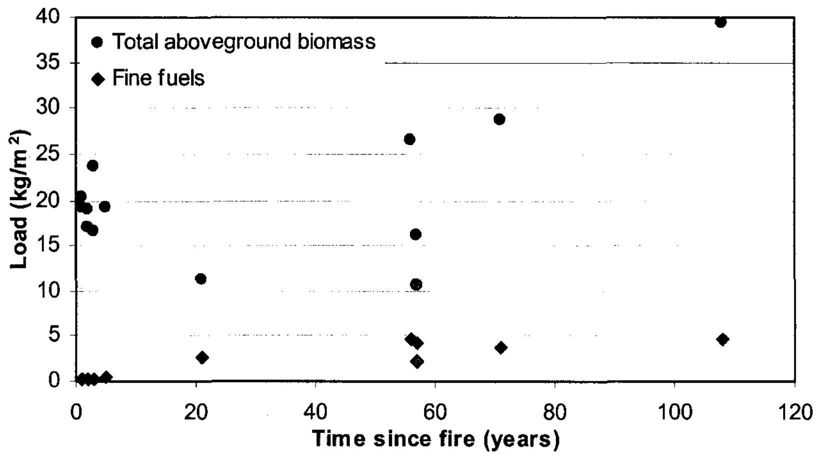


Figure 2-30. Total biomass and total fine fuel loads (kg/m^2) as a function of time since fire in the chronosequence (P15 is in red).

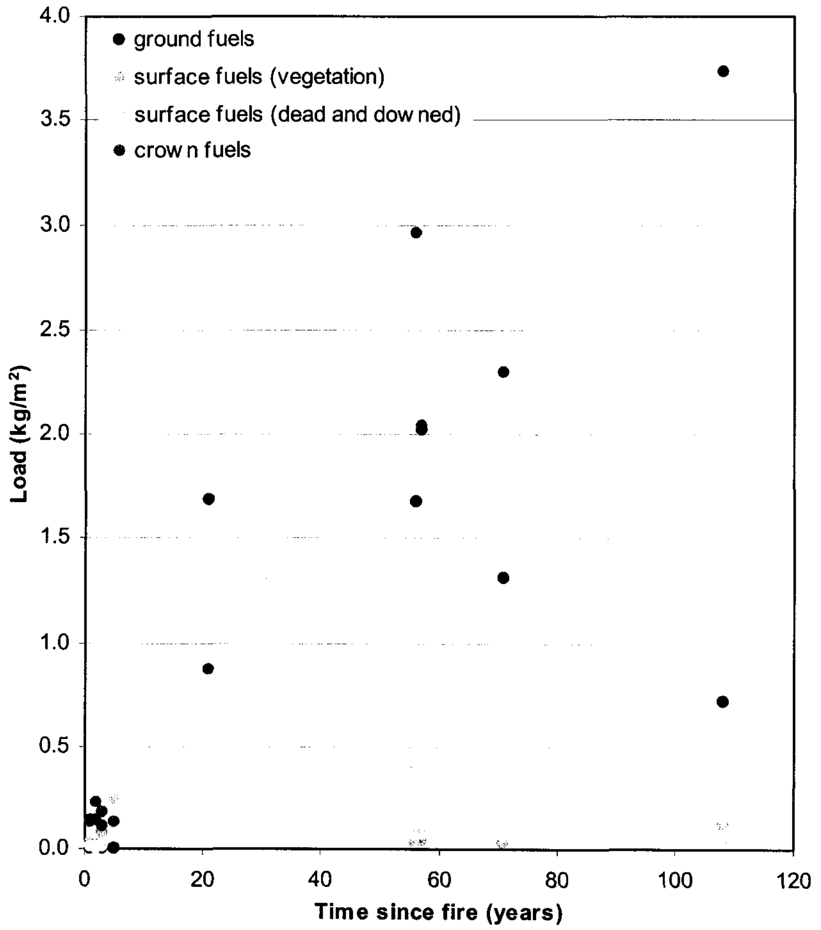


Figure 2-31. Fine fuel load (kg/m^2) per category as a function of time since fire.

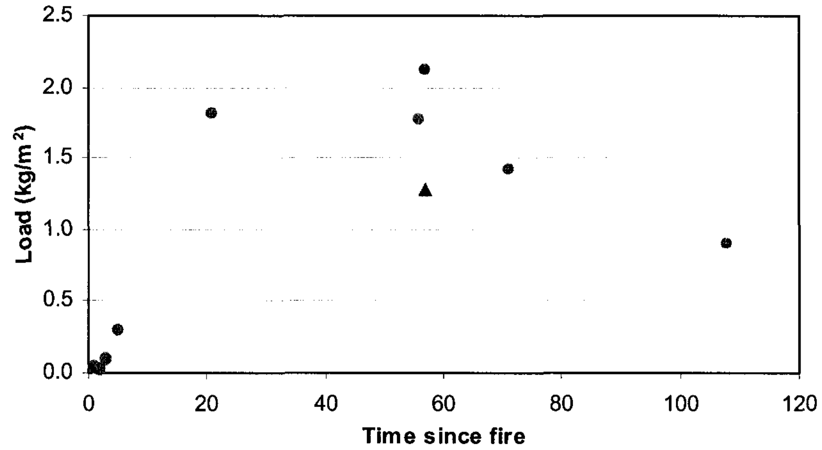


Figure 2-32. Total ground and surface fine fuel loads (kg/m^2) as a function of time since fire in the chronosequence (P15 is in red).

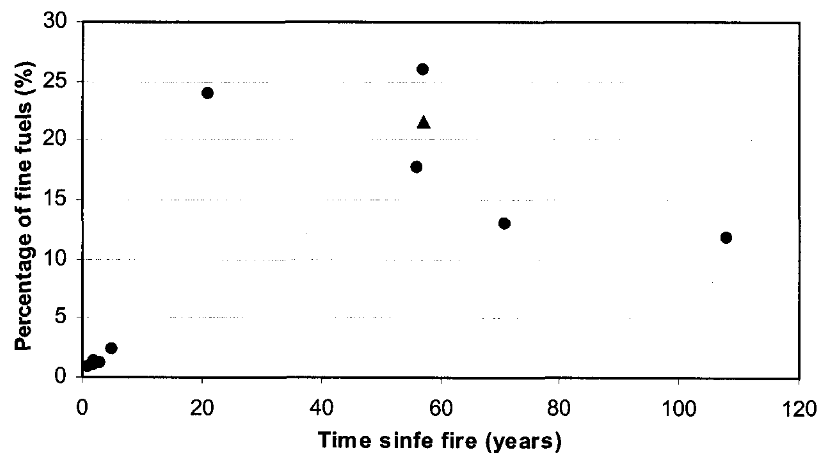


Figure 2-33. Ratio (%) of fine fuels over total stand biomass loads presented as a function of time since fire (P15 is in red).

Table 2-28. Vertical distribution (1-m sections) of the load (kg/m^2) and bulk density (kg/m^3) of the fine fuels and total stand biomass (excluding roots).

Height (m)	Stand (TSF)																				
	4 (1)			9 (1)			7 (2)			8 (2)			5 (3)			6 (3)			14 (5)		
	Fine	Total	%	Fine	Total	%	Fine	Total	%	Fine	Total	%	Fine	Total	%	Fine	Total	%	Fine	Total	%
BGD	0.000	2.368	--	0.000	2.615	--	0.000	3.682	--	0.000	4.447	--	0.000	3.260	--	0.000	5.991	--	0.000	4.966	--
0-1	0.046	3.657	1.2	0.041	3.630	1.1	0.035	2.250	1.5	0.063	3.047	2.1	0.106	3.439	3.1	0.111	3.547	3.1	0.306	2.952	10.4
1-2	0.004	2.306	0.2	0.008	2.197	0.3	0.014	1.776	0.8	0.039	2.193	1.8	0.007	1.735	0.4	0.019	2.483	0.8	0.005	1.412	0.4
2-3	0.005	2.323	0.2	0.007	2.180	0.3	0.012	1.729	0.7	0.029	1.994	1.5	0.006	1.706	0.4	0.016	2.394	0.7	0.006	1.438	0.4
3-4	0.007	2.152	0.3	0.009	1.992	0.4	0.011	1.584	0.7	0.022	1.732	1.3	0.007	1.544	0.5	0.014	2.144	0.7	0.007	1.379	0.5
4-5	0.010	1.851	0.6	0.010	1.687	0.6	0.009	1.365	0.7	0.014	1.415	1.0	0.008	1.290	0.6	0.013	1.788	0.8	0.008	1.257	0.6
5-6	0.014	1.499	0.9	0.014	1.348	1.0	0.011	1.133	1.0	0.015	1.147	1.3	0.011	1.017	1.1	0.016	1.431	1.1	0.009	1.099	0.8
6-7	0.016	1.161	1.4	0.015	1.026	1.5	0.011	0.891	1.2	0.012	0.855	1.4	0.012	0.766	1.6	0.016	1.084	1.5	0.010	0.927	1.1
7-8	0.017	0.863	1.9	0.016	0.747	2.1	0.012	0.686	1.7	0.013	0.646	2.0	0.012	0.549	2.2	0.016	0.793	2.0	0.011	0.765	1.4
8-9	0.016	0.661	2.5	0.015	0.561	2.6	0.011	0.523	2.1	0.011	0.484	2.4	0.011	0.414	2.7	0.015	0.605	2.5	0.011	0.615	1.7
9-10	0.012	0.430	2.9	0.011	0.363	3.0	0.009	0.372	2.5	0.009	0.325	2.7	0.008	0.258	3.1	0.011	0.390	2.9	0.010	0.491	2.0
10-11	0.010	0.336	3.1	0.009	0.296	3.1	0.009	0.303	2.8	0.008	0.278	2.9	0.007	0.234	3.1	0.010	0.335	3.0	0.009	0.396	2.3
11-12	0.009	0.305	3.0	0.009	0.318	2.9	0.007	0.234	3.0	0.006	0.217	2.9	0.006	0.200	2.9	0.008	0.273	2.9	0.008	0.327	2.6
12-13	0.008	0.287	2.7	0.004	0.127	2.8	0.005	0.192	2.8	0.004	0.130	2.9	0.002	0.089	2.8	0.005	0.174	2.8	0.008	0.286	2.6
13-14	0.001	0.042	2.7	0.002	0.058	2.6	0.004	0.135	2.7	0.003	0.118	2.7	0.001	0.032	2.6	0.002	0.084	2.7	0.005	0.191	2.7
14-15	0.001	0.023	2.6	0.000	0.000	--	0.001	0.054	2.7	0.001	0.036	2.6	0.000	0.000	--	0.001	0.033	2.6	0.004	0.158	2.8
15-16	0.000	0.000	--	0.000	0.000	--	0.000	0.010	3.0	0.000	0.000	--	0.000	0.000	--	0.000	0.000	--	0.003	0.092	2.8
16-17	0.000	0.000	--	0.000	0.000	--	0.001	0.032	2.5	0.000	0.000	--	0.000	0.000	--	0.000	0.000	--	0.003	0.108	2.7
17-18	0.000	0.000	--	0.000	0.000	--	0.000	0.000	--	0.000	0.000	--	0.000	0.000	--	0.000	0.000	--	0.002	0.056	2.7
18-19	0.000	0.000	--	0.000	0.000	--	0.000	0.000	--	0.000	0.000	--	0.000	0.000	--	0.000	0.000	--	0.001	0.047	2.7
19-20	0.000	0.000	--	0.000	0.000	--	0.000	0.000	--	0.000	0.000	--	0.000	0.000	--	0.000	0.000	--	0.002	0.056	2.9
20-21	0.000	0.000	--	0.000	0.000	--	0.000	0.000	--	0.000	0.000	--	0.000	0.000	--	0.000	0.000	--	0.000	0.015	2.9
21-22	0.000	0.000	--	0.000	0.000	--	0.000	0.000	--	0.000	0.000	--	0.000	0.000	--	0.000	0.000	--	0.000	0.013	3.0
22-23	0.000	0.000	--	0.000	0.000	--	0.000	0.000	--	0.000	0.000	--	0.000	0.000	--	0.000	0.000	--	0.000	0.011	3.0
23-24	0.000	0.000	--	0.000	0.000	--	0.000	0.000	--	0.000	0.000	--	0.000	0.000	--	0.000	0.000	--	0.000	0.010	3.1
24-25	0.000	0.000	--	0.000	0.000	--	0.000	0.000	--	0.000	0.000	--	0.000	0.000	--	0.000	0.000	--	0.001	0.015	3.4
25-26	0.000	0.000	--	0.000	0.000	--	0.000	0.000	--	0.000	0.000	--	0.000	0.000	--	0.000	0.000	--	0.000	0.006	3.1
26-27	0.000	0.000	--	0.000	0.000	--	0.000	0.000	--	0.000	0.000	--	0.000	0.000	--	0.000	0.000	--	0.000	0.005	3.1
27-28	0.000	0.000	--	0.000	0.000	--	0.000	0.000	--	0.000	0.000	--	0.000	0.000	--	0.000	0.000	--	0.000	0.014	3.3
28-29	0.000	0.000	--	0.000	0.000	--	0.000	0.000	--	0.000	0.000	--	0.000	0.000	--	0.000	0.000	--	0.000	0.014	3.3
29-30	0.000	0.000	--	0.000	0.000	--	0.000	0.000	--	0.000	0.000	--	0.000	0.000	--	0.000	0.000	--	0.000	0.000	--
Total	0.176	20.266	0.9	0.169	19.146	0.9	0.162	16.954	1.0	0.250	19.064	1.3	0.205	16.533	1.2	0.274	23.549	1.2	0.431	19.122	2.3

* The stand was not considered as part of the chronosequence for this project (refer to text for details)

Note: BGD = below ground (does not include roots), TSF = time since fire, % = percent of fine fuels

Table 2-28. (continued).

Height (m)	Stand (TSF)																	
	12 (21)			16 (56)			11 (57)			15* (57)			10 (71)			13 (108)		
	Fine	Total	%	Fine	Total	%	Fine	Total	%	Fine	Total	%	Fine	Total	%	Fine	Total	%
BGD	1.689	4.775	35.4	1.672	15.421	10.8	2.014	7.892	25.5	1.101	4.556	24.2	1.312	9.411	13.9	0.717	9.938	7.2
0-1	0.175	3.730	4.7	0.602	3.510	17.2	0.546	3.101	17.6	0.212	1.868	11.4	0.337	4.312	7.8	0.590	4.185	14.1
1-2	0.109	1.022	10.7	0.564	2.087	27.0	0.418	1.473	28.4	0.062	1.048	5.9	0.240	2.629	9.1	0.155	2.915	5.3
2-3	0.185	0.764	24.2	0.462	1.565	29.5	0.283	1.056	26.8	0.107	0.923	11.5	0.248	2.451	10.1	0.191	2.951	6.5
3-4	0.211	0.462	45.7	0.378	1.181	32.0	0.228	0.799	28.6	0.164	0.719	22.8	0.230	2.174	10.6	0.222	2.856	7.8
4-5	0.174	0.299	58.1	0.226	0.785	28.8	0.145	0.523	27.7	0.200	0.549	36.4	0.189	1.814	10.4	0.239	2.654	9.0
5-6	0.104	0.169	61.3	0.212	0.619	34.2	0.145	0.379	38.2	0.159	0.328	48.5	0.190	1.504	12.6	0.255	2.397	10.6
6-7	0.025	0.041	61.7	0.151	0.402	37.5	0.134	0.299	44.8	0.149	0.303	49.1	0.162	1.158	13.9	0.252	2.085	12.1
7-8	0.009	0.015	58.9	0.138	0.309	44.8	0.087	0.165	52.6	0.059	0.101	58.1	0.160	0.903	17.7	0.256	1.794	14.3
8-9	0.000	0.000	–	0.104	0.215	48.6	0.079	0.173	45.8	0.059	0.147	39.9	0.142	0.683	20.8	0.241	1.488	16.2
9-10	0.000	0.000	–	0.090	0.191	47.1	0.048	0.108	44.4	0.015	0.037	38.9	0.120	0.494	24.4	0.239	1.252	19.1
10-11	0.000	0.000	–	0.050	0.102	49.4	0.013	0.024	54.7	0.000	0.000	–	0.110	0.395	27.7	0.209	0.993	21.1
11-12	0.000	0.000	–	0.037	0.089	41.6	0.016	0.045	35.8	0.000	0.000	–	0.104	0.339	30.7	0.202	0.842	24.0
12-13	0.000	0.000	–	0.027	0.075	35.8	0.005	0.015	33.7	0.000	0.000	–	0.088	0.277	31.9	0.178	0.683	26.1
13-14	0.000	0.000	–	0.008	0.024	33.8	0.000	0.000	–	0.000	0.000	–	0.048	0.151	31.9	0.157	0.565	27.9
14-15	0.000	0.000	–	0.000	0.000	–	0.000	0.000	–	0.000	0.000	–	0.022	0.069	32.3	0.138	0.467	29.6
15-16	0.000	0.000	–	0.000	0.000	–	0.000	0.000	–	0.000	0.000	–	0.009	0.029	31.2	0.113	0.377	30.0
16-17	0.000	0.000	–	0.000	0.000	–	0.000	0.000	–	0.000	0.000	–	0.002	0.007	32.2	0.097	0.325	29.9
17-18	0.000	0.000	–	0.000	0.000	–	0.000	0.000	–	0.000	0.000	–	0.002	0.007	32.0	0.070	0.235	29.6
18-19	0.000	0.000	–	0.000	0.000	–	0.000	0.000	–	0.000	0.000	–	0.000	0.000	–	0.039	0.131	29.9
19-20	0.000	0.000	–	0.000	0.000	–	0.000	0.000	–	0.000	0.000	–	0.000	0.000	–	0.024	0.091	25.9
20-21	0.000	0.000	–	0.000	0.000	–	0.000	0.000	–	0.000	0.000	–	0.000	0.000	–	0.008	0.030	26.6
21-22	0.000	0.000	–	0.000	0.000	–	0.000	0.000	–	0.000	0.000	–	0.000	0.000	–	0.007	0.025	26.5
22-23	0.000	0.000	–	0.000	0.000	–	0.000	0.000	–	0.000	0.000	–	0.000	0.000	–	0.013	0.055	24.0
23-24	0.000	0.000	–	0.000	0.000	–	0.000	0.000	–	0.000	0.000	–	0.000	0.000	–	0.003	0.012	25.7
24-25	0.000	0.000	–	0.000	0.000	–	0.000	0.000	–	0.000	0.000	–	0.000	0.000	–	0.003	0.010	25.3
25-26	0.000	0.000	–	0.000	0.000	–	0.000	0.000	–	0.000	0.000	–	0.000	0.000	–	0.012	0.055	21.5
26-27	0.000	0.000	–	0.000	0.000	–	0.000	0.000	–	0.000	0.000	–	0.000	0.000	–	0.000	0.000	–
27-28	0.000	0.000	–	0.000	0.000	–	0.000	0.000	–	0.000	0.000	–	0.000	0.000	–	0.000	0.000	–
28-29	0.000	0.000	–	0.000	0.000	–	0.000	0.000	–	0.000	0.000	–	0.000	0.000	–	0.000	0.000	–
29-30	0.000	0.000	–	0.000	0.000	–	0.000	0.000	–	0.000	0.000	–	0.000	0.000	–	0.000	0.000	–
Total	2.681	11.278	23.8	4.723	26.574	17.8	4.162	16.051	25.9	2.286	10.581	21.6	3.715	28.806	12.9	4.628	39.410	11.7

* The stand was not considered as part of the chronosequence for this project (refer to text for details)

Note: BGD = below ground (does not include roots), TSF = time since fire, % = percent of fine fuels

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CHAPTER 3

Fire weather, fire danger, and fire potential climatology of the Fort Providence area, Northwest Territories (Canada).

INTRODUCTION

Fire behavior is the product of the environment in which the fire is burning (Countryman 1972). As a consequence, any evaluation looking at past, present, or forecasted fire behavior must consider the three main elements influencing it, i.e.: fuels, weather and topography.

Weather is the element of the fire environment that changes the most, both spatially and temporally. Although the study of individual weather elements is pertinent from a fire point of view, the components of the Canadian Forest Fire Weather Index (FWI) System (Van Wagner 1987) have the added advantage of considering the cumulative effect of the weather as it relates to fuel moisture and potential fire behavior. It is therefore pertinent to look at the historical distribution of both types of variables through the period of interest which, in this case, was the peak fire season. Although related studies are available for other parts of Canada (e.g., Nikleva 1973, 1989; Pouliot 1993), to our knowledge none were done in our area of interest.

As part of a larger project looking at the flammability of jack pine (*Pinus banksiana* Lamb.)/black spruce (*Picea mariana* (Mills.) B.S.P.) stands in a portion of the Hay River District (Northwest Territories, Canada), we proceeded to an analysis of the fire weather, fire danger, and fire potential climatology in our study area.

Working under the general hypothesis that the flammability of jack pine/black spruce stands in the study area varied according to the hypothetical model presented by Horn (1976) (see Chapter 1, Figure 1-2), we needed to define, for our region of interest, different burning conditions to characterise the drought periods to which he referred. To our knowledge, no one has attempted yet to define those conditions for a given area. Our main goal for this part of the project was therefore to derive four groups of typical fire weather/fire danger conditions representing “moist”, “moderate”, “dry”, and “extreme” burning conditions for the eventual construction of scenarios looking at the potential fire behavior in stands of different times since fire in our study area.

METHODOLOGY

Fire Weather Index System

The FWI System is a subsystem of the Canadian Forest Fire Danger Rating System (CFFDRS), which also includes the Canadian Fire Behavior Prediction (FBP) System (Figure 3-1). Both are currently the two major subsystems of the CFFDRS (Alexander *et al.* 1996; Forestry Canada Fire Danger Group 1992).

The FWI System (Van Wagner 1987) (Figure 3-2), the first subsystem of the CFFDRS, provides for the assessment of relative fire potential (Stocks *et al.* 1989). Although it refers to a standard pine fuel type, the FWI system is useful as a general measure of forest fire danger in Canada (Van Wagner 1987). It is composed of three fuel moisture codes (Fine Fuel Moisture Code (FFMC), Duff Moisture Code (DMC), and Drought Code (DC)) and three fire behavior indices (Initial Spread Index (ISI), Buildup Index (BUI), and Fire Weather Index (FWI)). These components are calculated using four weather observations: temperature, relative humidity, wind speed, and rain accumulated over the last 24-hour. Although the weather observations are measured daily at noon (local standard time (LST), or 1300 h daylight saving time (DST)), the FWI System is representative of the conditions generally encountered at the peak burning period (around 1600 h, LST) (Van Wagner 1987). Due to the manner in which the three fuel moisture codes are calculated, the FWI System considers the cumulative effect of the weather during the fire season.

Each component of the FWI System has its own scale, but for all of them a high value indicates more severe burning conditions (De Groot 1987; Canadian Forestry Service 1984). More details on each component of the FWI system are included in the "Results and Discussion section" of this chapter to help with the understanding of the different quantities discussed.

Fire Weather Observations

The study area was located (Chapter 2, Figure 2-1) in the Hay River District (Northwest Territories, Canada), within the rectangular zone delimited by 61° 36' 00" N, 117° 12' 00" W and 61° 03' 06" N, 119° 11' 01" W. For the fire weather analysis, we selected weather stations located within, or surrounding, that area.

The data of three weather stations, provided by the Government of the Northwest Territories' Department of Resources, Wildlife and Economic Development, were used for the study (Table 3-1): Fort Providence, Caen Lake Tower, and Kimble Tower. A fourth one, the Redknife Hills station, was rejected after a preliminary analysis despite the fact that its location was not very far from our study area. The reason for rejection was that the elevation of that weather station was much higher (by approximately 500 m) than the average elevation of the study area. The fire weather data and FWI System components indicated that the conditions at that station were colder and wetter than in our region of interest (as shown by the other stations used).

Fire weather observations were available for various periods between 1982 and 2001 (Table 3-1), depending on the weather station. All the stations had at least 10 years of records, which is traditionally considered a reasonable sample of past annual weather (Van Wagner 1988). The weather observations used in the analyses had all been taken at noon (LST) (or 1300 h (DST)) and collected according to the standards presented in Turner and Lawson (1978). The analyses were made for the period of June 15 to August 15, the time of year that usually coincides with the peak fire season (Lanoville and Mawdsley 1990) in the Northwest Territories and with the convective storm season of June and July (Kochtubajda *et al.* 2001) that results in lightning activity.

Since the stations did not all start at the same date on a given year, and because that date also varied from year to year, the time period was selected in order to keep a relatively constant number of days in the analyses for each year and for all the stations. Moreover, the procedure also removed some uncertainty concerning the startup values for the FWI System components on any given year, especially for the late starting stations. The number of days between the first day of operation of a station and June 15 was generally large enough to allow the power of self-correction of the Fine Fuel Moisture Code (FFMC) and the Duff Moisture Code (DMC) to compensate for any erroneous startup values. We used directly the startup values provided with the fire weather database, and made no further adjustments (e.g., overwinter adjustment of the Drought Code (DC)) to it. We therefore assumed that the required computations had already been made by the fire agency since the database had been used operationally during the years for which our analyses were made.

Fire Weather Elements

Our analyses of the fire weather were focused on the four fire weather observations required for the calculation of the FWI System components (Van Wagner 1987): temperature, relative humidity, 10-m open wind speed (and direction), and rain accumulated over 24-hour. Those are elements that influence the ease with which fires can be started, their rate of spread and difficulty of control, and their effect on the environment (Turner and Lawson 1978).

We first looked at the historical variation in each of those variables (temperature, relative humidity, 10-m wind speed, and rain accumulated over 24-hour) during the peak fire season (June 15-August 15) using the observations of all the years available for each weather station. For each day of that period we identified the highest, lowest, and average value of each variable. We also calculated the total average of each variable for the period, as well as the average for the highest and lowest values. The cumulative frequency and selected percentiles were also computed for each variable.

The rain accumulated over 24-hours was further analysed in terms of the magnitude of rain events and their frequency according to four different accumulation thresholds: 0.0 mm, 0.5 mm, 1.5 mm, and 2.8 mm. Except for the first one, which was chosen for comparison purposes, those values correspond to the quantities of rain that must be ignored before that variable starts to have an influence on the calculation of the fuel moisture codes of the FWI System (Turner and Lawson 1978; Canadian Forestry Service 1984; Van Wagner 1987), respectively: FFMC, DMC, and DC. Three different analyses were performed regarding those values. We first determined, for each day over all the years analysed, how much time had elapsed since the last rain event larger than the thresholds described above. Using that information, we then obtained the cumulative frequency of that number of days for the period of interest. We also calculated, for each day of the peak fire season, the average number of days since the last rain event larger than the values indicated above. Our last analysis on the 24-hour rain data looked at the frequency of different periods without rain accumulation larger than the thresholds mentioned above.

Finally, for the wind direction, we computed the percentage of days falling into each of the eight main directions (North, Northeast, East, Southeast, South, Southwest, West, and Northwest) for the entire period, and for four portions of 15 days within that period.

FWI System Components

Our analyses of the FWI System components included the three fuel moisture codes (i.e., the FFMC, DMC and DC) and the three fire behavior indexes (ISI, BUI, and FWI) mentioned above. Similar to what we did for the fire weather observations, we looked at the historical variation of each of those variables during the peak fire season (June 15-August 15) for all the years available for the three weather stations. For each day of that period we identified the highest, lowest, and average value of each variable. We also calculated the total average of each variable for the period, as well as the average for the largest and smallest values. The cumulative frequency and selected percentiles were also computed for each variable.

Following the individual analyses of each FWI System component for the peak fire season, we studied selected combinations of some of them. Grouping the ISI and the BUI values into the same classes as the ones presented in the field guide to the Canadian Forest Fire Behavior Prediction (FBP) System (Taylor *et al.* 1997), we calculated the percentage of days in each combined class. The information thus obtained allowed us to identify the percentage of days in each fire intensity class, for the main FBP System conifer fuel types present in the study area, for the peak fire season using the tables provided in Taylor *et al.* (1997). A similar procedure allowed us to obtain percentages for each probability of sustained flaming ignition class presented in Lawson and Dalrymple (1996) (a scientific and technical description of the equations is given in Lawson *et al.* (1994a) and illustrated in Lawson *et al.* (1994b)) for the "Dry" and the "Moist" Lodgepole Pine forest types, their two fuel types that most closely correspond to the stands present in our study area. We also looked at the percentage of days for different combinations of FFMC, DMC or BUI, and FWI classes. The latter were defined as: low (FWI 0-4), moderate (FWI 5-12), high (FWI 13-18), very high (FWI 19-24), and extreme (FWI $\geq$ 25) (Stocks *et al.* 1989).

Scenarios

The four different scenarios representing “moist”, “moderate”, “dry”, and “extreme” fuel moisture conditions in the study area were defined in terms of fire weather and FWI System components based on the different analyses described above (Figure 3-3).

Results and Discussion

Although they are intimately related, we have separated the results for the weather observations and the FWI system components in the following discussion, and treated each element of both categories individually. This approach was adopted to facilitate their access by people interested in the results of only some of the variables.

Fire Weather Elements

Weather is the state and the changing nature of the atmosphere surrounding the earth (Schroeder and Buck 1970). Our specific interest in the temperature, relative humidity, 10-m open wind speed, and 24-hour rain was prompted by their direct and cumulative effect on the moisture content of forest fuels and ensuing influence on fire behavior as expressed by the different components of the FWI System. Good drying days are favoured by a high temperature, a low relative humidity, a high wind speed and no precipitation.

We presented the results of our analyses mainly as seasonal graphs to better depict the general character of the fire season (Main *et al.* 1990). Tables summarising important values, and other figures were nevertheless used whenever deemed necessary.

Temperature

The seasonal results on the noon (LST) air temperature are presented in Figures 3-4 and 3-5, and in Table 3-2. On average, the air temperature during the peak fire season varied around 20°C in the study area, although 50% of the days had a temperature higher than that value. The daily averages, however, fluctuated between 16°C and 24°C, depending on the date and the weather station. In general, the lowest noon temperature recorded on each day of the peak fire season varied around 12°C (range between 7°C and 17°C), while the highest noon temperature oscillated around 28°C (range between 23°C and 36.5°C). Noon temperatures higher than 28°C occurred on only 3% of the days during the years analysed, as this value also represents the 97th percentile.

The cumulative frequency graphs represent the fraction (or percentage) of all the days during the peak fire season (June 15 to August 15) that had a temperature lower or equal to the one selected. Conversely, it is possible to know the percentage of days on which a higher temperature was recorded by subtracting the cumulative frequency (or percentage) from the number 1 (or 100). The 90th and 97th percentiles are often used in fire management (Main *et al.* 1990), although other values (or even the shape of the cumulative frequency curve) may also be useful, depending on the application they are destined for. Table 3-1 lists selected percentiles, while Figure 3-5 presents the curves of the cumulative frequency for the temperature measured at the three weather stations. Other percentiles can be obtained from those curves as needed.

It is important to note that the noon (LST) air temperature was not necessarily the maximum temperature reached during the day, but the temperature used in the calculation of the FWI System components. The temperature recorded later during the afternoon was often higher than the noon temperature, although that variable was not analysed for this project. Moreover, the high latitude of the study area, with low angles of incident solar radiation but very long days during the fire season, had an important consequence on the progression of the temperature (and relative humidity) curve during the day (Van Wagner 1977; Beck and Armitage 2004). As a reference, there were approximately 19.5 hours between sunrise and sunset by mid-June at Fort Providence, and 16 hours around mid-August. Consequently, the normal daily fluctuation in the fuel moisture may not be as pronounced as for areas located more to the south and night time recovery may not occur. Ward and Mawdsley (2000) indicated that in the NWT fires may continue to burn throughout the "night" with very little change in fire behavior.

Relative Humidity

The seasonal results on the noon (LST) relative humidity are presented in Figures 3-6 and 3-7, and in Table 3-2. The average relative humidity for the period, over all the years analysed, was in the vicinity of 56% (depending on the weather station). The seasonal daily averages varied around that value within a range delimited by 44% and 68%, and a little more then half the days had a relative humidity lower than that value. The highest noon relative humidity recorded on each day of the peak fire season varied between 60% and 100%, for an average around 91%. As seen on Figure 3-6, several days never recorded a high value of relative humidity at noon over all the years analysed. The lowest observation of that variable for each day of the peak fire season fluctuated between 11% and 54%, for an average close to 32% (depending on the weather station). In general, between 3 and 5% of the days had a relative humidity lower than that value.

Wind Speed and Direction

The results for the wind speed analysis are presented in Figures 3-8 to 3-9 and Table 3-2, while those on the wind direction are shown in Figures 3-10 and 3-11. On average, the noon (LST) wind speed in the study area fluctuated around 11 km/h, the mean being approximately the same as the 50^{th} percentile (median). The lowest values recorded on each day of the peak fire season varied between 0 and 10 km/h, for an average around 2 km/h, depending on the weather station. The highest wind speed measured on each day over all the years analysed fluctuated around 22 km/h and ranged between 15 km/h and 45 km/h. Less than 10% of the days had a wind speed larger than 15 km/h at noon (LST), and on only 3% of the days was it higher than 20km/h. It is important however to keep in mind that the wind speed often increases in the afternoon due to convective activity. Those values were not considered in our analysis but they will influence the fire behavior at the peak burning period.

Our analysis of the wind direction showed that the Fort Providence weather station had almost an equal percentage of days in all the wind directions over the peak fire season, with a slightly lower presence of northeast, southwest, and northwest winds. The two other stations, Caen Lake Tower and Kimble Tower, had a dominance of North (22% and 25%) and South (23% and 16%) winds between June 15 and August 15.

When studied in 2-week periods, the percentage of days in each wind direction category was similar to that of the entire peak fire season for Fort Providence, with a slight increase in east winds during the first half of July and in Southeast winds during the first two weeks of August. The analysis for Caen Lake Tower and Kimble Tower weather stations show the same dominance of north and south winds in each 2-week periods as the one observed for the entire season. North winds were predominant during the last half of June and the first half of August at the Caen Lake station, while South winds were observed more frequently at other times. An eastern component was observed in all of the 2-week periods, but it was complemented by Western winds during the first week of August at that station. At Kimble Tower weather station north winds were more frequent in all the two-week periods, with an almost constant proportion of days with south winds. The only exception was for the first two weeks of July where the percentage of days with south winds was slightly lower and the eastern component higher than during the other three periods.

Precipitation

The results from our analyses on the rain accumulated over 24 hour are presented in Figures 3-12 to 3-15 and Tables 3-2 to 3-4. The maximum amount of rain accumulated over 24-hours and recorded at the stations varied around 13 mm and ranged between 0.2 and 52 mm. That result indicates that some days during the peak burning season never had large accumulations of rain over the years analysed. Those days can be identified on Figure 3-12 for each weather station. Each day of the peak burning season had at least one occurrence, over the years analysed, where no rain fell. Although the average amount of rain that fell on each 24-hour period was between 1.5 and 2.0 mm in the study area during the peak burning season (depending on the weather station), our results show that in reality approximately 65% of the days had no rain.

Table 3-2 shows the percentiles for the 24-hour rain for the three weather stations. In general, more than 25% of the days had rain accumulations of more than 1 mm, an amount large enough to lower the FFMC. That percentage decreased to approximately 10 % for accumulations of more than 5 mm. Less than 1% of the days had rain events where more than 20 mm fell at the weather station. Kimble Tower weather station showed slightly greater rain accumulations than the two other stations located on the other side of the Mackenzie River.

Another way to examine rainfall patterns is to look at the 24-hour rain from the perspective of the number of days since the last rain event of some determined importance. As mentioned before, the choice of 0.0mm, 0.5 mm, 1.5 mm and 2.8 mm was not random. Except for the first one, which was selected for comparison purposes, those quantities represent the thresholds after which the rain accumulation will start to influence one of the fuel moisture codes of the FWI System.

We looked at each day (between June 15 and August 15) of each year for which we had the weather observations, and determined how many days it had been since the last rain event larger than each of the four quantities mentioned above. Figure 3-14 presents the average number of days since the last rain event larger than 0.5, 1.5, and 2.8 mm for each day of the peak fire season. Oscillations can be observed throughout the period between June 15 and August 15 for all the rain thresholds.

More than 50% of the days had been at least one day free of any rain (accumulation larger than 0.0 mm), while 25% had been between 3 and 4 days since the last rain event. In general, only 5% of the days studied had not had rain for periods of 7-11 days (depending on the weather station), a percentage that decreased sharply thereafter. For rain events larger than 0.5 mm (i.e., those that significantly affect the FFMC), the numbers resembled, but were slightly higher, than those mentioned above. This suggests that very often the amount of rain falling on a given day was sufficient to lower the FFMC in the study area.

For accumulations of more than 1.5 mm, the rain events that lower the DMC, more than 50% of the days had not received more than that amount for at least 2.5 days, a percentage that decreased to 5% for a 2-week period. Finally, more than half the days had been at least 4 days since the last rain event that lowered the DC, those days with an accumulation of more than 2.8 mm. Only 5% of them had been more than 20 days since that amount fell at the weather station. Those and other percentiles are presented in Table 3-3 and Figure 3-15. In general, Kimble Tower weather station, located more to the south, had longer periods between rain events of different magnitudes than the other stations.

Finally, we obtained a distribution of the frequency of occurrence of periods without rain accumulation above the different thresholds mentioned above. Table 3-4 show the average number of times, during the peak fire season, when intervals of days without rain accumulation larger 0.0, 0.5, 1.5, or 2.8 mm happened. Periods of more than 10 days without rain accumulation larger than any of the thresholds investigated occurred, on average, only every second year during the peak fire season.

Fire Weather Index System Components

Similar to the weather analyses presented above, the FWI System components are presented mainly as seasonal graphs. Those were complemented by tables summarising important values, and by other figures, when necessary.

Fine Fuel Moisture Code

The FFMC is a numerical rating of the moisture content of litter (0-2 cm in depth) and other cured fine fuels (typical fuel load of 0.25 kg/m^2) (Van Wagner 1987). An indicator of the relative ease of ignition and flammability of fine fuels (Canadian Forestry Service 1987), it is calculated daily using the four weather observations mentioned previously, i.e.: temperature, relative humidity, wind speed and rain accumulated over 24-hour. The FFMC has a timelag of 2/3 of a day, indicating that it would take that time for the fuels to which it refers to lose about 2/3 of their free moisture above equilibrium on a standard drying day (Van Wagner 1987). It has a short-term effective memory and will only reflect the weather conditions that have occurred during the last 3 to 5 days (De Groot 1987; Taylor and Lawson 1996).

The FFMC ranges between 0 and 101. In general, fires are not likely to spread in the surface litter when the FFMC is less than about 74 (Stocks *et al.* 1989), and fires will not start in most fine fuels at a moisture content below 25-30%, which is equivalent to a FFMC of approximately 78 (Taylor and Lawson 1996). Fire starts increase exponentially with an increase in the FFMC values at the high end of the scale, reaching a high potential at FFMC values of 86 to 89 or more in the boreal forest (De Groot 1987). An FFMC value of 90 or more indicates a high probability of spot fire development (Lanoville and Alexander 1997).

The results of our analyses on the FFMC are presented in Figures 3-16 and 3-17, and in Table 3-5. The average FFMC value for the peak fire season was close to 77, with values fluctuating between 61 and 87 depending on the days and the weather station. The lowest value recorded on each day of that period varied between 0 and 86 (for an average between 22 and 45, depending on the weather station), indicating that some days have never reached low FFMC values over all the years analysed. Those days can be identified for each station in Figure 3-16. The highest value recorded on each day varied between 87 and 96.5, for an average of 92. Substantially less variation was observed on the high of the FFMC scale on a daily basis than for low values.

Looking at the cumulative frequency data for the FFMC, we observed that fires were likely to spread in the surface litter (FFMC > 74) on almost 75% of the days during the peak fire season, and there was a high potential for fire ignitions (FFMC > 89) on approximately 25% of the days. Only 3% of the days between June 15 and August 15 had an FFMC larger than 92, and 1% reached a value higher than 93 for that code.

Days with FFMC values higher than the average for the peak fire season generally occurred more often at the beginning of the period, before July 11. A few more isolated days later during the season also had that characteristic.

Duff Moisture Code

The DMC is a numerical rating of the average moisture content of loosely compacted decomposing organic matter located at moderate depth (5-10 cm) and having a nominal fuel load around 5 kg/m^2. The code has a timelag of 15 days (Lawson *et al.* 1997a) and is calculated using three of the noon (LST) weather observations (i.e., temperature, relative humidity, 24-hour rain) as well as the month. The latter is used to take into consideration the changing day length through the fire season in the calculation of the drying phase (Van Wagner 1987).

The DMC provides an indication of fuel consumption in moderate duff layers and medium-size woody material (Canadian Forestry Service 1984, 1987) and is often used in the prediction of lightning fire starts (De Groot 1987). It is generally considered that the duff layer does not contribute to the frontal fire intensity and is not involved in combustion until the DMC reaches 20 or 25 (Van Wagner 1972; Stocks *et al.* 1989; Taylor and Lawson 1996; Alexander and Cole 2001). The scale of that code does not have an upper limit, but at a value of around 150 to 200 the duff will have lost most of its available moisture (Van Wagner 1987; Taylor and Lawson 1996). Lawson *et al.* (1997b) identified thresholds for smouldering ignition based on moisture content obtained from the DMC in upper feather moss and reindeer lichen/feather moss material. For a probability of smouldering ignition of at least 0.5 (they assumed that the moisture content at 50% probability could be interpreted as the moisture ignition limit for each duff type), their results indicated that upper feather moss had to have reached a moisture content of 76% (or less) and reindeer lichen/feather moss required a moisture content of 116% (or less), which can be converted to a DMC of at least 58 and 39, respectively, using an equation developed specifically for each of those duff types.

The results of our analyses on the DMC are presented in Figures 3-18 and 3-19, and in Table 3-5. Over all the years analysed, the average DMC for the peak fire season was between 36 and 42, depending on the weather station. The average value on each day varied between 25 and 66. The lowest value of the code obtained on each day was between 0 and 30, for an average value around 10, while the highest value varied between 61 and 159 and averaged 91. Approximately 75% of the days had a DMC higher than the threshold (DMC 20) identified for the duff layer to become involved in combustion. Regarding the probability of smouldering ignition in the upper feather moss and the reindeer lichen/feather moss material, we determined that approximately 15% and 30% of the days, respectively, were above the thresholds mentioned above. Finally, a DMC higher than 92 was observed on approximately 3% of the days while close to 1% of them had a value above 100. In general, the DMC was higher than the average during the first half of the peak fire season (June 15 to July 15).

Drought Code

The DC is a numerical rating of the average moisture content of deep (10-20 cm), compact, organic layers (nominal fuel load of 25 kg/m^2). The weather inputs for its calculation are the noon (LST) temperature and 24-hour rain, and the month is also used in its calculation for the same reasons as stated above for the DMC (Van Wagner 1987). With its time lag of 53 days (Lawson *et al.* 1997a), the DC is an indicator of seasonal drought effects on forest fuels, and of the expected amount of smouldering in deep duff layers and large woody debris (Canadian Forestry Service 1984, 1987).

A DC value of 300 is often considered a threshold at which the moisture content starts to decrease with depth in the humus (De Groot 1987; Alexander and Cole 2001), while persistent ground fire activity was observed at values higher than 400 (Stocks *et al.* 1989). Lawson *et al.* (1997b) identified a moisture content threshold of 81% (or less), equivalent to a DC of 482 (or more) using an equation developed for white spruce duff, in order to reach a probability of smouldering ignition of at least 0.5 in lower feather moss material.

The results of our analyses on the DC are presented in Figures 3-20 and 3-21, and in Table 3-5. There were relatively large differences in the average DC calculated for each of the weather stations. The lowest value was observed at Caen Lake Tower weather station, with an average DC of 247 for the period June 15 to August 15, and the highest value was calculated with the Fort Providence data, an average DC of 412. Kimble Tower weather station was somewhat between the two with an average DC of 337. In general, the average value recorded on each day of the peak fire season varied between 285 and 484 when the three stations are considered together. The lowest DC value recorded on each day of the same period ranged between 73 and 308, for an average close to 180. Conversely, the highest value for the code on those days fluctuated between 494 and 725, for an average approximating 610. Individual average values for each station are presented in Table 3-5 for the minimum, maximum and overall average DC recorded on each day of the peak fire season.

A look at the cumulative frequency of the DC values indicated that approximately 50% of the days were likely to be conducive to persistent ground fire activity (DC of 400 or more) in the northern part of the study area, while only 25% had that characteristic at the Kimble Tower weather station located south of the Mackenzie River. The 482 threshold identified by Lawson *et al.* (1997b) for a probability of smouldering ignition of at least 50% in the lower feather moss material was reached on more than 28, 33, and 9% of the days at the Fort Providence, Caen Lake Tower, and Kimble Tower fire weather stations, respectively. The DC generally increased as the fire season progressed and values higher than the average calculated for the peak fire season started to appear during the second week of that period, with lower values occurring between July 14 and 20.

Initial Spread Index

Combining the effects of wind and FFMC, the ISI is a numerical rating of the expected rate of fire spread that does not take into account the influence of variable quantities of fuel (Van Wagner 1987). Its value will generally double with a 13 km/h increase in wind speed, when the FFMC is being held constant (Van Wagner 1987). It is used in association with the Buildup Index (BUI) (or with the degree of curing in grass fuel types) in the FBP System (Forestry Canada Fire Danger Group 1992) to provide numerical values for fire behavior in pre-determined forest and slash fuel types.

The results of our analyses on the ISI are presented in Figures 3-22 and 3-23, and in Table 3-5. The lowest value for the ISI recorded on each day of the peak fire season was between 0 and 2.7, for an average of 0.2. Conversely, the highest ISI values fluctuated around 12 ranging between 5 and 35. On average, the index was around 3 in the study area during the years analysed, the daily average varying between 1.9 and 7.4. Less than 50% of the days had an ISI value higher than the average recorded at each weather station. ISI values larger than 10 were observed on 3, 5 and 10% of the days at the Fort Providence, Caen Lake Tower, and Kimble Tower weather stations, respectively. ISI values higher than the average for the peak fire season were more frequent during the first half of that period.

Buildup Index

Calculated from the DMC and the DC, the BUI is a numerical rating of the total amount of fuel available for combustion in the spreading fire (Canadian Forestry Service 1984; Van Wagner 1987) and is often used as a general guide to fire potential (De Groot 1987; Alexander and Cole 2001).

The results of our analyses on the BUI are presented in Figures 3-24 and 3-25, and in Table 3-5. The lowest BUI value recorded on each day of the peak fire season ranged between 0 and 49, for an average close to 18, all stations considered. The highest value for that index averaged 125 and fluctuated between 84 and 180 during the same period. On average, however, the BUI was close to 60 in the study area and the daily averages oscillated between 39 and 94.

In general, Fort Providence and Caen Lake Tower weather stations had similar BUI values, while the index was somewhat lower at Kimble Tower weather station. At the first two, approximately 3% of the days had a BUI larger than 130, while little more than 1% reached the same value at Kimble Tower. Similar to the DMC, the BUI was generally higher than the average for the peak fire season during the first half of that period.

Fire Weather Index

Used as a general index of fire danger throughout Canada, the FWI is a numerical rating of fire intensity calculated with the ISI and BUI (Canadian Forestry Service 1984, 1987). The combination of ISI, a numerical rating of the expected rate of spread, and BUI, a numerical rating of the total amount of fuel available for combustion, was conceived to represent Byram's (1959) frontal fire intensity (Van Wagner 1987). It can be used for the determination of fire suppression requirements and as a tool to inform the public about fire danger conditions (De Groot 1987). FWI values between 19 and 24 are generally considered very high in the Northwest Territories, and any larger value falls into the "extreme" category (Stocks *et al.* 1989).

The results of our analyses on the FWI are presented in Figures 3-26 and 3-27, and in Table 3-5. On average, the FWI was close to 12 in the study area over the years analysed, the daily average fluctuating between 6 and 20. The average FWI calculated for the three weather stations located in our study area is slightly higher than the one (FWI between 9 and 11) presented on the map prepared by Simard (1973) from FWI values obtained between 1957 and 1966 for the months of June, July and August. According to the classification performed by Simard (1973), an average FWI of 12 would put our study area in the fire weather zone "5 – High" (he defined 7 zones for Canada) a zone primarily found in western and southern Canada.

The minimum FWI value recorded on each day of the peak fire season varied between 0 and 8.5, for an average approaching 0.5 in the area. The maximum value varied between 18 and 60, for an average of approximately 32. More than 25% of the days had a "very high" (FWI at least 19) or "extreme" (FWI at least 25) FWI values, a percentage that decreased to 10% when only the "extreme" category was considered. Similar to several of the other FWI System components, the FWI component had more occurrences of values higher than the average for the peak fire season during the first half of that period.

The Daily Severity Rating (DSR) is a rescaling of the FWI by weighting it sharply as it rises (Van Wagner 1987). It was designed to reflect more directly control difficulty and to provide an objective basis of comparison. Harvey *et al.* (1986) provided several examples where the FWI System severity analyses were used, such as: i) objective comparisons between different weather stations or fire seasons, ii) development of fire danger climatologies, iii) comparisons of monthly or yearly severity ratings in relation to several fire characteristics (area burned, fire incidence, etc.), or iv) rationalisation of proposed levels of fire suppression funding.

The DSR is more suitable for averaging than the FWI. When the DSR is averaged over a whole fire season it is designated as the Seasonal Severity Rating (SSR) (Van Wagner 1970). Conditions favourable for extensive burning would be represented by any severity rating larger than 2.0, especially when averaged over longer time periods such as a month (Stocks *et al.* 1981 in Harvey *et al.* 1986). Stocks *et al.* (1998) reported that, in general, "SSR values above 7 represent extreme fire behavior potential, values between 3 and 7 represent high to very high potential, values between 3 and 7 represent high to very high potential, values between 1 and 3 constitute moderate fire potential, and values <1 equate low fire potential." In our study area, the mean SSR for Caen Lake Tower, Fort Providence, and Kimble Tower weather stations over all the years analysed (see Table 3-1) was 3.49, 2.56, and 3.59, respectively. Our study area would then be located in a region with relatively high fire behavior potential, according to the classification mentioned above. Our SSR values are slightly higher than the ones mapped by Stocks *et al.* (1998) for the period 1980-1989, where our area was classified as region 4 with an average SSR between 2.01 and 3.00. Compared to the rest of the country, and especially to the portion usually associated with the distribution of the boreal forest, the average SSR values calculated for our study area are relatively high.

ISI-BUI Combinations

The results of our frequency analysis on different combinations of ISI and BUI classes are presented in Tables 3-6 to 3-8 for the three weather stations. As mentioned previously, those two codes are used in the Canadian FBP System (Forestry Canada Fire Danger Group 1992) for the calculation of several fire behavior characteristics since they show a good correlation, in most Canadian fuel types, with the rate of spread (ISI) or the amount of fuel available for combustion (BUI), two variables used in the calculation of Byram's (1959) frontal fire intensity. Taylor *et al.* (1997) prepared a field guide for the FBP System where various characteristics of fire behavior could be predicted using the relevant ISI and BUI in a table provided for each fuel type.

By comparing the frequency tables for the different ISI-BUI combinations to the tables presented in Taylor *et al.* (1997) for selected fuel types, we were able to determine the percentage of days that fell in each fire intensity class during the peak fire season of the years analysed. The four fuel types we selected for the discussion were: a) C-1: Spruce-Lichen Woodland, b) C-2: Boreal Spruce, c) C-3: Mature Jack or Lodgepole Pine, and d) C-4: Immature Jack or Lodgepole Pine (De Groot 1993; Taylor *et al.* 1997). Although C-3 and C-4 are more closely related to the forest type studied in this project, the representation of those four fuel types in the study area prompted their selection. Two of those fuel types were actually identified by Ward and Mawdsley (2000) as the most common fuel types in the north: the spruce-lichen woodland and the boreal spruce fuel types. Other fuel types could also have been used, but other considerations (such as the percentage of deciduous/coniferous trees in mixed stands that is best assessed on an individual stand basis) would have complicated the analyses. In general, the four conifer fuel types selected are the forest fuel types that show the most severe fire behavior for given conditions of ISI and BUI in the study area. Logging activities are not frequent enough in that region of the Northwest Territories to justify the use of the slash fuel types. Nevertheless, anyone interested in the percentage of days in each intensity class for other fuel types can obtain the information using Tables 3-6 to 3-8 in combination with the appropriate fuel type table in Taylor *et al.* (1997).

We selected the head fire intensity class variable for comparative purposes. The classes we used were defined as (Taylor *et al.* 1997): 1 (<10 kW/m), 2 (10-500 kW/m), 3 (500-2000 kW/m), 4 (2000-4000 kW/m), 5 (4000-10 000 kW/m), and 6 (>10 000 kW/m). Although the rate of spread and the type of fire were also available from the tables in the field guide, the head fire intensity class was selected for its convenience and the limited but representative (in terms of fire behavior and suppression activities) number of classes it provided. Several decision aids were developed, based on fire intensity classes and fuel type, in Canada (e.g., Alexander and Cole 1995; Cole and Alexander 1995; Alexander and De Groot 1988; Alexander and Lanoville 1989). It is important to note that various combinations of ISI and BUI will give the same fire intensity but will differ in some of the fire behavior characteristics due to the variation in rate of spread or quantity of fuels consumed (Alexander 1982).

By adding the percentage of days (Tables 3-6 to 3-8) in each fire intensity class for the four fuel types analysed, we obtained the results presented in Table 3-9. In general, the Spruce-lichen woodland (C-1) fuel type had between 90 and 97% of the days in the first three fire intensity categories, depending on the weather station. Fires showing such head fire intensity will have moderately slow (Alexander 1997) rates of spread (between 0 and 4 m/min) and will become intermittent crown fires at ISI values between 9 and 12, for any BUI category. Those fires will be fairly easy to moderately difficult to control (Alexander and Lanoville 1989).

The Mature Jack or Lodgepole Pine (C-3) fuel type showed a similar pattern in terms of distribution of days among the different head fire intensity classes. We calculated that between 83 and 90% of the days were in the first three intensity classes over the years analysed, depending on the weather station. In that fuel type those intensities can mean rates of spread between 0 and 16 m/min in the study area, depending on the ISI, and no crown involvement (surface fires). Fires in intensity classes 1 and 2 can generally be controlled by ground crews, while at head fire intensity class 3, heavy equipment is generally needed in controlling the fire by constructing fireguards (Alexander and De Groot 1988; Alexander and Lanoville 1989; Alexander and Cole 1995; Cole and Alexander 1995).

The distribution of the days among the different head fire intensity classes for the two remaining fuel types, Boreal Spruce (C-2) and Immature Jack or Lodgepole Pine (C-4), was more uniform than for the fuel types discussed above. There was, therefore, a greater percentage of days in fire intensity classes where the potential fire behavior was more severe. In general the percentage in each category varied between 7% and 22%, and the highest fire intensity classes were not necessarily the ones with the lowest number of days. Between 40% and 56% of the days were in the last three fire intensity categories, a percentage much higher than for the C-1 and C-3 fuel types. Under those critical conditions, firefighting gradually becomes very difficult and is sometimes impossible.

Probability of sustained flaming ignition can be useful in gauging the likelihood of fire starts or fire arrivals, and in judging the potential for spot-fire ignition (Lawson and Dalrymple 1996). Although it is not a standard output of the FBP system, we included it here to provide a more complete representation of the fire potential in our study area. For that analysis, we selected the two forest types that Lawson and Dalrymple (1996) consider to be variants of the C-3 (Mature Jack Pine or Lodgepole Pine) FBP System fuel type: the "Dry" (S1.1) Lodgepole Pine forest type, and the "Moist" (S1.2) Lodgepole Pine forest type. The inputs for the probability of sustained flaming ignition in the "Dry" (S1.1) Lodgepole Pine forest type are the FFMC and the wind speed. However, for the "Moist" (S1.2) Lodgepole Pine forest type they are the ISI and BUI, as for the FBP fuel types. The results of our analyses on the number of days in each probability of sustained ignition class [low (0-49%), medium (50-75%), and high (76-100%)] for both forest types are presented in Table 3-10. The probability of sustained flaming ignition was low for approximately half (50% of the days) the peak fire season over the years analysed. The remaining days were divided more or less equally between the remaining two classes, depending on the weather station and the forest type. The percentage of days in the high category was slightly higher for the S1.1 forest type, while the medium class showed that trend for the S1.2 forest type.

Scenarios

The results of our analyses on the frequency (percentage) of days in each combination of FFMC, DMC or BUI, and FWI classes are presented in Tables 3-11 to 3-13. Those results, complemented by all the analyses presented above, were used in the definition of burning conditions selected to characterise, for our study area, the drought periods to which Horn (1976) referred.

The scenario representing "moist" conditions was loosely based on the 25th percentile and the average of the minimum value recorded for the different FWI System components during the peak fire season. Similarly, the 50th percentile and the average value for each FWI System component were used in the case of the "moderate" scenario. The 97th percentile and the average of the maximum value recorded for the various FWI System components helped in determining the "dry" scenario, while the "extreme" scenario was selected to have values at the limit of the range observed for the different weather stations over the years analysed.

In all cases, we often could not select the exact value as calculated with either the percentile or the average due to the fact that some combinations of the different FWI System components were never observed in the study area or were impossible to obtain when considering the inputs required for their calculation. The frequency analysis for the different combinations of FFMC-DMC-FWI or FFMC-BUI-FWI helped in refining our selection of the value to use for each FWI System component in the different scenarios. We also tried to select scenarios that were in different FWI System component categories and that allowed at least some fire potential (which put a limitation to the lowest value of FFMC to use). The final FWI System components selected for each scenario, and the equivalent moisture contents for the FFMC and DMC are presented in Table 3-14.

Although different combinations of ISI and BUI can lead to the same FWI value, in our fire weather/fire danger scenarios an increase in the FWI was also accompanied by an increase in ISI and BUI, which were caused by an increase in the FFMC, DMC, and DC.

The percentage of days during the peak fire season that had conditions more severe in terms of FFMC and DMC or BUI than the ones we selected (based on the categories used for each of those FWI components in Tables 3-11 to 3-13, not on the individual values of the FWI System components) are presented in Table 3-15. The percentages are very similar whether using the DMC or the BUI. In general, approximately 60% of the days had more severe conditions than the ones described by the "moist" scenario in that analysis. That percentage decreased to around 35% for the "moderate" scenario, and to less than 1% for the "dry" scenario. The "extreme" scenario had values that were never surpassed in that combined analysis.

Since the FWI System components integrate the effect of past weather conditions, it seemed appropriate to have fixed values for the temperature, relative humidity, wind speed and 24-hour rain to use in combination with the scenarios described above for a given assessment involving different fuels. The conditions selected were a temperature of 25°C, a relative humidity of 33%, a wind speed of 20 km/h (which was used in the calculation of the ISI values above) and no rain accumulation. Those nominal weather conditions are often representative of a good drying day, conducive to vigorous fire behavior if the fuels are dry enough.

The value for the temperature was based on the 90th percentile for that variable, which was slightly lower than the average maximum noon (LST) value, on each day of the fire season, over the range of years for which the information was available for each station (Table 3-2). The value for the relative humidity was calculated using the average of the minimum noon (LST) (1300 h DST) observation for that variable (Table 3-2). Finally, the 10-m open wind speed was taken from Lanoville and Mawdsley (1990). That value is also similar to the average of the maximum noon

(LST) wind speed recorded on each day of the peak fire season over the years analysed (Table 3-2).

Summary and Conclusion

We analysed, from a fire danger and potential fire behavior perspective, the noon (LST) weather observations taken at three different weather stations located in the vicinity of our study area, and the FWI components calculated from those observations. Although the study of individual weather elements is pertinent from a fire point of view, the FWI System components have the added advantage of considering the cumulative effect of the weather as it relates to fuel moisture and potential fire behavior. It is therefore advantageous to look at both types of variables.

We presented in detail the results of the frequency analysis we performed on each variable for the peak fire season through the use of figures and tables summarising the main percentile values. We also provided detailed figures of the seasonal distribution of the lowest, highest and average value of each variable, for each day of the same period, over all the years analysed. Finally, we produced figures and tables summarising the general wind direction (for the period of June 15 to August 15 as a whole, as well as for 2-week intervals during that period), the pattern of rain accumulation in reference to four pre-determined thresholds, and the combined analyses of different FWI System components.

The information is far too detailed to effectively summarise here and the reader is referred to the relevant sections of this document for individual information on the variables analysed. Nevertheless, an overview of the results indicated that the FWI System components had, on average, higher values during the first half of the peak fire season, before the week of July 14 (the DC being the main exception). During the week of July 14 to July 20, most fire weather observations and FWI System components exhibited values indicative of lesser burning conditions than the precedent or subsequent period. Individual variables were often lower (or higher in the case of the relative humidity and rain) than their average for the season on other days of the period, but never all at the same time as during that week. Overall, the analyses involving the SSR showed that our study area has high fire behavior potential, with relatively high SSR values compared to the rest of the country and, in particular, to the portion usually associated with the distribution of the boreal forest.

In reference to our main goal of identifying the four fuel moisture levels (i.e., "moist", "moderate", "dry", and "extreme") as envisioned by Horn (1976), we were able to identify these levels in terms of certain FWI System component combinations. For the case depicting "moist" conditions, we obtained the following values: FFMC 83, DMC 20, DC 142, ISI 4, BUI 30, and FWI 9. The FWI System components we identified for the "moderate" situation were: FFMC 87, DMC 39, DC 325, ISI 8, BUI 60, and FWI 20. The "dry" moisture periods were characterised by the following values: FFMC 92, DMC 93, DC 492, ISI 16, BUI 127, and FWI 46. Finally, we also identified conditions that were considered to be "extreme". In several cases, the FWI System component values selected for this particular case had never reached the indicated values based on the years of record analysed, although their range stopped just short of them. With climate change and a general warming in weather conditions (Flannigan *et al.* 1998; Stocks *et al.* 1998), it is quite possible that such values of the FWI System component would occur sometime in the near future. The FWI System component values selected for the "extreme" case were: FFMC 95, DMC 160, DC 514, ISI 24, BUI 180, and FWI 66.

Since the FWI System components integrate the effect of past weather conditions, it seemed appropriate to have fixed values for the temperature, relative humidity, wind speed and 24-hour rain to use in combination with the scenarios described above for an assessment involving different fuels. The weather conditions we selected were a temperature of 25°C, a relative humidity of 33%, a wind speed of 20 km/h, and no rain accumulation. Those conditions are often representative of a "good" burning day when the fuel moisture levels are low.

The detailed analyses on the fire weather, fire danger, and fire potential climatology presented in this chapter, besides their use in helping us reaching our main goal for this project, have the added benefit that they could potentially be of some use for other research and fire management activities in that region of the Northwest Territories.

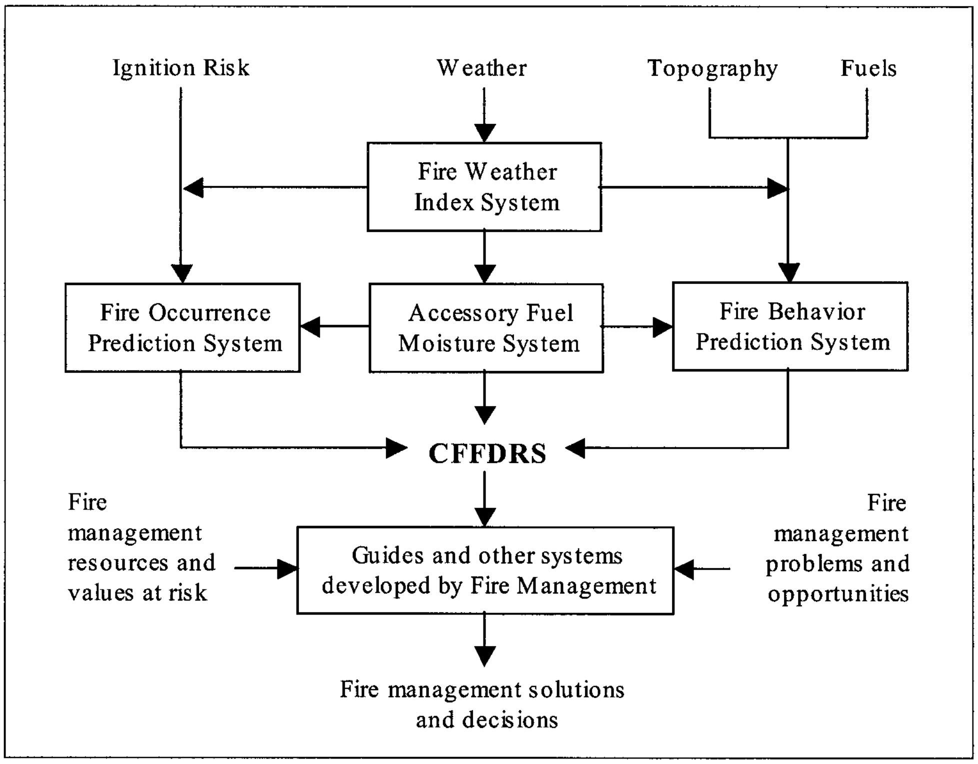


Figure 3-1. Simplified Canadian Forest Fire Danger Rating System (CFFDRS) structure diagram illustrating the linkage to fire management actions (adapted from Stocks *et al.* (1989) and Alexander *et al.* (1996)).

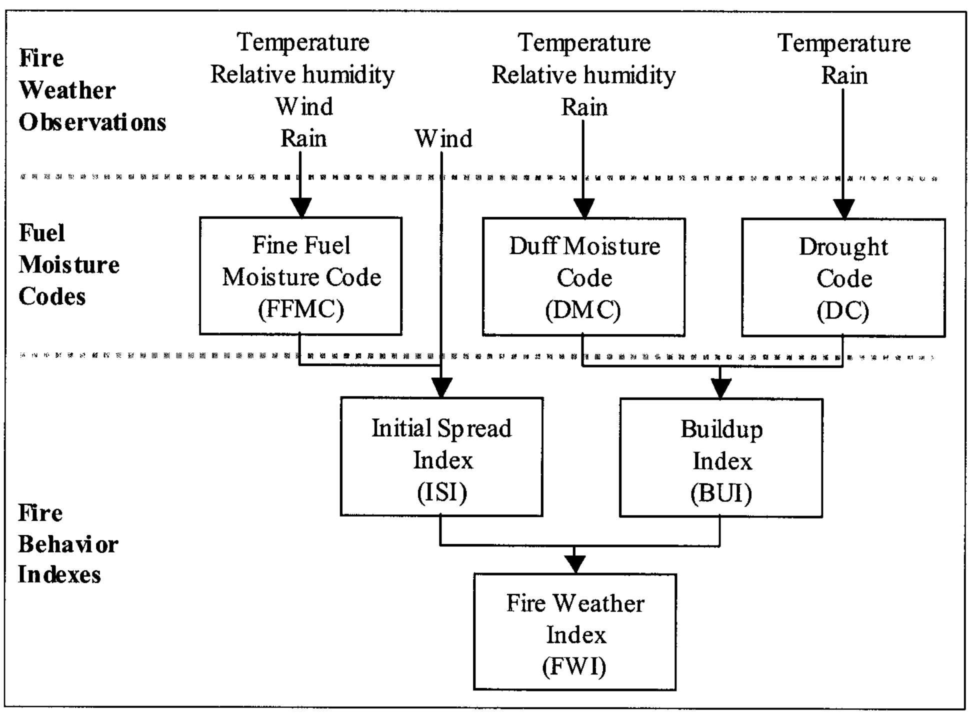


Figure 3-2. Structure of the Canadian Forest Fire Weather Index (FWI) System (adapted from Canadian Forestry Service (1987)).

Table 3-1. Characteristics of the weather stations selected for this project and years of weather data available.

Weather Station	Latitude	Longitude	Elevation[a] (m)	Number of years	List of years
Fort Providence	61° 21' N	117° 40' W	160	19	1982-1983, 1985-2001
Caen Lake Tower	61° 40' N	116° 58' W	220	11	1990-1991, 1993-2001
Kimble Tower	61° 03' N	117° 33' W	260	20	1982-2001

a. Approximation from a 1:250 000 scale topographic map of the area using the latitude and longitude of the station.

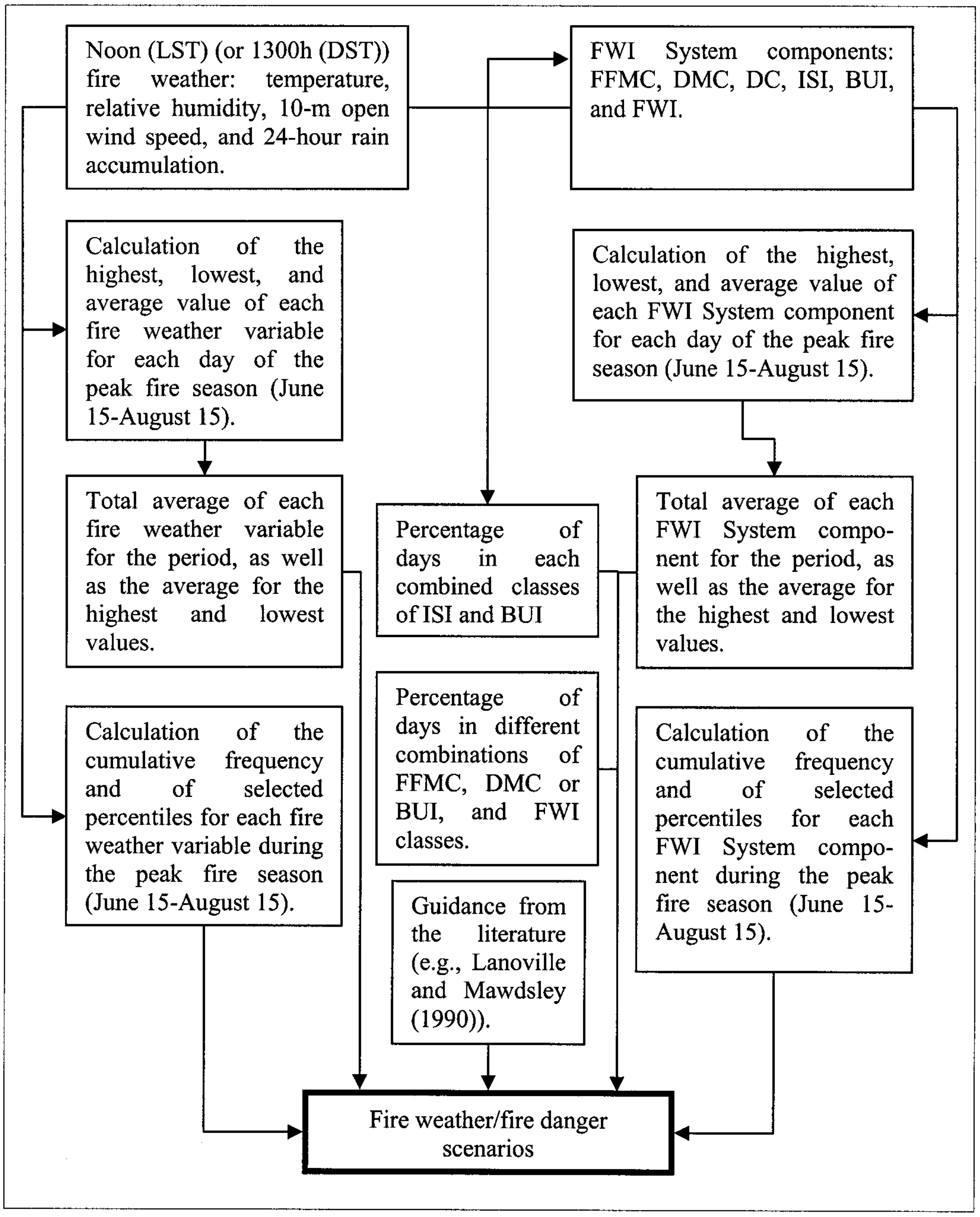
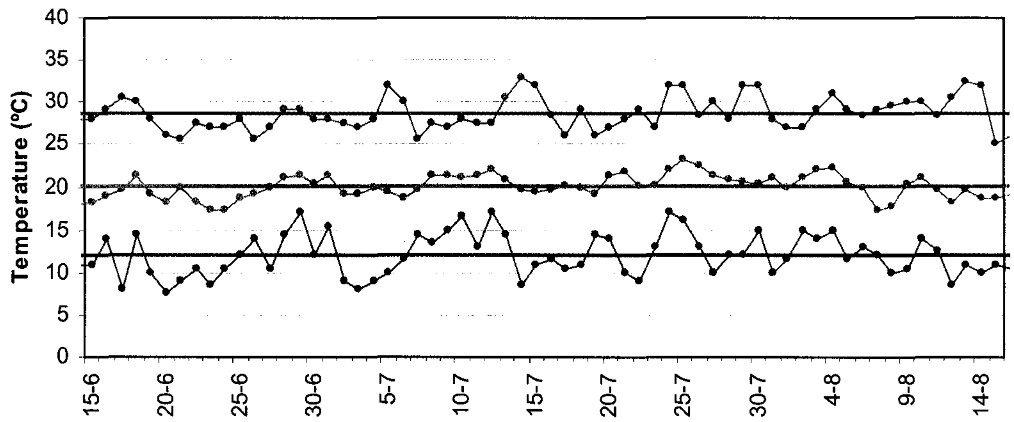
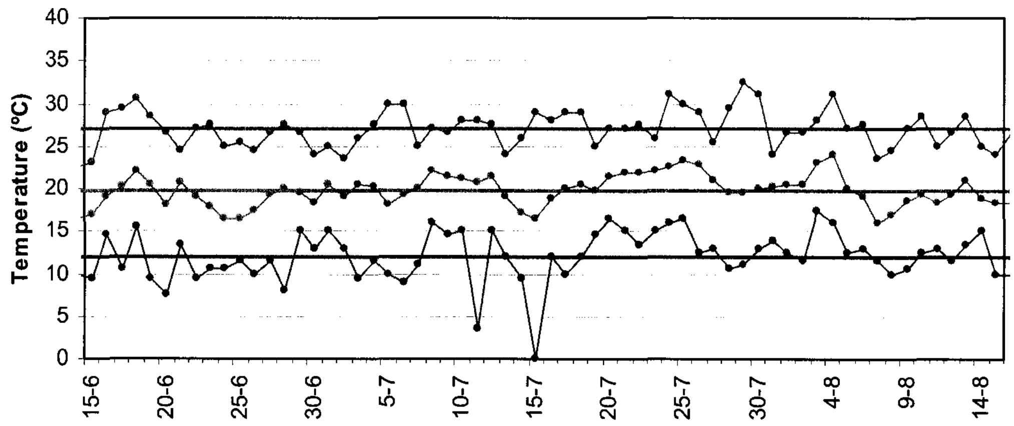


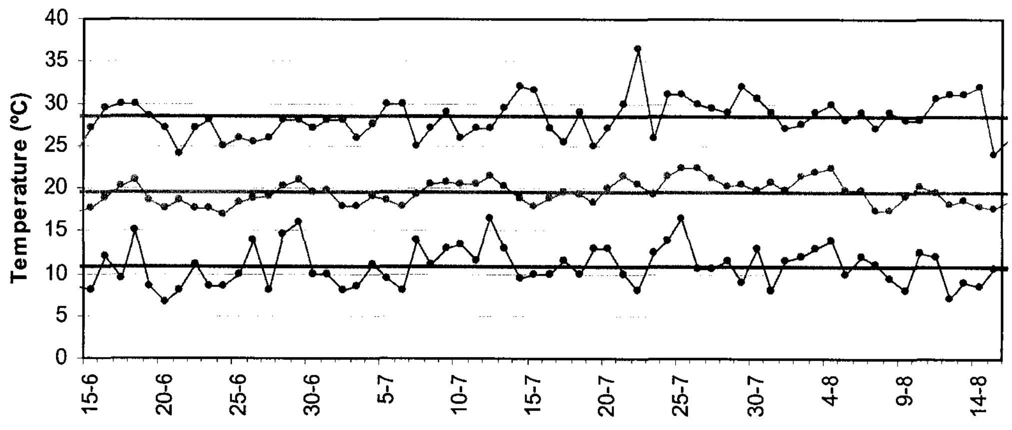
Figure 3-3. Diagram showing the steps involved in the determination of four fire weather/fire danger scenarios representing Horn's (1976) burning conditions in our study area.



a) Fort Providence

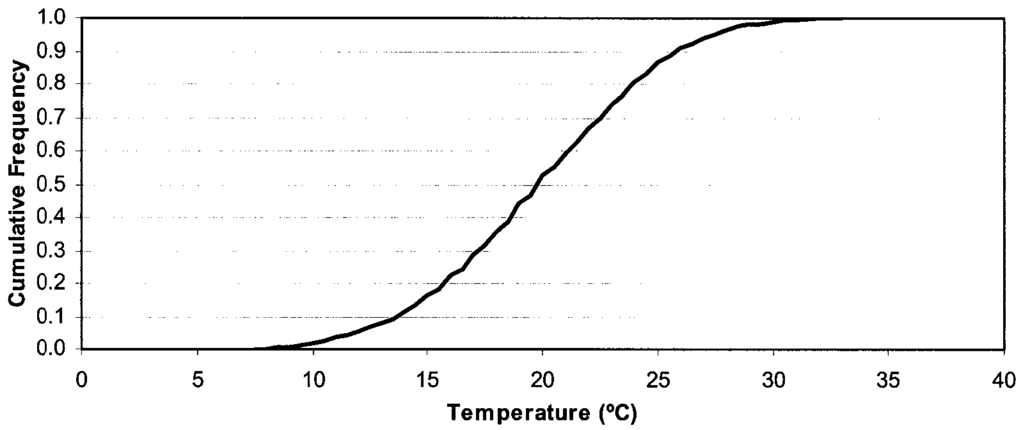


b) Caen Lake Tower

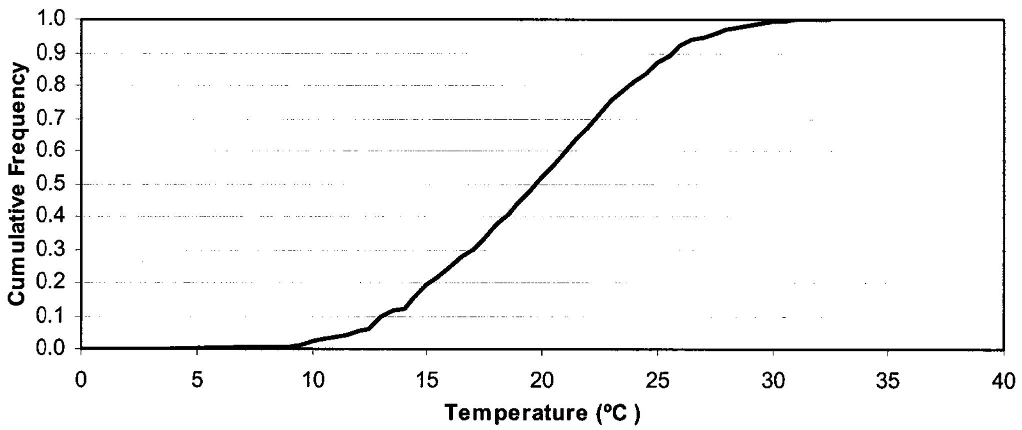


c) Kimble Tower

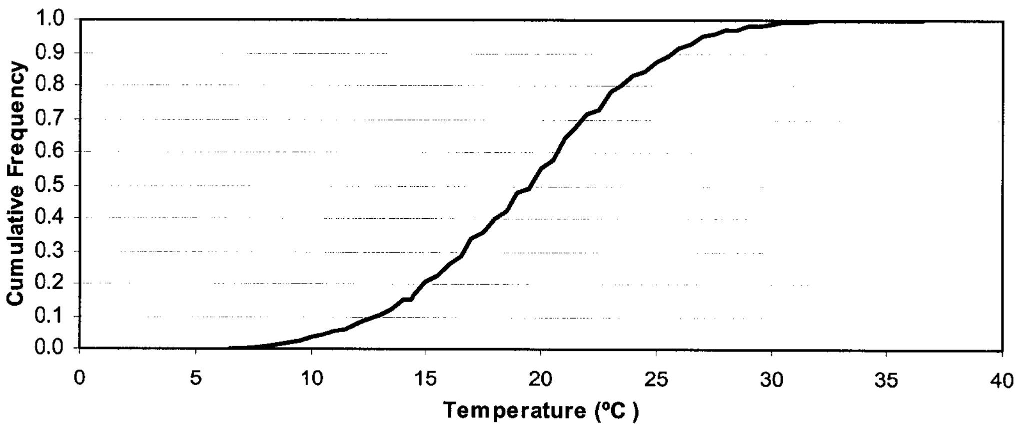
Figure 3-4. Minimum, maximum and average noon (LST) temperature for each day of the peak fire season (see Table 3-1 for years of data for each tower).



a) Fort Providence



b) Caen Lake Tower



c) Kimble Tower

Figure 3-5. Cumulative frequency of the noon (LST) temperature for the three weather stations.

Table 3-2. Selected percentiles and average values (over several years, see Table 3-1) for the seasonal daily observations of highest, average and lowest noon (LST) a) air temperature, b) relative humidity, c) wind speed, and d) 24-hour rain during the peak fire season (June 15 - August 15), based on data from three weather stations located near the study area.

a) Temperature

Station	Percentile							Mean		
	25	50	75	90	95	97	99	Min	Average	Max
Fort Providence	16.6	19.8	23.2	25.8	27.5	28.3	30.3	12.1	20.1	28.7
Caen Tower	16.1	19.7	22.9	25.6	27.1	28.0	29.9	12.1	19.8	27.1
Kimble Tower	15.9	19.6	22.7	25.7	26.9	27.9	30.0	10.9	19.5	28.4

b) Relative humidity

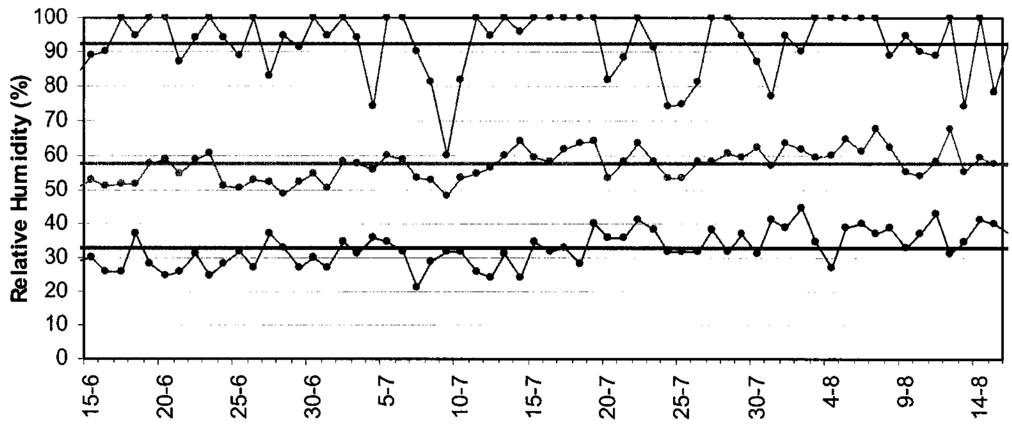
Station	Percentile							Mean		
	1	3	5	10	25	50	75	Min	Average	Max
Fort Providence	27	32	34	39	44	54	67	33	57	92
Caen Tower	27	30	33	37	44	53	65	34	56	87
Kimble Tower	24	28	31	34	41	52	66	29	55	95

c) Wind speed

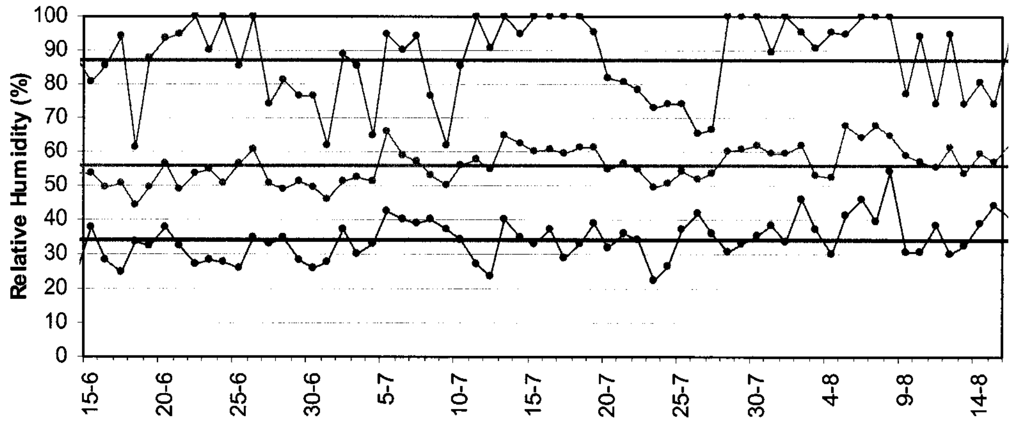
Station	Percentile							Mean		
	25	50	75	90	95	97	99	Min	Average	Max
Fort Providence	4.3	7.8	11.6	15.5	17.9	19.8	24.4	0.4	8.8	21.5
Caen Tower	7.6	10.1	14.0	15.6	19.1	19.9	24.0	4.0	11.1	19.0
Kimble Tower	8.1	11.8	16.0	19.9	22.9	24.6	31.1	2.0	12.7	25.5

d) Rain accumulated over the last 24 hours

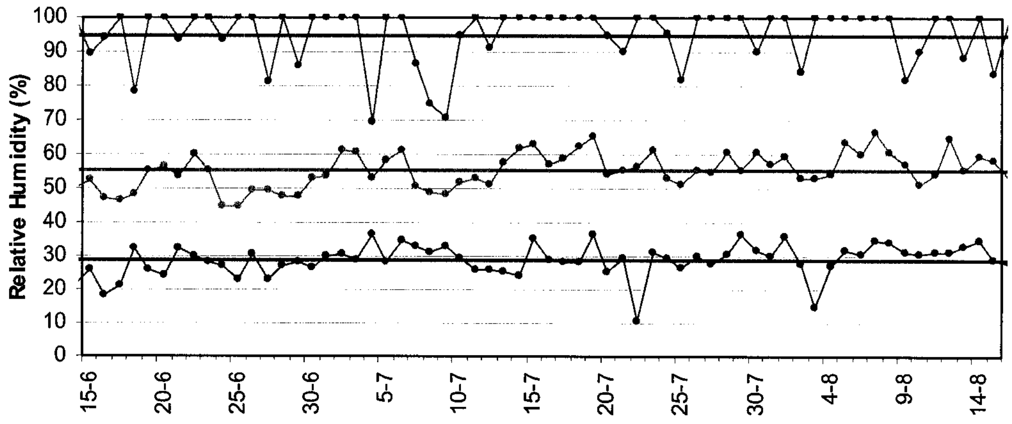
Station	Percentile					Mean		
	75	90	95	97	99	Min	Average	Max
Fort Providence	0.9	4.8	9.0	12.7	19.5	0.0	1.6	12.6
Caen Tower	0.7	4.2	9.6	13.1	18.8	0.0	1.5	9.0
Kimble Tower	1.0	6.1	12.0	17.0	26.3	0.0	2.0	16.7



a) Fort Providence

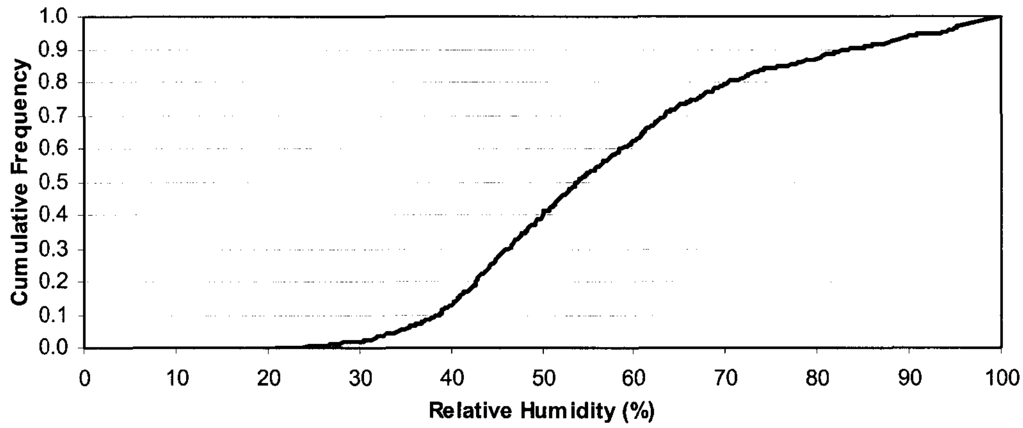


b) Caen Lake Tower

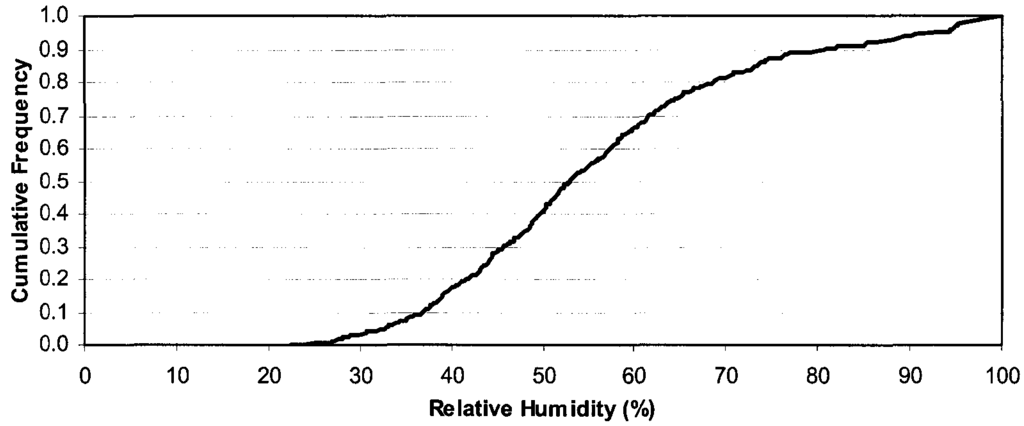


c) Kimble Tower

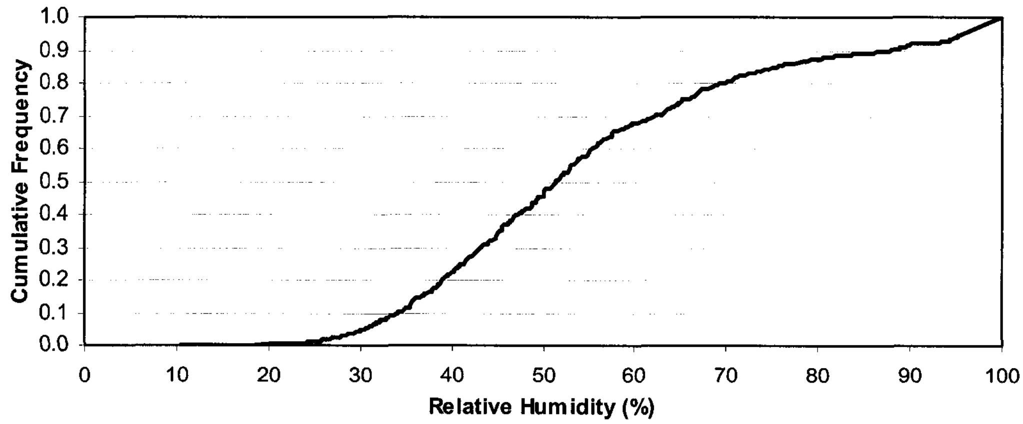
Figure 3-6. Minimum, maximum and average noon (LST) relative humidity for each day of the peak fire season.



a) Fort Providence

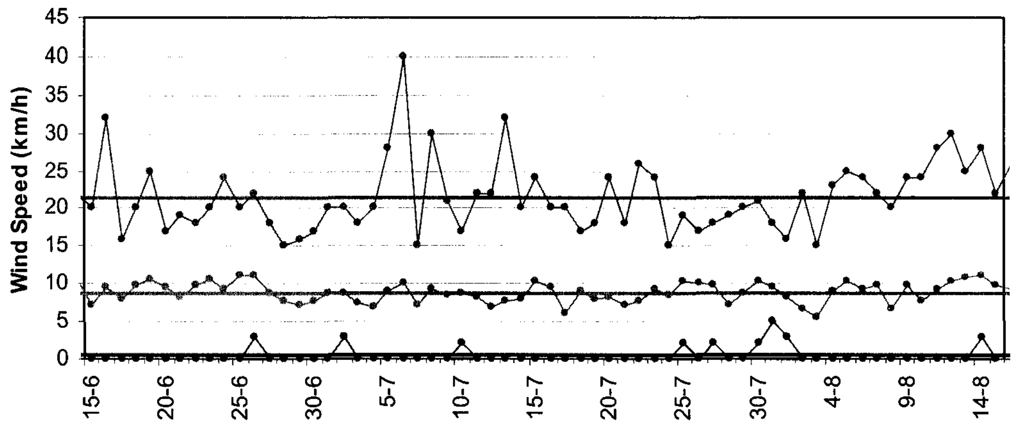


b) Caen Lake Tower

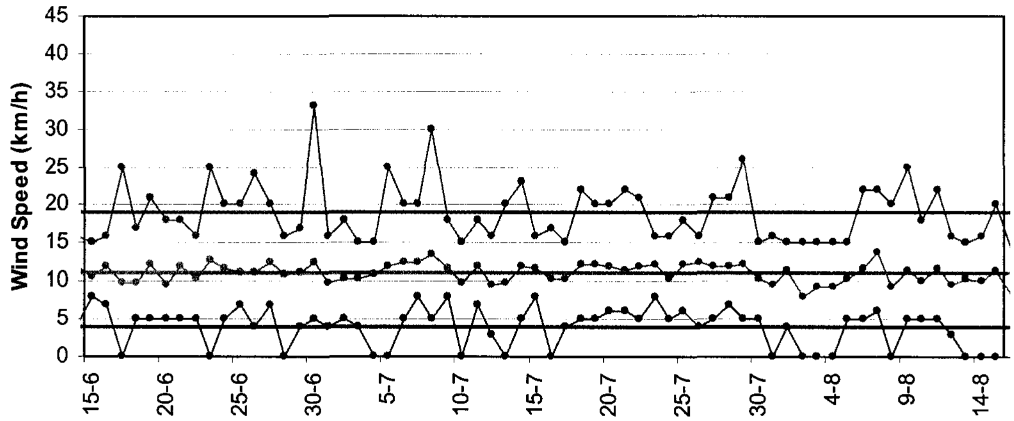


c) Kimble Tower

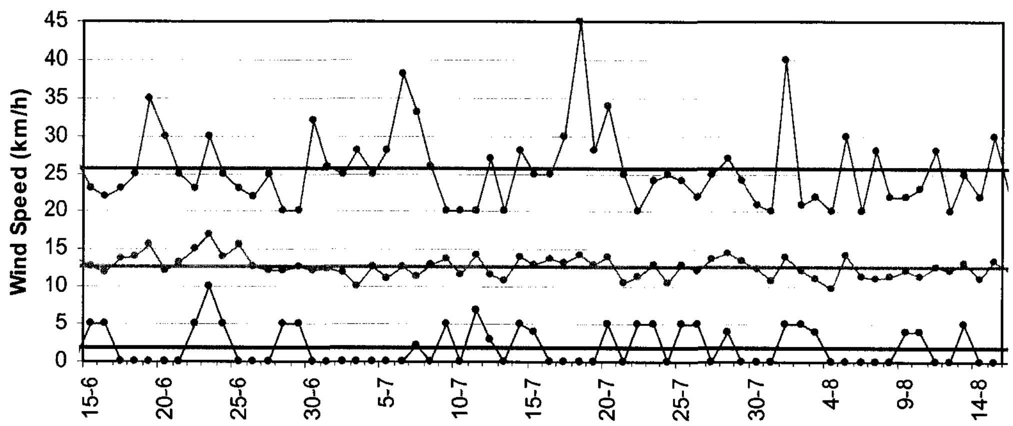
Figure 3-7. Cumulative frequency of the noon (LST) relative humidity for the three weather stations.



a) Fort Providence

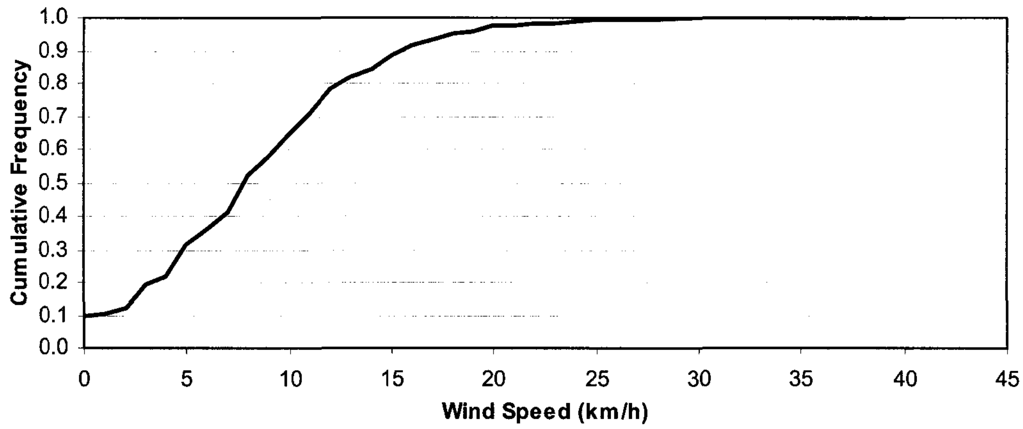


b) Caen Lake Tower

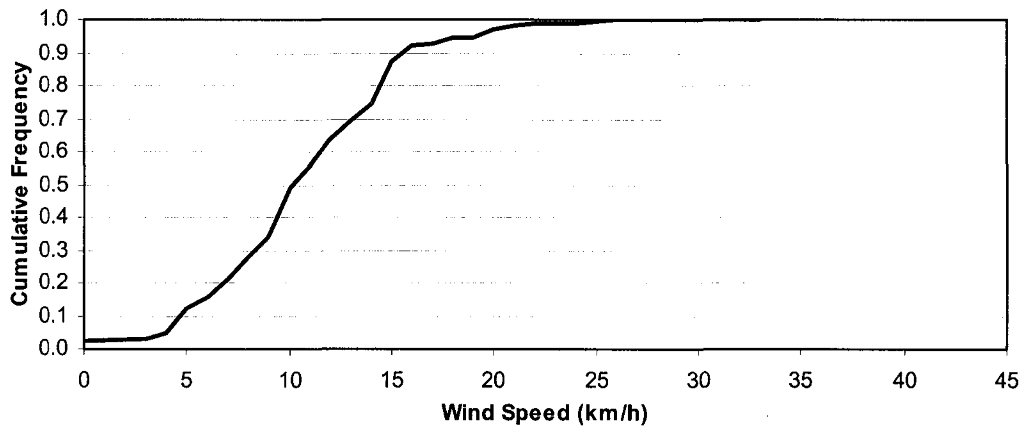


c) Kimble Tower

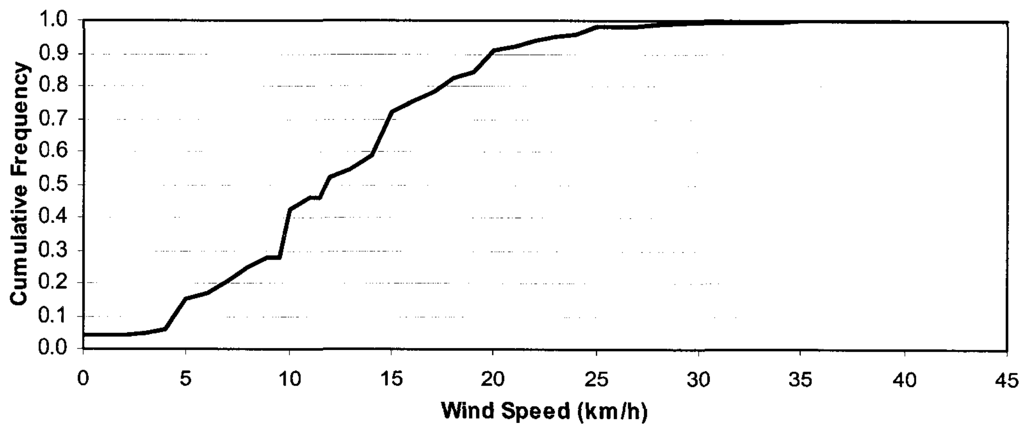
Figure 3-8. Minimum, maximum and average noon (LST) wind speed for each day of the peak fire season.



a) Fort Providence

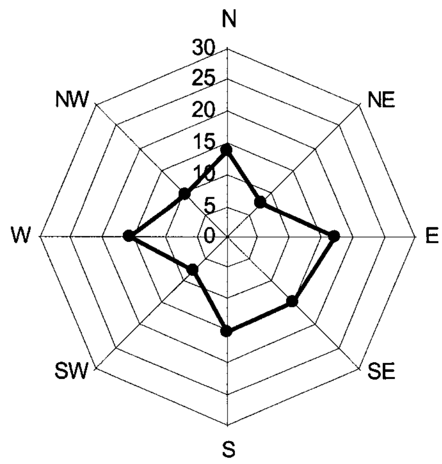


b) Caen Lake Tower

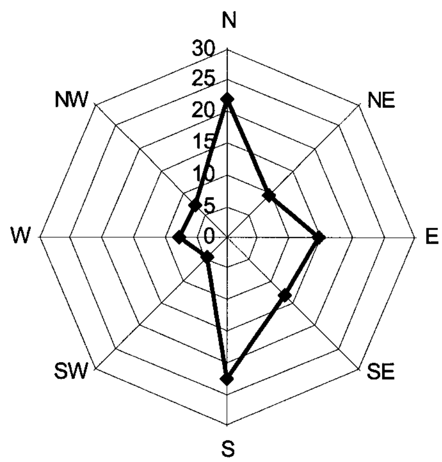


c) Kimble Tower

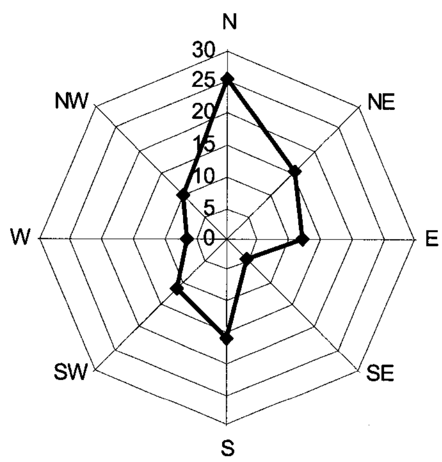
Figure 3-9. Cumulative frequency of the noon (LST) wind speed for the three weather stations.



a) Fort Providence

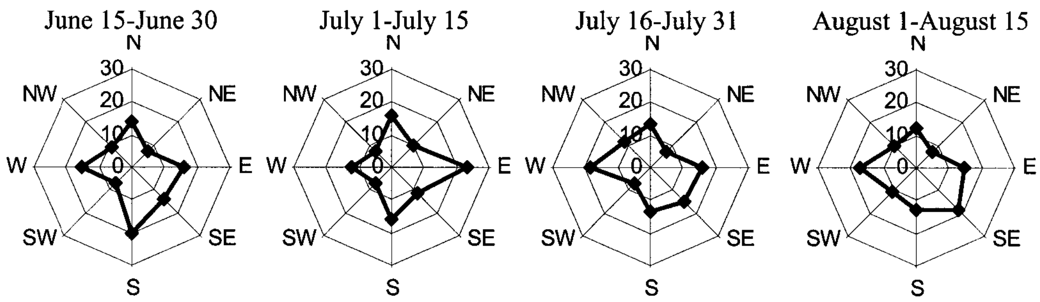


b) Caen Lake Tower

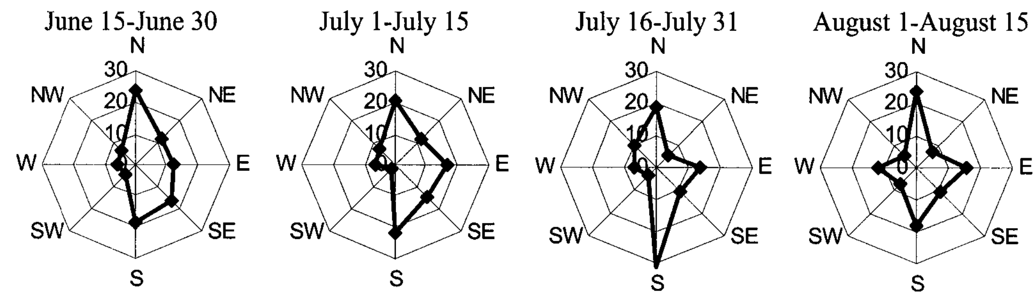


c) Kimble Tower

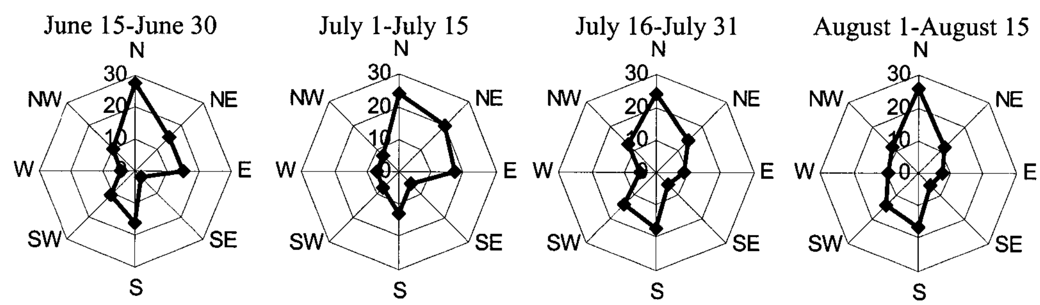
Figure 3-10. Percentage of days, during the peak fire season, in each wind direction category for the noon (LST) observation.



a) Fort Providence

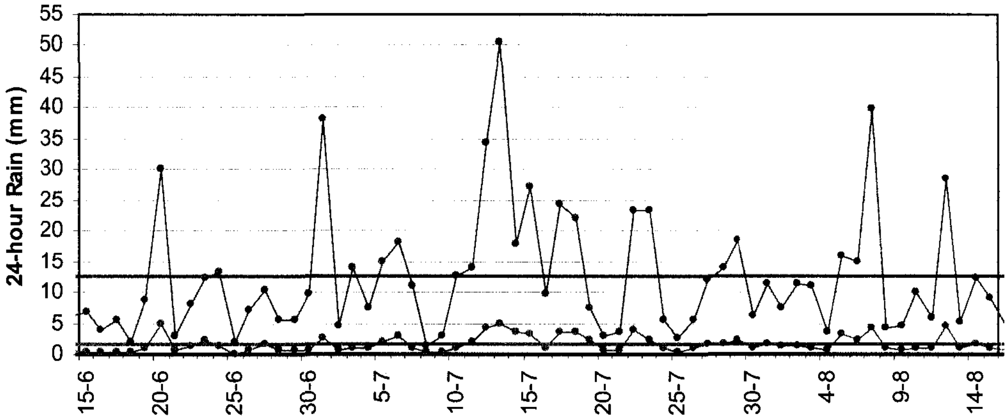


b) Caen Lake Tower

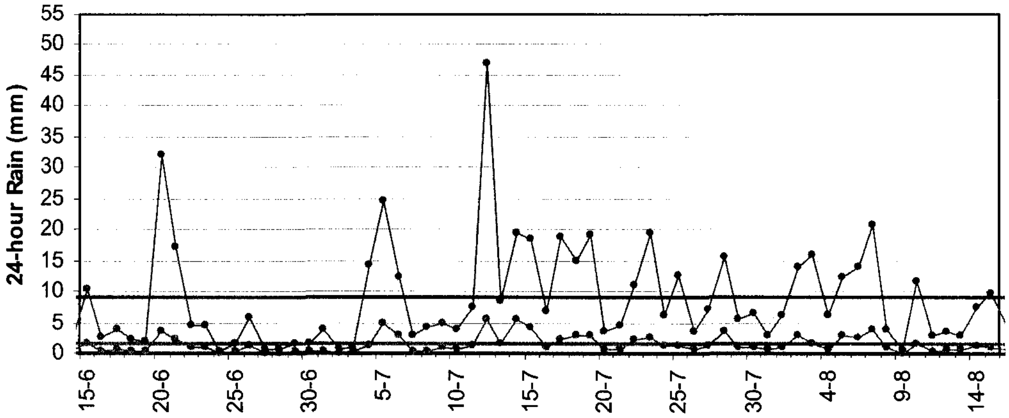


c) Kimble Tower

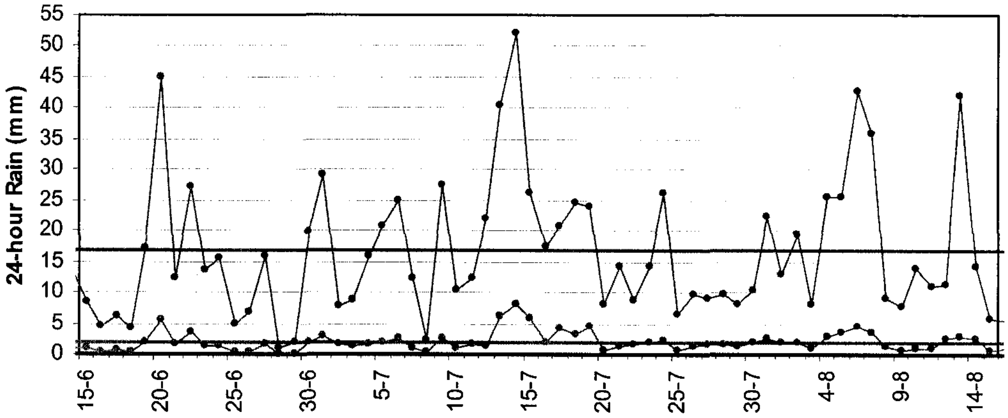
Figure 3-11. Percentage of days, for four 15-days periods of the peak fire season, in each wind direction category for the noon (LST) observation.



a) Fort Providence

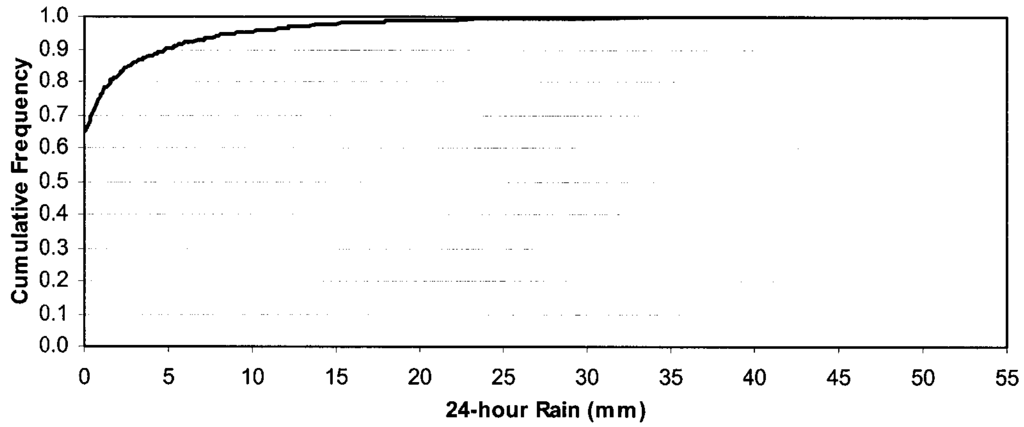


b) Caen Lake Tower

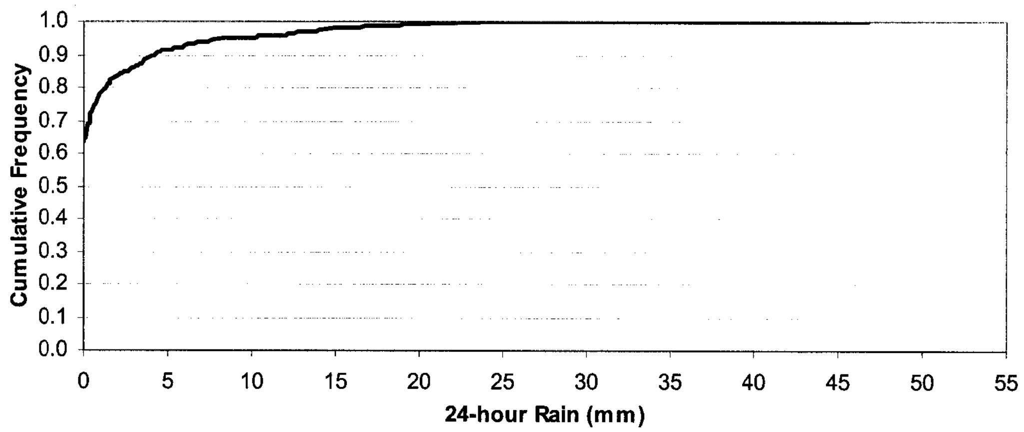


c) Kimble Tower

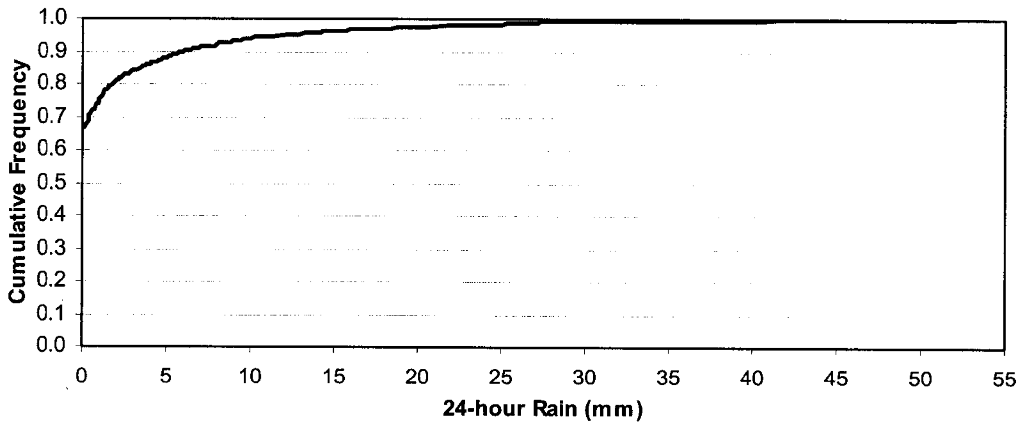
Figure 3-12. Minimum, maximum and average noon (LST) 24-hour rain for each day of the peak fire season.



a) Fort Providence

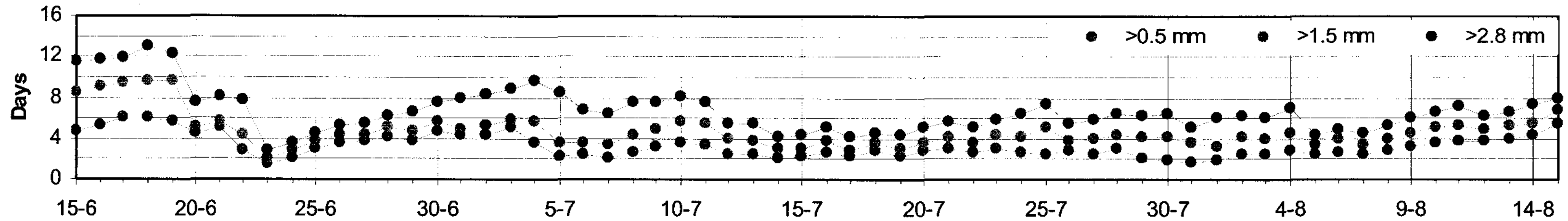


b) Caen Lake Tower

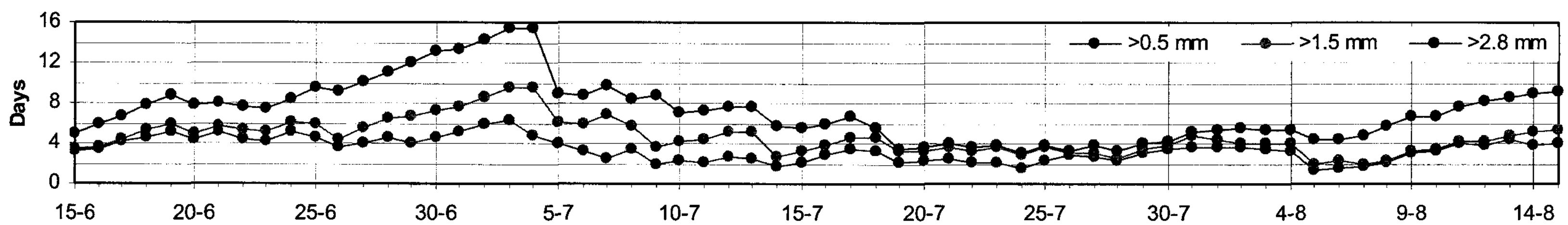


c) Kimble Tower

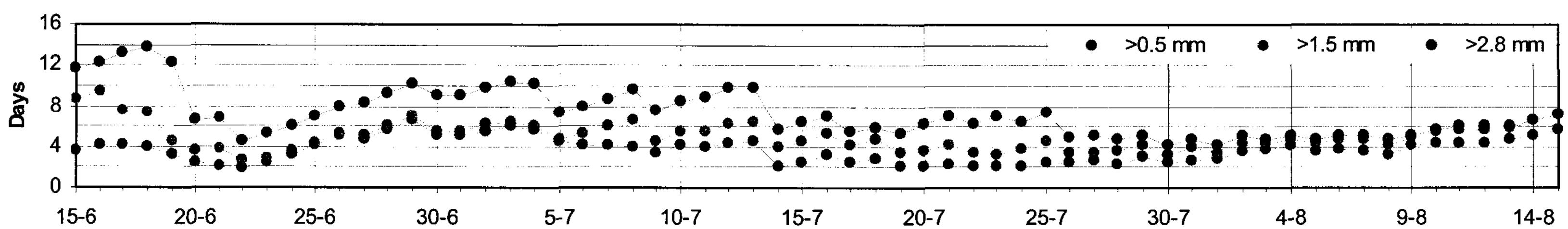
Figure 3-13. Cumulative frequency of the noon (LST) 24-hour rain for the three weather stations.



a) Fort Providence

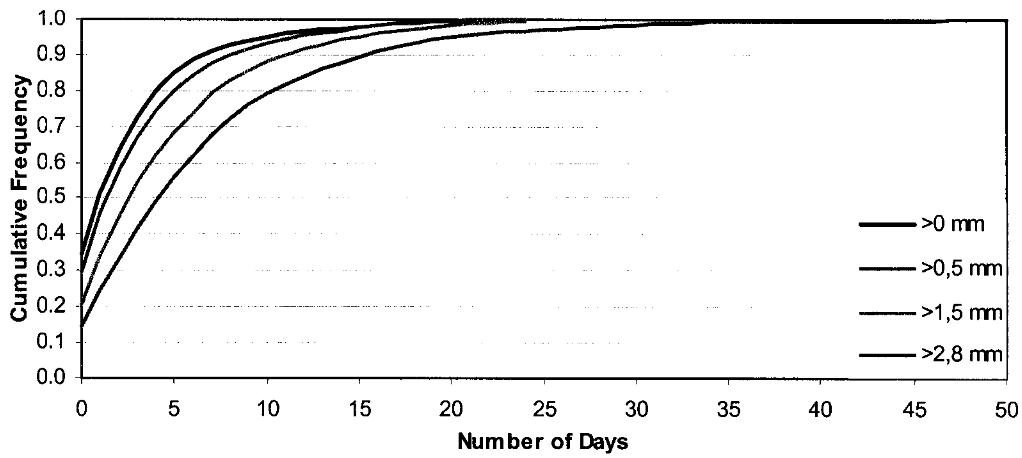


b) Caen Lake Tower

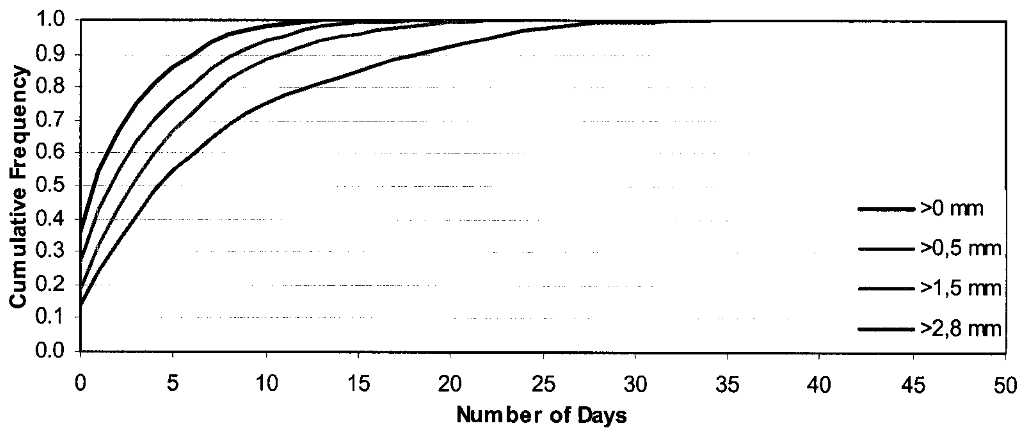


c) Kimble Tower

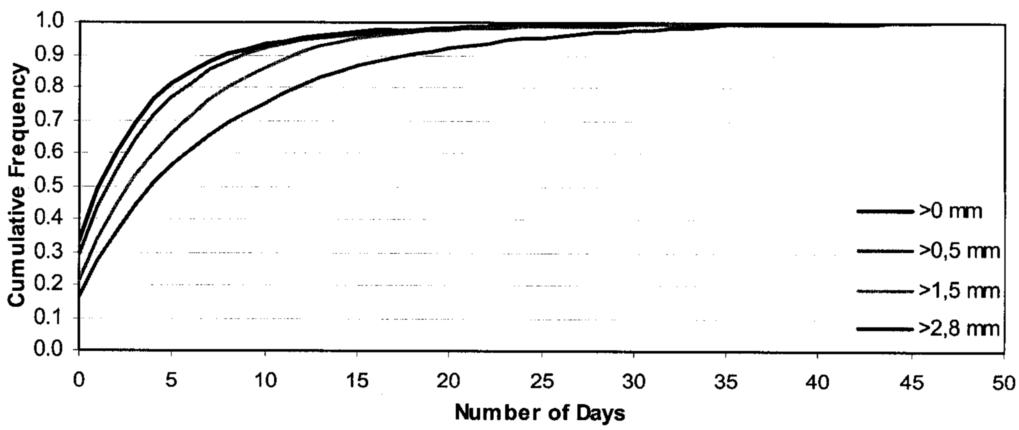
Figure 3-14. Average number of days since the last rain event of the magnitude mentioned for each day of the peak fire season.



a) Fort Providence



b) Caen Lake Tower



c) Kimble Tower

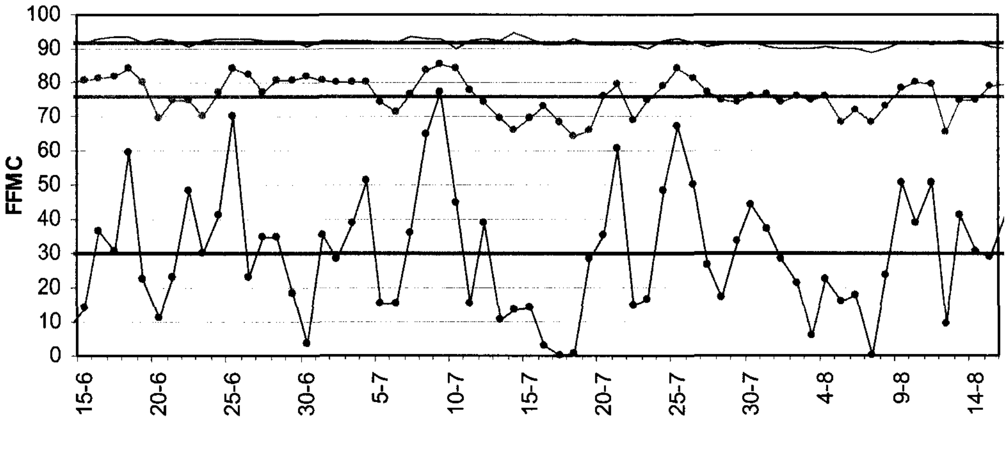
Figure 3-15. Cumulative frequency of the number of days, since the last rain event having the magnitude mentioned, for the three weather stations.

Table 3-3. Percentiles of the number of days since the last rain event of the magnitude mentioned during the peak fire season based on data over several years (see Table 3-1) for each day of the peak fire season (June 15 – August 15).

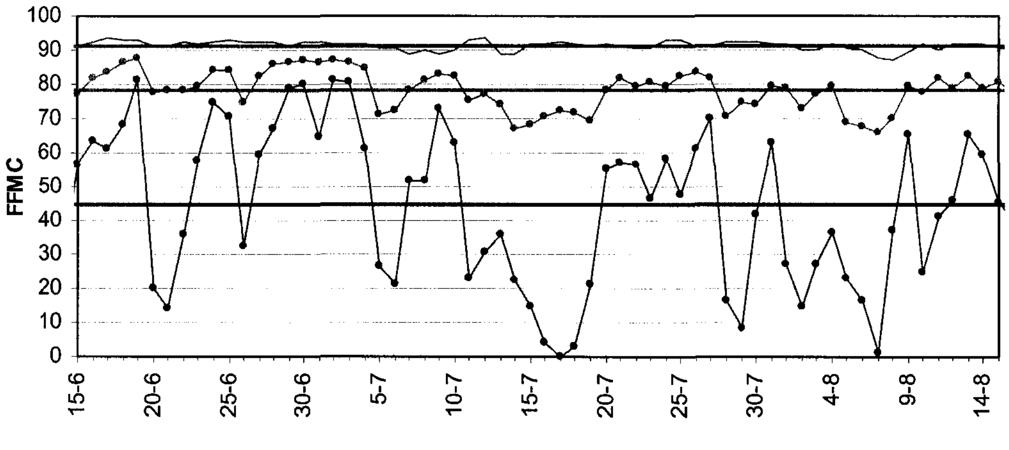
Rain event	Station	Percentile					
		50	75	90	95	97	99
>0.0 mm	Fort Providence	0.9	3.3	6.5	10.1	13.0	17.3
	Caen Tower	0.7	2.9	6.1	7.7	8.9	11.0
	Kimble Tower	1.1	3.8	7.9	11.8	15.0	22.4
>0.5 mm	Fort Providence	1.3	4.1	8.1	11.6	14.2	17.8
	Caen Tower	1.6	4.8	8.3	10.7	12.1	14.4
	Kimble Tower	1.5	4.6	8.9	12.7	15.8	22.7
>1.5 mm	Fort Providence	2.5	6.2	10.9	15.0	17.6	21.8
	Caen Tower	2.8	6.5	10.8	14.0	16.1	19.4
	Kimble Tower	2.6	6.7	11.7	14.9	18.2	28.0
>2.8 mm	Fort Providence	4.1	8.8	15.4	20.3	24.5	32.6
	Caen Tower	4.2	9.9	18.3	22.3	24.4	27.8
	Kimble Tower	3.9	9.9	17.8	24.2	28.7	34.4

Table 3-4. Average number of times, for occurrence of a given interval between rain events of the given magnitude. Based on data over several years (see Table 3-1) for the peak fire season (June 15 – August 15).

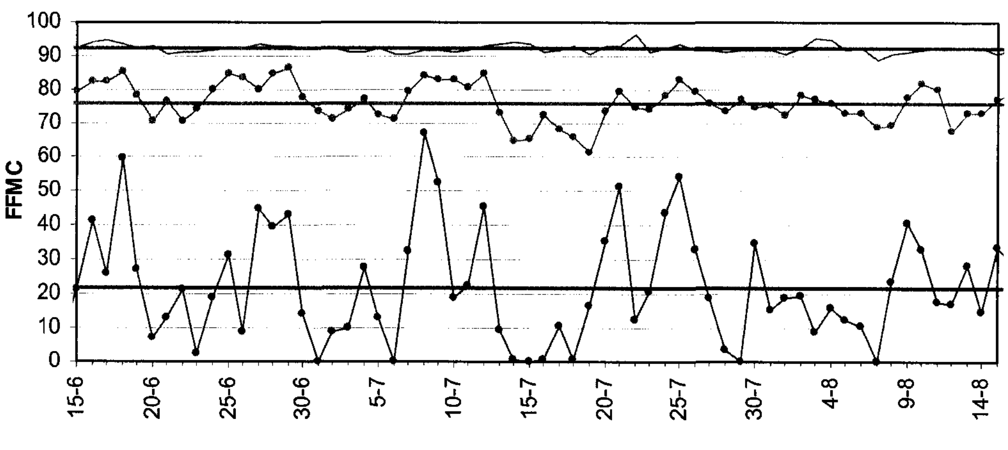
Rain event	Station	Number of days between rain event											
		0.0	1-3	4-6	7-9	10-12	13-15	16-18	19-21	22-24	25-27	28-30	>30
>0.0 mm	Fort Providence	21.5	5.5	3.2	0.8	0.3	0.1	0.1	0.1	0.0	0.0	0.0	0.0
	Caen Tower	22.4	7.9	1.6	1.3	0.4	0.3	0.0	0.0	0.0	0.0	0.0	0.0
	Kimble Tower	20.5	5.5	2.6	0.8	0.5	0.3	0.1	0.0	0.1	0.0	0.0	0.1
>0.5 mm	Fort Providence	18.3	5.2	2.6	1.0	0.6	0.2	0.1	0.2	0.0	0.0	0.0	0.0
	Caen Tower	16.9	5.4	1.3	1.6	0.5	0.6	0.0	0.1	0.0	0.0	0.0	0.0
	Kimble Tower	17.8	4.6	2.3	1.1	0.5	0.3	0.2	0.0	0.0	0.0	0.0	0.1
>1.5 mm	Fort Providence	12.7	3.4	1.6	1.6	0.8	0.3	0.2	0.2	0.1	0.0	0.0	0.1
	Caen Tower	11.6	3.4	1.5	1.6	0.6	0.5	0.1	0.3	0.1	0.0	0.0	0.0
	Kimble Tower	13.2	3.5	1.6	1.2	0.6	0.6	0.3	0.1	0.0	0.0	0.0	0.2
>2.8 mm	Fort Providence	9.0	1.7	1.3	1.4	0.8	0.4	0.4	0.2	0.0	0.1	0.1	0.2
	Caen Tower	8.7	1.5	1.5	1.2	0.6	0.2	0.2	0.1	0.2	0.0	0.3	0.1
	Kimble Tower	10.1	2.5	1.3	0.8	0.5	0.5	0.3	0.1	0.1	0.1	0.1	0.3



a) Fort Providence

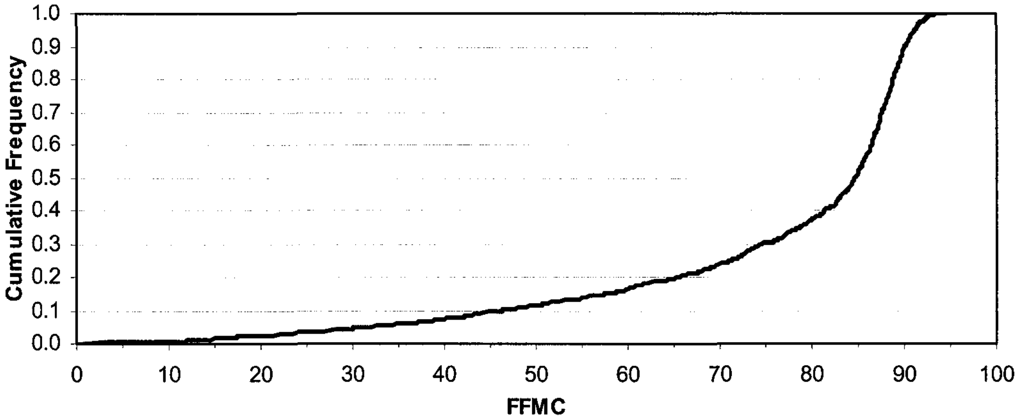


b) Caen Lake Tower

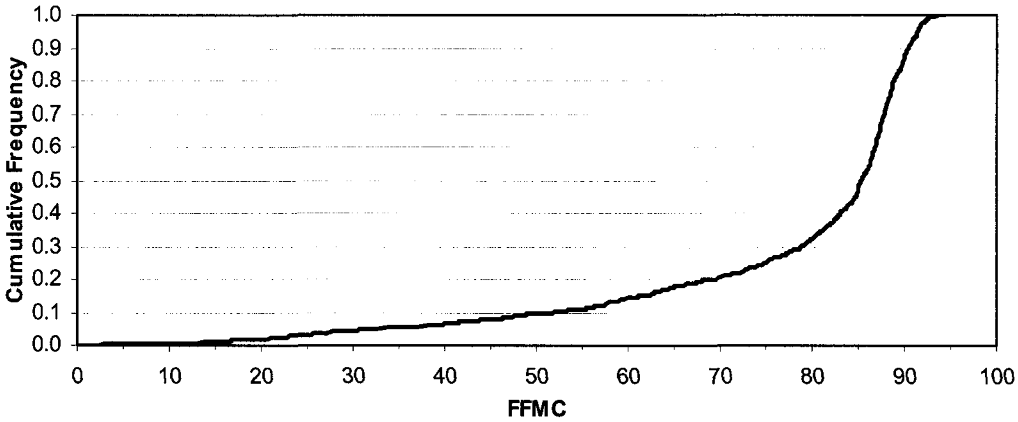


c) Kimble Tower

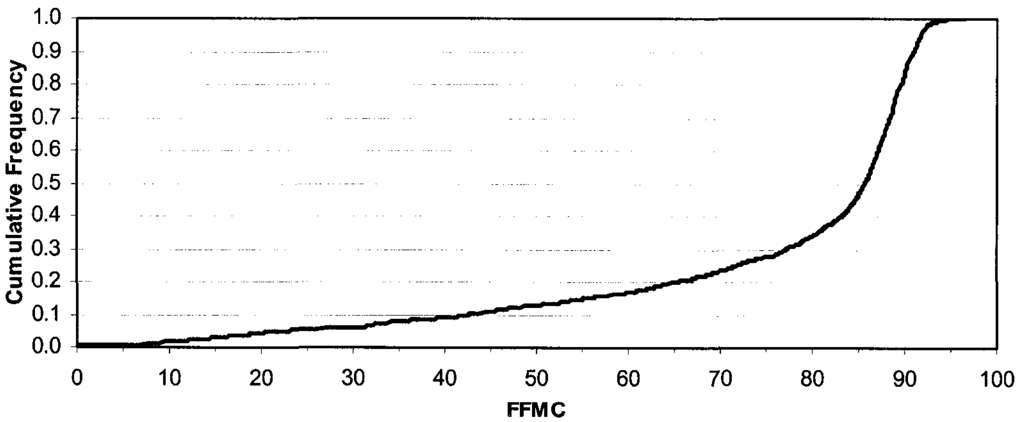
Figure 3-16. Minimum, maximum and average standard daily Fine Fuel Moisture Content (FFMC) for each day of the peak fire season.



a) Fort Providence



b) Caen Lake Tower



c) Kimble Tower

Figure 3-17. Cumulative frequency of the standard daily Fine Fuel Moisture Code (FFMC) for the three weather stations.

Table 3-5. Selected percentiles and average values (over several years, see Table 3-1) for the seasonal daily calculations of highest, average and lowest noon (LST) a) FFMC, b) DMC, c) DC, d) ISI, e) BUI, and f) FWI during the peak fire season (June 15 – August 15), based on data from three weather stations located near the study area.

a) Fine Fuel Moisture Code (FFMC)

Station	Percentile							Mean		
	25	50	75	90	95	97	99	Min	Average	Max
Fort Providence	71	85	88	90	91	92	93	30	76	92
Caen Tower	76	85	89	90	92	92	93	45	78	91
Kimble Tower	72	86	89	91	92	92	93	22	76	92

b) Duff Moisture Code (DMC)

Station	Percentile							Mean		
	25	50	75	90	95	97	99	Min	Average	Max
Fort Providence	19	33	54	76	87	94	103	9	39	96
Caen Tower	21	38	60	78	87	92	99	13	42	86
Kimble Tower	16	29	49	71	82	89	105	8	36	91

c) Drought code (DC)

Station	Percentile							Mean		
	25	50	75	90	95	97	99	Min	Average	Max
Fort Providence	317	410	493	565	619	645	670	222	412	630
Caen Tower	342	409	512	584	642	671	704	167	247	616
Kimble Tower	262	331	405	471	529	572	606	145	337	573

d) Initial Spread Index (ISI)

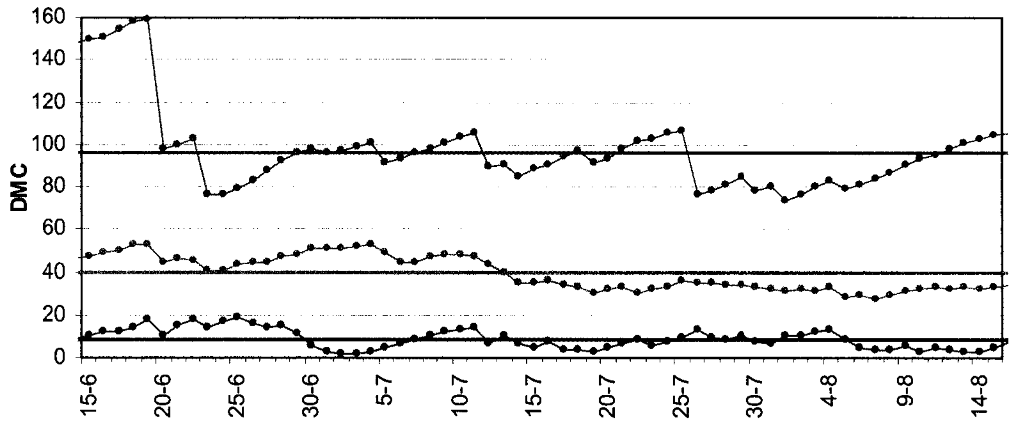
Station	Percentile							Mean		
	25	50	75	90	95	97	99	Min	Average	Max
Fort Providence	0.9	3.0	5.3	7.3	8.8	10.0	12.9	0.1	3.5	10.3
Caen Tower	1.4	3.9	6.2	8.4	10.5	11.4	13.6	0.5	4.2	10.3
Kimble Tower	1.2	4.1	7.2	10.3	12.5	14.6	17.7	0.1	4.8	14.5

e) Buildup Index (BUI)

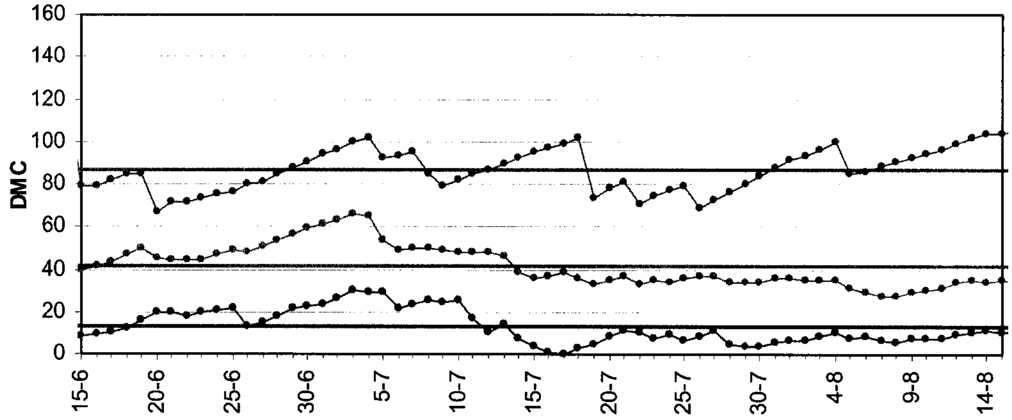
Station	Percentile							Mean		
	25	50	75	90	95	97	99	Min	Average	Max
Fort Providence	34	54	83	111	122	127	139	16	61	131
Caen Tower	36	61	89	112	124	131	141	23	64	124
Kimble Tower	29	48	73	99	111	120	135	14	53	121

f) Fire Weather Index (FWI)

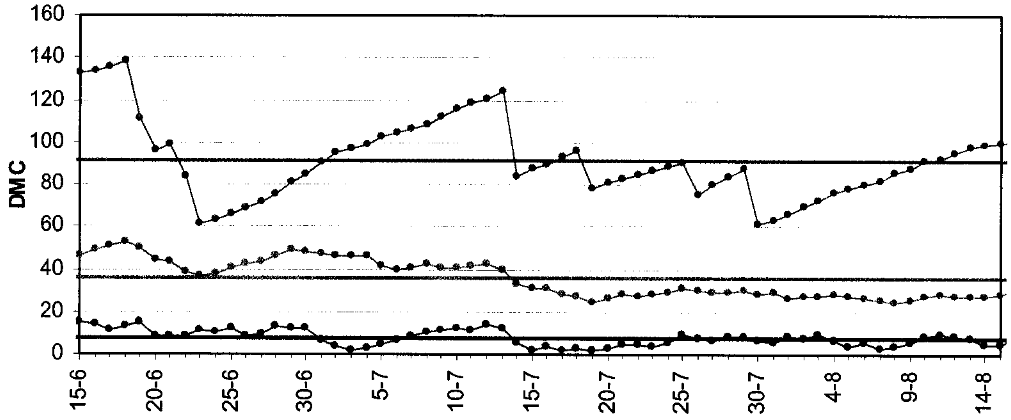
Station	Percentile							Mean		
	25	50	75	90	95	97	99	Min	Average	Max
Fort Providence	2	9	17	24	28	30	35	0	11	31
Caen Tower	4	12	20	26	30	34	38	1	13	30
Kimble Tower	3	11	20	28	32	34	41	0	13	35



a) Fort Providence

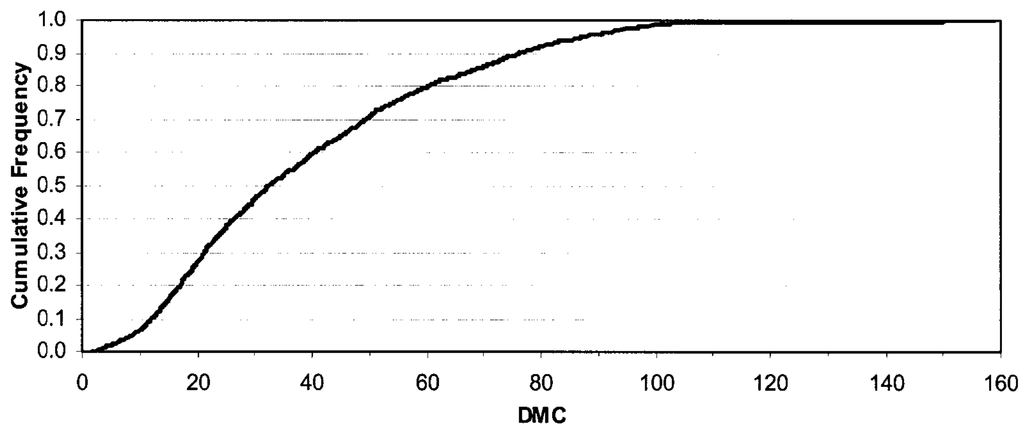


b) Caen Lake Tower

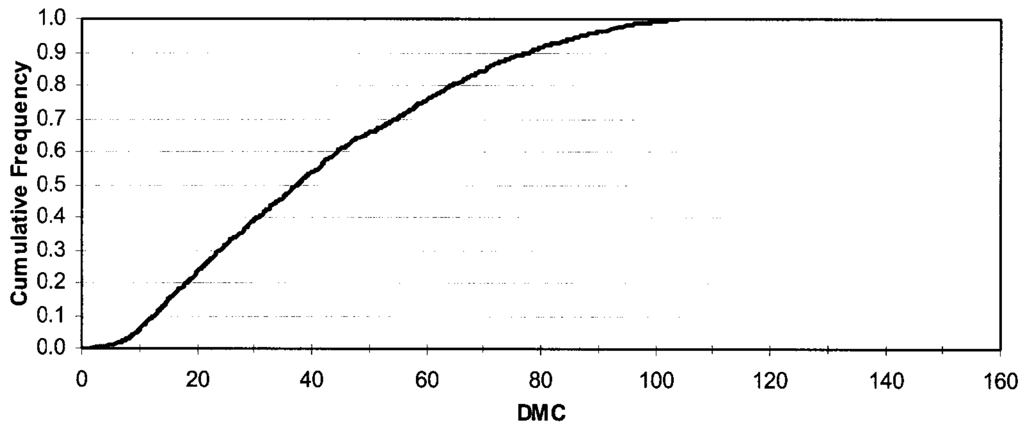


c) Kimble Tower

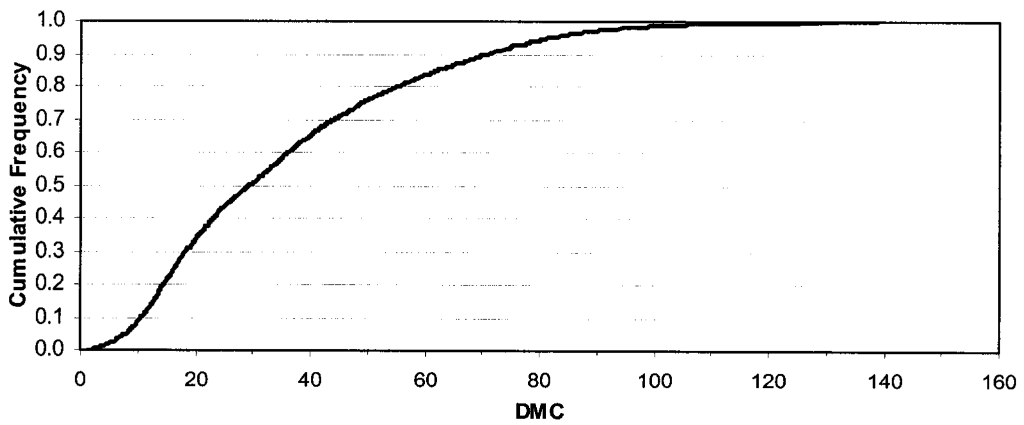
Figure 3-18. Minimum, maximum and average standard daily Duff Moisture Code (DMC) for each day of the peak fire season.



a) Fort Providence

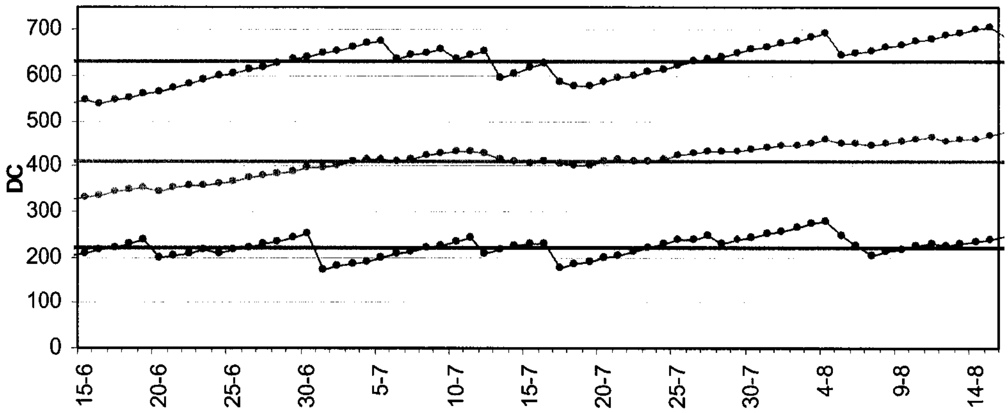


b) Caen Lake Tower

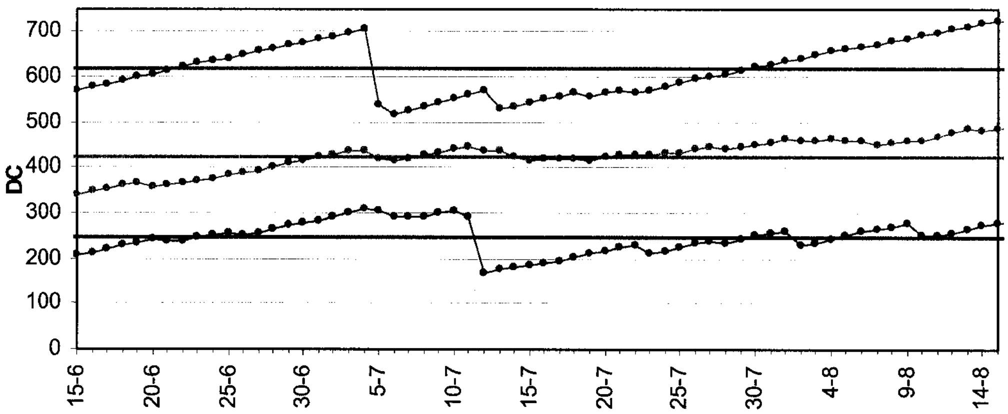


c) Kimble Tower

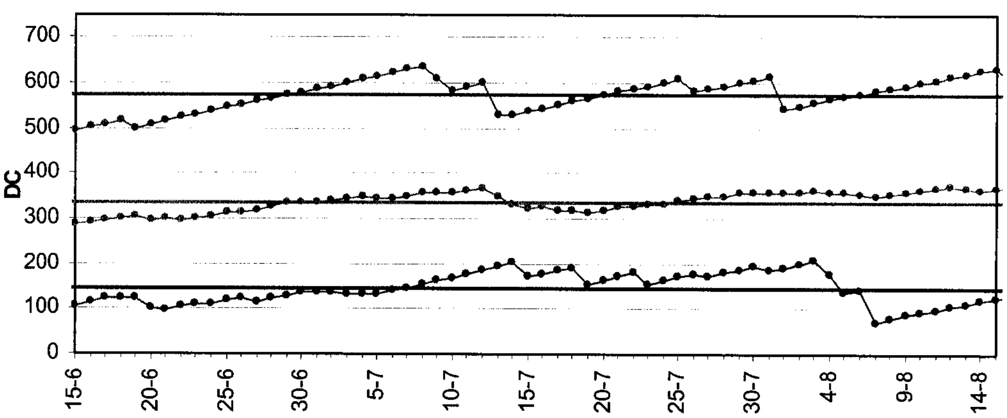
Figure 3-19. Cumulative frequency of the standard daily DMC for the three weather stations.



a) Fort Providence

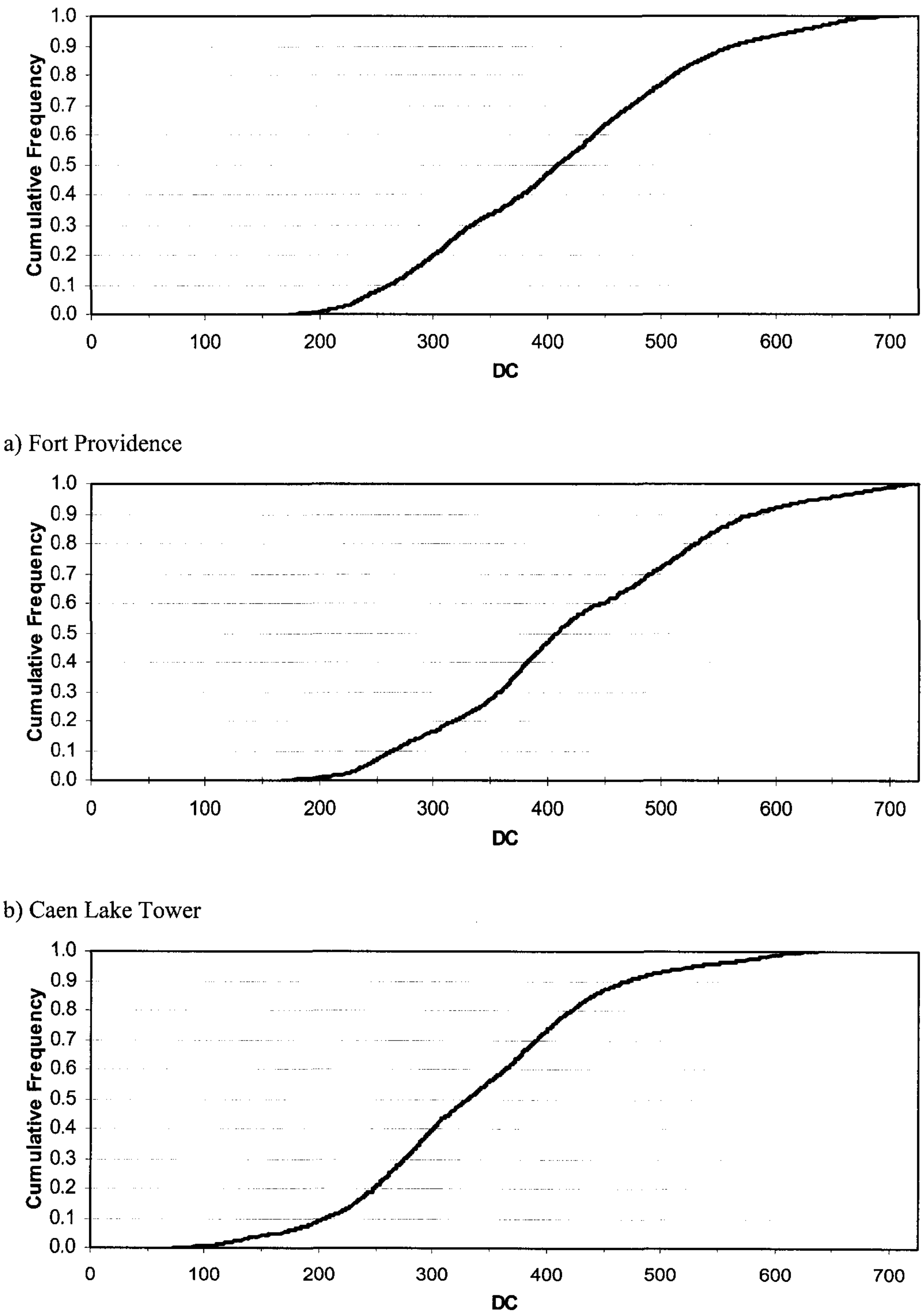


b) Caen Lake Tower



c) Kimble Tower

Figure 3-20. Minimum, maximum and average standard daily Drought Code (DC) for each day of the peak fire season.

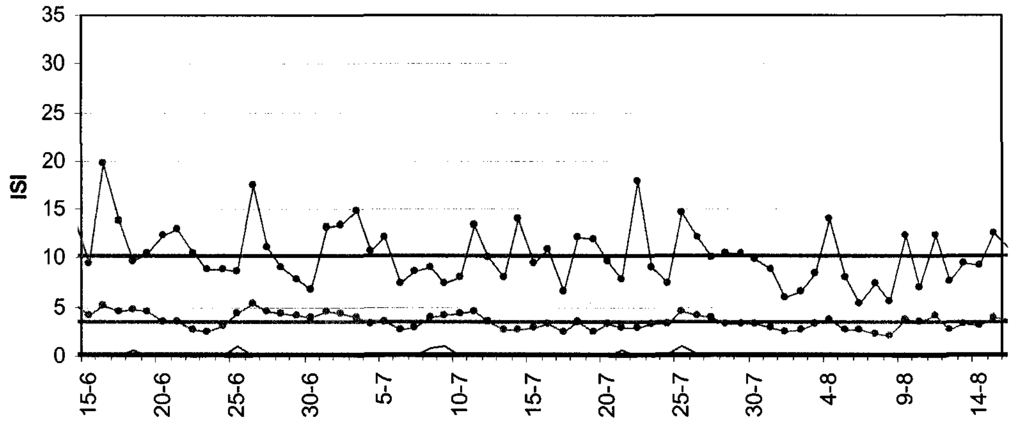


a) Fort Providence

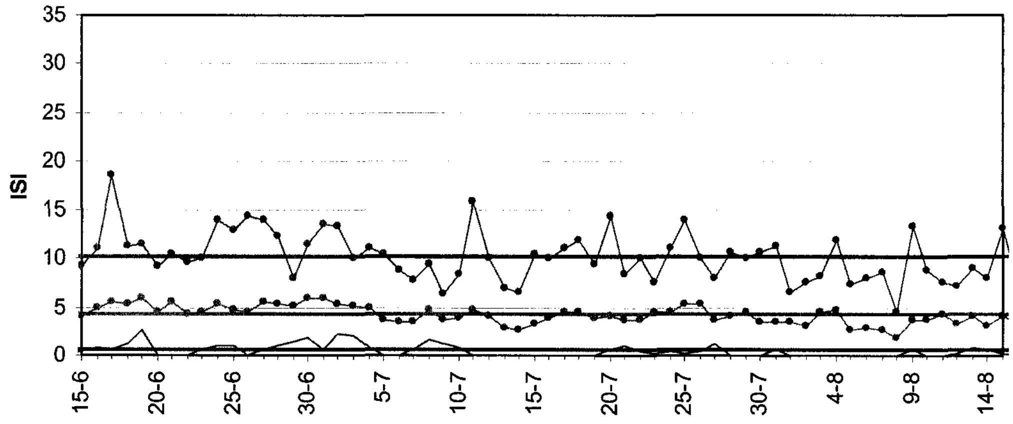
b) Caen Lake Tower

c) Kimble Tower

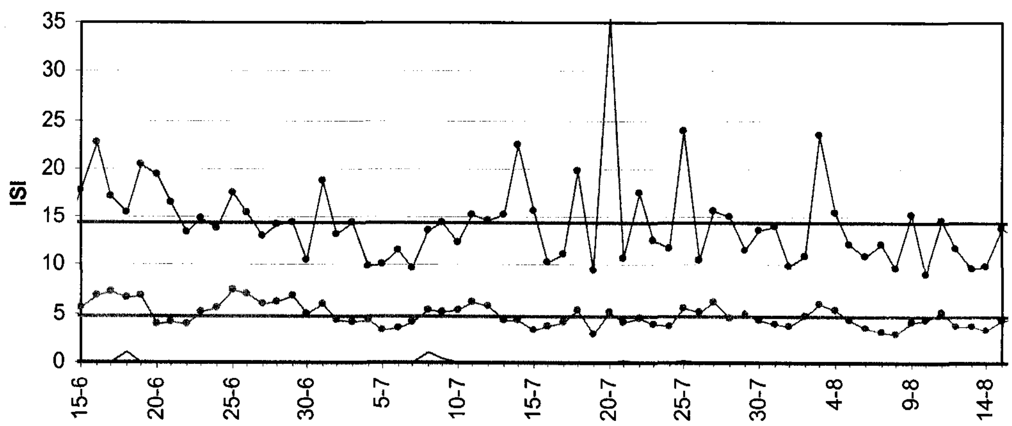
Figure 3-21. Cumulative frequency of the standard daily DC for the three weather stations.



a) Fort Providence

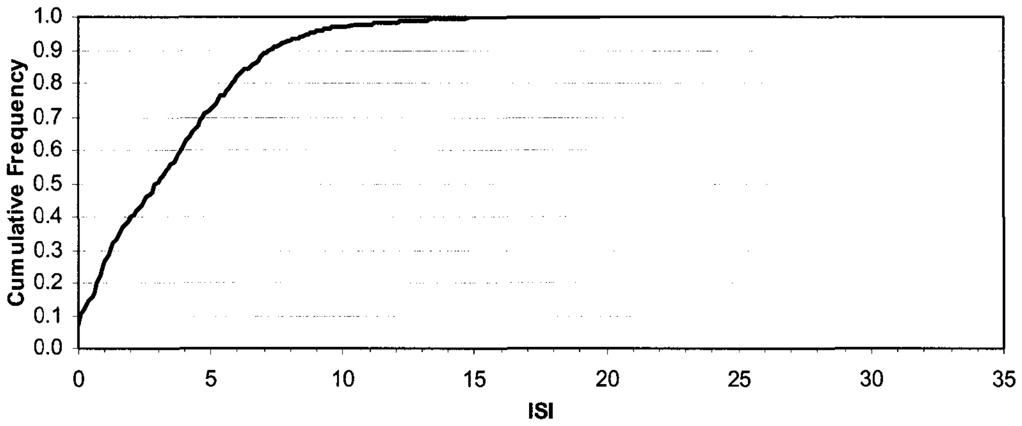


b) Caen Lake Tower

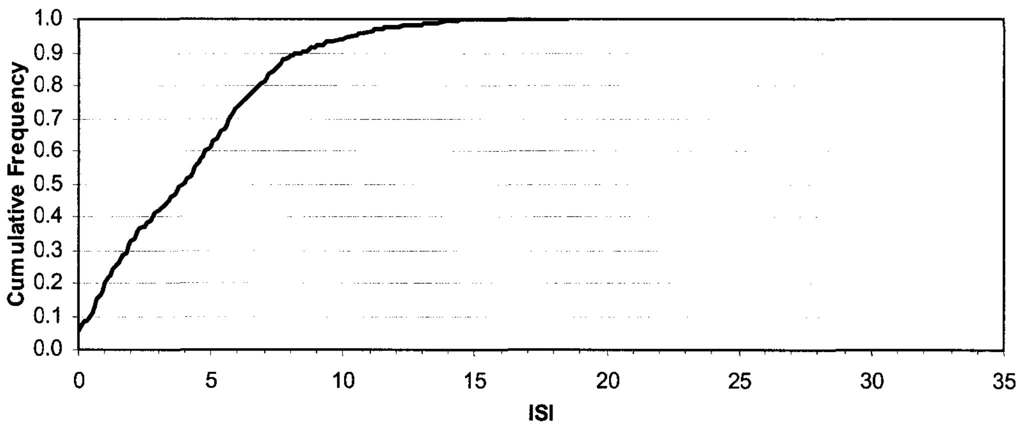


c) Kimble Tower

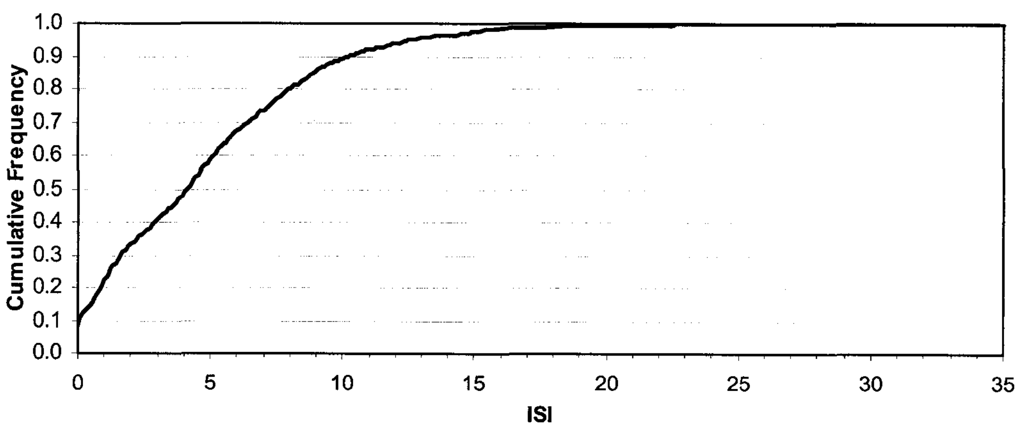
Figure 3-22. Minimum, maximum and average standard daily Initial Spread Index (ISI) for each day of the peak fire season.



a) Fort Providence

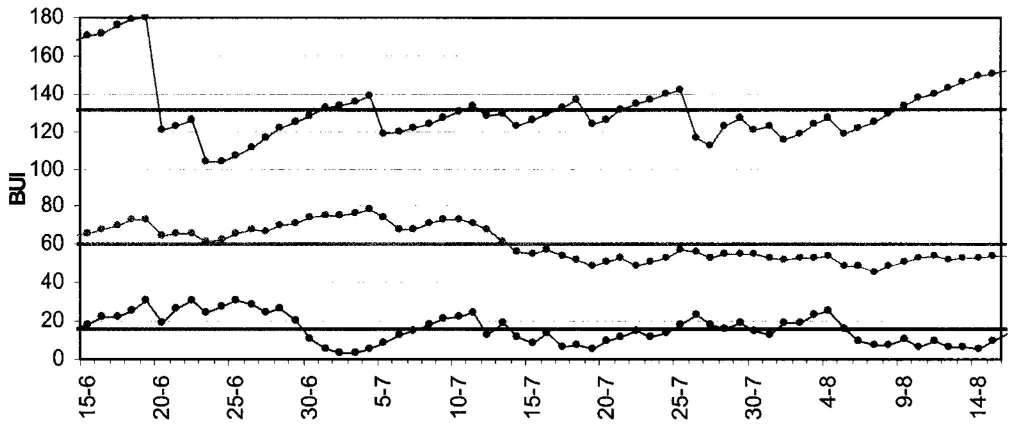


b) Caen Lake Tower

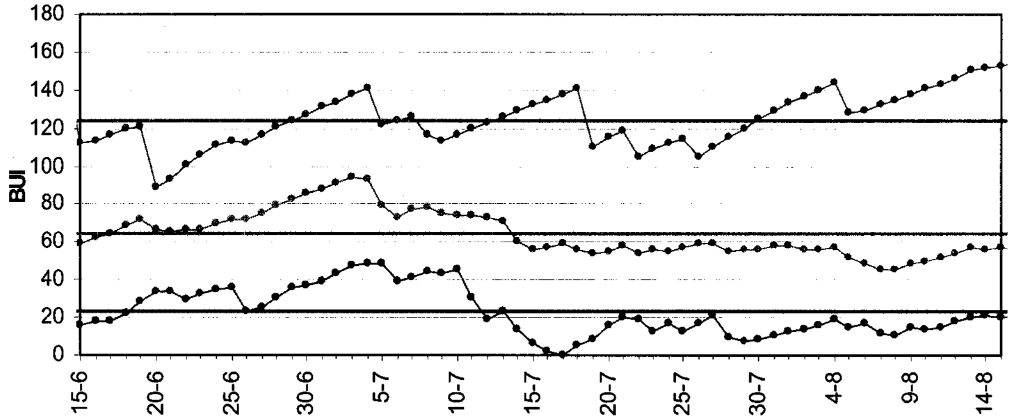


c) Kimble Tower

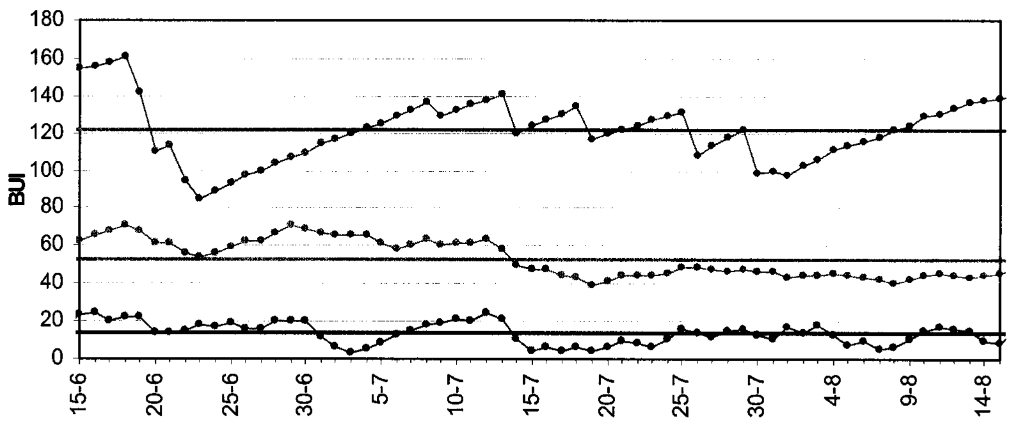
Figure 3-23. Cumulative frequency of the standard daily ISI for the three weather stations.



a) Fort Providence

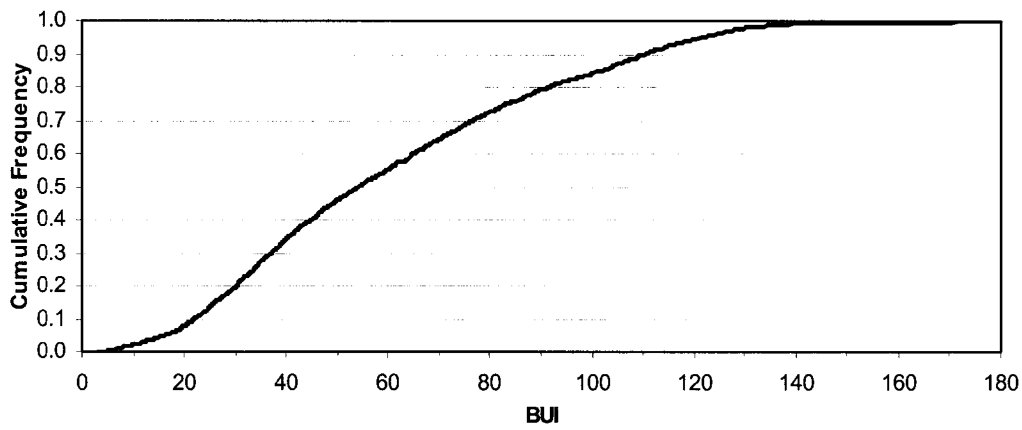


b) Caen Lake Tower

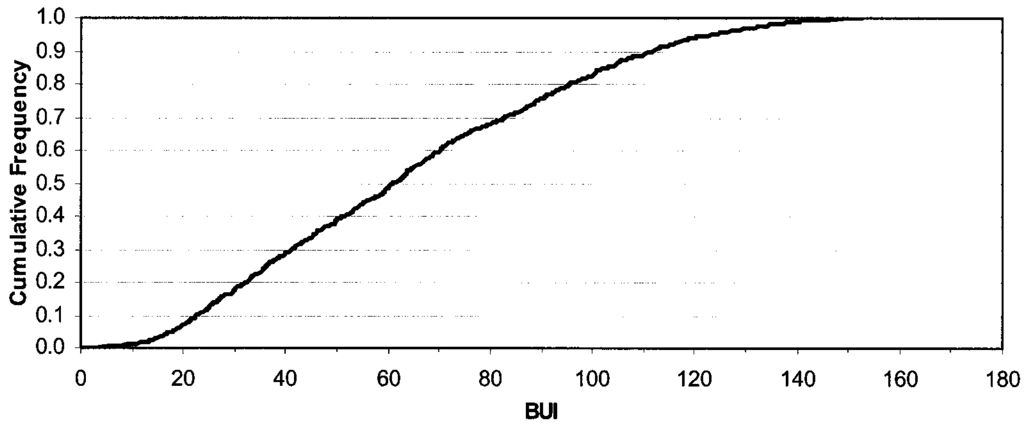


c) Kimble Tower

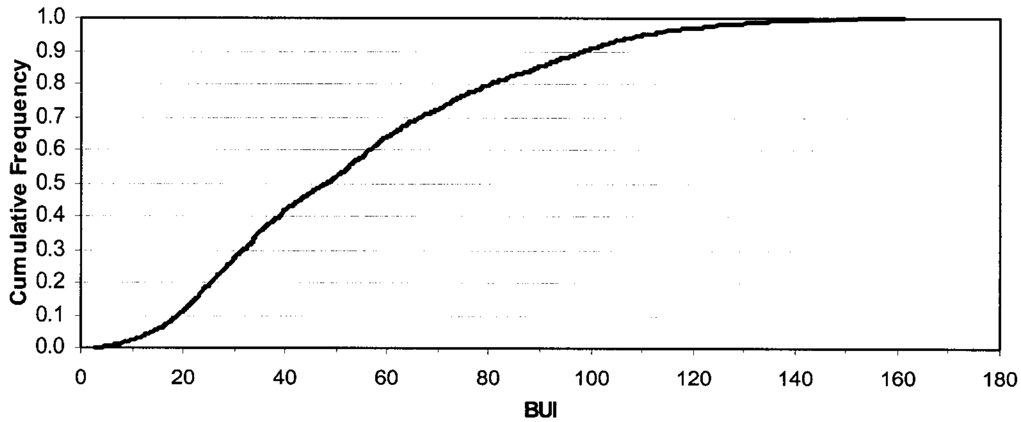
Figure 3-24. Minimum, maximum and average standard daily Buildup Index (BUI) for each day of the peak fire season.



a) Fort Providence

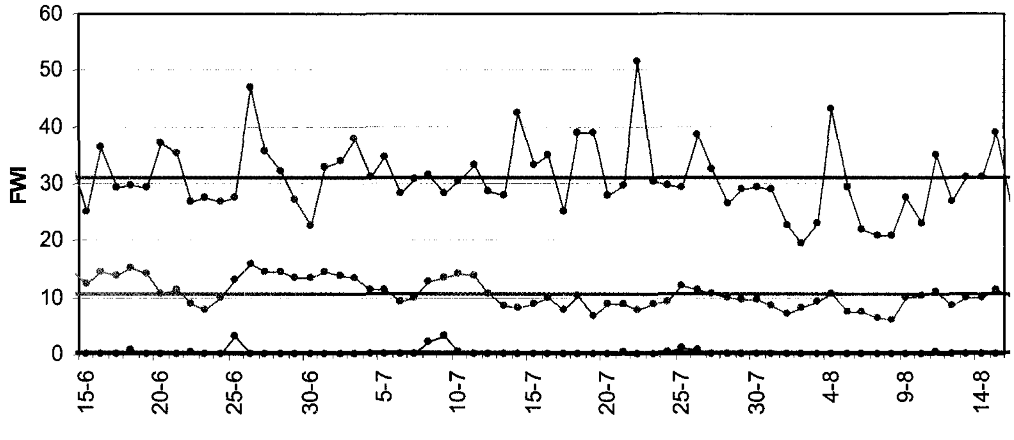


b) Caen Lake Tower

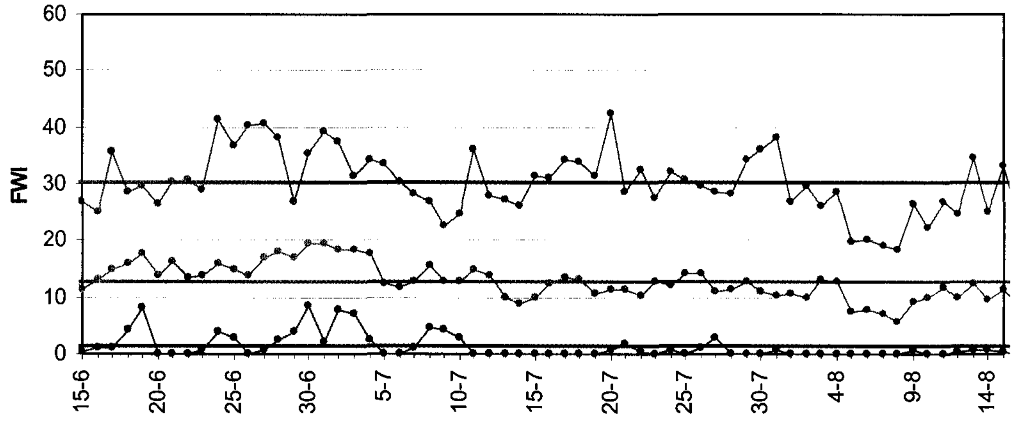


c) Kimble Tower

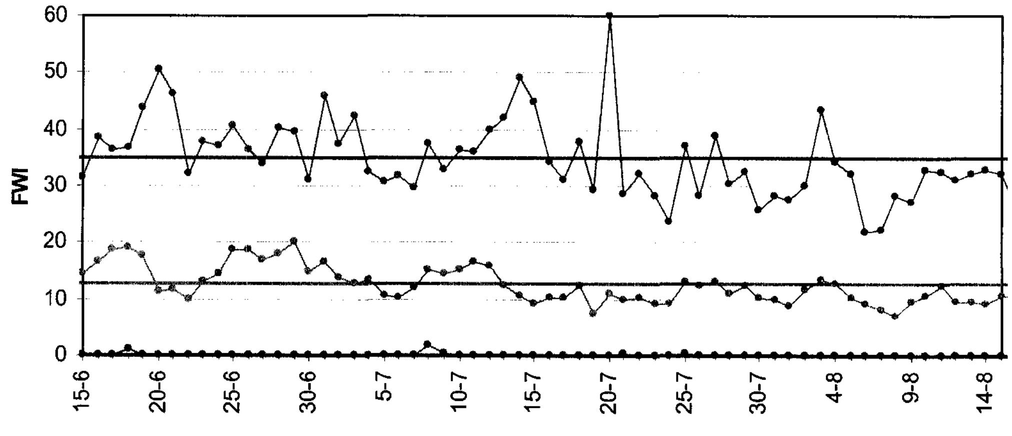
Figure 3-25. Cumulative frequency of the standard daily BUI for the three weather stations.



a) Fort Providence

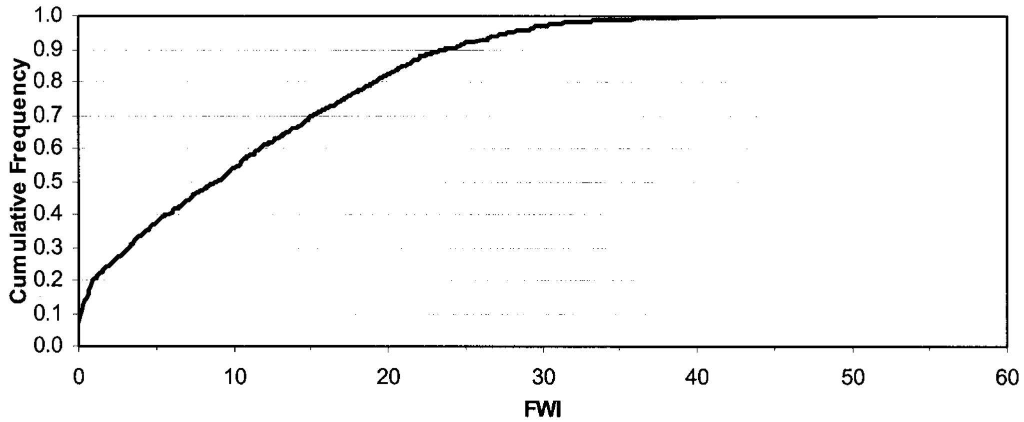


b) Caen Lake Tower

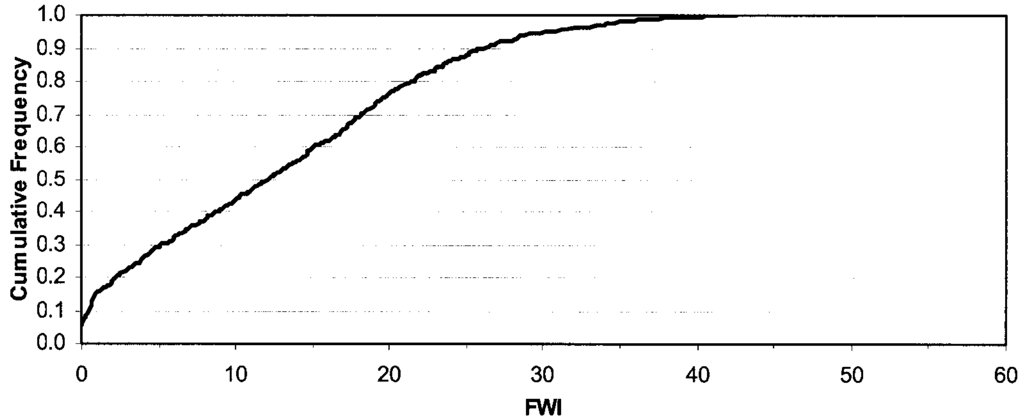


c) Kimble Tower

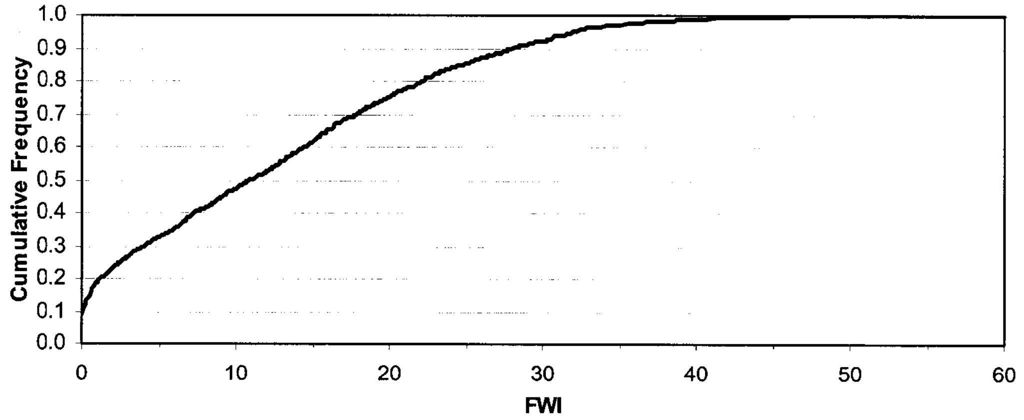
Figure 3-26. Minimum, maximum and average standard daily Fire Weather Index (FWI) for each day of the peak fire season.



a) Fort Providence



b) Caen Lake Tower



c) Kimble Tower

Figure 3-27. Cumulative frequency of the standard daily FWI for the three weather stations.

Table 3-6. Average percentage of days in each class of ISI and BUI for the Fort Providence weather station.

ISI	BUI								Total
	0-20	21-30	31-40	41-60	61-80	81-120	121-160	161-200	
0	4.7	3.1	2.4	2.1	1.1	1.4	0.0	0.0	**14.8**
1	2.5	4.4	3.1	3.8	3.0	1.8	0.0	0.0	**18.5**
2	0.5	1.6	2.8	2.4	1.6	1.4	0.2	0.1	**10.6**
3	0.4	1.0	2.1	2.7	1.8	2.0	0.4	0.1	**10.6**
4	0.1	0.5	1.9	3.6	1.9	2.8	0.8	0.1	**11.6**
5	0.1	0.4	0.8	2.5	2.1	2.7	1.3	0.1	**10.0**
6	0.0	0.5	0.8	1.0	2.1	3.6	0.3	0.1	**8.3**
7	0.0	0.2	0.4	1.0	1.5	2.1	0.9	0.0	**6.2**
8	0.0	0.0	0.0	0.5	0.4	1.4	0.8	0.0	**3.1**
9	0.1	0.0	0.3	0.3	0.7	1.2	0.2	0.0	**2.7**
10	0.0	0.0	0.2	0.1	0.1	0.3	0.0	0.0	**0.7**
11	0.1	0.0	0.0	0.2	0.3	0.3	0.0	0.0	**0.9**
12	0.0	0.0	0.1	0.1	0.0	0.4	0.1	0.0	**0.7**
13	0.0	0.0	0.0	0.0	0.3	0.1	0.0	0.0	**0.4**
14	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.0	**0.3**
15	0.0	0.0	0.0	0.1	0.0	0.1	0.0	0.0	**0.2**
16	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
17	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
18	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	**0.2**
19	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
20	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	**0.1**
21-25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
26-30	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
31-35	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
36-40	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
41-45	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
Total	**8.4**	**11.8**	**14.8**	**20.6**	**17.1**	**21.9**	**5.0**	**0.4**	**100.0**

Table 3-7. Average percentage of days in each class of ISI and BUI for the Caen Tower weather station.

ISI	BUI								Total
	0-20	21-30	31-40	41-60	61-80	81-120	121-160	161-200	
0	3.1	2.4	1.5	1.5	0.7	0.1	0.0	0.0	**9.3**
1	3.1	3.2	2.7	3.5	1.6	1.6	0.1	0.0	**15.9**
2	0.6	2.7	1.5	1.6	2.4	2.7	0.4	0.0	**11.8**
3	0.4	0.9	1.0	1.8	1.0	2.2	0.4	0.0	**7.8**
4	0.1	0.9	1.6	1.8	2.7	2.8	0.6	0.0	**10.5**
5	0.1	0.9	0.1	2.2	3.1	3.5	0.9	0.0	**10.9**
6	0.0	0.1	1.2	2.5	1.9	4.0	1.2	0.0	**10.9**
7	0.0	0.0	0.4	1.9	1.9	2.2	1.0	0.0	**7.5**
8	0.0	0.1	0.3	1.3	1.3	1.9	0.3	0.0	**5.3**
9	0.0	0.0	0.0	0.7	1.3	0.7	0.3	0.0	**3.1**
10	0.0	0.0	0.0	0.1	0.3	1.2	0.0	0.0	**1.6**
11	0.0	0.0	0.1	0.3	0.6	1.0	0.3	0.0	**2.4**
12	0.0	0.0	0.0	0.1	0.1	0.4	0.1	0.0	**0.9**
13	0.0	0.0	0.0	0.1	0.1	0.6	0.0	0.0	**0.9**
14	0.0	0.0	0.0	0.1	0.0	0.6	0.0	0.0	**0.7**
15	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	**0.1**
16	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	**0.1**
17	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
18	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
19	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	**0.1**
20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
21-25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
26-30	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
31-35	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
36-40	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
41-45	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
Total	**7.5**	**11.2**	**10.5**	**19.9**	**19.3**	**25.8**	**5.8**	**0.0**	**100.0**

Table 3-8. Average percentage of days in each class of ISI and BUI for the Kimble Tower weather station.

ISI	BUI								Total
	0-20	21-30	31-40	41-60	61-80	81-120	121-160	161-200	
0	5.8	3.7	1.8	2.4	0.5	0.1	0.0	0.0	14.2
1	2.8	4.2	2.1	2.2	1.1	1.0	0.1	0.0	13.4
2	1.2	2.0	1.4	1.9	1.5	0.7	0.1	0.0	8.7
3	0.6	1.7	1.2	1.5	1.3	1.1	0.2	0.0	7.7
4	0.9	1.4	1.9	1.9	1.5	1.5	0.2	0.0	9.2
5	0.2	0.9	1.1	2.9	1.7	1.5	0.7	0.1	9.3
6	0.1	0.7	0.7	2.1	1.5	1.5	0.4	0.0	7.1
7	0.2	0.6	1.0	1.2	1.5	1.6	0.6	0.0	6.7
8	0.2	0.3	1.1	1.3	1.2	1.5	0.0	0.0	5.7
9	0.1	0.1	0.7	1.2	1.0	1.7	0.5	0.0	5.2
10	0.0	0.2	0.2	0.7	0.7	1.3	0.0	0.0	3.3
11	0.0	0.1	0.3	0.5	0.4	0.7	0.1	0.0	2.1
12	0.0	0.2	0.2	0.4	0.8	0.6	0.0	0.0	2.1
13	0.0	0.0	0.0	0.3	0.2	0.6	0.0	0.0	1.1
14	0.0	0.0	0.1	0.2	0.2	0.3	0.0	0.0	0.7
15	0.0	0.1	0.1	0.4	0.4	0.7	0.0	0.0	1.6
16	0.0	0.0	0.1	0.0	0.0	0.2	0.0	0.0	0.2
17	0.0	0.0	0.2	0.1	0.1	0.1	0.0	0.0	0.4
18	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.2
19	0.0	0.1	0.0	0.0	0.0	0.3	0.0	0.0	0.4
20	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.2
21-25	0.0	0.1	0.0	0.2	0.1	0.0	0.0	0.0	0.3
26-30	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
31-35	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1
36-40	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
41-45	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	12.0	16.3	14.2	21.7	15.9	17.0	2.9	0.1	100.0

Table 3-9. Percentage of days in each fire intensity class for the main Fire Behavior Prediction (FBP) system conifer fuel types in the study area. Fuel types are from Taylor *et al.* (1997). Based on weather data over several years (see Table 3-1).

Fuel Type	Weather Station	Fire Intensity Class						Total
		1	2	3	4	5	6	
C-1	Fort Providence	44.4	46.3	6.6	1.5	0.9	0.3	100.0
	Caen Tower	37.5	47.2	10.0	3.4	1.8	0.1	100.0
	Kimble Tower	36.9	39.6	14.1	4.5	4.0	1.0	100.0
C-2	Fort Providence	14.8	19.5	18.8	14.7	21.0	11.2	100.0
	Caen Tower	9.3	18.1	17.0	12.4	26.1	17.1	100.0
	Kimble Tower	14.2	17.7	15.2	12.6	20.3	20.1	100.0
C-3	Fort Providence	36.0	35.1	18.4	5.6	4.1	0.8	100.0
	Caen Tower	29.1	31.0	25.5	7.4	5.0	2.1	100.0
	Kimble Tower	32.4	30.0	20.1	7.2	6.9	3.5	100.0
C-4	Fort Providence	17.2	21.5	22.0	7.5	20.6	11.1	100.0
	Caen Tower	12.4	18.3	18.1	8.4	25.8	17.0	100.0
	Kimble Tower	17.0	19.4	17.5	7.2	19.7	19.3	100.0

Table 3-10. Percentage of days in each probability of sustained ignition class for the S1.1 and S1.2 forest-types (Lawson and Dalrymple 1996). Based on weather data over several years (see Table 3-1).

Forest Type	Weather Station	Probability of sustained ignition class			Total
		Low	Medium	High	
S1.1	Fort Providence	53.2	26.3	20.6	100.0
	Caen Tower	43.8	25.8	30.4	100.0
	Kimble Tower	42.4	21.0	36.7	100.0
S1.2	Fort Providence	63.2	24.6	12.2	100.0
	Caen Tower	52.7	29.4	18.0	100.0
	Kimble Tower	53.6	23.0	23.4	100.0

Table 3-11. Average percentage of days in each class of FFMC, DMC or BUI, and FWI for the Fort Providence weather station. FWI classes are the standard classes used in the NWT (see Stocks *et al.* 1989). The cells with a black border are those representing the combinations for the four fire danger scenarios identified this project.

FFMC	DMC 0-20	DMC 21-40	DMC 41-60	DMC 61-80	DMC 81-100	DMC 101-120	DMC 121-140	DMC 141-160
0-76	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0.0	0.0
76	[illegible]	[illegible]	0.1	0.0	0.0	0.0	0.0	0.0
77	[illegible]	[illegible]	0.2	0.3	0.0	0.0	0.0	0.0
78	[illegible]	0.8	0.3	0.1	0.0	0.0	0.0	0.0
79	[illegible]	0.4	0.4	0.1	0.0	0.0	0.0	0.0
80	[illegible]	0.4	0.7	0.3	0.0	0.0	0.0	0.0
81	[illegible]	0.8	0.4	0.1	0.0	0.0	0.0	0.0
82	[illegible]	0.5	0.0	0.1	0.1	0.1	0.0	0.1
83	1.7	1.7	0.6	0.2	0.0	0.0	0.0	0.0
84	0.8	1.3	0.7	0.2	0.2	0.0	0.0	0.0
85	1.5	1.5	1.1	0.4	0.1	0.0	0.0	0.0
86	0.5	2.5	1.0	0.8	0.4	0.2	0.0	0.1
87	0.6	4.4	2.2	1.1	0.8	0.2	0.0	0.1
88	0.8	1.8	2.2	1.7				
89	0.6	2.7	2.6	2.0				
90	0.1	2.2	1.1	1.9				
91	0.3	0.9						
92	0.1	0.3						
93	0.0							
94	0.0							
95								
97								

FFMC	BUI 0-20	BUI 21-30	BUI 31-40	BUI 41-60	BUI 61-80	BUI 81-120	BUI 121-160	BUI 161-200
0-76	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
76	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
77	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.3	0.0	0.0
78	[illegible]	[illegible]	[illegible]	0.7	0.2	0.2	0.0	0.0
79	[illegible]	[illegible]	[illegible]	0.3	0.3	0.2	0.0	0.0
80	[illegible]	[illegible]	[illegible]	0.3	0.4	0.4	0.1	0.0
81	[illegible]	[illegible]	0.5	0.5	0.4	0.2	0.0	0.0
82	[illegible]	[illegible]	0.0	0.2	0.1	0.2	0.1	0.1
83	[illegible]	0.6	1.3	1.2	0.6	0.3	0.0	0.0
84	[illegible]	0.3	0.6	0.8	0.7	0.3	0.2	0.0
85	0.1	1.0	1.2	0.5	0.8	1.1	0.0	0.0
86	0.0	0.3	0.7	1.8	1.0	1.3	0.5	0.1
87	0.3	0.3	1.2	2.8	2.0	2.0	0.7	0.1
88	0.0	0.3	1.0	1.1	1.4	2.9		
89	0.0	0.1	1.1	1.9	2.0	2.9		
90	0.0	0.1	0.1	1.8	1.2	2.6		
91	0.0	0.1	0.2	0.7				
92	0.0	0.0	0.1	0.1				
93	0.0	0.0						
94								
95								
97								

FWI classes: [illegible] Moderate High Very High

Table 3-12. Average percentage of days in each class of FFMC, DMC or BUI, and FWI for the Caen Tower weather station. FWI classes are the standard classes used in the NWT (see Stocks *et al.* 1989). The cells with a black border are those representing the combinations for the four fire danger scenarios identified this project.

FFMC	DMC 0-20	DMC 21-40	DMC 41-60	DMC 61-80	DMC 81-100	DMC 101-120	DMC 121-140	DMC 141-160
0-76					0.1	0.0	0.0	0.0
76				0.0	0.0	0.0	0.0	0.0
77		0.1	1.0	0.1	0.0	0.0	0.0	0.0
78		0.6	0.1	0.0	0.1	0.0	0.0	0.0
79		0.7	0.3	0.6	0.0	0.0	0.0	0.0
80	1.0	0.9	0.1	0.1	0.1	0.0	0.0	0.0
81	1.0	0.4	0.0	0.9	0.3	0.0	0.0	0.0
82	0.7	0.7	0.4	0.3	0.3	0.0	0.0	
83	1.0	1.5	0.6	0.3	0.0	0.4	0.0	
84	0.4	0.3	0.3	0.6	0.1	0.0		
85	1.5	2.4	1.0	0.7	0.4	0.0		
86	0.6	1.3	0.7	0.6	0.4			
87	0.7	3.2	3.4	2.9	0.6			
88	1.0	2.4	3.1	1.8	0.9			
89	0.0	2.7	2.8					
90	0.0	3.2	2.1					
91	0.0	1.0	0.9					
92	0.0	0.7	1.5					
93	0.0	0.3						
94	0.0	0.0						
95	0.0							
96								
97								

FFMC	BUI 0-20	BUI 21-30	BUI 31-40	BUI 41-60	BUI 61-80	BUI 81-120	BUI 121-160	BUI 161-200
0-76	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.9	0.1	0.0
76	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0.0	0.0	0.0
77	[illegible]	[illegible]	[illegible]	0.1	0.6	0.6	0.0	0.0
78	[illegible]	[illegible]	[illegible]	0.3	0.0	0.3	0.0	0.0
79	[illegible]	[illegible]	[illegible]	0.3	0.3	0.7	0.0	0.0
80	[illegible]	0.4	0.6	0.1	0.4	0.8	0.1	0.0
81	[illegible]	0.9	0.1	0.1	0.1	1.0	0.1	0.0
82	0.0	0.6	0.1	0.6	0.6	0.3	0.3	0.0
83	0.0	0.9	0.6	0.9	0.4	0.7	0.3	0.0
84	0.0	0.1	0.3	0.3	0.1	0.9	0.0	0.0
85	0.4	0.4	1.2	1.6	0.7	1.2	0.4	0.0
86	0.0	0.1	0.6	0.7	1.0	0.9	0.3	0.0
87	0.1	0.6	0.7	1.9	3.2	3.7	0.6	
88	0.0	0.6	0.9	1.5	2.5	2.7	1.2	
89	0.0	0.0	0.3	2.2	1.6	4.1		
90	0.0	0.0	0.1	2.7	2.1	1.5		
91	0.0	0.0	0.0	0.7	1.2			
92	0.0	0.0	0.0	0.4	1.0			
93	0.0	0.0	0.1					
94	0.0	0.0	0.0					
95	0.0							
96								
97								

FWI classes: Moderate, High, Very High

Table 3-13. Average percentage of days in each class of FFMC, DMC or BUI, and FWI for the Kimble Tower weather station. FWI classes are the standard classes used in the NWT (see Stocks *et al.* 1989). The cells with a black border are those representing the combinations for the four fire danger scenarios identified this project.

FFMC	DMC 0-20	21-40	41-60	61-80	81-100	101-120	121-140	141-160
0-76	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0.0
76	[illegible]	[illegible]	0.2	0.0	0.0	0.0	0.0	0.0
77	[illegible]	0.6	0.2	0.2	0.1	0.0	0.0	0.0
78	[illegible]	0.3	0.0	0.1	0.1	0.0	0.0	0.0
79	1.1	0.2	0.2	0.1	0.0	0.0	0.1	0.0
80	0.4	0.7	0.3	0.1	0.0	0.0	0.0	0.0
81	0.9	1.0	0.2	0.1	0.0	0.0	0.0	0.0
82	0.9	0.2	0.5	0.1	0.1	0.0	0.0	0.0
83	0.9	0.7	0.3	0.1	0.1	0.0	0.0	0.0
84	1.6	1.4	0.3	0.1	0.1	0.0	0.0	0.0
85	1.3	1.1	1.2	0.4	0.1	0.1	0.1	
86	1.5	2.2	0.7	1.0	0.4	0.0	0.1	
87	1.4	3.4	1.5	1.1	0.2			
88	1.1	2.8	2.0	1.5				
89	1.2	3.0	2.6	1.1				
90	0.8	2.5	1.9					
91	0.2	2.2	1.6					
92	0.2	1.6						
93	0.1							
94								
95								
96								
97								

FFMC	BUI 0-20	21-30	31-40	41-60	61-80	81-120	121-160	161-200
0-76	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0
76	[illegible]	[illegible]	[illegible]	0.0	0.1	0.1	0.0	0.0
77	[illegible]	[illegible]	0.6	0.2	0.2	0.3	0.0	0.0
78	[illegible]	[illegible]	0.2	0.1	0.1	0.2	0.0	0.0
79	[illegible]	[illegible]	0.4	0.1	0.2	0.1	0.1	0.0
80	[illegible]	[illegible]	0.2	0.6	0.3	0.1	0.0	0.0
81	0.3	0.6	0.4	0.6	0.1	0.2	0.0	0.0
82	0.3	0.6	0.0	0.2	0.4	0.2	0.0	0.0
83	0.3	0.5	0.2	0.4	0.3	0.2	0.1	0.0
84	0.2	1.1	0.6	0.9	0.4	0.2	0.1	0.0
85	0.2	0.7	0.7	0.7	1.3	0.5	0.2	0.0
86	0.1	0.9	1.0	1.5	1.0	1.1	0.4	0.0
87	0.3	0.6	1.4	2.3	1.5	1.5	0.1	
88	0.2	0.6	1.2	2.0	1.5	2.0	0.5	
89	0.0	0.8	1.2	2.1	2.3			
90	0.1	0.4	1.0					
91	0.0	0.2	0.3					
92	0.0							
93	0.0							
94	0.0							
95								
96								
97								

FWI classes: [illegible] Moderate High Very High [illegible]

Table 3-14. FWI System components for the four scenarios selected.

Scenario	FFMC	DMC	DC	ISI	BUI	FWI
"Moist"	83	20	142	4	30	9
"Moderate"	87	39	325	8	60	20
"Dry"	92	93	492	16	127	46
"Extreme"	95	160	514	24	180	66

Table 3-15. Percentage of days during the peak fire season of the years analysed with higher values for combinations of FFMC and DMC or BUI than each of the scenarios (weather-related burning conditions) (based on Tables 3-11 to 3-13).

Weather Station	"Moist"		"Moderate"		"Dry"		"Extreme"	
	DMC	BUI	DMC	BUI	DMC	BUI	DMC	BUI
Fort Providence	56.9	57.3	34.2	33.5	0.6	0.3	0.0	0.0
Caen Lake Tow er	60.9	60.5	41.6	41.2	0.0	0.0	0.0	0.0
Kimble Tow er	60.4	59.3	37.0	33.8	0.3	0.0	0.0	0.0

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CHAPTER 4

Experimental reburns after high intensity crown fires in jack pine/black spruce stands, Northwest Territories (Canada)

INTRODUCTION

Commenting on the variation in flammability with time since the last fire, Heinselman (1981, pg. 399) stated that "nobody doubts that there is at least a short period after a major fire when the probability of a reburn is reduced. But is that period only a few years, or is there a continuing increase in probability for ignition, intensity and size?" The potential of recently burnt areas to impede the spread of a fire or to act as a fuelbreak is however somewhat controversial. It is possible to find publications in the literature that support both the view that such areas are a barrier to fire progression or that reburns are possible very soon after a fire.

For example, Philpot (1974, 1977) observed, by analysing the fire history on chaparral lands, that large fires occur almost exclusively in the older fuels (more than 15 to 17 years) in the San Bernardino and Angeles National Forests in southern California, and that fires stopped at age-class boundaries. Also in chaparral, Minnich and Chou (1997) noted that fires died out quickly after entering recent burns with few cases of major overlap between two fires before 20 years. Most of the burned stands in their study were older than 40-50 years. However, Keeley *et al.* (1999) found that large catastrophic fires are not dependant on old classes in California shrublands, which contradicts previous findings that stands less than 20 years of age prevent fire spread.

Still in California, Salazar and Gonzàlez-Cabàn (1987) reported that several recently burned areas (ranging from 1971 to 1984) affected the perimeter of the 1985 Wheeler Fire (chaparral was the predominant vegetation type in the fire area) on the Los Padres National Forest and suggested that recently burned areas with discontinuous fuels do not burn successfully. In Yellowstone National Park, Despain and Sellers (1977) observed that a "young" lodgepole pine stand (97-year-old) appeared to retard fire spread despite numerous fire brands received from the smoke column during the 1976 fire season. They noted that the two major differences between that area and the adjacent Engelman spruce-subalpine fir stand in which a spectacular crowning run was observed some time earlier were species and age. In the same park, Sweaney (1985) reported several instances of fires being retarded or stopped by old burns (ranging from a sapling-sized lodgepole pine stand to a 1879 burn), during the intense fire season of 1979 and 1981, and concluded that old burns played a role in limiting the size of subsequent fires. It may seem that a long time has elapsed since the previous fire in those areas of Yellowstone National Park that stopped or retarded fire spread, but Romme (1982) observed that the development of the fuel complex in the park appears to occur more slowly than in some other areas.

In the coniferous forest of the Pacific Northwest, Franklin and Hemstrom (1981) reported that there exist numerous examples of reburns that suggest an increased susceptibility of young stands 25-75 to burning compared to older forest stages. Also in the Pacific Northwest, Agee and Huff (1987) found that mature patches served as a better buffer against fire than very young or very old natural stands in western hemlock-Douglas-fir forests.

In the boreal forest, the fire history data collected by Niklasson and Granström (2000) suggested that recent burns up to 15-20 years have acted as fire breaks in their study area located in Sweden. This is in accordance to observations made in the field and on fire history maps (e.g., the 1995 Horn Plateau Fire (NWT) (Marty Alexander, personal communication), Amiro *et al.* 2001) where many fires stop their progression when they reach a recently burnt area in the Canadian boreal forest. In fact, Alexander and Quintilio (1990) commented that the use of unburned areas within the perimeter of recent wildfires should be considered in the selection of sites for experimental fires. Although stand age was identified as a key determinant in the incidence of forest fires in the

Northwest Territories (Ward and Mawdsley 2000), reburns were also reported in that area (e.g., Rouse 1976) and in the Canadian boreal forest in general (e.g., Kiil 1975; Foster 1983). Often, but not always, reburns were confined to a strip along the edge of a recent burn. These instances are very seldom documented thoroughly, which makes it very difficult to find common denominators among them.

In commenting on the reliability of younger stands to act as firebreaks, Heinselman (1985) observed that local conditions vary. According to him, we usually cannot rely on them in the boreal forest and the Pacific Coast Douglas-fir forests, while we can sometimes rely on younger stands to act as fire breaks in the Great Lakes and Acadian forests, and in the Rocky Mountain region. That variation mentioned by Henselman (1985) and noted in the different studies reported above may indicate that there is not a universal answer to the question, probably due to the fact that vegetation response to a fire varies widely both among ecosystems and landscapes, but also from location to location, and fire to fire (Chirstensen 1993).

Nevertheless it seems safe to assume that when a reburn occurs, the time elapsed since the last fire has allowed sufficient fuel accumulation since the disturbance, resulting in the right characteristics for a reburn. The key to answering the reburn question may therefore be a forest type approach, where the description of the fuels through time, linked with experimental reburns and knowledge of the past fire history, would provide much needed knowledge for fire management activities. As part of a larger project looking at the flammability of jack pine (*Pinus banksiana* Lamb.) stands having a black spruce (*Picea mariana* (Mills.) B.S.P.) understory, we took advantage of the opportunity provided by the International Crown Fire Modelling Experiment (ICFME)[1] in Fort Providence, Northwest Territories (Canada), to investigate the flammability of recently burned stands (up to 4 years since fire) and their potential for reburn during the first few years following high-intensity crown fire.

Most of the ICFME plots in which the reburns were attempted were also part of the chronosequence we used to determine the temporal variation in stand structure and fuel characteristics of jack pine/black spruce stands with time since fire (see Chapter 2).

METHODOLOGY

Study Area

Located in the Northwest Territories (Canada) at N 61° 36', W 117° 12', the study area for this project was a portion of the site (Figure 4-1) used for the International Crown Fire Modelling Experiment (ICFME) (Alexander *et al.* 1998). Before it was altered for the ICFME project, the area was a large jack pine (*Pinus banksiana*) stand having a black spruce (*Picea mariana*) understory. After an initial assessment, plots were located within the continuous stand and 50-m fireguards were built around them in preparation for the experimental fires (Stocks *et al.* 2004a). During the summers of 1997-2000 several plots were burnt for the ICFME project and some regeneration was often observed as early as a few weeks after the high intensity crown fires (usually undertaken at the end of June or the beginning of July). It is in five of the plots burnt in 1997, 1998, or 1999 that the data for the project described in this paper were collected (i.e., ICFME plots 5, 6, 8, 9, and A). The fire behavior and the fuel quantification for the (parent) mature stand in those plots are presented elsewhere (Stocks *et al.* 2004a; Alexander *et al.* 2004) but the FWI System components for those days, and their percentile from the analyses performed on the fire weather data of Caen Lake Tower (see Chapter 3), are presented in Table 4-1.

The present investigation was carried out over two consecutive summers: 2000 and 2001. To facilitate an understanding of the procedure used and of the results obtained in each case, they are

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[1] The author was a participant in the various phases of the International Crown Fire Modelling Experiment from 1998 to 2001, working with the Canadian Forest Service fire research team on fire environment and fire behavior documentation of these experimental fires.

presented separately in the following sections. However, the discussion and the conclusion cover the results obtained for the study as a whole.

In the following, the term "plot" will refer to the ICFME plots (see Figure 4-1) within which the reburn experiments were done. The term "subplot" will refer to an area 30 x 30 m located within one of the ICFME plots, while the term "microplot" will refer to an area 2 x 2 m located within one of the ICFME plots. We used three subplots in this study, each located in a different ICFME plot. We identified each subplot with the number of the corresponding ICFME plot (e.g., subplot 6 was located in ICFME plot 6). For the microplots, since several were located in given ICFME plots, we named them with a number where the first digit was an indication of the ICFME plot while the second digit identified the microplot number within that ICFME plot (e.g., microplot 6-3 is microplot number 3 in ICFME plot 6).

Methodology - 2000

In June 2000, a 30 x 30 m subplot was located in Plot 6 (burnt in 1997), Plot 8 (burnt in 1998), and Plot 9 (burnt in 1999) at the ICFME site (Figure 4-1). The location of the subplots was based on their representativeness of the entire plot and on the dominant wind direction in the area. Each subplot was located at one corner of the larger ICFME plot to facilitate access and to offer options for ignition under different or variable wind directions. A complete inventory of the fuels was not necessary for this specific project since Plots 6, 8, and 9 had recently been inventoried (see Chapter 2). An intensive sampling of the surface fuels was nevertheless done within each subplot.

A grid (Figure 4-2) was first established within each 30 x 30 m subplot. Pins were located 5 m apart, starting 2.5 m from the plot edge to ensure that the ignition procedure did not affect the fuels in the subplot and, consequently, the fire behavior. Those pins were used to mark the position of sampling points and to serve as references in the documentation of the fire growth following ignition.

At nine of the pins, we measured the dead and down woody fuels along a 10-m randomly oriented line using the line intersect method (Brown 1974; McRae *et al.* 1979; Van Wagner 1982). The decision to use a random orientation of the lines was made to avoid any orientation bias caused by windfall of the snags left after the crown fire, a condition often observed in the early years after a fire. A "go-no-go" gauge (McRae *et al.* 1979) was used to tally the pieces of wood less than 7.0 cm in diameter intersecting the line and to attribute them to one of the roundwood diameter size classes used by the Canadian Forest Service (i.e., 0.0-0.5, 0.6-1.0, 1.1-3.0, 3.1-5.0, and 5.1-7.0 cm), whereas a caliper was used to measure the diameter of the larger pieces of wood. The procedure allowed us to calculate the fuel load of these fuels per size class using the constants and formulas derived by Bown (1974), Delisle and Woodard (1988), and Nalder *et al.* (1997, 1999), the sampling in the latter having been done in part in the general ICFME study area.

Due to the very limited extent of the area that was actually affected by the reburns in each subplot, we were able to sample the vegetation after the fire at the same nine pins (the fire did not reach them) to obtain its fuel load. This procedure provided a better assessment of the surface vegetation fuel loads than was originally planned, since we were to sample outside the grid area in order to keep the fuels intended for the experiment undisturbed (Alexander and Quintilio 1990). We harvested all the vegetation in a 1 x 1 m square located at each of the nine pins, bagged it and weighed it in the field, and brought it back to the laboratory to be oven-dried at 85°C until a constant weight was reached. The procedure also allowed us to obtain the fuel loads (dry weight basis) and to calculate the percent moisture content of the live fuels in each subplot.

The fuel moisture content of the dead fuels was measured immediately before the reburns by collecting in separate containers a sample of the different categories of fuels present in each subplot (except for dead grass which was only present in Plot 6). The containers were sealed in the field and brought back to the laboratory where they were weighed (fresh), oven-dried, and weighed (dry) again to obtain the percent moisture content (dry weight basis).

Two types of ignition were used in each subplot: a line and a point ignition (Alexander *et al.* 1991). To perform the line ignitions we used a truck-mounted flame-thrower (Bradshaw and Tour 1993) (Figure 4-3), commonly referred to as a "terra-torch", and followed the same procedure as the one used to ignite the experimental crown fires in the ICFME project (Stocks *et al.* 2004a). The line ignitions for the three reburns, performed during the peak burning period, were completed just a few minutes apart (the time for the truck to travel from one plot to the other). These quasi-simultaneous ignitions allowed for the observation of the 3 fires under the same weather conditions. The point ignition was performed, in a representative area located 20 m outside each subplot (but within the same ICFME plot), immediately after the line ignition was completed. Diesel fuel was poured in a hole (10 cm diameter) made in the duff and a wooden match was used to ignite the fire.

At least three observers were present at each site during the fires. Their task was to document the behavior of the fire by: 1) making written notes on the fire behavior (e.g., vigour or character of flames, rate of spread, type of material burning, etc.), 2) taking still photos of the fires, and 3) capturing the event on videotape. During the fire, the observer taking notes had a map of the gridded plot area and was required, at 5 minutes interval, to draw the progression of the fire perimeter. If the fire had not advanced appreciably, the person just noted this fact and deferred any mapping until the next time interval. After 1 hour, an observer also had to put pins around the perimeter of the point ignition fire (i.e., at the head, flanks, and back), and complete a sketch of the fire growth.

Our rule was to cease active documentation when no noticeable changes in fire behavior could be detected or presumed to occur anymore after at least one hour of observation. Following this initial period of observation, no mop-up fire suppression activity was undertaken in the plots. However, one observer remained on site to monitor fire activity in the three plots for a few more hours.

A weather station located on site provided the weather observations before and during the fires, as well as the inputs used in the calculation of the Canadian Forest Fire Weather Index (FWI) System components (Van Wagner 1987). During the experimental fires, fire weather observations (i.e., temperature, relative humidity, and 10-m open wind speed and direction) were recorded at 1-minute intervals.

Methodology - 2001

As a result of the observations made the previous year, and considering the general patchy pattern of revegetation in the recently burned ICFME plots, the decision was made to downscale the experimental observations to 4-m^2 microplots for the June 2001 portion of the project.

Microplots have been used successfully in several fire studies. For example, Brown (1972) used microplots 8 by 30 feet (2.4 x 9.1 m) in tests to determine the accuracy of Rothermel's (1972) rate of fire spread model in slash fuels. Agee *et al.* (1978) investigated the quantity of fuel buildup and fuel reduction by fire in 6-m^2 microplots located in Sierra Nevada conifer stands. Simard *et al.* (1984) used 9-m^2 plots to measure the variation in rate of spread of an experimental fire. Ryan and Noste (1985) located 0.25-m^2 microplots, along a transect, to rate the severity of prescribed fires (and one wildfire). Hawkes (1986) used a microplot approach in a study looking at the effect of prescribed fire on short- and long-term tree growth and nutrient. The distribution of fire impact (slash and forest floor consumption) was assessed in approximately 7-m^2 microplots, and results were compared with the "large plot" approach. Smith *et al.* (1993) used 0.75 m^2 microplots to measure pre-burn descriptors and fire behavior in two deciduous stands. McAlpine (1995) tested if fuel consumption can influence the rate of spread of a fire in 3.0 x 3.0 m microplots burned with a variety of fuel loadings. Wotton *et al.* (1999) used simultaneous fires in plots with widths ranging between 0.5 m and 10.0 m to determine the effect of fire front width on surface fire spread rates. Schimmel and Granström (1996) studied plant survival and colonisation over a gradient of fire severity in 2-m^2 plots. Finally, Fernandes *et al.* (2000) used 1-m^2 microplots located in homogeneous vegetation to verify if microplot sampling scheme could be applied to empirical fire behavior modelling in shrubland vegetation.

The reburn in subplot 6 being the only one which showed any signs of sustained fire activity in 2000 (although admittedly limited, see "Results 2000" section, below), we located the microplots exclusively in the three ICFME plots burnt in 1997 (i.e., four years since the last fire): Plot A, Plot 5, and Plot 6 (Figure 4-1). The placement of the microplots was selected according to the pattern of vegetation development in each stand (see below). The rationale behind this procedure was that the limitation to fire propagation observed in the previous year may have been caused by the patchy nature of the vegetation reinvading each site and the unsuitability of the remaining compacted forest floor layer, the principal fuel connecting dead and down woody debris and vegetation, to carry the fire. By burning simultaneously: 1) areas that were largely covered by one patch of vegetation (often dominated by one species), 2) areas composed of an amalgam of the surface vegetation and fuel conditions present in each plot (and thus representing at a smaller scale the larger plot), and 3) areas located in a mature stand, we hoped to verify that hypothesis. This is in accordance with Fernandes *et al.* (2000) who suggested that studies using microplots to quantify the influence of fuel characteristics on fire behavior would presumably obtain the best results by locating the microplots in patches of individual species in areas where the spatial distribution of the fuels is not homogenous.

Considering the fuel type involved and the objective of the experiment (as per Fernandes *et al.* 2000), we selected a size of 2 x 2 m for the microplots. The area thus covered was generally small enough to keep the vegetative cover homogenous in the different patches of vegetation in recently burnt areas, but large enough to have microplots representative of the general conditions of the stands. Microplots were therefore established in areas mainly covered by low shrubs, carpets of twin-flower (*Linnaea borealis*), or grass (approximately 50% cured). These were the main components of the patches of vegetation reinvading the plots. Several microplots were also located in areas covered by a mixture of duff plus herbs, shrubs, grass and seedlings which were representative of the common conditions in the 30 x 30m subplot burnt the previous year in Plot 6. Finally, microplots were set up in an adjacent unburned section of the mature ICFME forest. The microplots were oriented in two pre-determined (North-South or Northeast-Southwest) orientations. This setting provided more flexibility for burning with respect to likely wind directions when conditions became suitable for burning.

Due to the localised nature of this part of the project, only the fuel load of the ground vegetation was sampled. Dead and downed woody debris were almost absent from the microplots and those few pieces that were present were considered too large to effectively contribute to the fire's spread. Data on the depth and bulk density of the continuous duff layer were already available for all the stands (except Plot A) (Chapter 2, Tables 2-3 and 2-5).

The original plan to sample the vegetation in areas adjoining each microplot (Smith *et al.* 1993) was abandoned due to the fire behavior experienced during the reburns (the fire failed to spread through the microplots (see "Results 2001" section, below)). The vegetation inside the microplots (2 x 2 m) was therefore harvested after the experimental fires, bagged, and oven-dried to obtain its exact fuel load. The only deviation to this procedure was for the microplots located in the mature stand. One randomly located 2x2 m plot was harvested in the vicinity of the microplots that were burnt. The vegetation was bagged and oven-dried to obtain the fuel load.

For each experimental fire event, we burnt one microplot located in the mature stand simultaneously with 1 or 2 microplot(s) located in a recently burnt area resulting from the previous ICFME experimental fires carried out in 1997. Before each fire event, we determined the moisture content of selected fuel components in the mature stand and in the previously burned ICFME plot areas following the method used the previous summer. We also measured the moisture content of American fuel moisture indicator sticks (Nelson 2000) located at the entrance of the ICFME site. The line ignitions were performed using a hand-held drip torch (Bradshaw and Tour 1993) along the windward edge of the plot (Figure 4-4). Coordination between the main study area weather station and the different burning sites was performed with the use of hand-held radios. At least three observers were present at each site to observe and document the fire behavior (i.e., take notes, still photographs and/or video).

An electronic fire weather station located on site provided the observations before and during the fires, as well as the FWI System components (Van Wagner 1987). Fire weather observations (i.e., temperature, relative humidity and 10-m open wind speed) were made every 10 minutes as part of the fire behavior documentation process.

RESULTS [2]

Results - 2000

Fuel Sampling

This investigation was undertaken only a few years (1, 2, or 3 years) after a high intensity, stand-replacing, crown fire. In each of the three subplots, the fuels present were mainly ground and surface fuels. Most of the readily available crown and ladder fuels (i.e., foliage, twigs, bark flakes) had been removed as a result of the experimental burning that had taken place and thus only the snags remained (Figure 4-5, a-c).

The surface fuels were composed, in part, of dead and downed woody material of various sizes. Overall, very few twigs and small pieces of wood were present on the forest floor. The average fuel load of the dead and downed woody material, in each plot, is presented in Table 4-2. The results show a general increase in average fuel load with size class. Although the amounts vary from one subplot to the other, this tendency was observed in all of them. One exception was observed for the coarse woody debris greater than 7.0 cm in diameter in subplot 8, where only 0.030 kg/m^2 were measured.

The other component of the surface fuels was the surface vegetation that had started reinvading the site following burning. Composed mainly of herbs and shrubs, it was patchy in each plot. These gaps in the continuity of the surface fuels were more evident in the plots that had been burned more recently. The average fuel load of each subplot, for herbs and shrubs combined, is presented in Table 4-3.

Ground fuels were also present, mainly in the form of a duff layer that was left after the passage of the previous crown fire. Although it was not measured intensively for this project in the subplots, data on its depth and bulk density were collected as part of fuel sampling associated with the jack pine – black spruce chronosequence in ICFME plots 6, 8 and 9 (as described in Chapter 2). Some of the results are summarised in Table 4-4. In terms of fuel loads, the duff layer was 6.2, 5.4, and 3.0 kg/m^2 in plots 6, 8, and 9 respectively.

Experimental Fires

On June 28, a day where fuel moisture and current weather conditions were conducive to crowning (a successful crown fire (Figure 4-6) was carried out in ICFME Plot 3 half an hour earlier (Stocks *et al.* 2004a)), the 3 subplots were ignited.

The fire weather observations taken at 1300 h (daylight saving time (DST)) and the FWI System components associated with the reburn experimental fires are presented in Table 4-5. The last significant rain event (i.e., >0.5 mm) had occurred 2 days earlier, on June 26, with an accumulation of 0.7 mm of rain. Despite that fact, the values computed show extreme burning conditions for that day based on an 11-year analysis (see Chapter 3) of fire weather observations for Caen Lake Tower weather station, located only a few kilometres north of the ICFME site. In general, only 1.5% of the days had a temperature higher than the one recorded at 1300 h DST on June 28 in that area, while 1% of the days had a lower relative humidity. In terms of the FWI

[2] Preliminary results for the reburns were presented in Lavoie and Alexander (2004).

System components, the Fine Fuel Moisture Code (FFMC) was above the 99th percentile, while the Initial Spread Index (ISI) and the FWI component itself were at the 96th percentile. Finally, the Duff Moisture Code (DMC) was at the 81st percentile, the BUI was at the 78th percentile, and the Drought Code (DC) was at the 48th percentile.

The results of the fuel moisture content sampling are presented in Table 4-6. The fine (0-1 cm diameter), dead and downed woody fuels on the forest floor and the outside shell of decomposing logs had a moisture content between 4 % and 7 %, while the top portion of the humus layer had a moisture content varying between 12 % and 14 %. Moisture content increased with depth in the humus layer. The moisture content of the live vegetation was considerably higher with values ranging between 157 % and 237 %. Since those percentages were obtained from only 2 or 3 fuel moisture sampling for each category, in each subplot, those values are only indicative of the moisture content of the fuels.

The quasi-simultaneous ignitions allowed for the observation of the 3 fires under the same fire weather conditions. Table 4-7 shows the 1-minute fire weather observations starting after the last ignition line was completed and ending one hour later. On average, the conditions were: temperature 26°C, relative humidity 37 %, and 10-m open wind 23 km/h. However, they varied quickly during the first hour following ignition of the experimental fires. The temperature gradually decreased while the relative humidity increased. The wind speed increased to a maximum of 30 km/h.

The fire in subplot 6 (3 years since the last stand-replacing crown fire - the oldest burn) was the only experimental fire that kept burning after the line of fuel from the terra-torch ignition had been consumed (Figure 4-7). However, the fire was only burning in certain types of material (i.e., punky wood, logs, and stumps) and several sections of the line went "out" just a few moments after ignition with the terra-torch.

After 30 minutes no visible flame could be observed, although some small areas within the perimeter of the fire kept smouldering for approximately 24 hours, with no appreciable spread, before the fire was declared "out". A small amount of rain (0.4 mm accumulation which was not sufficient to lower the FFMC) was recorded on site on the evening of June 28, which may have contributed to the extinction of the fire in subplot 6.

None of the other fires (line or point ignitions) continued to burn after the fuel used for their initial ignition had burned out.

Results - 2001

Fuel Sampling

The fuel loads associated with each microplot are presented in Table 4-8. Seven microplots were located in recently burnt areas, while four microplots were located in the adjacent, mature unburned forest. The fuel loads varied considerably between microplots according to the type of vegetation dominating each 4-m^2 area. In the case of the mature stand, the needles present on the forest floor increased the amount of fine fuel present on site. Overall, the pre-burn fuel load varied between 0.067 and 0.327 kg/m^2 for the microplots located in the recently burnt ICFME experimental fire plots while it was around 0.772 kg/m^2 (0.034 kg/m^2 of vegetation only) in the mature stand.

The forest floor data (depth, bulk density, and load) for Plot 6 was previously presented in Table 4-4. In Plot 5, the depth of the remaining organic layer was 1.7 ± 0.5 cm, its bulk density was 266.8 ± 67.9 kg/m^3, and its fuel load (calculated from duff depth and bulk density) was 4.5 kg/m^2 (see Chapter 2, Tables 2-3 and 2-5). For Plot A, considering that the parent stand was the same as that of the other ICFME plots, and that a similar high intensity crown fire burnt through that plot, we can assume similar values for the duff as those measured for the other recently burnt ICFME plots and presented in Chapter 2 (plots 4-9 in Tables 2-3 and 2-5). Finally, the forest floor sampling in the mature stand was performed within 10 m of the microplots, in an area located southwest of Plot 7 (Figure 4-1). The forest floor depth was 6.9 ± 1.1 cm, the bulk density 125.8 ± 16.9 kg/m^3, and the duff fuel load 9.4 kg/m^2 (see Chapter 2, P10 in Tables 2-3 and 2-5) in that area.

Experimental Fires

The 2001 reburns were performed on four different days: June 14-16, and June 19. The range in the FWI System components under which the microplots were burnt were: FFMC 89.9-92.6, DMC 49-65, DC 175-210, ISI 7.8-14.5, BUI 58-73, and FWI 21-35. The 10-m open wind speed recorded during the fires was between 10 and 13 km/h. The detailed information on fire weather observations and FWI System components is presented in Table 4-9. Although lower than the previous year, the fire danger conditions were still conducive to moderately vigorous fire behavior in a mature pine stand with the fire danger varying between "very high" and "extreme" based on the FWI component classification scheme used in the NWT (Stocks *et al.* 1989).

The moisture content of the fuels that were destructively sampled before the fires in the recently burned microplots and the mature stand are presented in Table 4-10. The moisture content of the American fuel moisture indicator sticks (Nelson 2000) varied between 6 and 8%, while the twigs on the forest floor varied in moisture content between 6 and 11 %, with no noticeable difference between the mature stand and the recently burnt microplot areas. Generally, the punky wood appeared to be slightly drier in the recently burnt areas than the mature stand. Finally, the moisture content of the live vegetation was generally higher (Table 4-10) in the reburn areas than in the mature stand.

For every paired ignition trial (i.e., recently burned ICFME microplot(s)-mature stand microplot pairs), the fire burning in the microplots located in the mature stand spread across the entire length of the microplot and had to be subsequently extinguished. Rates of spread between 0.4 and 0.7 m/min were observed (0.6 m/min on June 14, 0.7 m/min on June 15, 0.4 m/min on June 16, 0.4 m/min on June 19 (0.3 m/min when considering that a downed log temporarily stopped fire spread soon after ignition)) and the average flame length was between 0.2 and 0.4 m in the mature stand (0.2 m on June 14, 0.4 m on June 15, 0.3 on June 16, and 0.3 on June 19).

In the reburn microplot(s), there was no noticeable fire spread and the fire went "out" as soon as the line of fuel from the drip torch had been consumed (Figure 4-8). In several cases, a second ignition was attempted without any difference in the outcome.

Discussion

The fuel sampling performed in 2000 and 2001 showed that fuels were present in the recently burnt ICFME plots even though only 1 to 4 years had passed since a stand-replacing crown fire. The vegetation reinvading each plot was usually patchy, its continuity increasing considerably with time. The dead and downed woody debris were generally of medium to large size, the fine surface, ladder and crown fuels having been consumed in the crown fire. The duff remaining after that fire was horizontally continuous and provided a bridge between the discontinuities in the surface fuels. However, it had a high bulk density, with values approximating that of the lower layers of the duff in the mature stand (see Chapter 2). Despite the presence of such fuels, the experimental fires ignited in recently burned areas did not sustain themselves and eventually self-extinguished, the method of ignition (i.e., terra-torch or pressurised flame thrower and the hand-held drip torch) having no noticeable impact on the results.

We observed a similar response to point ignitions in recently burnt areas during the ICFME experimental fire in Plot 9 (burnt in 1999)[3]. The high intensity crown fire burning through Plot 9

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[3] From Stocks *et al.* (2004): Plot 9 was ignited on June 19, 1999 at 1608 h (DST). The weather observations were: temperature 31.4°C, relative humidity 23%, wind speed 25 km/h, and 4 days

(Stocks *et al.* 2004a) was sending a large quantity of fire brands downwind, into Plot 5 (burnt in 1997) (Figure 4-1). An investigation showed that the spot fires were not able to spread in that recently burnt area. Only live embers or firebrands falling on to stumps, rotten logs, and punky wood (the same materials that were observed to burn in subplot 6 in 2000) were showing any kind of sustained combustion, and merely for the time it took to burn the material in question (Figure 4-9). The spot fires were not able to spread beyond the material into which they were burning. Smouldering at low intensities with periodical flare-ups in dead woody debris of different stages of decomposition has been reported in several instances in the literature (e.g., Romme 1982; Despain and Sellers 1977). Logs resist ignition when they are sound, but they become easy to light by firebrands as they become splintered and punky (Clarr and Chatten 1966, in Bunting and Wright 1974). The ability of punky wood to act as a good receptive fuel, easy to ignite, is also well documented (e.g., Bunting and Wright 1974; Stockstad 1979; Pyne *et al.* 1996; Latham *et al.* 1997).

For the line ignitions, a result similar to what we obtained when burning our subplots in 2000 was also obtained (albeit at a larger scale) when the west half of ICFME Plot B (Figure 4-1) was burnt on June 26, 2000, during the 2000 phase of the ICFME project. The eastern section of the plot had been burnt a few days earlier (on June 13, 2000), leaving behind snags, some medium and large dead and down woody material, a continuous and moderately compacted duff layer, and no live vegetation. When ignited, the western part of the plot burnt towards the recently burnt area as a crown fire but failed to spread past the limit between the two halves (the 1300 h DST weather and FWI System components were: temperature 24.4 °C, relative humidity 32%, wind speed 10 km/h, FFMC 90.8, DMC 54, DC 387, ISI 7.9, BUI 80, and FWI 24). It stopped at that physical boundary despite the momentum of the high intensity flame front associated with the crown fire (Figure 4-10). The duff remaining from the fire in the eastern portion of the stand did not have the right characteristics to sustain the fire. Some spotting was also observed in the eastern half of Plot B, with the numerous spot fires springing up in the previously burnt half of the plot as observed in ICME Plot 5 in 1999 during the burning of Plot 9.

There are several universal requirements that must be met for a fire to start and spread (Heinselman 1978; Van Wagner 1983; Fonda *et al.* 1998): a) there must be sufficient fuel of appropriate size and arrangement in space, b) this fuel must be of sufficient dryness to support a spreading combustion reaction, and c) there must be an agent of ignition. Those three requirements are discussed below in relation to our results.

Ignition

The procedures used for the line and point ignitions were proven methods and had successfully been used in other projects (Alexander and Quintilio 1990; Stocks *et al.* 2004a). Moreover, the use of the terra-torch or truck-mounted pressurised flame-thrower in 2000 should have provided all the momentum needed for a fire to spread through the subplots, given adequate fuels were present and moisture conditions were appropriate. Finally, the use of microplots and their ignition with a hand-held drip torch in 2001 were successful in the mature stand and do not appear to be related to the fire behavior observed in the recently burnt areas.

Fuel Moisture and Weather Conditions

In terms of fuel moisture and weather conditions, the experimental crown fire performed in 2000, just before the three subplots were ignited, is an indication of good burning conditions. The fire weather conditions and FWI System components observed on that day had values not often encountered in the study area, as indicated by the percentiles described in Chapter 3.

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since the last rain event. The FWI System components were: FFMC 94.1, DMC 66, DC 332, ISI 27.0, BUI 88, and FWI 56. The rate of spread was 1.163 m/sec and the frontal fire intensity 89 681 kW/m.

As a reference, the sustained flaming ignition probability (Lawson and Armitage 1997) calculated using the DMC and an adjusted ISI (using the daily FFMC and the average wind speed at the time of the fires) for that day was 99% in the mature fuel type (Wildfire Ignition Probability Prediction System (WIPP) equation 6A). The probability of sustained smoldering ignition, calculated from Frandsen (1997) using the reindeer lichen/ feather moss duff type, was 93% in the mature fuel type (Equation MC-2 presented in Lawson *et al.* (1997) for converting DMC to moisture content was used in the calculation). Unfortunately, we could not find similar equations developed for the duff present in recently burnt areas. However, with an increased exposure to solar radiation and darker surfaces, the fuel moisture of recently burnt areas is not expected to be a limiting factor to the probability of ignition under the FWI System components obtained for that day. In fact, exposure to direct solar radiation in an open area usually results in lower average moisture content than under an adjacent canopy (Simard 1968). The fuel moisture sampling performed on the recently burnt ICFME plot areas in 2000 actually indicated a low moisture content in most fuel categories.

In 2001, the burning conditions were generally less severe than those observed the previous year but were nonetheless quite dry. Although no ICFME plot was burnt on the days we did the reburns in the microplots in 2001, we can obtain an indication of the potential fire behavior in a full scale mature stand on those days using the Canadian Fire Behavior Prediction (FBP) System (Forestry Canada Fire Danger Group 1992). Based on the FWI System components and fire weather conditions that prevailed on the days of burning in 2001, the predicted rates of fire spread and intensities for FBP System fuel types C-2 (Boreal Spruce), C-3 (Mature Jack or Lodgepole Pine) and C-4 (Immature Jack or Lodgepole Pine) are, respectively, 7.8-16.3, 1.9-7.0 and 8.2-16.8 m/min and 7567-17 711, 1059-5763 and 6878-17 165 kW/m. The type of fire would in turn range from a surface fire to intermittent crowning (C-3 fuel type) and from intermittent to continuous crown fire (C-2 and C-4 fuel types).

The DMC and adjusted ISI (using the wind speed at the time of the fire) on those days indicated a probability of sustained flaming ignition of 79% on June 14, 73% on June 15, 69% on June 16, and 92% on June 19 (Wildfire Ignition Probability Prediction System (WIPP) equation 6A) based on equations provided in Lawson and Armitage (1997). The probability of sustained smoldering ignition, calculated from Frandsen (1997) using the reindeer lichen/ feather moss duff type, was 73 %, 78 %, 83 %, and 93 % for the same days, respectively (Equation MC-2 presented in Lawson *et al.* (1997) for converting DMC to moisture content was used in the calculation).

The moisture content of the duff sampled on June 15 and June 19 in the burnt area immediately before the reburn attempt appeared to be quite high given the fire weather observations and FWI System components for that day. The limited sample size, combined with the patchiness of the vegetation in the recently burnt areas and the large variability generally encountered in fuel moisture sampling of the duff is likely responsible for those high values. Potts *et al.* (1983) found that to obtain a desired precision, at least 40 or more observations are needed in a simple random sampling of duff moisture content, while in a stratified random sampling 16 samples should provide acceptable precision. When sampling the duff (on different days) of ICFME Plot 5 and Plot 6 for another portion of the project (see Chapter 2), a larger sample size provided a 95% confidence interval of ±14% ($\bar{x}$=36%, n=25) and ±15% ($\bar{x}$=104%, n=25) in the first centimetre of duff, and of ±26% ($\bar{x}$=99%, n=10) and ±19% ($\bar{x}$=151%, n=21) in the second centimetre of duff in plot 5 and 6, respectively (N. Lavoie, unpublished data). This provides an indication of the variability generally encountered in the moisture content of the duff.

Duff moisture content was identified as a factor influencing duff consumption in jack pine stands (Chrosciewicz 1978). Nevertheless, the moisture content of the litter and the top portion of the duff in our subplots and microplots did not appear to be a constraining factor in the spread of a fire as it was often below the 134% threshold identified by Van Wagner (1972) in pine stands, the 110% observed by Frandsen (1987) in peat moss, or even the 80% below which several studies have indicated major consumption of duff layers (Dyrness and Norum 1983).

The moisture content of the dead and down woody material was also low enough to support combustion. However, the higher moisture content of the live vegetation in the recently burnt areas may be a reason why they did not burn, although Ching and Stewart (1962) suggested that the moisture content of fresh leaves is not necessarily related to the burning quality of the plant. Interestingly, their test fire in a five-year-old bush of *Atripex halimus* produced similar results to the ones we obtained with the *Salix spp.* shrubs. In their experiment, the bush (over eight feet high, with many woody stems, and with dead leaves and branches accumulated at the base of the plant) burned while the gas burner they were using for the ignition was burning but, despite repeated attempts, they were not able to ignite the plant and produce a sustained fire. However, in a study looking at the relative fire potential of 12 northern forest-tundra ground species in the NWT, Sylvester and Wein (1981) rated the relative importance of the fuel parameters as, in decreasing order: moisture content, biomass, fineness (surface/volume ratio), packing ratio, silica-free ash content, and caloric content.

Fuels

Although the patchiness of the ground vegetation might have been a factor limiting the spread of the fire in the recently burnt areas when considering the results we obtained in 2000, it was eliminated as a probable cause in 2001 when we used the microplot approach. At least one microplot on each burning day was entirely covered by some ground vegetation (although the species varied) in the recently burned areas but did not burn.

Since the surface fuels were connected by a continuous duff layer remaining following the burning of the ICFME plots, the characteristics of this fuel layer may have limited the spread of the fires in the recently burnt areas. The first aspect that may have played an important role in the fire behavior we observed was its bulk density. Hartford (1989) found that the probability of ignition decreased with increasing bulk density. The results of our test fires performed in 2000 and 2001 are similar to those obtained by Schimmel and Granström (1997) in Sweden who attributed the restriction on fire propagation in early stages of plant succession or development following fire to the fuel conditions. The compact mat of litter and bark on the forest floor in their stand in the first year after fire was comparable to the continuous, compacted organic matter present in our plots in terms of the effect on fire behavior. Note that in the mature stand in 2001 the fire did spread across all of the microplots.

Another aspect of the forest floor or organic layer that may have been responsible for the results we obtained in the recently burnt areas (absence of reburn) is the percentage of inorganic material, which has been shown to affect the ignition and combustion in forest duff (e.g., Fandsen 1987, 1997; Pyne *et al.* 1996). We did not measure that characteristic of the duff for this project but Alexander *et al.* (2004) observed that the percentage of inorganic material was low (2.3% on average, with a standard deviation of 10.5% and a sample size of 99) in the first two centimetres of the mature stand forest floor at the ICFME site, and it sharply increased with depth to reach a more or less constant percentage with an average of 13.7% (standard deviation 21.8%, sample size 38) between 2 and 4 cm, 13.2% (standard deviation 18.1%, sample size 13) between 4 and 6 cm, and 10.0% (standard deviation 17.3%, sample size 3) between 6 and 8 cm. Those results indicate that in the recently burnt areas, where only the lower portion of the duff from the original stand remains, and where the time elapsed since the last fire had not been sufficient to allow much change in the duff from what it was immediately after the stand-replacing crown fire, the percentage of inorganic materials would be at least that of the lower portion of the duff in the mature stand (around 13 %). In fact, it may be much higher than that if the inorganic materials from the portion of the duff that did burn during the crown fire were not removed during the perturbation and just accumulated on top of the remaining duff and started to gradually integrate within it. On average, it would then be in the vicinity of 20-25 % according to the percent inorganic content and load of the forest floor presented in Alexander *et al.* (2004) and our duff load measurements in recently burned areas, but could reach percentages above 50% if we consider the high standard deviation associated with the measurement of the inorganic content.

Such quantities may be sufficient to impede the progression of a fire even under good burning conditions. Although there is no equation available to calculate the probability of sustained smouldering ignition in the duff of recently burned areas, the equations proposed by Frandsen (1997) offer the possibility to vary percent inorganic content, percent moisture content, and organic bulk density. When using an average moisture content of 67% (from the moisture content of the duff sampled before the experimental reburns of 2000), a total average bulk density of 177 kg/m^3, and varying the inorganic content from 13.5 % to 50%, the probability of sustained smouldering ignition changes from 100% to 0% in some of the duff type presented in Frandsen (1997) that have characteristics similar to the ones sampled in our recently burned areas.

More research is needed before any definite conclusions can be drawn regarding the effect of inorganic materials on fire behavior in recently burnt areas.

SUMMARY AND CONCLUSION

The present investigation has presented evidence showing that areas exhibiting the same characteristics as the recently burnt stands associated with the International Crown Fire Modelling Experiment do not burn readily (although some spot fires may be ignited in specific types of material (rotten logs, punky wood, stumps) provided that fire brands fall on them under appropriate burning conditions) soon after a stand-replacing crown fire, even under "high" to "extreme" fire danger conditions. All the experimental fires ignited in those recently burnt stands did not continue to burn after the fuel for their initial ignition had been consumed. Surprisingly, the remaining continuous duff layer left after the preceeding stand-replacing crown fire did not sustained smouldering combustion despite dry weather and fire danger conditions on the days of the reburns. These results suggest that the flammability of the jack pine/black spruce stands studied in this project may be low for some time after a stand-replacing fire. This is in agreement with models presented by Horn (1976), but also by others such as Van Wagner (1979, 1983) and Brown (1975).

After an analysis of the different requirements that must be met for a fire to start and spread (Heinselman 1978; Van Wagner 1983; Fonda *et al.* 1998), we concluded that the ignition methods and the burning conditions under which the fires were ignited were not responsible for the lack of significant fire activity. Instead, the limitation appears to be related to the nature of the fuels present in the recently burnt areas. There was some variability in the moisture content of the various fuels present in recently burned areas but in general the punky or rotten pieces of wood that serve as ready receptor to airborne firebrands were relatively dry.

It is the lack of suitable fuels that appears to be the limiting factor to sustained ignition and spread of both ground fires and surface fires in the recently burnt stands. In terms of fuel loads, surface and ground fuels were present in all the subplots and microplots. Although the vegetation reinvading each site was patchy, our microplot approach showed that even when ignited in an area of continuous ground vegetation a fire could not sustain itself. The ratio of the dead/live fuels may have affected the fire behavior. The live vegetation generally had a high moisture content while the dead and down woody material was quite dry. The latter however was only present as large branches and logs. The dry, fine fuel accumulations needed for the fire to spread in were sparse to absent since there had not been sufficient litter fuel development from the jack pine seedlings and ground vegetation in the few years since the last stand-replacing fire to support a surface fire.

Some characteristics of the organic layer remaining following a high intensity crown fire, which bridged the patchy surface fuels in our subplots and microplots, were also identified as potential inhibitors of combustion during our experimental reburns. The first one was the high level of compaction (bulk density) of the organic matter remaining on the recently burnt areas, which was considerably higher than what was observed in the mature stands, while the second was the inorganic content of the forest floor. More research on those characteristics of the organic matter left following fire in recently burnt areas and on their effect on fire behavior under different burning conditions would be needed to confirm these conclusions.

Care should be taken in generalising about the results of this investigation regarding the potential fire behavior in recently burnt areas. It cannot be assumed, at this point, that all coniferous stands in the boreal forest are not able to sustain a spreading fire during the four first years following a high intensity, stand-replacing crown fire. The potential for reburn is a function of the previous fire history of a stand, the ground vegetation and the fuels present in the area, and the interaction of those fuels with the prevailing fire weather conditions. Some young stands have been known to burn only a few years after a stand-replacing fire (e.g. 3 years after: Chisolm Fire, Alberta, 2001 (ASRD 2002). However, it is likely that the vegetation reinvading them was more abundant or more flammable (e.g. cured, dry grass in large quantities) than what we observed on our plots.

It would be most beneficial to our knowledge if similar experimental fires could be performed on the other ICFME plots (or on other sites providing a similar opportunity) after a longer period of time had elapsed following burning (e.g., 5-25 years) than undertaken in the present study. Very little is known about the variation in flammability with time in most Canadian fuel types and long-term opportunities to study this aspect of fire behavior are very few.

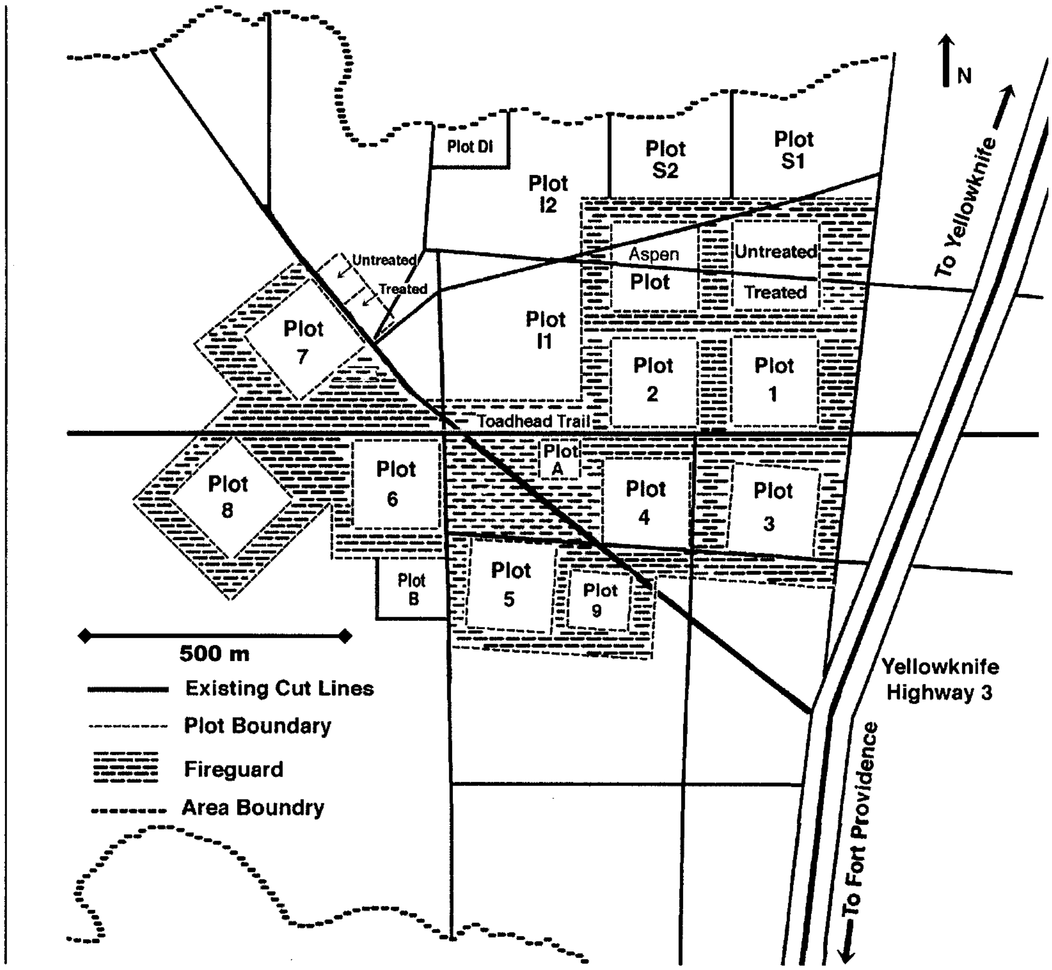


Figure 4-1. Plot layout for the International Crown Forest Modelling Experiment (ICFME) study area (adapted from Stocks *et al.* 2004b). Plots 5, 6, 8, 9, and A were used in the current study.

Table 4-1. FWI System components at the time of the ICFME fire (from Stocks et al. 2004a) in the plots used for the reburns, and percentile obtained from the analysis of 11 years of noon (LST) weather observations at Caen Lake Tower (see Chapter 3), the closest permanent weather station.

	Date	Ignition time	FWI System component (percentile[b])					
ICFME Plot	burnt[a]	(DST)	FFMC	DMC	DC	ISI	BUI	FWI
A	01-07-97	1426	91.8 (96.0)	35 (45.8)	348 (26.8)	12.3 (97.9)	51 (39.9)	26 (89.8)
5	04-07-97	1730	89.4 (82.9)	43 (57.9)	363 (31.7)	7.4 (84.7)	63 (52.2)	20 (76.5)
6	09-07-97	1406	89.9 (87.1)	59 (74.6)	410 (50.6)	10.1 (94.7)	82 (69.3)	29 (94.2)
8	04-07-89	1604	91.9 (96.6)	37 (49.3)	343 (25.3)	11.6 (97.3)	58 (46.2)	27 (91.6)
9	19-06-99	1608	94.1 (1.00)	66 (81.1)	332 (22.7)	27.0 (1.00)	88 (73.7)	56 (1.00)

a. Day-Month-Year

b. Using Caen Lake Tower noon (LST) fire weather analyses (see Chapter 3)

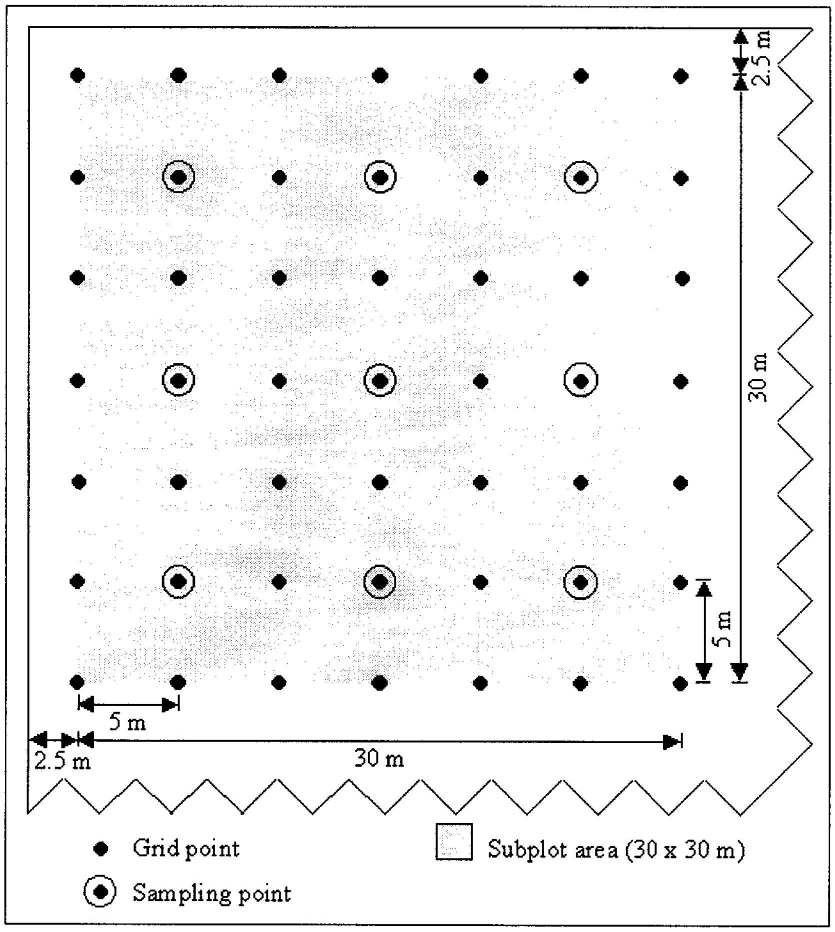
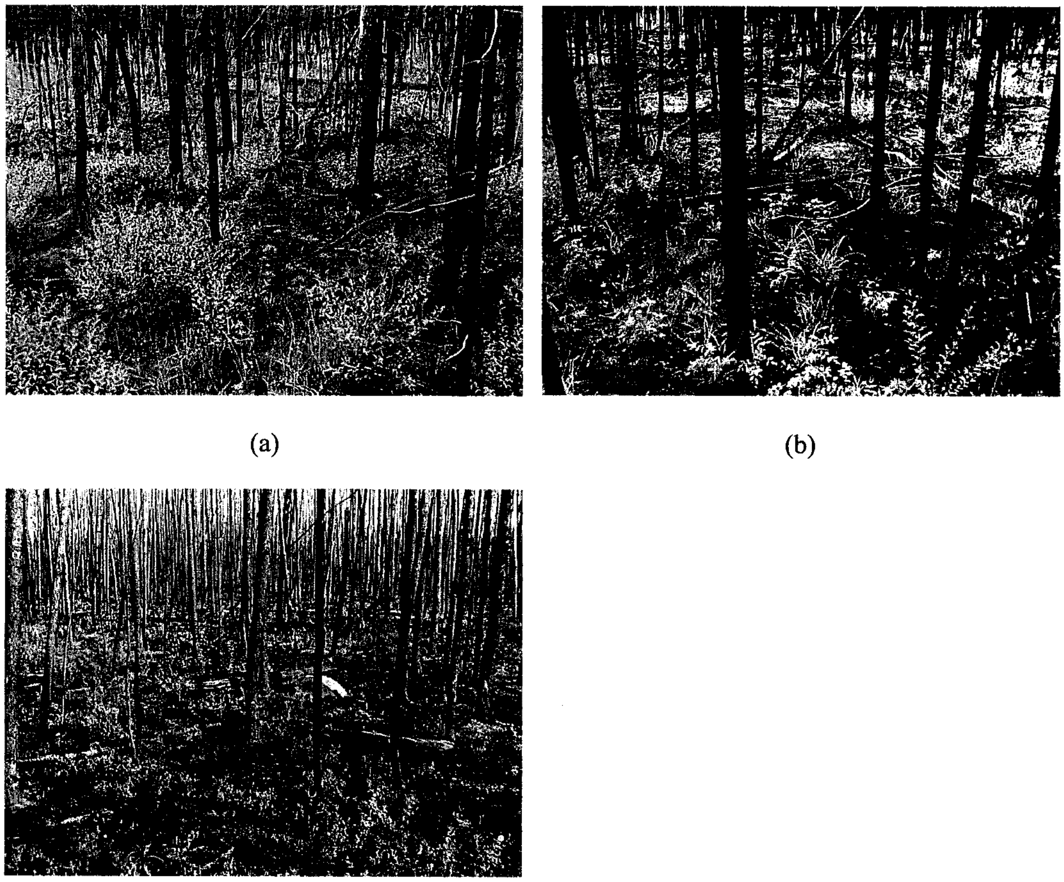


Figure 4-2. Representation of the grid located in each subplot.

Figure 4-3. Ignition of a subplot with a truck-mounted flame thrower, also known as "terra-torch".

Figure 4-4. Ignition of a microplot with a hand-held drip torch.



(a) (b)

(c)

Figure 4-5. Photo of subplots 6 (a), 8 (b), and 9 (c) taken before the 2000 reburn.

Table 4-2. Average fuel loads (kg/m^2) of the dead and downed woody material, per size class, in each subplot (n=9)

Subplot	Dead and down woody material, by roundwood diameter size class						
	0.0-0.49 cm	0.50-0.99 cm	1.00-2.99 cm	3.00-4.99 cm	5.00-6.99 cm	≥7.00 cm	Total
6	0.001 ± 0.001	0.010 ± 0.005	0.116 ± 0.032	0.220 ± 0.094	0.281 ± 0.143	0.401 ± 0.363	1.029 ± 0.431
8	0.003 ± 0.002	0.007 ± 0.002	0.104 ± 0.032	0.245 ± 0.063	0.242 ± 0.168	0.030 ± 0.059	0.631 ± 0.155
9	0.003 ± 0.001	0.005 ± 0.002	0.155 ± 0.041	0.160 ± 0.112	0.171 ± 0.075	0.703 ± 0.317	1.197 ± 0.362

Table 4-3. Average fuel loads (kg/m^2) of the ground vegetation in each subplot (n=9).

Subplot	Live vegetation
6	0.081 ± 0.037
8	0.015 ± 0.003
9	0.003 ± 0.002

Table 4-4. Depth (cm) and bulk density (kg/m^3) of the forest floor layer in each subplot.

Subplot	Sample Size	Average Depth	Average Bulk Density
6	25	3.9 ± 0.9	158.4 ± 13.5
8	25	3.1 ± 0.7	174.0 ± 50.6
9	24	1.6 ± 0.4	188.6 ± 36.3

Figure 4-6. Experimental crown fire in ICFME Plot 3 on June 28, 2000.

Table 4-5. Fire weather observations and FWI System components for time on June 28, 2000.

Fire weather observations	
Temperature (°C)	29.2
Relative Humidity (%)	27.0
10-m Wind Speed (km/h)	9.2
Rain accumulated over the last 24 hours (mm)	0.0
FWI System components	
Fine Fuel Moisture Code (FFMC)	93.2
Duff Moisture Code (DMC)	65
Drought Code (DC)	404
Initial Spread Index (ISI)	10.8
Buildup Index (BUI)	93
Fire Weather Index (FWI)	31.9

Table 4-6. Percent fuel moisture content of live and dead fuels sampled in each subplot before the reburns in 2000.

Fuel category	Subplot 6	Subplot 8	Subplot 9
Duff depth 0-1 cm	14	14	12
Duff depth 1-2 cm	74	79	60
Duff deprh 2-4 cm	169	92	93
Punky wood	7	4	6
Cured grass	12	---[a]	---[a]
Dead roundwood 0.0-0.49 cm diam.	6	5	6
Dead roundwood 0.50-0.99 cm diam.	6	6	7
Live vegetation	157	226	237

a. Not sampled, was not present in sufficient quantities

Table 4-7. Fire weather observations (at 1-minute intervals) during the first hour of the experimental fire reburns in 2000.

Time	T	RH	10-m wind speed	Wind Direction		Time	T	RH	10-m wind speed	Wind Direction	
h[a]	°C	%	km/h	deg.		h[a]	°C	%	km/h	deg.	
1617	29.9	30	17.4	88	(E)	1649	25.6	36	26.3	65	(NE)
1618	29.6	30	17.9	81	(E)	1650	25.5	37	25.9	65	(NE)
1619	29.7	31	19.0	75	(E)	1651	25.5	37	25.2	67	(NE)
1620	29.5	30	20.2	69	(E)	1652	25.5	37	24.2	65	(NE)
1621	29.0	31	21.3	70	(E)	1653	25.4	37	23.9	65	(NE)
1622	28.8	31	23.2	62	(NE)	1654	25.3	37	23.8	65	(NE)
1623	28.3	32	24.5	56	(NE)	1655	25.4	37	22.8	64	(NE)
1624	28.2	33	24.4	51	(NE)	1656	25.3	37	22.0	66	(NE)
1625	28.2	33	23.0	48	(NE)	1657	25.3	37	21.3	65	(NE)
1626	28.1	33	22.5	44	(NE)	1658	25.3	37	21.1	64	(NE)
1627	28.0	32	22.5	42	(NE)	1659	25.2	37	20.6	66	(NE)
1628	27.8	32	24.2	42	(NE)	1700	25.2	37	19.9	65	(NE)
1629	27.0	32	24.8	43	(NE)	1701	25.2	37	20.1	67	(NE)
1630	27.9	32	24.8	43	(NE)	1702	25.2	37	20.3	69	(E)
1631	27.7	32	25.6	52	(NE)	1703	25.2	37	20.1	69	(E)
1632	27.5	33	25.1	57	(NE)	1704	25.2	37	19.9	69	(E)
1633	27.4	33	25.1	59	(NE)	1705	25.2	38	20.2	70	(E)
1634	27.2	33	25.8	61	(NE)	1706	25.2	38	20.3	70	(E)
1635	27.0	34	26.3	65	(NE)	1707	25.25	38	20.2	72	(E)
1636	26.6	34	27.4	68	(E)	1708	25.3	38	20.0	74	(E)
1637	26.4	34	27.9	71	(E)	1709	25.3	40	20.0	76	(E)
1638	26.1	34	28.4	72	(E)	1710	25.0	40	19.6	79	(E)
1639	26.0	35	29.5	70	(E)	1711	24.7	43	19.2	83	(E)
1640	26.1	35	29.5	71	(E)	1712	24.5	44	19.3	86	(E)
1641	25.9	35	30.0	68	(E)	1713	24.2	44	19.0	88	(E)
1642	25.9	36	29.9	67	(NE)	1714	24.0	47	19.7	92	(E)
1643	25.9	36	29.8	66	(NE)	1715	23.8	49	20.2	94	(E)
1644	25.8	36	29.8	66	(NE)	1716	23.7	50	19.9	95	(E)
1645	25.8	36	29.7	67	(NE)	1717	23.5	49	20.0	96	(E)
1646	25.7	36	29.0	67	(NE)	1718	23.3	51	20.0	96	(E)
1647	25.6	36	28.3	66	(NE)	1719	23.2	49	20.0	95	(E)
1648	25.6	36	27.2	65	(NE)	1720	23.2	51	19.5	93	(E)

a. Daylight saving time (DST)

Figure 4-7. Ignition line in subplot 6 a few minutes after application of the terra-torch.

Table 4-8. Fuel load (kg/m^2) of the ground vegetation and forest floor needle litter in each microplot for the 2001 reburning experiment.

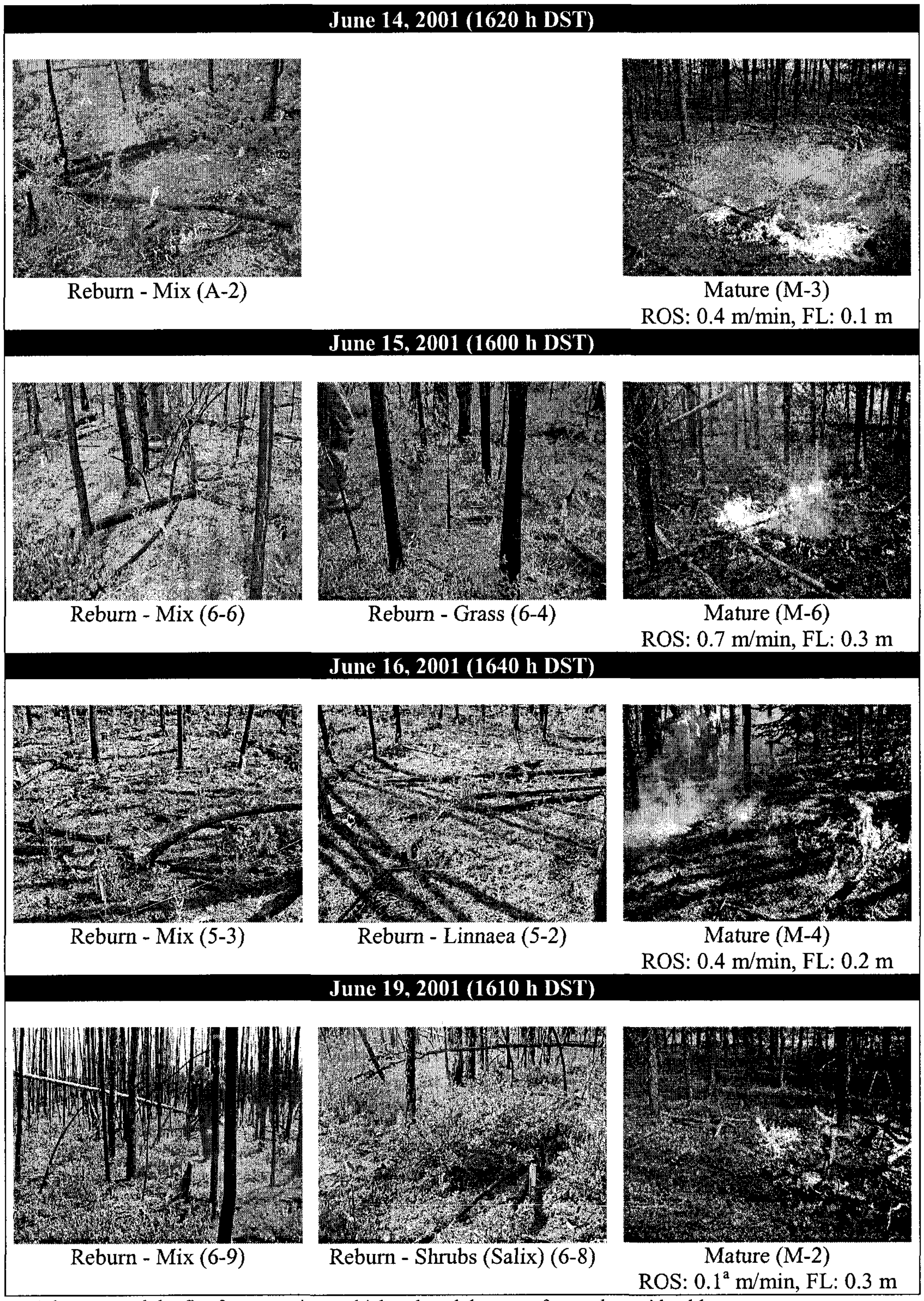
Fuel category	Plot A-2 Mix	Plot 5-2 Linnaea	Plot 5-3 Mix	Plot 6-4 Grass	Plot 6-6 Mix	Plot 6-8 Shrubs	Plot 6-9 Mix	Mature Mix
Herbs	0.088	0.146	0.029	0.077	0.058	0.012	0.012	0.029
Shrubs	0.039	0.007	0.031	0.018	0.050	0.309	0.144	0.005
Seedlings	0.024	0.002	0.007	0.003	0.002	0.006	0.001	---
Needles	---	---	---	---	---	---	---	0.738
Total	0.151	0.154	0.067	0.098	0.111	0.327	0.157	0.772

Table 4-9. Fire weather observations at the time of the fires and the FWI System components for each burning day in 2001.

Date	14-06-01	15-06-01	16-06-01	19-06-01
Time (h DST)	1620	1600	1640	1610
Fire weather observations				
Temperature (°C)	18.8	16.2	19.5	27.7
Relative Humidity (%)	36	42	29	24
10-m Wind Speed (km/h)	13	13	10	13
Rain accumulated over the last 24 hours (mm)	0	0	0	0
FWI System components				
Fine Fuel Moisture Code (FFMC)	91	90	90	93
Duff Moisture Code (DMC)	49	51	54	65
Drought Code (DC)	175	182	188	210
Initial Spread Index (ISI)	8.4	8.6	7.8	14.5
Buildup Index (BUI)	58	60	63	73
Fire Weather Index (FWI)	21	22	21	35

Table 4-10. Moisture content (%) of different fuel categories at the peak burning period on each burning day when the microplot reburning was attempted in 2001.

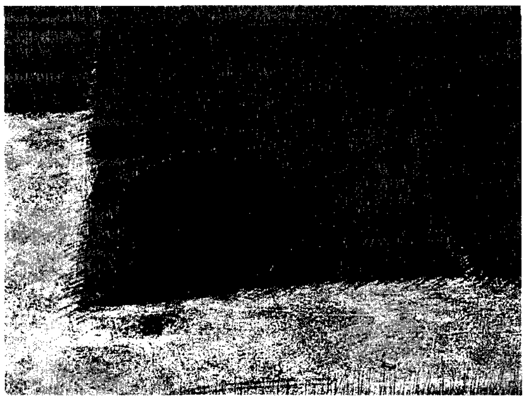
Fuel Category	14-06-01		15-06-01		16-06-01		19-06-01	
Fuel moisture sticks	7		8		7		6	
	Mature	Reburn	Mature	Reburn	Mature	Reburn	Mature	Reburn
Lichen	11	---	14	---	10	---	9	---
Moss	23	---	15	---	14	---	11	---
Dead roundwood 0.0-0.49 cm diam.	9	8	9	9	8	8	6	7
Dead roundwood 0.50-0.99 cm diam.	9	8	11	10	8	8	7	8
Needles (dead)	8	---	10	---	70	7	---	---
Punky (decaying) wood	55	12	11	6	49	11	10	11
Litter (mix of elements)	15	---	14	---	9	13	9	18
Duff depth 0-2 cm	153	19	105	146	132	45	89	94
Live Shrubs	134	149	142	189	143	176	114	169
Live Herbs	138	260	95	208	162	156	120	210
Live spruce branch tips	82	142	81	182	86	161	101	233
Dry herbs	---	---	---	22	---	10	---	---



a. A log stopped the fire for some time, which reduced the rate of spread considerably.

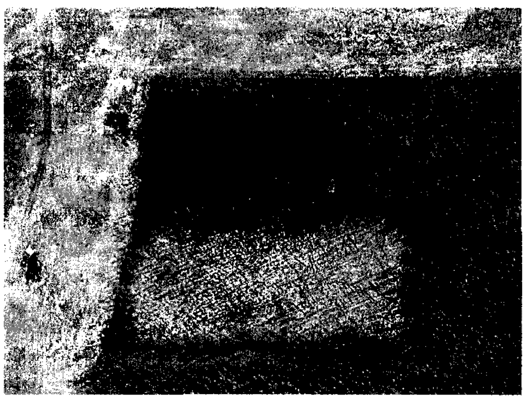
Figure 4-8. Ground views of the experimental fires carried out in the microplots on different days in 2001. Rates of spread (ROS) and flame lengths (FL) observed in the mature stand are also provided.

Figure 4-9. Examples of spot fires in ICFME Plot 5 (then 2 years since fire) resulting from a large quantity of firebrands emitted from a crown fire burning directly upwind, in Plot 9. Only the firebrands falling on to stumps, rotten logs, and punky wood were showing any kind of sustained combustion, and merely for the time it took to burn the material in question.



(a) photo taken from the North side

(b) photo taken from the West side



(c) photo taken from the West side

Figure 4-10. Plot B of the ICFME project: a) before the crown fire in the western half (but after the fire in the eastern half), b) during the burning of the western half, and c) after both fires (the ashes are still visible in the western half of the plot).

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CHAPTER 5

Modelling the relation between stand development and flammability in a northern jack pine/black spruce forest: an expert judgement approach[1]

INTRODUCTION

In the boreal forest, the landscape is composed of a mosaic of stands representing different times since the last fire. Although the information is greatly needed for many aspects of forest management, we know very little about the temporal changes in flammability of stands, at least in quantitative terms, and the length of time after an area is burned before it is, again, able to readily support a spreading fire. As a result of this knowledge gap, we considered the hypothesis that the flammability of jack pine/black spruce stands in the Hay River District of the Northwest Territories (Canada) vary according to the hypothetical model (Chapter 1, Figure 1-2) presented by Horn (1976).

Due to the impossibility of obtaining fire behavior information through the entire continuum of stand development and under all possible burning conditions, other sources of information were considered to complement the data collected from fuel sampling, experimental burns, and fire behavior models as described in chapters 2, 5, and 6. Considering that the relative flammability of northern plant communities is generally known from fire control experience (Hardy and Franks 1963 in Sylvester and Wein 1981; Kiil 1971), and that the ideal flammability guide is thought to be one that combines systematic scientific approach with fire manager assessment (Fogarty 2002), we decided to adopt an expert judgement approach as one of those alternate sources of information. The combined experience, judgement, and observations of fire behavior experts was considered a very valuable source of information.

Meyer and Booker (1991) defined expert judgement (or opinion) as data given by an expert in response to a technical problem. It represents the expert's state of knowledge, at the time of response, to the question(s) requiring his/her expertise (Keeney and Von Winterfeldt 1989). As a consequence, the judgement made on a problem by an expert may change if new information becomes available, and it may validly vary between experts (Meyer and Booker 1991).

Expert judgement is generally used when universally accepted laws or extensive data on the quantities of interest are not available (Keeney and von Winterfeldt 1989; Joseph *et al.* 1985), when analytical models and published studies are limited (Cleaves 1994), when the information cannot be readily obtained from other sources (e.g., measurements, observations, experimentation, simulation) (Meyer and Booker 1991), or to supplement existing data (Meyer and Booker 1991). The approach has been widely used in technical fields (Meyer and Booker 1991) and forestry is particularly well suited for its use. Forest management problems are often based on judgement and experience (Schmoldt and Martin 1986). This 'art' side of forestry builds upon the science side with lessons learned from years of practical experience (Gisborne 1948; Kourtz 1990). Expert judgement can therefore capture that invaluable knowledge and document it. Fire management, with its objective and subjective inputs, also corresponds to that profile. Van Wagner (1985) presented an interesting discussion on the blend of art and science in fire behavior modelling, and on their tendency to converge to similar final practical states.

The value of expert opinion in fire management has been acknowledged for several decades and has been used for different purposes, including fuel and flammability assessments and evaluation of potential fire behavior (Alexander and Thomas 2003). For example, Hornby (1936) presented a procedure where the assessment of several fire characteristics (e.g., fire danger, fire potential,

[1] This project was approved by the Human Research Ethics Board of the University of Alberta, Faculty of Agriculture, Forestry, and Home Economics.

resistance to control) was made by people having extensive experience in fire management. A few years later, Lyman (1945, in Brown 1975) consulted experienced fire control officers regarding the temporal variation of fire hazard in lodgepole pine forests. Gisborne (1948) observed that experienced judgement is the final determinant of several fire management actions. Experienced judgement was also part of the process aimed at the interpretation of fuel data to predict fire behavior suggested by Anderson (1974). The same year, Muraro (1974) suggested the application of field experience through Delphi techniques as possible sources of data for some variables related to vertical fire spread. Brown *et al.* (1977) suggested the use of mathematical modelling and experienced judgement for the evaluation of the potential fire behavior of downed woody debris. They commented on the importance of experienced judgement in fuel appraisal even when more sophisticated methods are available, partly due to the fact that an experienced person can integrate many factors, including some that may elude quantification. Brown (1978) later commented that both mathematical modelling and experienced judgement are valid and useful for fuel appraisal.

More recently, Fischer (1981) used expert opinion of fuel and fire behavior to evaluate the fire behavior potential, for an average bad fire weather situation, of several Montana fuel types. In addition to an overall fire potential rating, he assessed five elements of fire behavior on each plot: rate of spread, intensity, torching, crowning, and resistance to control. Andrews and Latham (1984) commented on the classification of the American BEHAVE fire behavior model as an expert system integrating data from several sources, including experts' knowledge. Brown and Simmerman (1986) selected an approach to appraise flammability that involved expert opinion and mathematical prediction of fire behavior. Wilson (1992, 1993) used the experience of fire personnel (e.g., fire behavior specialists, field fire managers, and field fire practitioners) in the production of photo guides relating elevated fuels (scrub and bark) to fire hazard in Australian eucalypt forests. Hargrove *et al.* (2000) combined empirical data with expert opinion to create a table of spread probabilities among successional fuel classes under moderately dry conditions in lodgepole pine (*Pinus contorta*) stands. Fogarty (2002) obtained information about the flammability of native New Zealand plant species through two questionnaires administered to fire managers and produced a summary guide presenting their state of knowledge on the topic.

Other applications of expert judgement relating to fire included: fireline production rates (Fried and Gilless 1989), dispatching of resources (Kourtz 1987), fire occurrence prediction (Cunningham and Martell 1976), effectiveness of initial attack crews (Hirsch *et al.* 1998), development of fire management plans (Greenlee and Wilson 1980), fuels management using prescribed fires (Hirsch *et al.* 1980; Stock *et al.* 1996), factors influencing fire-risk behavior (Cortner *et al.* 1990), fire prevention (Schmoldt 1989), large fire suppression (Joseph *et al.* 1985), and the development of expert systems (Kourtz 1990).

There are several main advantages of expert judgement studies in fire management. For example, they can generally be completed in a reasonable time frame and at relatively low cost (Fried and Gilless, 1989; Hirsch and Martell 1996; Fogarty 2002). These studies are non-destructive in nature, although they are implicitly based on knowledge gained during a very large number of fires (Fried and Gilless 1989). They also provide up-to-date information on the topic studied (Hirsch and Martell 1996). Finally, they are not in conflict with the fire management activities of the organisations involved, and are not a threat to values at risk (Fried and Gilless 1989).

The goal of this chapter is to describe how the information regarding the temporal variation in flammability of jack pine/black spruce stands was elicited from fire behavior experts and to present the results from the survey.

METHODOLOGY

We selected a traditional mail survey as our mode of communication with the experts, since it was reported to work well for the exchange of simple data from a large sample of experts (Meyer and Booker 1991). It also had the advantage of being less expensive than the other available approaches (e.g., personal interviews) considering the large number of people to be contacted and their geographical dispersion.

Survey Procedure

Participants were recruited based on the investigators' knowledge of the potential candidate, on the potential candidates' reputation within the fire community, and on a list of people having successfully completed the Canadian Interagency Forest Fire Centre (CIFFC) nationally sponsored Wildland Fire Behavior Specialist Course (Alexander and Van Nest 1995) between 1996 and 2000; this course represents the most advanced training in wildland fire behavior currently available in Canada. This last source was deemed acceptable in view of a study done by Booker and Meyer (1988), in which no correlation (dependence) was found between expert estimates and any feature of their professional backgrounds (e.g. common educational background and work experience).

The experts selected had extensive experience (Hornby 1936; Harmon and King 1985; Rauscher 1987; Andrews and Latham 1984) working with forest fires and assessing fuels and weather to predict fire behavior. All had a good knowledge of the Canadian Forest Fire Weather Index (FWI) System (Van Wagner 1987) and had worked in the field and observed the behavior of forest fires under diverse conditions. They were familiar with fires in the boreal forest and were taken from (or had worked in) different regions of Canada where jack pine stands exist. Finally, they were recognised as experts or very experienced people within the fire behavior community.

As multiple contacts are essential for maximizing the response rate of mail surveys (Scott, 1961; Linsky, 1975; Dillman, 1991) we adapted the method presented by Dillman (2000) to our project. We first sent a prenotice letter, electronically or by mail (when no electronic address was available), to the fire behavior experts we had pre-selected. In that first contact (Appendix 2) we described briefly the study and asked the person for his/her help through the completion of a questionnaire. The letter also mentioned that all answers would be confidential and that a copy of the compilation would be sent to the participants requesting it.

Within a few days of receiving a favourable reply from an expert, a questionnaire was sent to the person by mail. Each questionnaire was identified only by a number to respect our confidentiality pledge. In our package for the second contact, we also included a stamped return envelope and a letter (Appendix 3) in which we thanked the expert for accepting to participate to our study and provided some specific information on the procedure to follow to complete the survey.

Three weeks after the questionnaire was mailed, we sent a third contact (electronically) to the participants (Appendix 4) to remind them to complete the questionnaire and/or to thank them if they had already returned the completed questionnaire. A replacement questionnaire was sent to the few people who had misplaced their copy and required a new one.

Finally, we sent a letter (Appendix 5) to each expert who participated in the project to formally thank the person for his/her help.

Questionnaire

The core of the questionnaire was composed of several scenarios, an approach often selected in studies pertaining to natural resources (e.g., Joseph *et al.* 1985; Fried and Gilless 1988, 1989; Cortner *et al.* 1990; Kourtz 1990). For this project we selected six fuel complex scenarios and four fire weather/fire danger scenarios that we combined to provide 24 situations on which we questioned the experts.

The use of photographs to rate fuels and fire behavior is widely used in fire management and research (e.g., Muraro 1971; Fischer 1981; Fried and Gilless 1988, 1989; Ottmar and Vihnanek 1998). It was even observed (Schmoldt 1989) that visual aids can help application-oriented experts to make the transition from experience to more abstract concepts. We used that approach in the presentation of the fuel complex component of our scenarios. We selected six stands (Figure 5-1) in our study area, each representing a different time (3, 5, 20, 56, 71, and 108 years) since the last stand-replacing fire along a chronosequence. For each stand, we assembled on one page of the questionnaire the information pertaining to the fuels. We included a pair of stereophotos, since the three-dimensional image improves the ability of a person to appraise the fuels (Ottmar and Vihnanek 1998). Three other colour photographs were also presented: i) the stand viewed from outside, ii) the forest floor and surface fuels, and iii) a typical jack pine tree stem. The remainder of the page was filled with inventory information summarising the fuels and biomass data in each stand. The age of the stand was also given (time since fire). We did not include a written description of the stands nor one for the fuels since the content and the manner in which such information is presented may have an impact on decisions made about the situation depicted (Vinning 1987). Moreover, in light of the observations made by Anderson (1981), we did not label the photographs (which were identified to a stand by the page header) to limit the influence of such descriptions on the judgement of the experts.

Fire weather/fire danger scenarios were determined through an analysis of the historical weather observations and associated FWI components for three weather stations located within or adjacent to our study area, as described in Chapter 3. Since the various components of the FWI System integrate the effect of past weather conditions on ignition and fire behavior potential, it seemed appropriate to have fixed values for temperature, relative humidity, wind speed and 24-hour rain to use with four different combinations of FWI System components representing the “moist”, “moderate”, “dry”, and “extreme” burning conditions suggested by Horn (1976). Those fire weather conditions are often representative of a day when a fire will burn well if fuel moisture is low enough.

More specifically, we selected July 15 as the day of the year for the assessments, that date being in the middle of the peak fire season which generally lasts from June 15 to August 15 (Lanoville and Mawdsley 1990). In our four weather scenarios, we kept the "current" weather conditions constant with a temperature of 25°C, a relative humidity of 33 %, and a wind speed of 20 km/h. The value for the air temperature was based on the 90th percentile for that variable, which was slightly lower than the average of the maximum temperature recorded at noon local standard time (LST) on each day of the fire season, over the range of years (between 11 and 20 years) for which the information was available for each station (Chapter 3, Table 3-1). The value for the relative humidity was selected on the basis of the average minimum noon (LST) observation for that variable on each day of the fire season. Finally, the 10-m open wind speed was taken from Lanoville and Mawdsley (1990) who mentioned that a 10-m open wind speed of 20km/h is a typical average value for the daily burning period in the Northwest Territories. That value is also similar to the average of the maximum noon (LST) wind speed recorded on each day of the peak fire season over the years analysed. The different combinations of FWI System components representing each fire weather/fire danger scenario are presented in Table 5-1.

Using the six different stands, we produced alternative situations by changing the weather assumptions according to our four fire weather/fire danger scenarios in a procedure similar to the one described by Cortner *et al.* (1990). The situations, both in terms of fuel complex and fire weather/fire danger conditions, presented in the questionnaire were comparable to the ones usually encountered by the experts during their work. To reduce bias and improve expert judgement (Armstrong *et al.* 1975; Merkhofer 1987), we decomposed our main flammability question into several questions related to elemental fire behavior variables. We first questioned the expert on the probability of a fire spreading through each stand, given the four fire weather/fire danger scenarios, for a point and for a line ignition. We then asked them, for each (24) combination of stand type and fire weather, the equilibrium rate of spread category, the flame length, the torching category, and the crowning category. All the assessments were to be made for the peak burning period. The rate of spread categories were taken from Alexander (1997). The torching and crowning categories were the ones used by Fischer (1981) who adopted a similar approach in the rating of fire potential for photo guides. The different categories used in the survey are listed and defined in Table 5-2.

The fire behavior elements we used were selected because of their relation to flammability. Although its definition varies in the literature, several authors have considered the rate of spread (e.g., Anderson 1970; Brown 1975; Fogarty 2002) and/or the intensity (e.g., Anderson 1970; Brown 1975; Bond and Midgley 1995; Johnson *et al.* 1998; Fogarty 2002) of a fire to be indicators of the state of flammability. Fire intensity cannot be measured directly but it can be calculated using the rate of fire spread and the quantity of fuels consumed at the fire front, or it can be estimated by using the flame length (Byram 1959). This prompted the use of those variables in the questionnaire. The difficulty in modelling torching and crowning also led us to ask the experts' opinion on those characteristics of fire behavior for the different situations provided by our scenarios.

We printed the questionnaire in a booklet format (Appendix 6) and followed several recommendations made by Dillman (2000) for the integration of the information with the navigational guides through the questionnaire and for the design of the front and back cover pages. The information and the questions related to each scenario were placed in front of the expert at the same time. Moreover, we used the same fire behavior related questions for each stand and kept them in the same order. This procedure was chosen to reduce the number of variables the expert had to commit to memory and increase the amount of information that could be manipulated by the experts (Harmon and King 1985), since most people are limited in the number of things they can consider at the same time (Miller, 1956; Harmon and King 1985; Gordon *et al.* 1987). Overall, the questionnaire was designed to ease the cognitive burden of the respondents by keeping them focused on the topic investigated (Dillman 2000). Randomisation of the scenarios in the questionnaire, to minimise the occurrence of some biases, was not appropriate for the type of survey used in this project. In addition to the extra resources needed to print a different questionnaire for each expert, this approach had the potential to irk the respondents and to lower the quality of their answers as new topics evoke top-of-the-head responses (Dillman 2000). Moreover, in a self-administered questionnaire the respondents have the possibility (even when in the instructions it is explicitly mentioned that questions should be answered in their numerical order) to return to a question or to temporarily skip one component, actions that would have negated the effect of randomisation.

We provided detailed general instructions at the beginning of the questionnaire to limit the procedural decisions made by the respondents (Joseph *et al.* 1985). Whenever a question required more information on some aspect, the details were included with the question itself (Dillman 2000). We also included in the questionnaire a definition of all the quantities and abbreviations used in the survey to avoid inappropriate assumptions, reduce bias, and improve the accuracy of the answers (Murphy and Winkler 1974; Spetzler and Staël Von Holstein 1975; Merkhofer 1987; Booker and Meyer 1988). In another attempt to reduce bias in the experts' answers, we informed them at the beginning of the questionnaire of the biases that were the most likely to affect their judgement (Saveland *et al.* 1988).

For each question, we made clear to the respondents which units we wanted them to use. We selected units that were commonly used in operational work on fire behavior and with which all the experts were familiar (Spetzler and Staël Von Holstein 1975; Joseph *et al.* 1985; Merkhofer 1987). Moreover, we made no restriction on how the experts were to elicit the information of each scenario and obtain their answer to the questions. They therefore had the possibility to use any guides available to them in order to make their judgement, including outputs from fire behavior models. We did not expect this to affect the results since a study by Murphy and Winkler (1974) showed that guidance forecasts had little impact on forecasts made by weather forecasters, and fire behavior prediction is in many aspects similar to weather forecasting. Our decision was also supported by the results obtained by Cortner *et al.* (1990) who found that fire managers tend to trust their own knowledge and experience, even when they are facing contradictory information.

Following the presentation of each scenario and the related fire behavior questions, we placed in the questionnaire a section for general questions. The questions we asked in that section were more directly related to the temporal variation of the flammability in jack pine/black spruce stands. We first inquired about the time (during stand development after a stand-replacing crown fire) the expert thought it would take, for each fire weather/fire danger scenario, for fire spread to be possible. We then asked the respondents if they had ever observed, or heard of, a fire in young stands (0-15 and 16-30 years old) of fire origin. If they answered in the affirmative, we asked them if the fire had been documented and to provide as many details as they could on the event. Finally, we asked the expert some general questions about his/her education and experience to complete the information and help in the analysis process.

Overall, the questions were orchestrated so that the questionnaire took at the most two (2) hours to complete. We emphasised to the expert that there were no wrong answers and that they were to complete the questionnaire to the best of their knowledge. The pre-testing of the questionnaire was made through its careful review by three researchers, since the critical reading of a questionnaire by an experienced person can point out more problems than a practical testing (Payne 1951). None of the pre-test readers were included in the survey.

Analysis

For the first section of the questionnaire related to the 24 (6 fuel complex scenarios x 4 fire weather/fire danger scenarios) situations, the answers collected were first assessed by looking at their distribution in reference to pre-defined classes. Those groupings provided an assessment of the dispersion in the answers of the experts and, when put into graphs, a visual display of their agreement or disagreement regarding each question in relation to fuels and weather. When classes were suggested to the respondents for their answers (for rate of spread, torching, and crowning categories), those were used in that analysis. For the probability of fire spread for point or line ignition, we used 20 % classes. For flame length, we could not use a reasonable number of classes of equal range due to the manner in which that variable varies in regard to fire behavior. For example, with answers varying between 0 and 60 m, 5-m groupings would have put together flame lengths covering several fire intensity classes despite the fact that a very different fire behavior is generally observed between each intensity class. Instead, we grouped the data according to their relation with commonly used (e.g., Alexander and De Groot 1988, Taylor *et al.* 1997) fire intensity classes and the flame lengths were based on the relationship of that variable with fire intensity according to Byram (1959). The flame length classes used were: <0.20 m, 0.20-1.39 m, 1.40-2.59 m, 2.60-3.49 m, 3.50-5.39 m, 5.40-9.99 m, 10.00-25.00 m, and >25.00 m. The last three categories are generally grouped into one intensity class >10 000 kW/m but after a first look at the distribution of the answers from the survey, we decided to separate them.

Due to the design of the questionnaire, where the same 24 situations were presented to each expert, the only independent information available for each situation is an estimate of the central measure obtained from the answer of all the respondents (Milliken and Johnson 1989). We opted for the median as estimator of central measure since it has been proposed as the estimator that consistently provides the best coverage of the correct answer in the aggregation of subjective judgements (Martz *et al.* 1985 in Booker and Meyer 1988). Moreover, the median is not affected by extreme values, it and may be preferable to the mean in situations where marked skewness is observed, it can be determined for open-ended distributions, and it can be estimated also for classes with equal or unequal intervals (Leabo 1976). The median was calculated following Leabo (1976), Sanders (1990) and Healey (1996) for ungrouped and grouped data, depending on the variable. The semi inter-quartile range (SIQR) (or quartile deviation) was also calculated following the methods presented by the same authors. This measure of dispersion, often used in association with the median, is obtained by subtracting the value of the first quartile from that of the third quartile, and by dividing the difference by two. In the case of a bell-shaped distribution, the median plus or minus the SIQR includes the middle 50% of all cases. Even when the distribution is markedly skewed, the median plus or minus the semi inter-quartile range provides a crude approximation of the values that include the middle 50% of the cases (Runyon and Haber 1991). The SIQR was used in this project to complete the information provided by the distribution of the experts' answers per classes (see above) for each of the 24 situations that were presented to them.

Milliken and Johnson (1989) observed that in cases where the treatments under study correspond to different levels of a quantitative factor, it is possible to obtain good information from the collected data if we assume that the true effect of the different factor levels can be modelled by a simple polynomial model. After an exploratory analysis of different models for our two-way experiment, we selected a quadratic response surface model of the form:

$$Y = a + bX_1 + cX_2 + dX_1X_2 + eX_1^2 + fX_2^2 \quad (5.1)$$

where Y is the dependent variable, X_1 and X_2 are the independent variables related to the fuel and fire danger scenarios (respectively), and a to f are the coefficients obtained by linear regression. The natural logarithm of both independent variables was used to respect the assumptions of the regression analysis. Besides its general use with that quadratic response surface model and preliminary analyses showing its significance for this project, the inclusion of the interaction term in the equation was further supported by observations made by Hargrove *et al.* (2000) who observed that the flammability of lodgepole pine stands in Yellowstone National Park seemed to increase with succession but who also noted an important interaction with weather conditions. We also explored the use of the logistic equation following its use by Lawson *et al.* (1994) and Lawson *et al.* (1997) for probability of ignition, but eventually rejected it for this project. Although not perfect, the fit of the quadratic model (equation 5.1) had a better fit with our data.

For the regressions, the time since fire was used for X_1 and the FWI component was used for X_2. Those variables were chosen since they were the ones that integrated most of the different components describing each fuel and each weather scenario. As a consequence, the regression results cannot be interpreted directly in terms of time since fire or of FWI component value. They must also consider the forest type involved and how it progresses with time since fire in terms of fuel characteristics, as well as the other FWI System components leading to the final FWI component value for the "current" fire weather conditions provided to the experts. Although different combinations of ISI and BUI can lead to the same FWI value, in our fire weather/fire danger scenarios an increase in the FWI was also accompanied by an increase in ISI and BUI, which were caused by an increase in the FFMC, DMC, and DC. To keep a certain constancy in our results involving each dependent variable, we used the FWI component in all the regressions despite the fact that other FWI System components are favoured over it in relations describing probability of ignition, rate of spread, and fire intensity (e.g., Forestry Canada Fire Danger Group 1992, Lawson *et al.* 1994, Lawson and Dalrymple 1996; Lawson *et al.* 1997). For the same reason, we kept all the terms in equation 5.1 for each dependent variable. The median of the dependent variables (probability of fire spread for a point or line ignition, rate of spread, flame length, torching category, crowning category) in each situation presented to the experts was used for Y. If that variable was collected as a class defined by a qualitative description (e.g., torching and crowning categories), a rank was assigned to each class (0, 1, 2, 3, etc.) prior to the calculation.

Finally, the answers to the remaining questions were analysed to obtain the percentage of experts who answered in each category.

RESULTS AND DISCUSSION

Survey

The first contact was sent to 133 fire behavior experts, of which 130 were contacted electronically and 3 received a letter by mail. A total of 91 (68 %) experts initially agreed to participate in the survey. We sent them a copy of the questionnaire and 46 people completed and returned it. This number represents 51 % of the people who received the questionnaire, and 35 % of all the people who were contacted. Of the 46 experts who answered the questionnaire, 3 provided answers that contained at least one major inconsistency (e.g., their answer to question number 49 contradicted their answers to questions 1-48, see Appendix 6 for the details on each question) and their responses were removed from the study.

The respondents represented all the Canadian provinces/territories except Newfoundland, Prince Edward Island, and Nunavut. Using the boundary between Manitoba and Ontario as the demarcation between eastern and western Canada, 23 % of the experts were from eastern Canada and 77 % were from western Canada classified on the basis of current work location. Two respondents having experience with the Canadian Forest Fire Danger Rating System (CFFDRS) and fire behavior prediction/observation in the boreal forest but living outside the country also answered our questions and were classified as being from eastern or western Canada based on the location of their work experience. We did not attempt to investigate the influence of the expert's working area on their answers due to the fact that most of them had moved considerably during their career. They had work experience in several provinces (both in eastern and western Canada) as a consequence of different positions.

The people who completed the questionnaire were between 36 and 66 years old (median: 45 years) (Figure 5-2) and had between 3 and 37 years (median: 20 years) of experience in fire behavior prediction and/or observation (Figure 5-3). Experts ordinarily emerge after about ten years of work in their field (Harmon and King 1985; Rauscher 1987). Consequently the data from all the respondents were used in the part of the project based on field observations, but for the answers to our survey requiring expert opinion we only used the data provided by respondents having at least 10 years of experience. An exception was made for respondents who had almost ten years of experience but who generally spent a high percentage of their working time on fire behavior-related tasks. The answers provided by those four people were also retained for the expert opinion section of the project.

On average, the respondents characterised their work as: 58% technical/operational, 23% management, 3% research, 10% teaching, 3% engineering/consultant, and 3% other. Those percentages varied on an individual basis and a detailed distribution of the number of respondents in each category of work is presented in Figure 5-4. In the field, their experience predicting, observing, or documenting fire behavior during wildfires, experimental fires, prescribed burns, or others types of fires was distributed as presented in Figure 5-5. The experience of the respondents was mainly with wildfires, followed by prescribed fires.

Probability of Fire Spread

We first questioned the experts on the probability of a fire spreading through each stand (fuel scenarios), given the four fire weather/fire danger scenarios, for a point (i.e., lightning strike, abandoned camp fire, spot fire) and for a line (e.g. well-established flame front) ignition. We asked the question for both ignition types because a line ignition will already have some momentum while a point ignition will need some time to develop to its full potential given the prevailing environmental conditions (McAlpine and Wakimoto 1991). The distinction between the two might cause differences in the probability of a fire spreading through a stand under given weather and drought conditions and we wanted the opinion of the experts on this aspect.

Point Source Ignition

A summary of the answers provided by the respondents for the probability of a point source fire spreading through a stand, as a function of the fuel complex and fire weather/fire danger scenarios, is presented in Figure 5-6. In general, the experts were more in agreement in situations involving older stands and drier weather scenarios or younger stands and moister weather scenarios than for other combinations. In those instances, almost all the respondents provided the same answer to a given question. The more the situations differed from those extremes, the larger the range of probabilities expressed in the answers. In fact, at the other extremes involving younger stands and drier weather scenarios or older stands and moister weather scenarios, answers eventually covered the full range of possible probabilities. This may suggests a gap in our knowledge and experience regarding the probability of fire spread from a point source ignition in those situations, and a need for more documentation of cases meeting those characteristics or research involving experimental fires performed under those conditions. Other sources of variation may however also have been responsible for that trend in the variation of the experts' answers, as discussed in a separate section, below.

In order to model the state of our knowledge on the probability of fire spread from a point ignition as a function of the fuel and fire weather/fire danger scenarios, we used the median of the experts' answer for each question pertaining to that variable (Table 5-3). The trends are presented in Figures 5-7 and 5-8 as a function of time since fire for the different fire weather/fire danger scenarios and as a function of the fire weather/fire danger scenario for each stand (time since fire). Those data were used in the regression of a quadratic response surface model (equation 5.1) that explained 98 % of the variation in the dependent variable (Table 5-4). All the terms in the equation were significant at the 0.05 level. A graphical representation of the model is presented in Figure 5-9 for five different percentages: 0, 25, 50, 75, and 100 %. Note that all the regression equations presented in Table 5-4 described well the data points within the ranges of time since fire and FWI System component values considered, but interpretations outside that range should be made with caution.

Those results suggested a general increase in the probability of a point source fire spreading through a stand with an increase in both time since fire (as represented by the six stands submitted to the experts) and the severity of the fire weather/fire danger scenarios (as represented by the FWI component). Using the age and the FWI component at a probability of 50% (the cut-off between equal probabilities of something happening and not happening) as the limits for fire spread through a stand when ignited from a point ignition, the answers from the respondents indicated that no fire spread would occur in a stand of the jack pine/black spruce forest type before it reached at least 4 years since fire or a FWI of 11 (indicating that minimum conditions would have to be slightly drier than our "moist" fire weather/fire danger scenario). Under the “moderate” fire weather/fire danger scenario (FWI of 20), the 50% probability is reached after approximately 8 years, while at the “dry” and “extreme” scenarios (FWI of 46 and 66) a stand must be more than 4 years.

Those results are consistent with observations made in 2000 during experimental reburns (see Chapter 4) ignited under fire weather conditions intermediate between those for the “moderate” and the “dry” fire weather/fire danger scenarios (for all FWI System components but the FFMC, which reached 93.2). Point ignition fires in 1-, 2-, and 3-year-old stands failed to spread once the fuel used for the ignition had been consumed.

The answers from the respondents suggested that the probability of fire spread through a stand ignited by a point source increases quite rapidly between 3 and 9 years when conditions are between those set for the “moderate” and “extreme” weather scenarios, and then levels off to eventually reach a plateau (the probability of fire spread is then around 75%). The probability also increased with the severity of the weather conditions but young stands (3-5 years since fire) plateaued at probabilities between 0 and 50% while older stands had probabilities that varied between 0 and 75 to 100% depending on the weather scenario. For stands that are old enough to reach the 50% probability, a change in the fire weather/fire danger scenario does not translate into much change in the probability of fire spread when the fire weather/fire danger scenario was moderate or drier. The probability of fire spread levels off under those conditions at values between 75 and 100%.

Line Source Ignition

A summary of the answers provided by the respondents for the probability of fire ignited by a line source spreading through a stand as a function of the fuel complex and fire weather/fire danger scenarios is presented in Figure 5-10. As was the case for the probability of fire spread given a point ignition, the experts were more in agreement amongst themselves in situations involving older stands and drier weather scenarios or younger stands and moister weather scenarios. As the conditions moved away from those divergent conditions, their answers covered a larger range of probabilities. However, this phenomenon was less pronounced than for a point ignition since more agreement was noted in younger stands under moister conditions than for a point source ignition fire. This suggests that the gap in our knowledge is less (but still present) for the probability of a fire spreading from a line source fire ignition than for a point ignition at younger ages and drier conditions and at older ages but under moister conditions.

The median of the answers provided by the experts was calculated for each question related to the probability of fire spread when ignited by a line source fire ignition (Table 5-3). The trends are presented in Figure 5-11 as a function of time since fire for the different weather scenarios and in Figure 5-12 as a function of the weather scenario for each stand (time since fire). A regression (equation 5.1) with time since fire and the FWI component as independent variables explained 98% of the variation in the probability of fire spread with a line source ignition (Table 5-4). As opposed to the regression for the probability of fire spread when ignited by a point source, not all the terms in the regression were significant in this case. The interaction term was not significant at the 0.05 level. It was, however, kept for consistency and comparative purposes. A graphical representation of the model is presented in Figure 5-13 for five different percentages: 0, 25, 50, 75, and 100 %. The results obtained for a line source ignition fire are similar to those obtained for a point ignition. In fact, the two regression equations were not significantly different when comparing the 95% confidence interval of each coefficient, although the interaction term was on the border of being significantly different. For that reason we kept the results for the line source ignition fire situations separate from those of the point ignition.

Again, the answers from the experts indicated a general increase in the probability of a line ignition fire spreading through a stand with an increase in both time since fire and the severity of the weather. Using the stand age and the FWI component at a probability of 50% (the cut-off between equal probabilities of something happening and not happening) as the limits for fire spread through a stand, the results from the regression suggest that even under the "extreme" condition fire weather/fire danger scenario a fire would not spread through a stand of the jack pine/black spruce forest type before more than 3 years had elapsed since the last stand-replacing fire. Moreover, the analysis of the experts' answers indicated that for a line ignition, a probability of spread of 50% could be reached even under moist conditions (i.e., our "moist" fire weather/fire danger scenario) after approximately 17 years of stand development, where with a point ignition a probability of 50% was never reached under those weather conditions. At the "moderate" fire weather/fire danger scenario a stand would need to be 5 years old to reach 50% probability of spread while at the dry and extreme scenarios it would need at least 3 years old to reach 50 % probability.

As for the point source ignition fire case, the results for line source ignition fire situations are in accord with the experimental fires we performed, as described in Chapter 4, under conditions between the "moderate" and "dry" fire weather/fire danger scenario (for all FWI System components but the FFMC, which reached 93.2). In those fires, a 30+ m "line of fire" ignited with a pressurised flame thrower in three 3-year-old stands failed to spread much beyond the ignition line let alone across the experimental plot. Similarly, microplots ignited with a drip torch also did not burn in 4-year-old stands the following year.

Similar to point source fires, the modelled probability of fire spread for a line ignition based on the answers from the respondents increased quite rapidly between 3 and 7 years, and then levelled off and eventually reached a plateau at 75% probability. The probability also steadily increases with the severity of the fire weather/fire danger conditions and eventually reaches a plateau where the maximum probability reached is also a function of time since fire.

Rate of Spread

We also questioned the experts on the equilibrium rate of spread (ROS) they expected to see in a fire burning under the conditions presented in each of the 24 situations (6 fuel complex scenarios x 4 fire weather/fire danger scenarios) described in the questionnaire.

A summary of the number of respondents who answered in each rate of spread category for the 24 situations is presented in Figure 5-14. Similarly to their answers for the probability of a fire spreading through a stand when ignited by a point or a line source fire ignition, the expert's answers for the expected rate of spread were more in agreement for older stands under drier weather conditions or for younger stands under moister weather conditions. Although their answers showed a gradually larger dispersion as the conditions changed from those extremes, they were nevertheless more similar than for the probability of spread questions.

The state of our knowledge on the equilibrium rate of spread as a function of the fuel complex and fire weather/fire danger scenarios was also modelled using the median of the experts' answers for each question related to that variable (Table 5-3). The trends are presented in Figures 5-15 and 5-16 as a function of time since fire for the different fire weather/fire danger scenarios and as a function of the fire weather/fire danger scenario for each stand (time since fire). A visual representation of the linear regression performed on those values is shown in Figure 5-17 for seven rates of spread. The regression (Table 5-4) explained 95% of the variation observed in the dependent variable and only the quadratic term for time since fire was not significant at the 0.05 level. It was however kept for consistency and comparative purposes.

According to the analysis of the expert's answers, weather conditions do not have a major influence on rate of spread during the early stages of stand development following a high intensity stand-replacing fire. Similarly, time since fire does not much affect the rate of spread when the fire danger conditions are relatively moist. As conditions get further from those two extremes both time since fire and fire danger conditions affect the rate of spread.

Little quantitative fire behavior data exist for the forest type studied in this project. Consequently, very few sources of comparison exist besides the International Crown Fire Modelling Experiment (ICFME) (Stocks *et al.* 2004). During that experiment, parts of our 71 year-old stand were burnt under conditions varying between the "moderate" (FWI 20) and "dry" fire weather/fire danger (FWI 46) scenarios considered in the survey. Rates of spread between 15.8 and 69.8 m/min were measured in those fires, and all but one were above 24 m/min. A comparison of those observations with the results from the expert opinion survey suggested that the experts may have underestimated the rate of spread, at least at that age and under those conditions, although fire behavior predictions within a factor of two are generally considered relatively good (Albini 1976). More field observations at different times since fire and under various weather scenarios would be needed to confirm this hypothesis.

Although the standard fuel types presented in the Canadian Fire Behavior Prediction (FBP) System (Forestry Canada Fire Danger Group. 1992; De Groot 1993) do not exactly correspond to the forest type studied in this project, we looked at the rate of spread of the C-2 (Boreal Spruce) and C-3 (Mature Jack or Lodgepole Pine) fuel types for comparative purposes. In the first case (C-2), the "moist", "moderate", "dry" and "extreme" fire danger scenarios would lead to rates of spread of approximately 3, 9, 22, and 43 m/min respectively. In the second case (C-3) those rates of spread would be 0.3, 3, 16, and 33 m/min. The median for the rate of spread answers provided by the experts were in between what the FBP System models would give for the C-2 and C-3 fuel types (for the same order of fire danger conditions, 0.5, 6.6, 21.6, and 30 m/min).

Flame Length

As a complement to the rate of spread assessment, we also questioned the experts about the flame length they expected to see in a fire burning under the 24 situations presented in the questionnaire. Although we did not provide classes of flame length for their answers, we grouped the flame length into *a posteriori* categories in our summary of their answers presented in Figure 5-18. At least for the first 6 categories, the groupings correspond to the fire intensity classes generally used in Canada, since fire intensity can be calculated from flame length (Byram 1959; Alexander 1982). As for the other variables mentioned previously and assessed by the experts, more agreement in the experts' answers was noted for older stands under drier conditions or for younger stands under moister conditions.

The state of our knowledge on flame length as a function of the fuel complex and fire danger scenarios was modelled using the median of the experts' answers for each question related to that variable (Table 5-3). The trends are presented in Figures 5-19 and 5-20 as a function of time since fire for the different fire danger scenarios and as a function of the fire danger scenario for each stand (time since fire). A high coefficient of determination was again obtained in the regression performed on those values using time since fire and FWI component as independent variables. The regression explained 96 % of the variation observed in the dependent variable (Table 5-4). The only term of the equation that was not significant at the 0.05 level was the quadratic term for FWI. A visual representation of that linear regression is shown in Figure 5-21 for six fire intensities.

In a similar manner as for the rate of spread, the experts did not think that flame length would vary much as a function of the weather conditions early during stand development or, conversely, as a function of time since fire under moister weather conditions. However, as conditions got further from those two extremes both time since fire and weather conditions affected flame length.

Using, once again the results from the ICFME project, we compared the flame lengths estimated by the experts to the flame lengths calculated from the frontal fire intensity of experimental crown fires in the 71 year old stand under "moderate" to "dry" conditions (Stocks *et al.* 2004). Byram's (1959) equation (equation 5.2 (in metric units from Alexander (1982)) is generally used for calculating flame lengths of surface fires from frontal fire intensity values, but it underestimates the flame length of crown fires (Byram 1959). Its author suggested adding one-half of the mean canopy height to flame length (L) to correct for that underestimation. However, it was later suggested that Thomas' (1963) equation (equation 5.3) is a better estimate of the flame length of crown fires (Rothermel 1991, Alexander 1998). The flame length of the ICFME fires calculated with equations 5.2 and 5.3, plus the flame length calculated with the corrected version of Byram's equation (using an average canopy height of 10.1 m (Stocks *et al.* 2004)), are presented in Figure 5-22.

$$L = 0.0775 \cdot I^{0.46} \tag{5.2}$$

$$L = 0.0266 \cdot I^{0.667} \tag{5.3}$$

where is flame length (m) and I is fire intensity (kW/m). Assuming that Thomas' (1963) equation is the one that provides the best estimation, it seems that in general the experts have underestimated flame lengths, at least in stands that age and under those fire weather/fire danger conditions. Surprisingly, their estimates appear to agree well with the uncorrected version of Byram's (1959) equation generally used for surface fires.

Using a similar approach, we also looked at the consistency of the rate of spread and flame length estimates provided by the experts through their respective relation with fire intensity. We first calculated fire intensity for each of the 24 situations presented in the questionnaire based on the quantity of fine fuels (as described in Chapter 2) (to estimate w in equation 5.4) and the rate of spread estimated by the experts (as per above) using Byram's (1959) intensity equation (equation 5.4).

$$\mathrm{I} = \mathrm{Hwr} \tag{5.4}$$

where H is the fuel low heat of combustion (a constant value of 18 000 kJ/kg was used), w is the weight of fuel consumed per unit area in the flaming zone (kg/m^2) and r is the rate of spread (m/sec).

The calculated fire intensity was then transformed to flame length, using equations 5.2 for surface fires and equation 5.3 for crown fires. A crown fire was assumed when the answers to the survey indicated that the respondents expected a crown fire (crowning classes 3 and 4, see section on crown involvement below) to occur in a given situation. We compared the results with the median value for flame length estimated by the respondents. The results (Figure 5-23) indicated that the answers for rate of spread and flame length provided by the experts were in general consistent when compared through their relation with fire intensity. The data points in Figure 5-23 are located close to the line of perfect fit, although there appears to be a small trend for calculated values to be larger than estimated ones in situations where crown fires were expected. Those results are however only indicative, and comparisons with actual flame length observed in wildfires or experimental fires under the conditions defined in the questionnaire presented to the experts would be needed to confirm them.

Vertical Fire Growth

Crown involvement is still difficult to assess despite the availability of several operational fire behavior models. We therefore questioned the experts on the torching and the crowning category they thought corresponded best to each of the 24 situations presented in the questionnaire.

Summaries of their answers for the expected torching and crowning category are presented in Figures 5-24 and 5-25. Once again the experts agreed more in situations when the stands were older and the weather conditions were drier. One major difference, as compared to the other variables, was that the experts agreed on the torching and crowning categories in very young stands under all weather conditions instead of only under moist conditions. This was most likely due to the fact that the canopy of the parent stand had completely burned during the previous fire and had not had time to regrow after only 3 to 5 years. More variability in the answers was present at 21 years since fire.

Table 5-3 and Figures 5-26 to 5-28 and 5-29 to 5-31 show the trend from the calculation of the median for each question and a visual representation of the subsequent regression analysis for torching and crowning assessments, respectively. The regressions explained 95 and 96 % of the variation observed in the torching and crowning categories, respectively (Table 5-4). The interaction term of the two independent variables was the only significant one for crowning, while for torching the quadratic term associated with time since fire was also significant. All other terms were not significant at the 0.05 level but were kept for consistency and comparison purposes.

The experts did not expect crown involvement in young stands (below 5 years old) under any weather conditions or in older stands under moist conditions. It was the expert's opinion that torching (class 2) becomes possible around approximately 11 years after a stand-replacing fire in the fuel type studied in this project, but only under dry and extreme weather conditions. At any time during stand development after that, crown involvement was expected under moderate weather conditions or drier. Although most understory and occasional overstory trees are likely to torch (class 3) around 12 to 13 years after a stand-replacing fire under moderate to extreme conditions, the answers collected in the survey indicated that sustained crowning becomes likely only after 25 years. Intermittent crowning is, however, possible earlier during stand development, after approximately 13 and 15 years under extreme and dry conditions, respectively. This is in accordance with some observations made in our study area where a fire crowned for a short distance in an approximately 15 years old jack pine stand (Figure 5-32) (N. Lavoie, personal observation). Despite the presence of a few cones in the crown of some jack pine trees, after the reburn the tree regeneration was mainly composed of deciduous species in that stand.

Minimum age to possibly reburn

When asked directly, the experts indicated that after a stand-replacing crown fire, they expected fire spread to be possible after 9, 10, 20, and 35 years under "extreme", "dry", "moderate", and "moist" fire danger conditions, respectively. The regression equation we obtained from their answers to the probability of fire spread for a line ignition gives probabilities around 80% for all those combinations of time since fire and the FWI component, except for the last one for which the probability was approximately 60%.

More than 51% of the respondents reported that they have observed, or heard of, a jack pine stand younger than 15 years since fire burning in Canada. This percentage climbed to 67% for stands between 16 and 30 years since fire. Although their answer to those questions was partly influenced by the location of their assignments during their career, it indicated that stands younger than 16 years since fire can burn, which is in accordance with other results presented in this document. However generalisations must be made with caution since not all areas will regenerate in the same way. Where grass or other flammable vegetation grows early during stand development, surface fires are more likely, especially when the degree of curing is high. Experts report surface fires in such areas only a few years after a stand-replacing crown fire. In our study area, grass was present but not in great abundance in the regenerating stands. This difference between areas might be the cause of some of the variation we noted in the experts' answers for young stands.

Agreement Between Experts

In general, the experts agreed more in their answers for situations involving older stands and drier weather conditions or younger stands and moister weather conditions. In contrast, their answers covered a larger range of values for young stands under dry conditions (except for torching and crowning) and for old stands under moist conditions. This pattern held for all the variables assessed in this survey. Although these latter conditions may not be the ones that generally lead to extreme fire behavior, the gap we identified in our knowledge of their influence on fire behavior may be important. We could use those conditions to our advantage if we knew more what to expect in given situations. To provide a better understanding of flammability and fire behavior under those conditions it would be beneficial to document any type of fire (experimental, prescribed, wildfire) occurring under them.

The variability in the experts' answers cannot, however, all be attributed to a gap in our knowledge. It is also possible that the experts made different assumptions when answering the questions, despite the efforts we made to provide them with as much data as possible. This is a disadvantage of the self-administered questionnaire versus an interview situation where the researcher can ask further questions to each expert on his thought processes while answering each question.

Moreover, it is not unusual to observe some variation between predicted and observed fire behavior. Brown (1978) reported that, given a description of the fuels in a stand, rate of spread and intensity can commonly vary from predicted values by 0.5 to 2 times. Differences between 0.25 and 4 times are to be expected, and once in a while observed values could be 0.1 or 10 times the predicted values. Predictions within a factor of two of observed fire behavior are however generally considered relatively good (Albini 1976). Although they were considered as experts, the level of expertise of all the respondents was not the same. This could also be a contributing factor to the different answers obtained for each question. To cite Gisborne (1948):

> *"For what is experienced judgement except opinion based on knowledge acquired by experience? If you have fought forest fires in every different fuel type, under all possible different kinds of weather, and if you have remembered exactly what happened in each of these combinations of conditions, your experienced judgement is probably very good. But if you have not fought all sizes of fires in all kinds of fuel types under all kinds of weather then your experience does not include knowledge of all the conditions."*

SUMMARY AND CONCLUSION

Of the 133 fire behavior experts we contacted, 46 answered our questionnaire. A quadratic response surface model with time since fire and the Fire Weather Index component of the FWI System as independent variables explained between 95 to 98 % of the variation in each of the dependent variables on which the experts were questioned: probability of fire spread (for a point or a line source ignition fire), rate of spread, flame length, and crowning or torching categories.

In general, the experts agreed more in their answers for situations involving older stands and drier weather conditions or younger stands and moister weather conditions. In contrast, their answers covered a larger range of values for young stands under dry conditions and for old stands under moist conditions. This may suggest poorer knowledge of fire behavior under those conditions and a need for more documentation of fires (prescribed, experimental, wildfire) occurring under them.

Modelling of the experts' answers indicated that all dependent variables generally increased both with time since fire and with the severity of the weather conditions and there was often a significant interaction between these two independent variables. At low values of each one of the independent variables variation in the other independent variable had generally less influence on a given dependent variable. In other words, the experts answers suggested that under moist conditions time since fire does not affect much the dependent variables (e.g., rate of spread, flame length, etc.) and in very young stands, the dependent variables are not much affected by a change in fire weather and fire danger conditions.

The survey indicated that fire originating from a point source ignition would not spread through a stand of the jack pine/black spruce forest type before it reached at least 4 years since fire or a FWI of 11, which indicated that minimum conditions would have to be slightly drier than our "moist" weather scenario in order for fire spread to occur. Looking at specific fire weather/fire danger scenarios, the results suggested that under the "moderate" fire danger scenario, the 50% probability of fire spread is reached after approximately 8 years, while under the "dry" and "extreme" fire danger scenarios a stand must be more than 4 years. For the line source ignition, the survey indicated that fire spread is possible under moist weather conditions after approximately 17 years. At the "moderate", "dry", and "extreme" fire weather/fire danger scenarios a stand would need to be 5, 4, and 3 years old, respectively, to reach the 50% probability of fire spread.

Those values for probability of fire spread differed, however, from those provided by the experts when asked directly if they expected fire spread to be possible in a stand of given age after a stand-replacing fire. Their answer was then 9, 10, 20, and 35 years under "extreme", "dry", "moderate", and "moist" weather conditions, respectively. Those ages correspond to probabilities of fire spread around 80% for a line source ignition fire, except that last one which corresponds to a probability of 60%.

Rate of spread and flame length were also modelled as a function of time since fire and fire danger conditions. Our results indicated that the experts may have underestimated the rate of spread and flame length of crown fires for conditions specified in our survey, although within the factor of two generally considered acceptable in fire behavior predictions (Albini 1976). The estimated flame lengths were however generally consistent with the corresponding rate of spread estimated by the experts under given fuels and weather conditions.

Finally, the results from the survey suggested that some vertical fire is possible approximately 11 years after a stand-replacing fire in the fuel type studied in this project, but only under "dry" and "extreme" weather conditions. The results also indicated that although most understory and occasional overstory trees are likely to torch around 12 to 13 years after a stand-replacing fire under "moderate" to "extreme" fire weather/fire danger conditions, sustained crowning becomes likely only after 25 years. Intermittent crowning is, however, possible earlier during stand development, after approximately 13 and 15 years under extreme and dry conditions, respectively. At any time since fire, "moderate" fire weather/fire danger conditions (Table 5-1) must at least be reached before some torching or crowning activity can be expected.

Although expert opinion is generally used when the information needed is not readily available from other sources, the approach has limitations that may prevent its indiscriminate use in the development of fire behavior guides. In this project, most of the results were in concordance with those obtained from experimental reburns (Chapter 4) and fire behavior models (Chapter 6), which adds to our confidence in their use. However, the wide range of answers collected from the experts in some situations indicated that experts do not always agree. Interestingly, that variation in their answers was not constant, nor did it appear to be random. We opted to present it as a function of both time since fire (fuel scenario) and fire danger. Although the approach may have emphasised the variation in the experts' answers compared to other studies involving expert opinion, it also had the function of pointing to more specific areas where experts did not agree and where our current knowledge of the topic may be less.

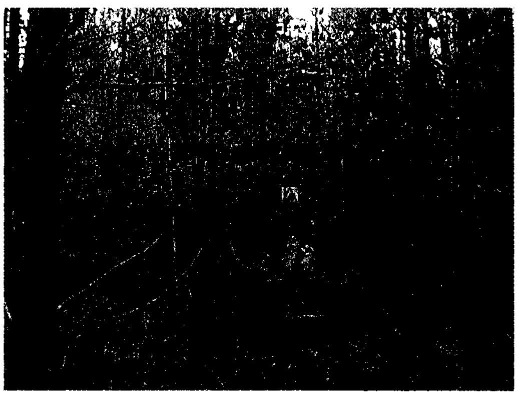
Unfortunately, we could not compare our observations on the variability of the experts' answers in this project to the one generally present in similar studies. The integration of expert judgement to fire behavior research takes many aspects and, to our knowledge, none of the results published to this day are directly comparable to the ones we obtained both for the variation in the experts' answers and for the fire behavior variables. Moreover, the variation in the experts' answers is not always explicitly mentioned in fire behavior or fire management publications that used an expert judgement approach.

The main finding in this project was probably the one related to the probable age of reburn in young stands and it was supported by the experimental reburns we ignited under relatively dry fire danger conditions. The modelled answer for each variable was also quite valuable as it helped us bridge the data from different sources (experimental fires and fire behavior models).

Although expert judgement can be very valuable in situations like the one we were facing for this project, we must not forget when we use its results that experts are human and, as such, are limited by their knowledge and their experiences. Moreover, the faculty of transforming those into wisdom is not the same for everyone. Experts are also not immune to bias and to false assumptions. A better approach for future projects similar to this one may be one where the researcher can interact directly with the expert in an individual interview, preferably in the field. However, this would require much more resources and may limit the number of experts that participate in the project.

(a) 3 years since fire

(b) 5 years since fire



(c) 21 years since fire

(d) 57 years since fire

(e) 71 years since fire

(f) 109 years since fire

Figure 5-1. Sample photo of each of the stands presented to the experts in the questionnaire.

Table 5-1. The Fire Weather Index System component value combinations for the four fire weather/fire danger scenarios presented to the experts in the questionnaire according to Horn's (1976) general classification.

Fire Weather System Components	"Extreme"	"Dry"	"Moderate"	"Moist"
Fine Fuel Moisture Code (FFMC)	95	92	87	83
Duff Moisture Code (DMC)	160	93	39	20
Drought Code (DC)	514	492	325	142
Initial Spread Index (ISI)	24	16	8	4
Buildup Index (BUI)	180	127	60	30
Fire Weather Index (FWI)	66	46	20	9

Table 5-2. Definition of the rate of spread, torching and crowning categories used in the expert opinion survey.

Rate of spread categories	
Nil	Fire cannot sustain itself.
Very slow	Spread will be generally discontinuous, with maximum ROS less than 0.1 m/min.
Slow	Spread will be occasionally discontinuous, with maximum ROS 0.1 - 1.0 m/min.
Moderately slow	Spread will be continuous with maximum ROS 1.1 - 3.0 m/min.
Moderately fast	Spread will be continuous with maximum ROS 3.1 - 10.0 m/min.
Fast	Spread will be continuous with maximum ROS 10.1 - 18.0 m/min
Very fast	Spread will be continuous with maximum ROS 18.1 - 25.0 m/min
Extremely fast	ROS exceeds 25.0 m/min
Torching categories	
Nil	No chance of torching
Low	Occasional tree may torch-out
Medium	Pole-sized understory tree likely to torch-out
High	Most understory and occasional overstory trees likely to torch-out
Extreme	Entire stand likely to torch out
Crowning categories	
Nil	Sustained spread in crowns will not occur
Low	Sustained spread in crowns unlikely
Medium	Some crowning likely but will not be continuous
High	Sustained crowning likely
Extreme	Sustained crowning will occur

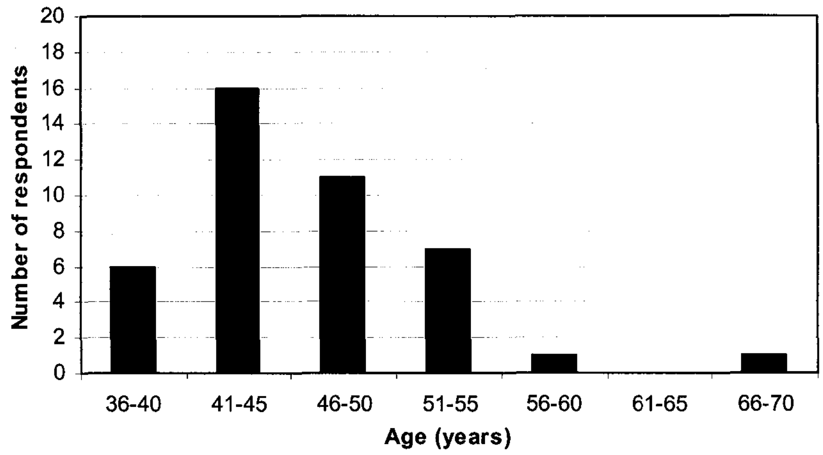


Figure 5-2. Number of respondents in each 5-year age group.

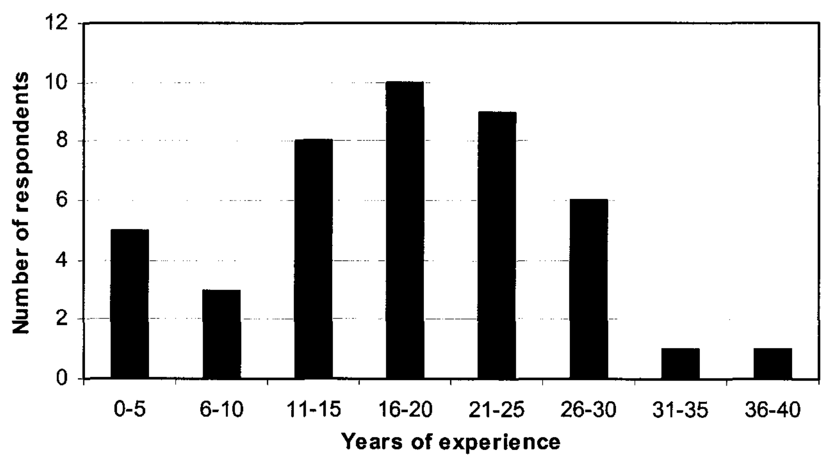


Figure 5-3. Number of respondents in each 5-year experience group. The graph includes the 43 respondents retained for the analyses in the sections of the project requiring expert opinion and/or field observations (see Methodology for further details).

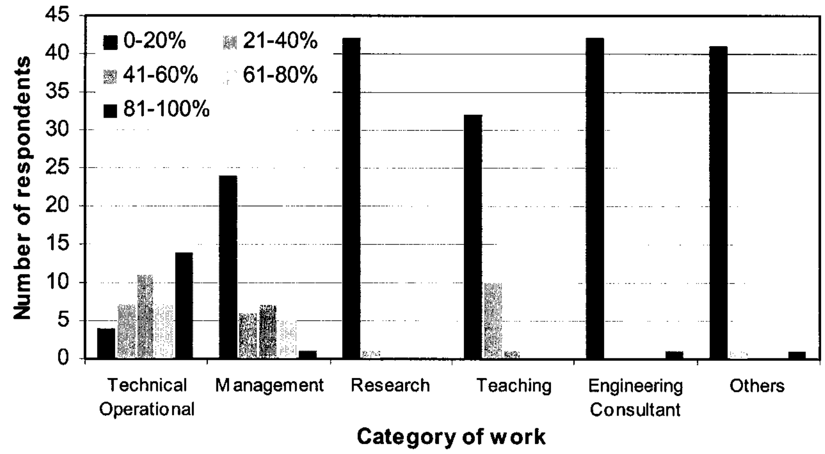


Figure 5-4. Distribution of the respondents as a function of their percentage (20-percent classes) of working time related to each category of work.

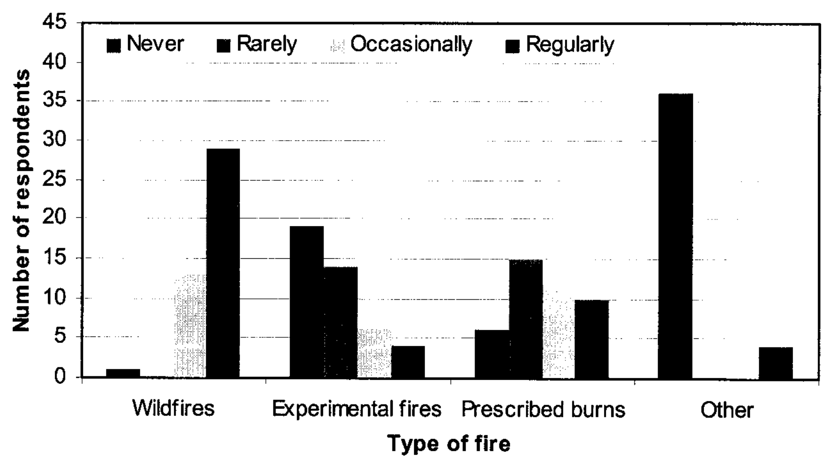


Figure 5-5. Distribution of the respondents as a function of the frequency (never, rarely, occasionally, or regularly) with which they predict, observe, or document fire behavior during different types of fire situations.

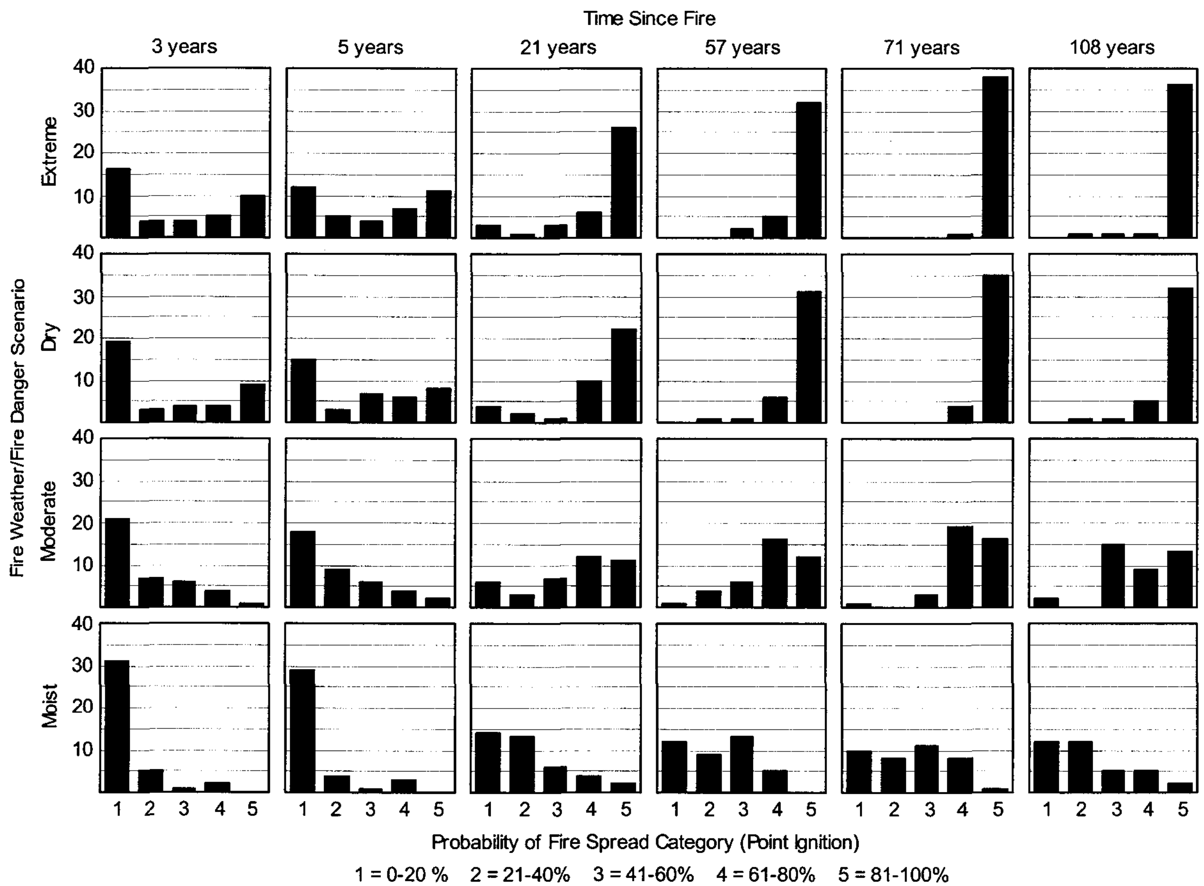


Figure 5-6. Summary of the number of respondents who answered in each probability class of fire spread (for a point ignition) for the 24 (6 fuel complex scenarios x 4 fire weather/fire danger scenarios) situations presented in the questionnaire.

Table 5-3. Median and semi inter-quartile range (for each fire weather/fire danger scenario and time since fire (stand) on which the experts were questioned) of the: probability of fire spread for a point and a line ignition, rate of spread, flame length, torching category, and crowning category.

Variable	Unit	Fire weather/danger scenario	Time since fire											
			3		5		21		57		71		108	
			Med	SIQR	Med	SIQR	Med	SIQR	Med	SIQR	Med	SIQR	Med	SIQR
Probability of fire spread point ignition	%	Extreme	40	36	60	36	99	10	100	3	100	1	100	3
		Dry	30	34	50	33	90	13	100	6	100	5	100	6
		Moderate	20	24	25	23	70	19	75	16	80	10	75	20
		Moist	3	5	5	5	30	21	40	16	48	19	30	16
Probability of fire spread line ignition	%	Extreme	50	39	70	30	100	4	100	0	100	0	100	0
		Dry	40	38	60	33	100	8	100	3	100	0	100	0
		Moderate	25	30	35	29	85	16	90	13	90	8	90	10
		Moist	10	15	15	20	50	23	60	19	60	15	60	18
Rate of spread	m/min	Extreme	0.7	1.4	1.2	1.4	19.1	12.5	23.6	15.4	35.4	17.9	34.3	18.0
		Dry	0.2	0.8	0.7	1.1	12.5	9.4	19.3	5.9	21.0	4.2	18.4	5.7
		Moderate	0.0	0.2	0.1	0.3	3.7	3.4	6.4	3.7	9.2	5.4	5.0	4.1
		Moist	0.0	0.0	0.0	0.0	0.5	0.7	0.7	1.2	0.8	0.9	0.4	0.4
Flame length	m	Extreme	0.5	0.4	1.0	0.7	10.0	4.0	16.0	5.0	25.0	8.1	25.0	7.5
		Dry	0.5	0.4	0.6	0.6	7.0	3.5	12.0	5.9	20.0	7.0	20.0	8.8
		Moderate	0.2	0.2	0.5	0.2	2.5	1.3	5.0	3.6	8.0	6.0	6.0	6.9
		Moist	0.1	0.2	0.1	0.2	0.5	0.4	1.0	1.0	1.0	1.0	1.0	1.0
Torching category	Nil	Extreme	0.0	0.5	0.0	0.5	4.0	0.5	4.0	0.0	4.0	0.0	4.0	0.0
		Dry	0.0	0.0	0.0	0.3	3.0	1.0	4.0	0.5	4.0	0.0	4.0	0.5
		Moderate	0.0	0.0	0.0	0.0	2.0	1.0	3.0	0.5	3.0	0.5	3.0	1.0
		Moist	0.0	0.0	0.0	0.0	1.0	0.5	1.0	0.5	1.0	0.5	1.0	1.0
Crowning category	Nil	Extreme	0.0	0.0	0.0	0.0	3.0	0.5	4.0	0.0	4.0	0.0	4.0	0.0
		Dry	0.0	0.0	0.0	0.0	3.0	1.0	4.0	0.5	4.0	0.5	4.0	0.5
		Moderate	0.0	0.0	0.0	0.0	1.0	0.5	2.0	1.0	2.0	0.5	2.0	0.8
		Moist	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.5	0.0	0.5	0.0	0.5

NOTE: "Med" is median, and "SIQR" is semi inter-quartile range.

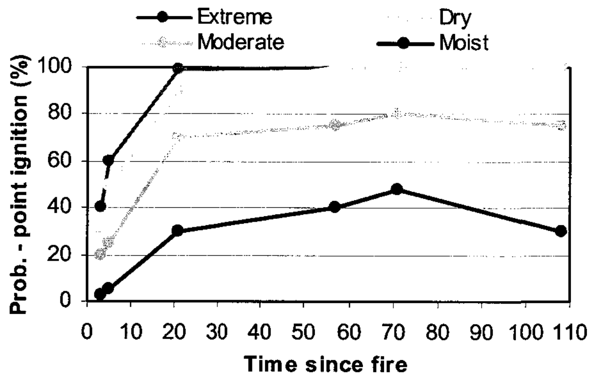


Figure 5-7. Median of the responses for probability of fire spread for a point ignition as a function of time since fire for each fire weather/fire danger scenario.

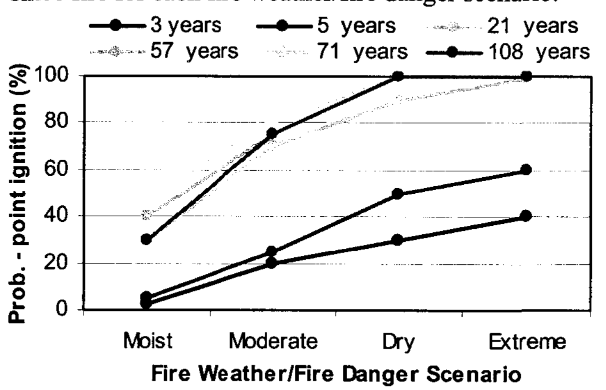


Figure 5-8. Median of the responses for probability of fire spread for a point ignition as a function of fire weather/fire danger conditions for each fuel complex scenario.

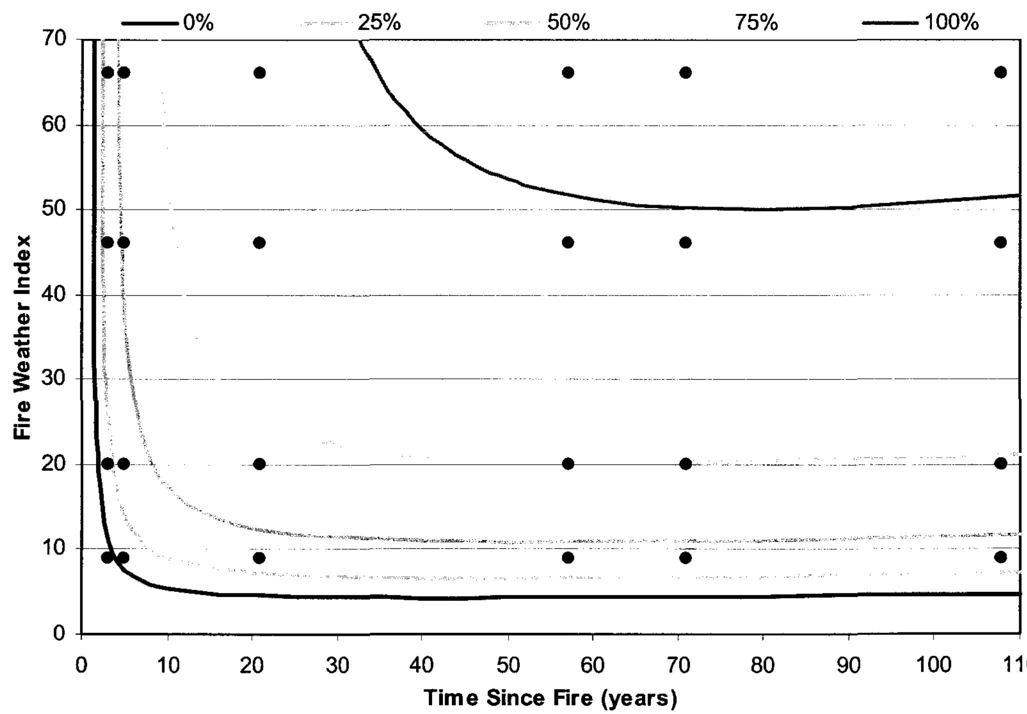


Figure 5-9. Modelled probability of fire spread (0, 25, 50, 75, and 100%) for point ignition as a function of time since fire and Fire Weather Index component based on medians of responses in the expert survey (the black dots are the (x_1, x_2) data points used for the regressions).

Table 5-4. Results of the regressions for the quadratic response surface model (equation 5-1) for different dependent variables.

Dependent Variable	R^2	R^2_{adj}	SE	Coefficients		p
Probability of fire spread point ignition (%)	0.98	0.97	5.69	a	-179.035	< 0.001
				b	40.831	< 0.001
				c	77.659	< 0.001
				d	3.115	0.012
				e	-6.079	< 0.001
				f	-9.171	0.005
Probability of fire spread line ignition (%)	0.98	0.97	4.98	a	-192.737	< 0.001
				b	56.986	< 0.001
				c	83.768	< 0.001
				d	-1.089	0.278
				e	-6.483	< 0.001
				f	-9.142	0.002
Rate of spread (m/min)	0.95	0.94	2.84	a	54.480	0.002
				b	-10.092	0.011
				c	-33.814	0.002
				d	4.759	< 0.001
				e	-0.170	0.750
				f	4.388	0.007
Flame length (m)	0.96	0.94	2.00	a	33.079	0.007
				b	-12.491	< 0.001
				c	-16.289	0.023
				d	3.543	< 0.001
				e	0.801	0.044
				f	1.801	0.089
Torching category	0.95	0.93	0.45	a	-4.413	0.088
				b	0.701	0.229
				c	1.850	0.226
				d	0.492	< 0.001
				e	-0.237	0.011
				f	-0.374	0.116
Crowning category	0.96	0.95	0.39	a	-1.696	0.430
				b	-0.812	0.110
				c	0.970	0.453
				d	0.686	< 0.001
				e	-0.112	0.134
				f	-0.279	0.168

Model: $\ln(Y) = a + b\ln(X_1) + c\ln(X_2) + d\ln(X_1)\ln(X_2) + e(\ln(X_1))^2 + f(\ln(X_2))^2$
Y = dependent variable, X_1 = time since fire, X_2 = Fire Weather Index, R^2 = coefficient of determination, R^2_{adj} = adjusted coefficient of determination, SE = standard error, p = probability

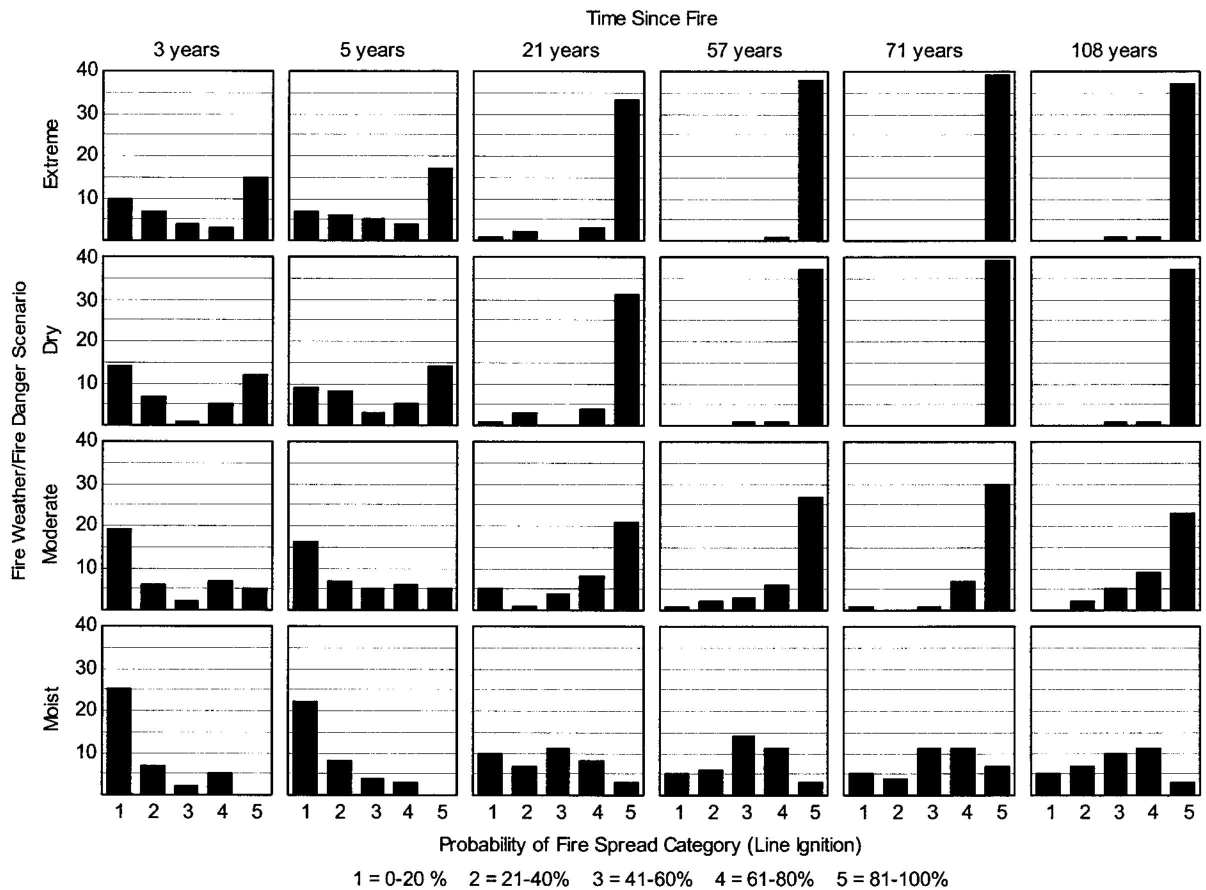


Figure 5-10. Summary of the number of respondents who answered in each probability class of fire spread (for a line ignition) for the 24 (6 fuel complex scenarios x 4 fire weather/fire danger scenarios) situations presented in the questionnaire.

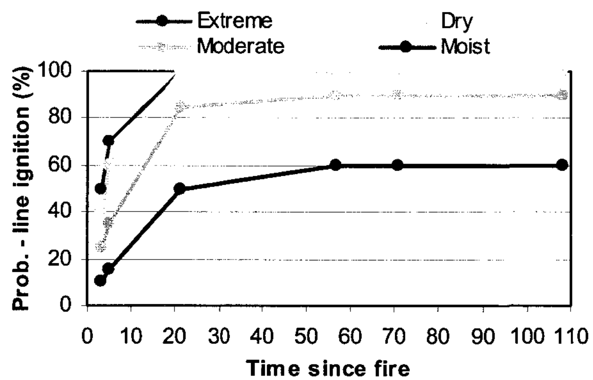


Figure 5-11. Median of the responses for probability of fire spread for a line ignition as a function of time since fire for each fire weather/fire danger scenario.

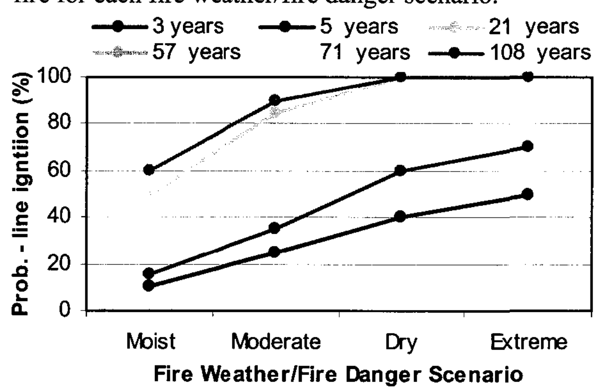


Figure 5-12. Median of the responses for probability of fire spread for a line ignition as a function of fire weather/fire danger conditions for each fuel complex scenario.

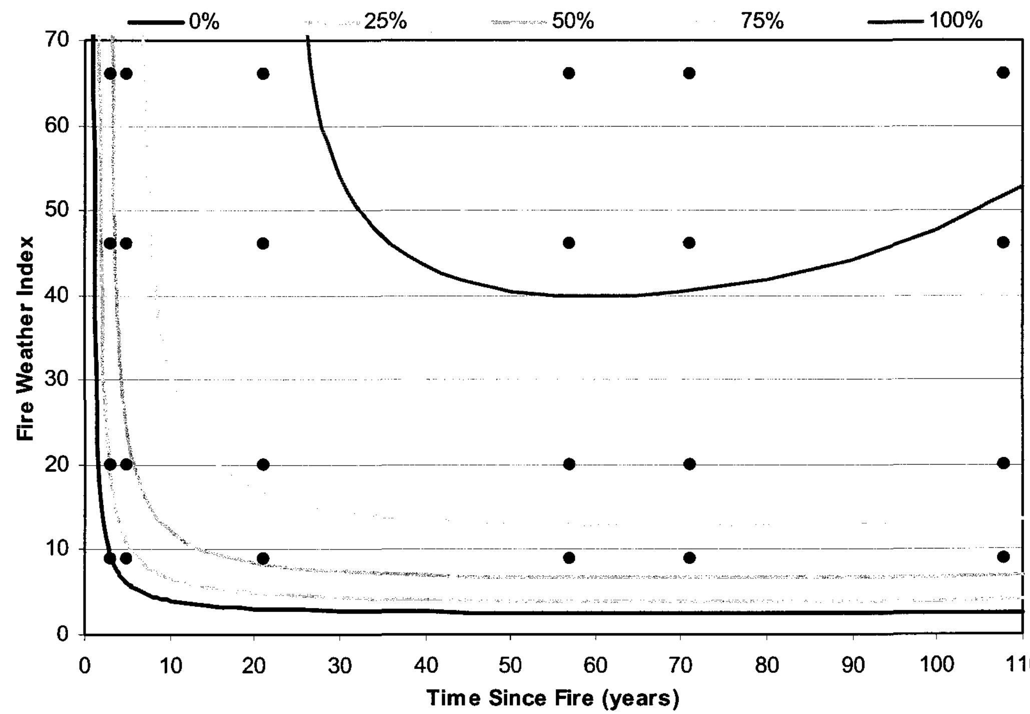


Figure 5-13. Modelled probability of fire spread (0, 25, 50, 75, and 100%) for a line ignition as a function of time since fire and Fire Weather Index component based on medians of responses in the expert survey (the black dots are the (x_1, x_2) data points used for the regressions).

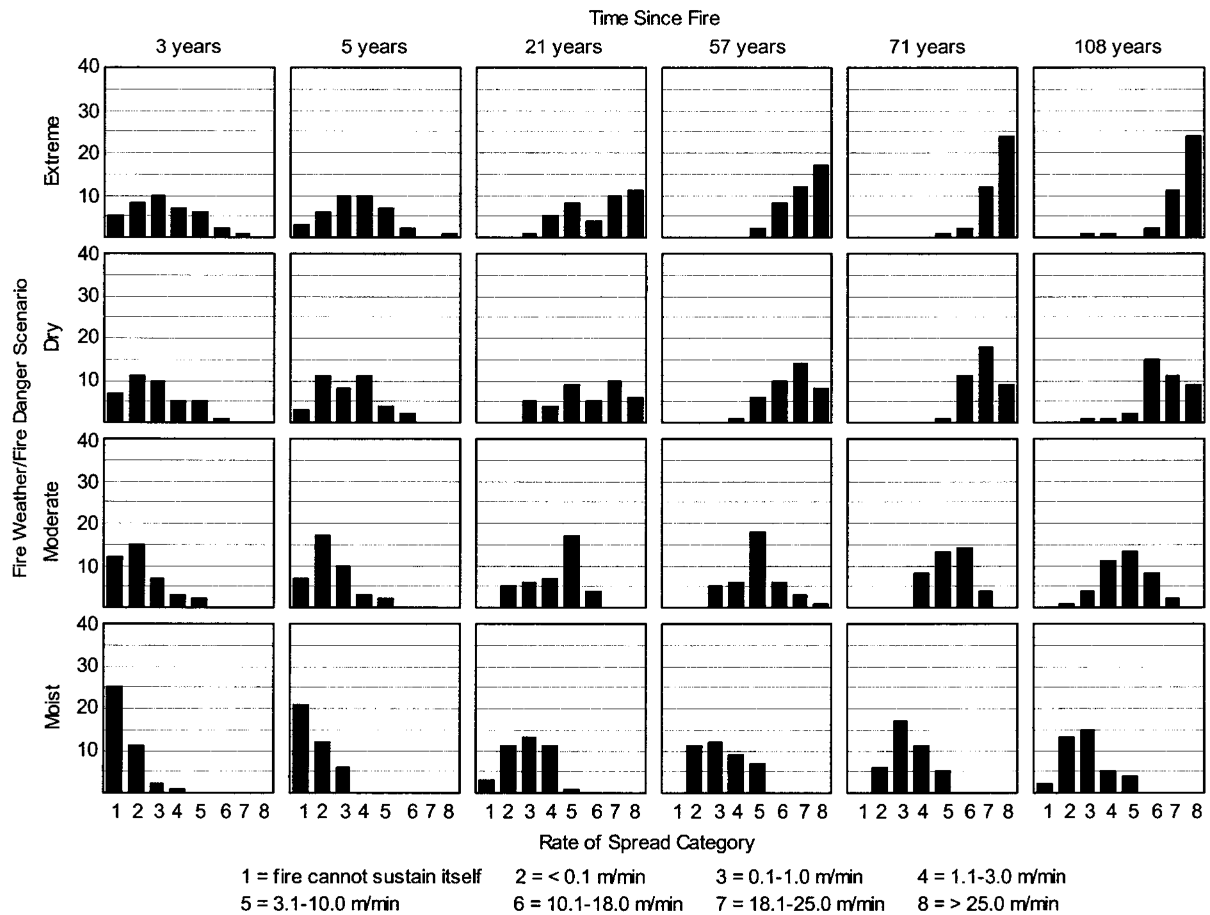


Figure 5-14. Summary of the number of respondents who answered in each rate of spread category for the 24 (6 fuel complex scenarios x 4 fire weather/fire danger scenarios) situations presented in the questionnaire.

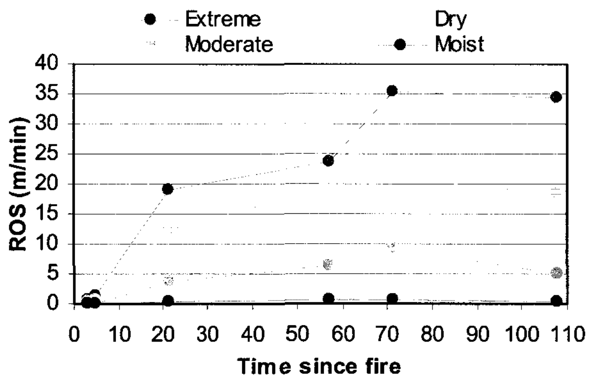


Figure 5-15. Median of the responses for rate of spread as a function of time since fire for each fire weather/fire danger scenario.

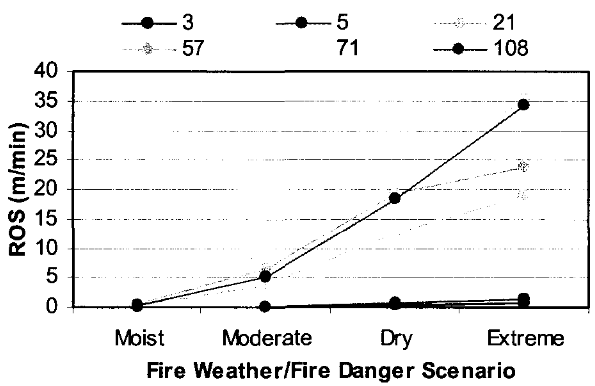


Figure 5-16. Median of the responses for rate of spread as a function of fire weather/fire danger conditions for each fuel complex scenario.

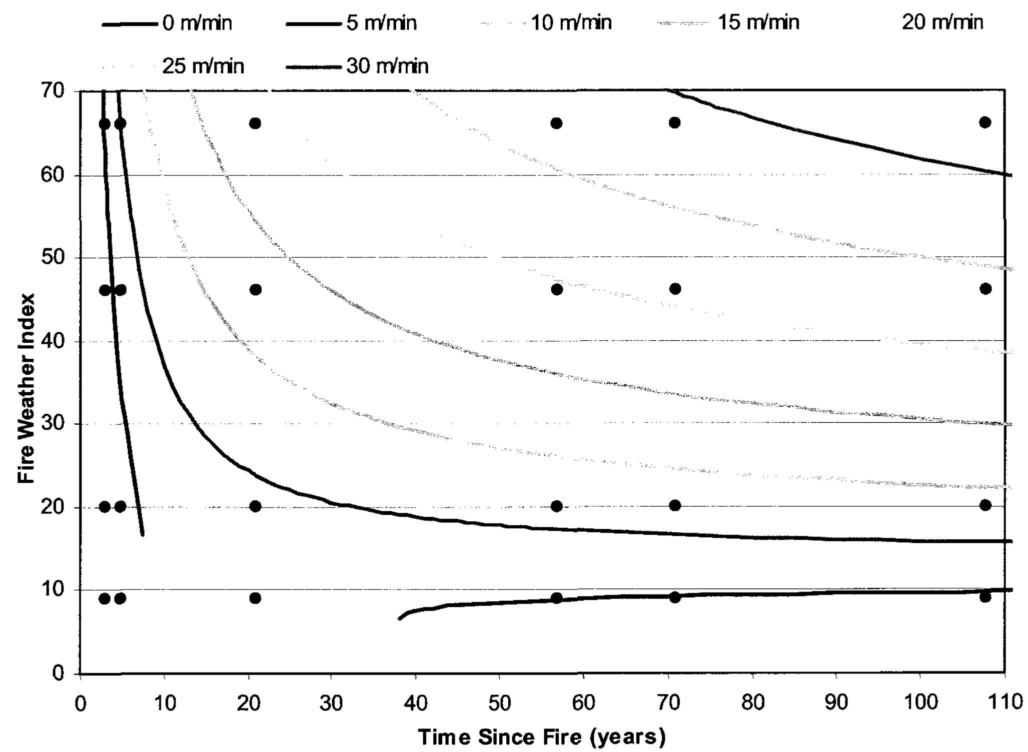


Figure 5-17. Modelled rate of spread (0, 5, 10, 15, 20, 25, and 30 m/min) as a function of time since fire and Fire Weather Index component based on responses to the expert survey (the black dots are the (x_1, x_2) data points used for the regressions).

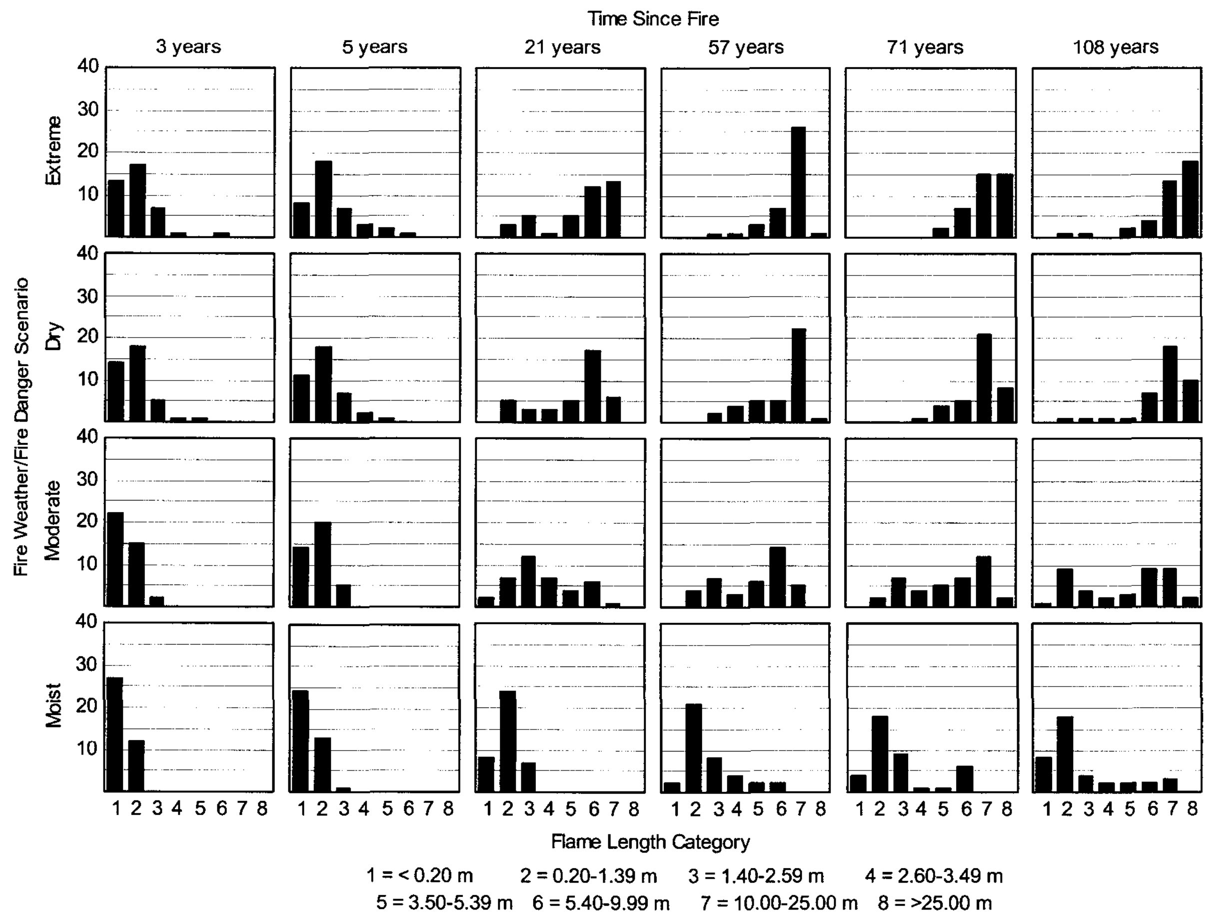


Figure 5-18. Number of experts who selected each flame length category for each of the 24 questions (6 times since fire x 4 fire weather/fire danger scenarios) related to that variable in the survey.

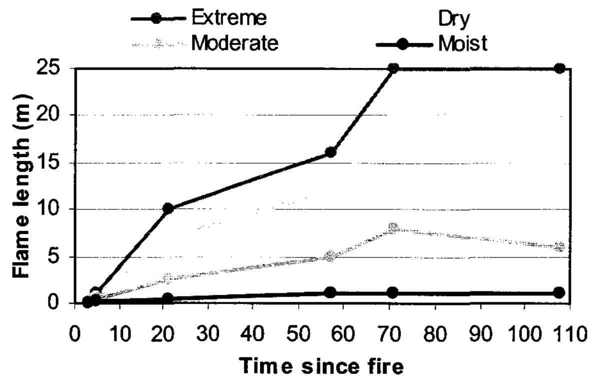


Figure 5-19. Median of the responses for flame length as a function of time since fire for each fire weather/fire danger scenario.

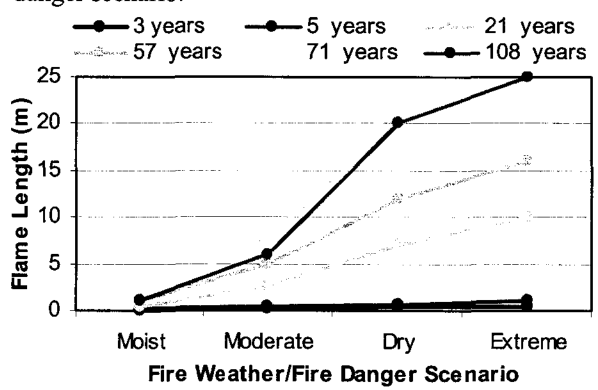


Figure 5-20. Median of the responses for flame length as a function of fire weather/fire danger conditions for each fuel complex scenario.

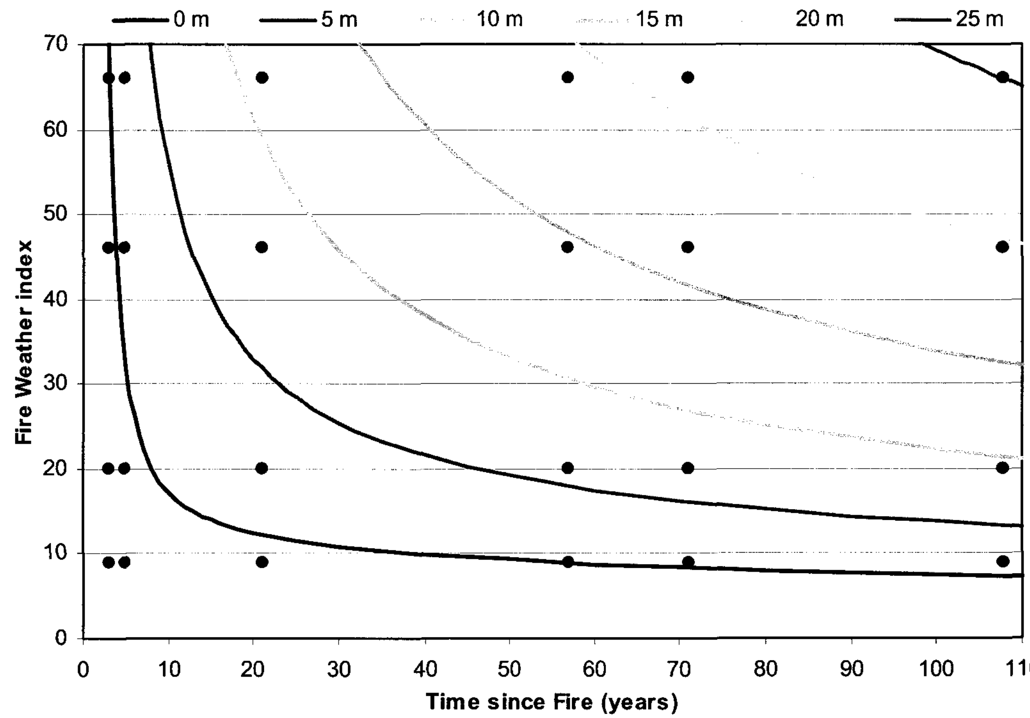


Figure 5-21. Model of flame length (0, 5, 10, 15, 20, and 25 m) as a function of time since fire and Fire Weather Index component based on responses to the expert survey (the black dots are the (x_1, x_2) data points used for the regressions).

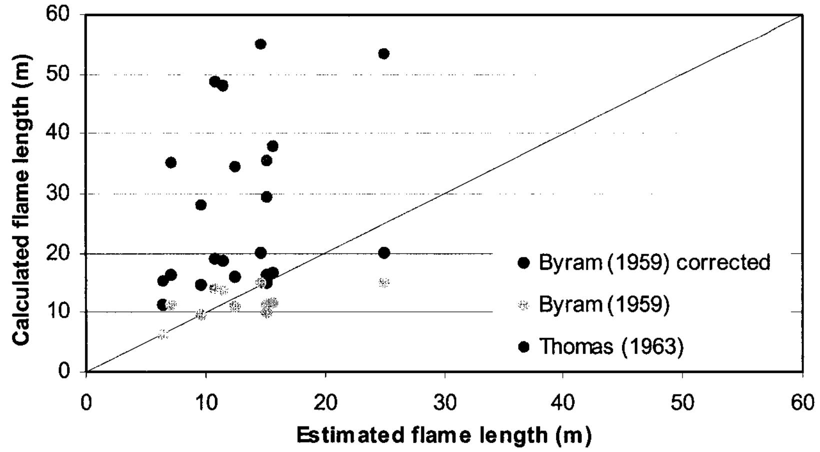


Figure 5-22. Flame length of the ICFME crown fires (Stocks *et al.* 2004) calculated from frontal fire intensity using equations from Byram (1959) (corrected and uncorrected) and Thomas (1963) compared to flame length estimated from the equation for that variable in Table 5-4.

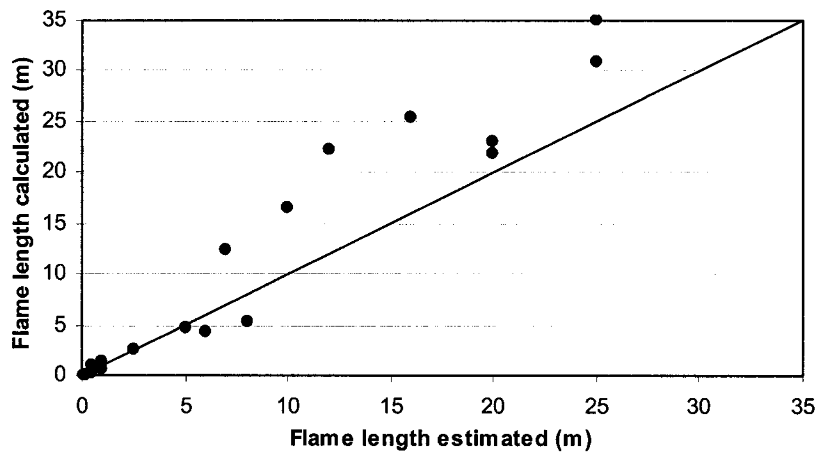


Figure 5-23. Comparison of flame length as calculated from the rate of spread estimation and the flame length directly estimated by the experts in the survey (the line indicates perfect agreement between both values).

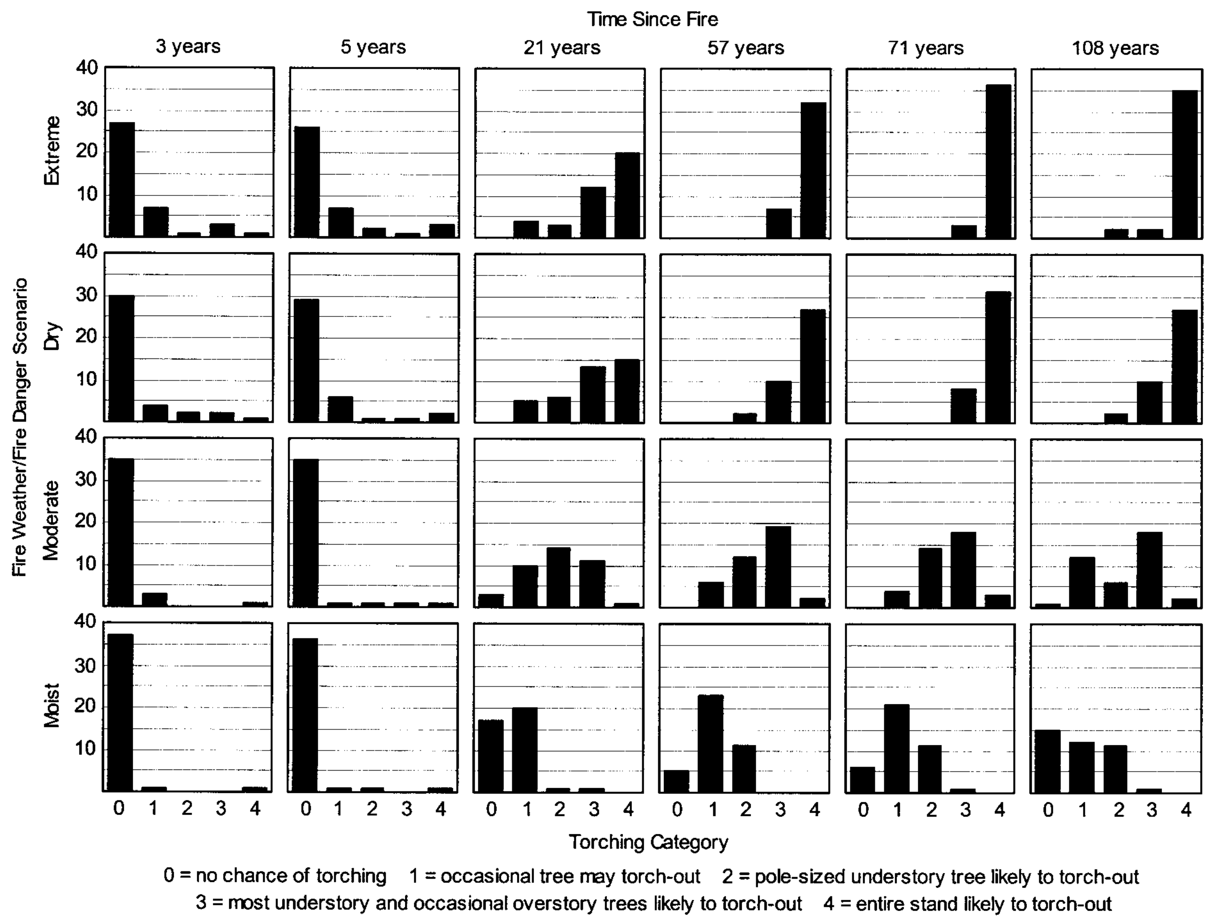


Figure 5-24. Number of experts who selected each torching category for each of the 24 questions (6 times since fire x 4 fire weather/fire danger scenarios) related to that variable in the survey.

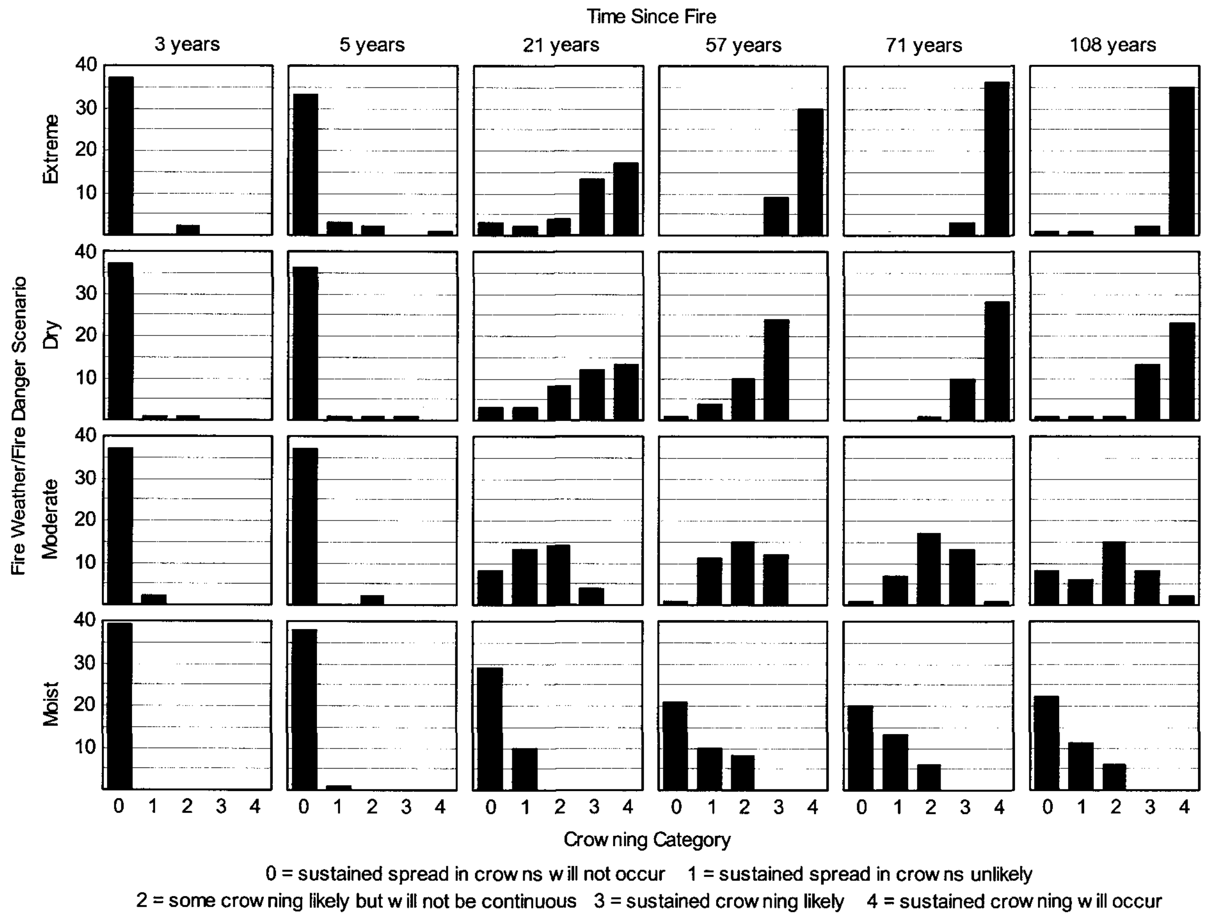


Figure 5-25. Number of experts who selected each crowning category for each of the 24 questions (6 times since fire x 4 fire weather/fire danger scenarios) related to that variable in the survey.

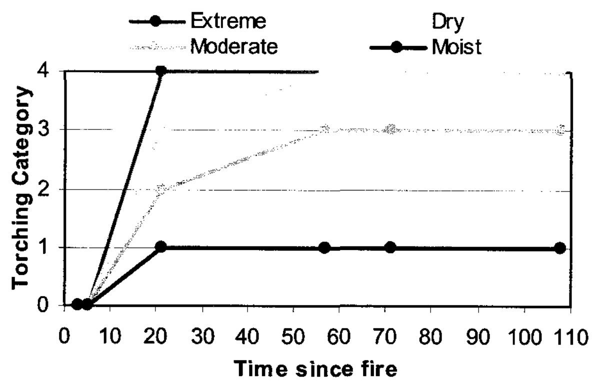


Figure 5-26. Median of the responses for torching category as a function of time since fire for each fire weather/fire danger scenario.

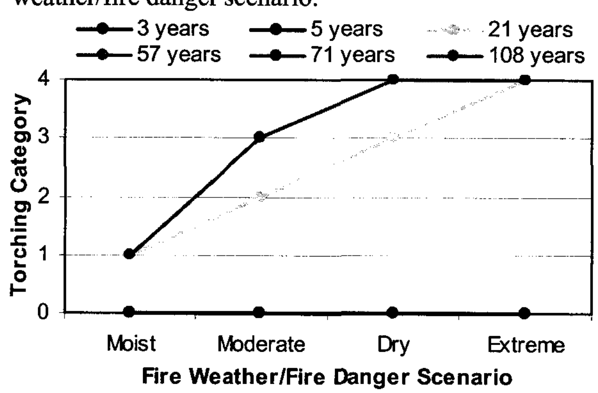


Figure 5-27. Median of the responses for torching category as a function of fire weather/fire danger conditions for each fuel complex scenario.

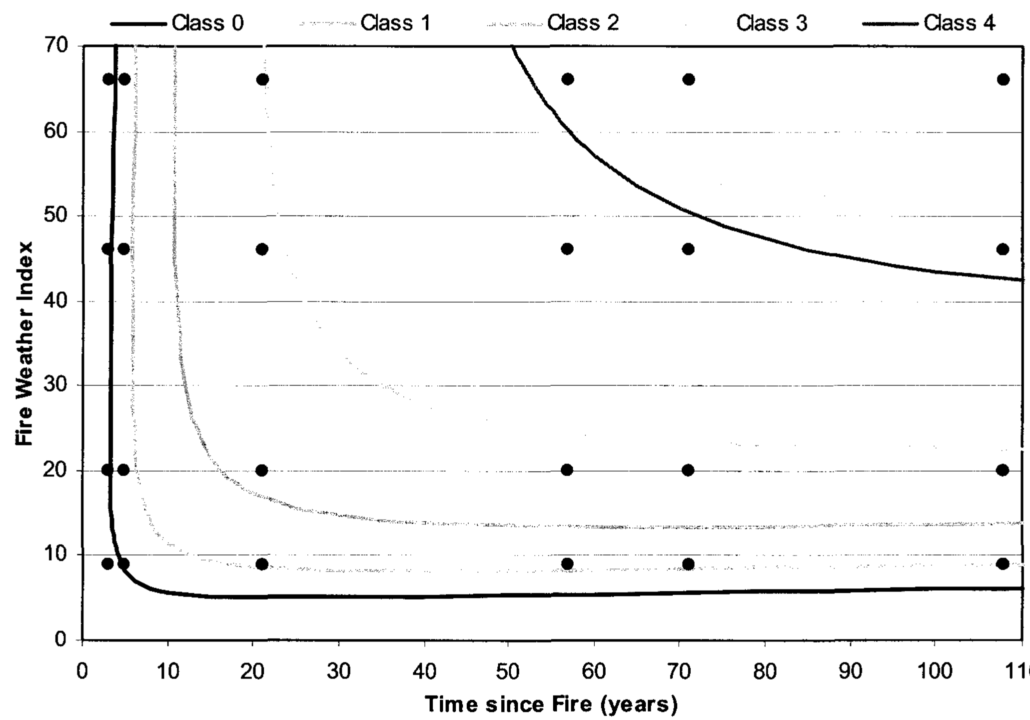


Figure 5-28. Modelled torching category (0, 1, 2, 3, and 4) as a function of time since fire and Fire Weather Index component based on responses to the expert survey (the black dots are the (x_1, x_2) data points used for the regressions).

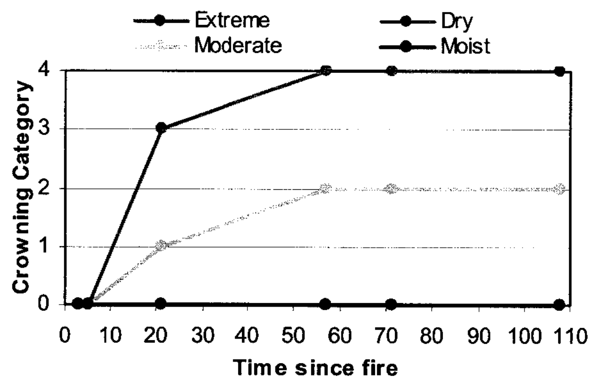


Figure 5-29. Median of responses for the crowning category as a function of time since fire for each fire weather/fire danger scenario.

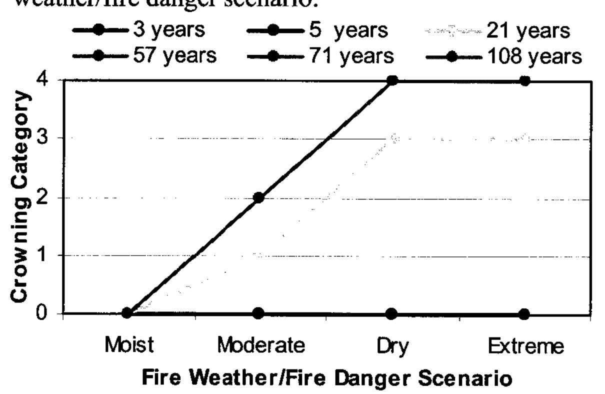


Figure 5-30. Median of the responses for crowning category as a function of fire weather/fire danger conditions for each fuel complex scenario.

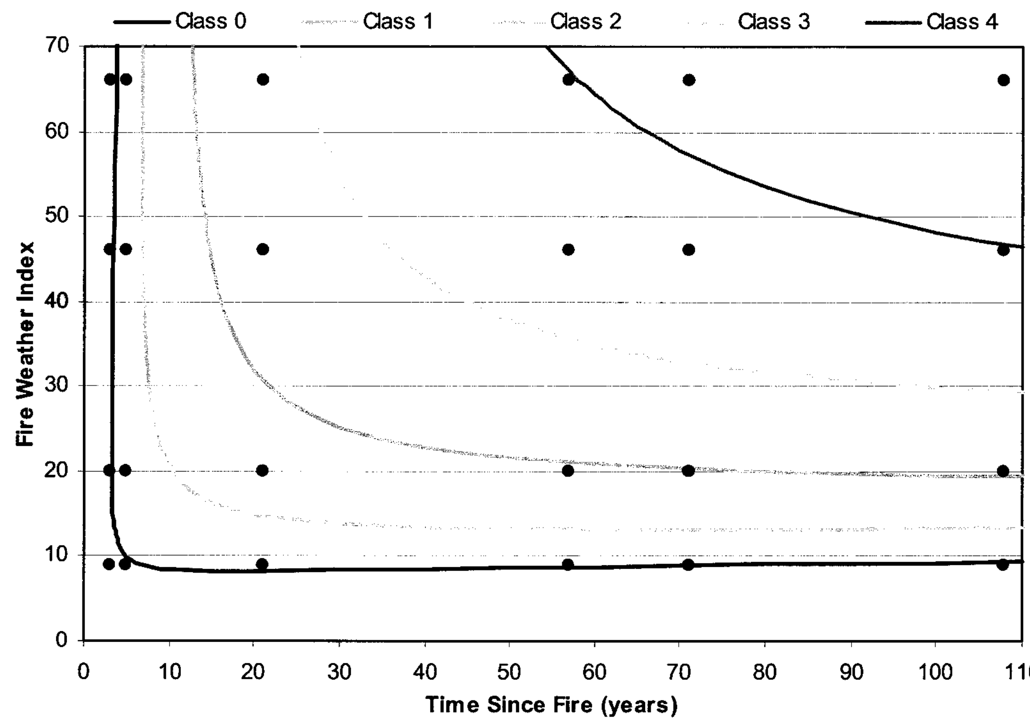
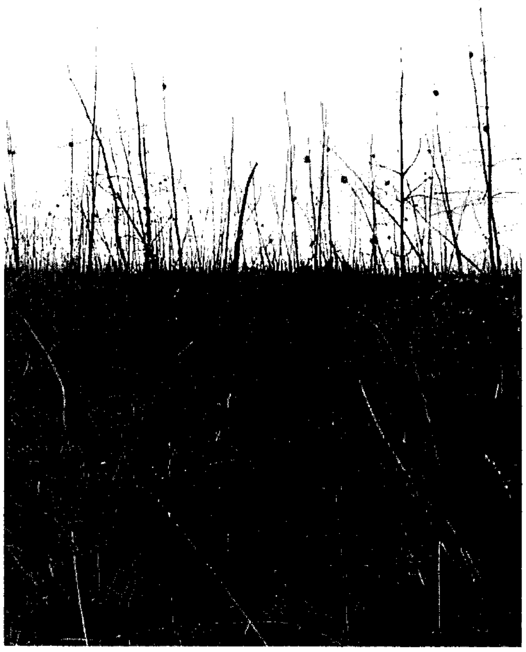
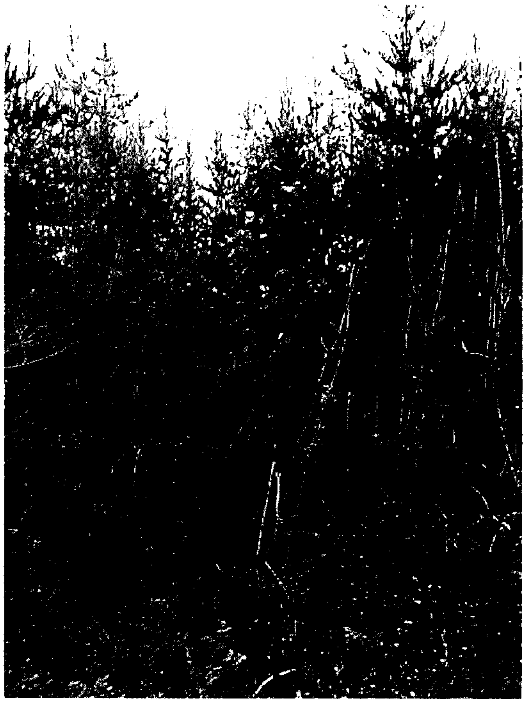


Figure 5-31. Modelled crowning category (0, 1, 2, 3, and 4) as a function of time since fire and Fire Weather Index component based on responses to the expert survey (the black dots are the (x_1, x_2) data points used for the regressions).



(a) Dead jack pine trees killed in the reburn. Some trees had already started to have cones when the fire occurred.



(b) Edge of the reburn area with live jack pine trees behind the dead jack pine trees (originally from the same stand).

(c) Forest floor in the reburn area with an abundance of shrub and deciduous tree seedlings.

Figure 5-32. Photos of a jack pine stand that burned approximately 15 years after a stand-replacing crown fire in our study area. (photos taken 5 years after the reburn).

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CHAPTER 6

Variation in flammability and potential fire behavior through stand development in jack pine/black spruce forests of the Northwest Territories: a model based on expert judgements, experimental fires and simulation data

Introduction

In the boreal forest of Canada, the typical fire regime is one of long interval crown fires, or severe surface fires, that kill entire stands and result in their total replacement (Heinselman 1978, 1981a, 1981b; Van Wagner 1979; Heathcott and Cornelsen 1992; Bonan and Shugart 1989; Epp and Lanoville 1996). The ensuing landscape is composed of a mosaic of stands of different times since the last fire which, given the right conditions, will eventually burn again. Although knowledge of the conditions that determine if and when a stand will reburn is essential for judicious management of our boreal ecosystems, they are generally not systematically nor quantitatively documented.

Over the years, several researchers have attempted to answer this challenging question, directly or indirectly, for several areas and vegetation types (e.g., grasslands (Morgan and Lunt 1999); chaparral (Minnich and Chou 1997); banksia low woodlands (Burrows and McCaw 1990); eucalypts (Raison *et al.* 1983); slash pine-palmetto stands (McNab *et al.* 1978); giant sequoia forests (Parson 1978); lodgepole pine forests (Muraro 1971; Brown 1975); Scots pine forests (Schimmel and Granström 1997); western hemlock/Douglas-fir forest (Agee and Huff 1987); western redcedar (Habeck 1985); mixedwood forests (Hély *et al.* 2000); subalpine forests (Romme 1982)) obtaining different answers. Researchers also have tried to find a definite answer as to which component of the fire behavior triangle is driving the variation in flammability of stands with stand age. Again results differed and Agee (1997) eventually grouped them according to two hypotheses: the "fuel hypothesis" and the "weather hypothesis".

The fire behavior triangle represents the three interacting components of the fire environment that influence fire behavior: fuels, fire weather, and topography. Variation in any one of those components will bring observable changes in fire behavior. An approach that considers interactions between the different components of the fire environment could be one of overlapping gradients. Fuels, weather and topography vary both spatially and temporally, albeit on different scales. Marked differences in the state of all three components are observed as one moves through the landscape. However, only fuels and weather are likely to vary with time, with topography usually considered static in the time frame dictated by the question of interest introduced above.

In the concept of overlapping gradients as intended here, an area is subject to temporal variation of both fuels and weather. From a fire perspective, the resulting effect of those gradients is best described in terms of flammability, the interaction between plant communities and environment over time (Mutch 1970; Habeck and Mutch 1973; Troumbis and Trabaud 1989).

Below a certain site-specific flammability threshold, a fire cannot sustain itself without a sustained ignition source. This is due to limitations imposed by the fuels gradient, the weather gradient, or an interaction of both. Eventually, under conditions that increasingly favour combustion, flammability will reach a threshold above which a fire has the potential to start and spread, given an ignition source. As the conditions progress above that limit, the flammability varies and the behavior of the fire is affected accordingly by the fire environment. The overlapping gradients approach has a multi-dimensional character that is difficult to represent and to work with in an applied research context. Fortunately, a hypothetical model presented by Horn (1976) provides a means to overcome that difficulty by bringing back the concept to a two-dimensional representation (Figure 6-1).

Horn's model describes an increase in flammability with time since fire during which thresholds of combustion occur at younger ages with increasingly extreme drought periods. The intrinsic shape (a sigmoidal curve was represented) of the flammability curve in that model is said to be related to vegetation development after a fire, and the temporal pattern of fires depends as much upon it as on the temporal pattern of droughts that favour fires.

The main objective of the present study was to describe the variation in flammability (and potential fire behavior) as a function of time since fire for jack pine/black spruce stands located in the Hay River district, Northwest Territories (Canada). The hypothesis considered in this project was that the flammability of jack pine/black spruce stands in the study area varies according to the hypothetical model presented by Horn (1976).

METHODOLOGY

The development through time of the forest type studied in this project was previously described (see Chapter 2) through a chronosequence approach where detailed inventory data on the structure and composition of stands between 1 and 108 years since fire were obtained. Detailed information on the fuels as they vary through time was therefore available but still needed to be appraised in terms of potential fire behavior and flammability.

Anderson (1974) and Brown (1978) suggested that an interpretation of fuels in terms of potential fire behavior and flammability should incorporate: (1) experienced judgement; (2) comparison to referenced fuel and vegetation; and (3) mathematical models of fire phenomena. We chose to adopt this approach where limited resources forced us to consider means other than the ideal scenario of replicated simultaneous fires, burning in stands of different time since fire covering the entire continuum of stand development, and ignited under a wide range of weather and drought conditions.

The variation in flammability as a function of time since fire was therefore assessed through the combined use of fire behavior models, experimental fires (see Chapter 4), and the results of an expert opinion survey (see Chapter 5) in relation to the fire weather/fire danger scenarios identified in Chapter 3. Although the following discussion focuses more on the fire behavior modelling, results and conclusions from the experimental fires and the expert opinion survey, the two other sources of fuel appraisal, were integrated in the discussion whenever appropriate. A summary of the methodology used in this project is presented in Figure 6-2.

POTENTIAL FIRE BEHAVIOR

Very few fire behavior models allow the user to make predictions on both surface and crown (intermittent and continuous) fire behavior. The Canadian Forest Fire Behavior Prediction (FBP) System (Forestry Canada Fire Danger Group 1992), which is used operationally in Canada, is one which does. Unfortunately, the mature jack pine/black spruce forest type studied in this project cannot readily be related to any of the seven coniferous fuel types included in the FBP System.

The FBP System has mature and immature jack pine fuel types but the presence of a substantial black spruce understory in our stands is suspected to lead to a different fire behavior than the one predicted in the jack pine fuel types of the FBP System. This was partially confirmed, at least for the portion of our chronosequence (Chapter 2) around 70-75 years since fire, by the fire behavior observed during the International Crown Fire Modelling Experiment (ICFME) project (Stocks *et al.* 2004). A new fuel type that represents the jack pine – black spruce fuel complex (Alexander *et al.* 2004) may eventually be added to the FBP System based on the results of the experimental fires carried out during International Crown Fire Modelling Experiment (Stocks *et al.* 2004) and on further experimental fires performed to cover the surface portion of the fire behavior spectrum, but it is presently not available (M.E. Alexander, personal communication). Another reason why we chose not to use the FBP System in this project is the fact that it only covers two periods of stand development (immature and mature pine stand) while this study is concerned with the whole period between two stand-replacing fires.

We therefore had to consider other models for this project. Rothermel's (1972) model is the basis, in part, for many fire behavior prediction systems in the United States such as the BEHAVE fire behavior prediction system (Rothermel 1983; Burgan and Rothermel 1984; Andrews 1986; Burgan 1987; Andrews and Chase 1989), the FARSITE fire area simulator (Finney 1998), NEXUS (Scott and Reinhardt 2001), and many more (Andrews and Queen 2001). It has been used extensively, in one form or another, to model fire behavior in studies similar to this one or in studies looking at changes in fire behavior associated with different management strategies (e.g., Philpot 1977; Sylvester and Wein 1981; Romme 1982; Habeck 1985; Brown and Simmerman 1986; Agee and Huff 1987; Bessie and Johnson 1995; Sapsis *et al* 1996; van Wagtendonk 1996; Schimmel and Granström 1997; Stephens 1998; Hély *et al.* 2001; Hummel and Agee 2003). Rothermel's (1972) model has also been used in the development of dynamic fuel models (Rothermel and Philpot 1973; Hough and Albini 1978). Rothermel and Rinehart (1983) listed several studies that compared data on observed and predicted (with the model) fire behavior in several fuelbeds (e.g., logging slash (Brown 1972; Bevins 1976), grass (Sneeuwjagt and Frandsen 1966), and southern rough (Hough and Albini 1978)) (Rothermel and Rinehart 1983). After re-examining the results of several of those studies, Andrews (1980) concluded that the mathematical fire model can be effectively used to predict fire behavior in wildland fuels. More specific to forest stands, Lawson (1972), Norum (1982), van Wagtendonk and Botti (1984), and Schimmel and Granström (1997) also compared observed versus predicted fire behavior variables and obtained relatively good results.

One of the systems that use Rothermel's (1972) surface fire model, the BEHAVE fire behavior prediction system (Rothermel 1983; Burgan and Rothermel 1984; Andrews 1986; Burgan 1987; Andrews and Chase 1989), was selected for this project. Although 13 standard fuel types are available for use with BEHAVE (Anderson 1982), the model also offers the opportunity to build custom fuel models (Burgan and Rothermel 1984; Burgan 1987). This property of the model contributed to its selection for this project but limited us to the prediction of surface fire behavior. Since the fuel type studied was suspected to be susceptible to crowning during several periods of stand development, we needed a model to determine when crown fire behavior would occur and to predict fire behavior in situations where crowning was likely.

This type of fire behavior prediction was made possible by the recent development of two crown fire initiation models (Cruz *et al.* 2003, Cruz *et al.* 2004a) and a crown fire rate of spread model by the same authors (Cruz *et al.* 2004b), which is a slightly modified version of the one they presented in Cruz *et al.* (2002). Other models are available for crown fire initiation or behavior (e.g. Van Wagner 1977, Rothermel 1991; Alexander 1998; Scott and Reinhardt 2001), but their limitations (see a review of several of those models in Cruz (1999) and Cruz *et al.* (2002, 2003, 2004a, 2004b)) precluded their use in this project.

Therefore, the procedure used in this project first involved the determination of the potential type of fire (i.e., surface, intermittent crown or continuous crown fire) through the use of the Cruz *et al.* (2003 and 2004a) crown fire initiation models. When a surface fire was likely, the new version of the BEHAVE model, the BehavePlus fire modeling system (Andrews *et al.* 2003), was used. Otherwise the Cruz *et al.* (2004b) model for coniferous stands was used to obtain the rate of spread and to further distinguish between intermittent and continuous crown fires. The two fire behavior models were limited to situations involving a line of fire burning steadily in uniform, continuous fuels. Details on the calibration and the selection of the inputs for the different models are presented below.

Crown Involvement

Two crown fire initiation models were considered. Both use a logistic regression approach but require different inputs. The first model (Cruz *et al.* 2003) calculates the probability of crown fire occurrence using four variables (their LOGIT1 model): canopy base height, 10-m wind speed, Fine Fuel Moisture Code (FFMC), and Drought Code (DC) (equations 6.1 and 6.2). The latter two input variables are components of the Canadian Forest Fire Weather Index (FWI) System (Van

Wagner 1987). In this model, canopy base height and the 10-m open wind speed are the variables that most strongly influence crown fire initiation (Cruz *et al.* 2003). The use of FFMC and DC by this model made it very attractive since the different fire weather/fire danger scenarios selected for this project (see Chapter 3) were defined through different combinations of the FWI System components, to which the FFMC and the DC belong. Moreover, the encouraging results obtained by the authors in a limited evaluation of their model involving, in part, the ICFME experimental fire data in the jack pine/black spruce forest type studied in our project also seemed promising. The model also had the advantage of being independent of other fire behavior models since outputs like rate of spread, fuel consumption, or fire intensity are not included as independent variables in the Cruz *et al.* (2003) model.

$$P(y_i = 1) = \frac{e^{g(x)}}{1 + e^{g(x)}} \tag{6.1}$$

$$g(x) = \beta_0 + \beta_1 \cdot CBH + \beta_2 \cdot U_{10} + \beta_3 \cdot FFMC + \beta_4 \cdot DC \tag{6.2}$$

where $P(y_i=1)$ is the probability of crown fire occurrence, CBH is canopy base height (m), U_{10} is 10-m open wind speed (km/h), FFMC is the Fine Fuel Moisture Code, DC is the Drought Code, and β_0 to β_4 are the parameters of the equation: $\beta_0 = -66.620$, $\beta_1 = -0.993$, $\beta_2 = 0.568$, $\beta_3 = 0.671$, and $\beta_4 = 0.018$.

Probability of crown fire initiation through stand development was calculated for the four fire weather/fire danger scenarios (Chapter 3) used to represent Horn's (1976) drought conditions in his flammability with time relationship (i.e., "moist": FFMC 83 and DC 142; "moderate": FFMC 87 and DC 325; "dry": FFMC 92 and DC 492; and "extreme": FFMC 95 and DC 514). One modification to the scenarios was made in this chapter. Instead of using a unique 10-m open wind speed (the 20 km/h set in Chapter 3 and used in the expert opinion survey (Chapter 5)), we used a range of wind speed conditions that varied between 0 and 30 km/h (using increments of 5 km/h). Canopy base height (CBH) was the only factor linking stand development to the probability of crown fire initiation in this model. CBH was measured in the stands selected for development of the chronosequence for the jack pine – black spruce fuel complex under study (see Chapter 2).

The second model considered was developed by the same authors (Cruz *et al.* 2004a) but uses a slightly different approach. Instead of estimating the onset of crowning within the context of the Canadian Forest Fire Danger Rating System (CFFDRS) like the first one (Cruz *et al.* 2003), it relies on: 10-m wind, fuel strata gap, surface fuel consumption, and estimated fine fuel moisture (equations 6.3 and 6.4). Thus in this model the last three variables could potentially vary with stand development. However, preliminary results indicated that a change in surface fuel consumption (a categorical variable with three levels) with time since fire occasioned sharp and unrealistic discontinuities in the probability curve derived from the model through stand development. As a consequence, that variable was only modified as a function of the fire weather/fire danger scenario to indicate changes in the quantity of available surface fuels caused by the fuel moisture, but there was no inclusion of change in category through stand development. Since most of the stands that had a canopy and a potential for crown fires had close to 2 kg/m^2 of fine fuels, it was decided that the "moist" scenario had a surface fuel consumption (SFC) less than 1 kg/m^2, the "moderate' fire weather/fire danger scenario had a SFC between 1 and 2 kg/m^2, and the "dry" and "extreme" fire weather/fire danger scenarios had a SFC larger than 2 kg/m^2. In the FBP System, the surface fuel consumption in mature and immature jack pine stands (fuel types C-3 and C-4) is calculated as a function of the Buildup Index (BUI). We compared our estimates of surface fuel consumption for the different fire weather/fire danger scenarios (above) with the surface fuel consumption calculated using equation 11 of the FBP System (Forestry Canada Fire Danger Group 1992) and the BUI of each scenario ("moist": BUI 30, "moderate": BUI 60, "dry": BUI 127, and "extreme" BUI 180). The surface fuel consumption thus calculated was 0.6, 1.8, 3.7, and 4.4 kg/m^2 for the "moist", "moderate", "dry" and "extreme" scenarios, respectively. Those values agree well with our decision concerning the range of surface fuel consumption associated with each fire weather/fire danger scenario.

$$P(y_i = 1) = \frac{e^{g(x)}}{1 + e^{g(x)}} \tag{6.3}$$

$$g(x) = \beta_0 + \beta_1 \cdot U_{10} + \beta_2 \cdot FSG + \beta_3 \cdot SFC\_CAT1 + \beta_4 \cdot SFC\_CAT2 - \beta_5 \cdot EFFM \tag{6.4}$$

where $P(y_i=1)$ is the probability of crown fire occurrence, U_{10} is 10-m open wind speed (km/h), FSG is fuel strata gap (m), and EFFM is the estimated fine fuel moisture. For the total surface fuel consumption (SFC), if SFC < 1.0 kg/m^2 then SFC_CAT1=1 and SFC_CAT2=0, if 1.0 ≤ SFC ≤ 2.0 kg/m^2 then SFC_CAT1=0 and SFC_CAT2=0, and if SFC > 2.0 kg/m^2 then SFC_CAT1=0 and SFC_CAT2=0. β_0 to β_4 are the parameters of the equation: $\beta_0 = 4.236$, $\beta_1 = 0.357$, $\beta_2 = -0.710$, $\beta_3 = -4.613$, $\beta_4 = -1.856$, and $\beta_5 = -0.331$.

Wind speed was varied in the same manner as for the previous model and the fuel strata gap of this model was considered equal to crown base height of the previous model. Finally, the estimated fine fuel moisture contents used at different stages of stand development were the same as the ones used with the BehavePlus model (see below).

For both crown fire initiation models, we used the probability value of 0.5 suggested by Cruz *et al.* (2003, 2004a) to identify the threshold between surface and crown (intermittent or continuous) fires. The model from Cruz *et al.* (2004b) was used to differentiate between intermittent and continuous crown fires (see below in rate of spread section).

For those few situations where the output of the two crown fire initiation models differed, the selection of one model over the other would have been arbitrary in our situation where field observations were not available for all ages under all environmental conditions. We therefore decided on a compromise between the outputs of the two models. For a given combination of wind speed and fire weather/fire danger scenario where the type of crown fire activity differed, we used a different temporal resolution (through regression or interpolation) for the inputs of each model as a function of time since fire (CBH in the Cruz *et al.* (2003) model and FSG and EFFM in the Cruz *et al.* (2004a) model) to calculate the type of fire predicted on a finer time scale (increments of 5 years since fire) (note that the type of fire data presented for the 15 year old stand in the results come from that calculation since we did not have a stand that age in our chronosequence). Then we compared the outputs from the two models and adjusted them. For example, if for a 10 km/h wind speed and under the "moderate" moisture scenario, one model predicted S, S, S, S, IC, IC, IC for the range of 20 to 50 years since fire, and the other model predicted S, S, IC, IC, IC, IC, IC for the same range of 20 to 50 years since fire, we compromised by modifying the data to S, S, **S**, **IC**, IC, IC, IC.

The crown fire initiation models were only used on stands that were at least 15 years old (time since fire). This limit was set for two reasons. The first one concerns the statistics associated with the dataset used in the development of the Cruz *et al.* (2003, 2004a) models, while the second one is related to the structure of the jack pine/black spruce stands during stand development. Crown closure generally occurs around 17 years after a stand-replacing fire in our study area for that forest type, at which time the tree canopy is well separated from the surface vegetation. This spatial separation between canopy and surface vegetation begins to appear a few years before that time. We therefore assumed that stands younger than 15 years old had a continuous vertical layer, where the trees are part of the surface vegetation. Fire in the crown of those trees is then not referred to as a crown fire in the following discussion although it may have been interpreted that way by the experts who answered crown involvement questions in the survey (see Chapter 5) to which some of the results presented below are compared.

Surface Fire Behavior

The surface fire behavior was modelled using the BehavePlus [1] fire modelling system v. 2.0.2 (Andrews *et al.* 2003). Custom fuel models were created for each stand of the chronosequence following the procedure described in Burgan and Rothermel (1984) and Burgan (1987) (and, when necessary, adapting for BehavePlus v.2.0.2).

The dead and downed woody material loads inventoried with the line intersect method using the Canadian diameter classes (see Chapter 2) had to be converted to the 1-hour (h), 10-h, 100-h, and 1000-h timelag (TL) classes used in the United States in order to be used as inputs in the custom fuel models. To do so, a procedure similar to the one described in Brown *et al.* (1985: appendix 1) for adjusting fuel diameter classes was used. The conversion factors used for each stand are presented in Table 6-1.

The different inputs used for each custom fuel model are presented in Table 6-2. Andrews (1991) identified the most important fuel descriptors as: fuel bed depth, load in each size class, and surface area-to-volume ratio of the fine dead fuel. Similar to other studies (e.g., Schimmel and Granström 1997), the 1-h fuel loads were composed of multiple 1-h fuel components that we combined through a weighting procedure in the NEWMDL module of the BEHAVE system (Burgan and Rothermel 1984). Those components (see Chapter 2 for sampling methodology and load of individual fuel components) were: litter (which included jack pine and black spruce needles), dead and downed woody material 0-0.6 cm in diameter, and moss/lichen. The latter were included in the dead 1-h category due to the manner in which they respond to atmospheric moisture and temperature, which is similar to that of fine dead fuels (Sylvester and Wein 1981; Norum 1982; Péch 1989; Schimmel and Granström 1997). The load of the 1-h fuels used in the construction of the custom fuel models was approximately that of the L layer of the forest floor, from the surface to the interface with the fermentation layer. Consequently, the loads presented in Table 6-2 are different than those used to represent the fine fuels component of the ground fuels in Chapter 2, where the load for the first 2 cm of the forest floor profile was used in all stands to simplify calculations and provide a basis for comparison.

In BEHAVE, the litter depth is defined as "the vertical distance from the top of the F layer to the general upper surface of the L layer" (Burgan and Rothermel 1984), although is has been interpreted as the litter material (e.g. freshly cast leaves, bark flakes, miscellaneous vegetative parts and matted grass) that is expected to burn during the passage of a flaming fire front (Brown and Simmerman 1986). Trial runs (under the range of fire weather/fire danger scenarios and wind speeds used in this project) of the fire behavior model with the load of 1) only the 0-2 cm layer (such as used by Sylvester and Wein 1981) and 2) the litter layer from the surface to approximately the top of the fermentation layer have indicated that although the differences in rate of spread were not generally important between predictions made with the two different loads, those for the head fire intensity were noticeable. The head fire intensity predicted with the litter load obtained from only the first two centimetres of the forest floor were considered unrealistically too low and created sharp and unrealistic discontinuities when the predictions from the surface fire behavior model were later combined with those of the crown fire behavior model. Attempts to adjust other parameters (other than the load of the litter) of the model failed to provide realistic outputs of both rate of spread and fire intensity at the same time under all fire weather/fire danger conditions. Burgan and Rothermel (1984) mentioned that an increase in fuel load will usually cause reaction intensity to increase more than rate of spread. Reaction intensity is the frontal fire intensity divided by the active horizontal flame depth (Alexander 1982).

Measurements of the thickness of the freshly cast needle layer or the moss/lichen carpet in each stand were therefore used in determining the depth of the forest floor for which the load had to be calculated. These measurements provided an approximation of the L layer from the surface down

[1] The author took the S-490 Advanced Wildland Fire Behavior Calculations course in Missoula, Montana (U.S.A.), in 2001.

to the top of the fermentation layer. Moreover, that layer of forest floor for which the load was determined corresponds well to the one that generally burns in the active flaming zone of a fire. Equations of the depth of burn as a function of the DMC or the BUI presented by Stocks (1987, 1989) for mature and immature jack pine stands indicated that the depth of burn under conditions similar to at least the "moderate" fire weather/fire danger scenario used in this project (the range of values used by Stocks (1987, 1989) for the regression analysis were similar to those of our "moderate" fire weather/fire danger scenario) corresponded well to the depth of the layer used for the determination of the litter load.

The load in each of the other fuel categories was obtained directly (see Chapter 2). The fuel bed depth was obtained by weighting the surface fuel depth by their respective loadings (Brown and Simmerman 1986). Relevant values for moisture of extinction, surface area to volume ratio, and heat content were obtained from the literature (Brown 1970; Rothermel 1972; Sylvester and Wein 1981; Norum 1982, Brown and Bevins 1986; Brown and Simmerman 1986; Bessie and Johnson 1995; Schimmel and Granström 1997) or, when applicable, from the outputs of the NEWMDL module of the BEHAVE system. They were then adjusted, if required, for the different custom fuel models built in this project following the method presented in Burgan and Rothermel (1984) and Burgan (1987).

The mid-flame wind speed is used in BehavePlus. It was calculated from the 10-m wind speed (values of 0 to 30 km/h, with 5 km/h increments) by first reducing it to the 20-ft wind speed. This was done by following guidelines in the software that recommended a division of the 10-m wind speed by 1.15 to obtain the 20-ft (approximately 6.1 m) wind speed. The procedure provides slightly higher wind speeds (difference between 0 and 0.6 km/h for the wind speed range 0-30 km/h) than the 15% wind reduction suggested by Turner and Lawson (1978) (the 10-m wind speed is then divided by approximately 1.18 to obtain the 6.1 m wind speed). We then used a reduction factor to obtain the mid-flame wind speed. The model from Albini and Baughman (1979) for situations with no canopy (equation 6.5) was used for young stands in the first few years following a stand-replacing fire. The equation for the ratio of the midflame windspeed to the windspeed 20-ft over the vegetation cover is (Albini and Baughman 1979):

$$\frac{\overline{\overline{U}}}{U_{20+H}} = \frac{1+0.36\cdot H/H_F}{\ln\left(\frac{20+0.36\cdot H}{0.13\cdot H}\right)}\cdot\left[\ln\left(\frac{H_F/H+0.36}{0.13}\right)-1\right] \tag{6.5}$$

where H is vegetation height (ft) (1 m = 3.28084 ft), and H_F is the extension of the flame above the fuelbed (ft). For the calculation, we assumed that flame height is twice the fuel bed depth, so H= H_F, as suggested in the documentation (help menu) accompanying the BehavePlus 2.0.2 software.

For all the other stands, the model from Cooper (1965), as adjusted to the metric system units by Alexander (1998) (equation 6.6), was used to obtain the effective within-stand wind speed (km/h):

$$\mathrm{U_s} = 0.1033 - 0.0084\cdot\mathrm{U}_{10} + 2.3179/\mathrm{BA} + 0.0211\cdot(\mathrm{SH})\cdot\mathrm{U}_{10} \tag{6.6}$$

where U_{10} is the 10-m open wind speed (km/h), BA is the stand basal area (m^2/ha) and SH is stand height (m). That wind speed was then divided by a 20 km/h (assumed constant) 20-ft wind speed to obtain the adjustment factor. This allowed an adjustment of mid-flame wind speed as a function of stand structure as it varies with time since fire.

Fuel moisture content is an input to the fire behavior model which requires the 1-h, 10-h, 100-h, live herbaceous, and live woody moisture contents. We obtained those values (Table 6-3) for our different fire weather/fire danger and fuel complex (stages of stand development following fire) scenarios according to the procedure described below for the live and dead fuels. We considered stands 0-14, 15-40, 41-89, and 90+ years since fire as young, immature, mature, and senescent, respectively.

Dead fuel moisture

We first determined the 1-h, 10-h, and 100-h fuel moisture data corresponding to our four fire weather/fire danger scenarios as defined by FWI System components and described in Chapter 3 (Table 3-14). In his comparison of the American and Canadian systems of forest fire danger rating, Van Wagner (1975) studied the degree of correlation between and within the systems. Using the data for one season (May 1 to October 31) recorded at Petawawa (Ontario, Canada), he observed that while there is really no true Canadian counterpart in the FWI System to the U.S. 1-h TL fuel moisture content, there is a good correlation (simple linear correlation coefficients between 0.71 and 0.74) between: a) the FFMC and the 10-hr moisture content, b) the FFMC and the 100-hr moisture content, c) the 1-hr moisture content and the 10-hr moisture content, and d) the 10-hr moisture content and the 100-hr moisture content.

Keeping the results found by Van Wagner (1975) in mind, we looked at a limited data set collected in the ICFME mature jack pine/black spruce stands (located in our study area) and containing the measured moisture content of different fuels on several days for which the FWI System components were also available. We calculated the moisture content from the FFMC (range: 89.6-93.0) using the equation presented in Van Wagner (1987):

$$\mathrm{MC} = 147.2(101 - \mathrm{FFMC})/(59.5 + \mathrm{FFMC}) \tag{6.7}$$

where MC is the moisture content (%), and FFMC is the Fine Fuel Moisture Code.

We then compared the calculated moisture content to the sampled moisture content of the different fuel categories. In general, the moisture content calculated from the FFMC corresponded relatively well to the sampled moisture content of fuels corresponding to the 10-h fuel category of the American system (Figure 6-3). We therefore decided to use the moisture content calculated from the FFMC as the 10-hr fuel moisture of the mature stands of our chronosequence. The 1-h fuel moisture was then obtained by subtracting 1.0% from the 10-h fuel moisture, while the 100-h fuel moisture was calculated by adding 1.0% to the 10-h fuel moisture following the approximation suggested by Rothermel (1983).

The 10-h moisture content was reduced by 1.0% in open stands, which corresponded to the early stages of stand development in our fuel type, where the fuels are very exposed to direct solar radiation due to the absence of a canopy. This reduction was supported by the moisture content measured almost simultaneously in young and mature stands before some of the experimental fires performed for this project (see Chapter 4, Table 4-10) and by the difference in the correction to the moisture content in the tables presented in Rothermel (1983) for open and closed stands. The 1-h TL fuel moisture was then obtained by subtracting 1.0% from the 10-h fuel moisture, while the 100-h fuel moisture was calculated by adding 1.0% to the 10-h fuel moisture in a similar manner as for mature stands.

In the dense immature stage, where we suspected that crown closure limited the amplitude of variation in moisture content for different fire weather/fire danger conditions (Simard 1968 in Simard and Main 1982), we kept the same moisture contents as for the mature stage for "moderate" and "dry" fire weather/fire danger conditions but altered slightly the moisture contents for the "moist" and "extreme" fire weather/fire danger conditions. In the first case, we assumed that dense canopy would intercept more of the rainfall and limit the amount of moisture reaching the forest floor. Accordingly, we decreased by 1.0 percent the moisture content of the 10-h fuels (in relation to the mature stands). Conversely, we assumed that the same dense canopy would also limit the evaporation of the moisture from the dead fuels under very dry conditions and increased by 1.0 percent the moisture content of the 10-h TL fuels under the "extreme" fire weather/fire danger conditions. The 1-h and 100-h fuel moisture values were obtained as described above for the mature and young stands.

Finally, we also made a slight adjustment to the moisture content of the senescent stage of stand development in our forest type, where the jack pine trees were dying and the spruce was taking over in the overstory canopy. The structure of the stands and the deep carpet of moss seemed to be associated with moister conditions under most weather conditions which prompted us to add 1 percent to the 10-h moisture content of the mature stands under all the fire weather/fire danger scenarios. The 1-h and 100-h fuel moisture values were obtained as described above for all the other stands.

Live fuel moisture of surface vegetation

Live fuel moisture is the result of physiological changes in the plants brought about mainly by the time of the season, precipitation events, temperature trends, and species (Rothermel 1983). Unfortunately, herbaceous moistures are not well documented (Loomis *et al.* 1979) and we could not find in the literature the information we needed to vary the live moisture content of herbs and shrubs in our four fire weather/fire danger scenarios.

However, although we did not investigate the variation in moisture content of the live surface vegetation in the stands of our chronosequence as a function of time of year or fire weather/fire danger conditions, the biomass sampling of herbs and shrubs (Chapter 2) provided some information on their moisture content. Sampling was performed during the peak fire season, mainly in July and the beginning of August, and the species, although they varied in relative abundance with time since fire, were generally the same in the different stands.

For most stands of our chronosequence, we weighed the samples in the field immediately after their harvest (the surface vegetation was divided in two categories, herbs and shrubs, and was not sampled by individual species), and again in the lab after oven-drying them. With the two measures we were able to calculate the percent moisture content (on a dry-weight basis) of herbs and shrubs. We considered those values to be representative of average conditions based on the weather and Fire Weather Index System components of the days on which they were collected and used them to fix the live moisture content of herbs and shrubs for the "moderate" scenario. Those moisture contents were approximately 150% and 135%, respectively. The live moisture content for the other fire weather/fire danger scenarios was then set by increasing the moisture content if the conditions were moister or lowering it if the conditions were dryer. For very young stands (the stands of our chronosequence 1-5 years since fire) the live moisture content of herbs and shrubs was set at a higher percentage than for the other stands based on the sampling performed in those recently burned areas.

Our estimates seemed reasonable in regard to the sensitivity of BEHAVE to live moisture levels. On that aspect, Rothermel (1983) mentioned: "above 200 percent, estimate to the nearest 100 percent; between 100 and 200 percent, estimate by 50 percent; below 100 percent, try to achieve 25 percent or better." As a comparison, in the BehavePlus software the low, medium and high moisture scenario have live moisture contents for herbs and shrubs (the same percentage is used for both) of 70 %, 120 %, and 170 %.

Crown Fire Behavior

Crown fire rate of spread was obtained using the model developed by Cruz *et al.* (2004b) which uses as a baseline the basic heat balance equation for forward rate of spread presented by Thomas and Simms (1964). In that model, 10-m open wind speed, crown bulk density, and an index of fine dead fuel moisture are needed to calculate the active crown fire rate of spread ($\mathrm{CROS_A}$):

$$\mathrm{CROS_A} = \beta_1 \mathrm{U}_{10}^{\beta_2} \cdot \mathrm{CBD}^{\beta_3} \cdot \exp(-\beta_4 \cdot \mathrm{EFFM}) \qquad (6.8)$$

where U_{10} is 10-m open wind speed (km/h), CBD is canopy bulk density (kg/m^3), and EFFM is the estimated fine fuel moisture content (% dry weight basis).

The $CROS_A$ is then compared to Van Wagner's (1977) critical minimum spread rate for active crown fire (R_o):

$$R_o = \frac{MFR_o}{CBD} \tag{6.9}$$

where MFR_o is the critical mass flow rate determined empirically by Van Wagner (1977) to equal approximately 3.0 kg/m^2/min, and CBD in the canopy bulk density (kg/m^3).

If the ratio of those values ($CROS_A$ / R_o), the criteria for active crowning (CAC), is at least unity, the fire is expected to be an active crown fire and the rate of spread previously calculated is the potential rate of spread of the fire. Otherwise, the fire is more likely to be a passive crown fire and the active crown fire rate of spread previously calculated is reduced to a passive crown fire rate of spread ($CROS_P$) through the use of the value obtained for the criteria for active crowning (equation 6.10). Wind speed is the variable with the strongest effect on the spread rate of active crown fires in the Cruz *et al.* (2004b) model.

$$CROS_P = CROS_A \cdot \exp(-CAC) \tag{6.10}$$

The same 10-m open wind speed values were used for the crown fire initiation and crown fire rate of spread models. Crown bulk density was calculated from measures taken in the stands of the chronosequence that were inventoried for this project. We assumed that crown bulk density was equal to the average fine fuel load of the crown (Chapter 2, Table 2-28) divided by the average crown length, the latter calculated from the average stand height minus the live crown base height of the black spruce tree component of our stands (see Chapter 2, Table 2-16). Finally, the estimate of fine dead fuel moisture used in the model was the 1-h fuel moisture used in the surface fire behavior model (see above).

The Cruz *et al.* (2004b) model does not provide an estimation of fire intensity. That quantity was therefore calculated using Byram's (1959) fire intensity equation (see also Alexander 1982):

$$I = Hwr \tag{6.11}$$

where I is the frontal fire intensity (kW/m), H is the fuel low heat of combustion (kJ/kg) (a constant value of 18 000 kJ/kg was used), w is the weight of fuel consumed in the active flaming zone per unit area (kg/m^2), and r is the rate of spread (m/sec). In the case of a continuous crown fire, the total load of fine fuels in the canopy of the stands was used as the amount of fuel consumed per unit area in the active flaming zone (Chapter 2, Table 2-27). For intermittent crown fires, this value was reduced as a function of the criteria for active crowning by multiplying it by the CAC (whose value is always less than 1 in intermittent crown fires).

Flammability

The hypothesis considered in this project was that the flammability of jack pine/black spruce stands in the study area varies according to the hypothetical model (Figure 6-1) presented by Horn (1976). Since flammability in itself is a state and is not readily measurable, we needed an indicator to quantify it. Anderson (1970) suggested that flammability consists of three components: ignitibility, sustainability, and combustibility. He went further and proposed that, in a fuel continuum, ignitibility would be governed by the ignition of fuel elements, sustainability would be more closely associated with the rate of spread, and combustibility would be represented by the intensity of the fire. Although the definition of flammability varies in the literature, several authors have considered the rate of spread (e.g., Brown 1975; Fogarty 2002) and/or the intensity (e.g., Brown 1975; Bond and Midgley 1995; Johnson *et al.* 1998; Fogarty 2002) of a fire as indicators of its state.

The values for potential rate of spread and intensity are presented to help in comparisons with other studies that used them to represent flammability, but we decided to go further in our assessment of flammability by developing a flammability index. We used Anderson's (1970) suggestion and built our index so it would be representative of the ignitibility, sustainability, and combustibility (ISC) of each situation. Rate of spread and head fire intensity were used for sustainability and combustibility, respectively. For ignitibility, we first considered the probability of ignition models presented in the literature, but further study of those models indicated that they could not be applied to the time since fire-fire weather/fire danger scenarios used in this project. The main limitation was the variation of the surface fuels with time since fire as most of these models (e.g., Lawson and Armitage 1997; Frandsen 1997; Lawson *et al.* 1997) did not consider situations like the ones encountered in our forest type during the young and immature stages of stand development. We therefore opted for a different approach and used a modelisation of the answers provided by the fire behavior experts concerning the probability of a point source fire spreading through a stand (see Chapter 5). Although that probability of fire spread is not a probability of ignition *per se*, it is directly related to it and was considered sufficient, when integrated to the index calculation, to represent the ignitibility of the stands under the various conditions used in this project. The polynomial model built from the experts' answers considered time since fire and, through the use of the FWI component of the FWI System, the fire weather/fire danger scenarios.

Two flammability indices were constructed from standardised values of those measures of ignitibility, sustainability, and combustibility. In each case, it was considered that the three elements of flammability were additive and contributed equally to the index since they have been used individually in the past to represent flammability. Only the standardisation procedure varied in the calculation of the two indices.

The first flammability index, called the Specific ISC Index, was standardised over specific conditions of wind speed and fire weather/danger scenarios and was used to locate the most flammable stage(s) of stand development for each combination of wind speed (0-30 km/h with 5 km/h increments) and fire weather/danger scenarios used in this project. It was calculated with the following formula:

$$Specific\_ISC_{ijk} = \frac{1}{3}\left[\left(\frac{P_{ijk} - P_{ij\bullet}^{Min}}{P_{ij\bullet}^{Max} - P_{ij\bullet}^{Min}}\right) + \left(\frac{R_{ijk} - R_{ij\bullet}^{Min}}{R_{ij\bullet}^{Max} - R_{ij\bullet}^{Min}}\right) + \left(\frac{I_{ijk} - I_{ij\bullet}^{Min}}{I_{ij\bullet}^{Max} - I_{ij\bullet}^{Min}}\right)\right] \qquad (6.12)$$

Where P is the probability of ignition (%), R is the rate of spread (m/min), I is the head fire intensity (kW/m), and each of these varies with: i, which is the 10-m open wind speed (km/h); j, the weather scenario (no unit); and k, the time since fire (years). Min is the minimum value, and Max is the maximum value for a given independent variable.

The second flammability index, called the Global ISC Index, was standardised over all the conditions of wind speed and fire weather/fire danger scenarios used in this project. It was used to find the conditions over which the flammability was maximum, and how it varied under those conditions for different combinations of time since fire, wind speed, and fire weather/fire danger scenarios used in this project. It was calculated with the following formula:

$$Global\_ISC_{ijk} = \frac{1}{3}\left[\left(\frac{P_{ijk} - P_{\bullet\bullet\bullet}^{Min}}{P_{\bullet\bullet\bullet}^{Max} - P_{\bullet\bullet\bullet}^{Min}}\right) + \left(\frac{R_{ijk} - R_{\bullet\bullet\bullet}^{Min}}{R_{\bullet\bullet\bullet}^{Max} - R_{\bullet\bullet\bullet}^{Min}}\right) + \left(\frac{I_{ijk} - I_{\bullet\bullet\bullet}^{Min}}{I_{\bullet\bullet\bullet}^{Max} - I_{\bullet\bullet\bullet}^{Min}}\right)\right] \qquad (6.13)$$

Both flammability indices can vary between 0 and 1, with 0 being the least flammable and 1 the most flammable.

RESULTS AND DISCUSSION

The main objective of the present study was to describe the variation in flammability (and potential fire behavior) as a function of time since fire for jack pine/black spruce stands studied in this project. To do so, we investigated the potential crown fire involvement, rate of spread and head fire intensity for stands of different time since fire under different fire weather and fire danger conditions. We also calculated two flammability indices. The results from those different analyses are presented and discussed below, and then compared to certain aspects of the fire regime generally observed in similar stands.

Data from expert opinion and experimental fires were integrated in the outputs from fire behavior models; thus, the results presented below should be used with caution. They are limited by the compounded assumptions we made in each situation, and by the limitations associated with the means (survey, models, empirical setting) through which they were obtained. The recurrent assumptions that were made in each situation assumed flat terrain (no slope), homogeneous fuels, and constant fire weather (e.g., wind speed) and fire danger conditions (i.e., no variations with time of day).

Fire behavior is a highly variable phenomenon that shows both spatial and temporal variation (Van Wagner and Methven 1980). Specific situations will likely vary from their modelised representation. Given a fuel description for a particular stand, Brown (1978) estimated that variations in the rate of spread and intensity of 1/2 to 2 times predicted values occur commonly, variations of 1/4 to 4 times are to be expected, and of 1/10 to 10 times would occur infrequently. In those estimates, more homogenous fuels were expected to lead to less variation in fire behavior.

Nevertheless, the similarities we observed between the results of the different approaches used in this project (experimental fires, expert opinion survey, fire behavior models) lead us to believe that they may in fact provide a good representation of what would be observed in the field for situations similar to those used in the different scenarios.

Crown Fuel Involvement

The outputs of the two crown fire initiation models (Cruz *et al.* 2003; Cruz *et al.* 2004a) were similar, although some differences were noted mainly along the axis going from drier weather scenarios at low wind speed to moister weather scenarios at high wind speed. Those differences were essentially in the discrimination of surface fires and intermittent crown fires (the latter was differentiated from continuous crown fires with the Cruz *et al.* (2004b) model).

The results from the crown fire initiation models for different times since fire, wind speed, and fire weather/fire danger scenario are presented in Table 6-4. As expected, the models indicated that crown involvement generally increased with both wind speed and the severity of the fire weather/fire danger conditions. The relation with stand age (from 15 years and older) was, in general, less straightforward since in some instances the crown fire activity predicted in young stands was more severe than in older stands, while the opposite was predicted under other combinations of wind speed and fire danger conditions. Intermittent or continuous crown fire activity was predicted in stands as young as 15 years since fire.

Looking first at the situation of wind speed set at 20 km/h, in order to compare the results from the expert opinion survey (see Chapter 5, Figures 5-29 to 5-31) and the crown fire initiation models, we noted that the results obtained from those two independent methods agree relatively well for all stages of stand development. However, the crown fire initiation models appeared to predict a slightly higher level of crown fire activity at that wind speed. Thus, for stands 21 years since fire the Cruz *et al.* (2003, 2004a) models predicted surface, intermittent crown, continuous crown, and continuous crown fires for the "low", "moderate", "dry", and "extreme" fire weather/fire danger scenarios, respectively. The median of the experts responses for crowning category and the modelled crowning categories as a function of time since fire obtained from the survey suggested surface, surface to intermittent crown, intermittent crown to continuous crown, and intermittent crown to continuous crown fires for the same order of fire weather/fire danger scenarios. For the stands of 57, 71, and 108 years since fire, the Cruz *et al.* (2003, 2004a) models predicted surface, continuous crown, continuous crown, and continuous crown fires for the "low", "moderate", "dry", and "extreme" fire weather/fire danger scenarios, respectively. The results from the expert opinion survey, for the same order of weather scenario, suggested surface, intermittent crown, continuous crown, and continuous crown fires, respectively.

When considering all the wind speeds and fire weather/fire danger scenarios used, the results from the models indicated that crown fire activity was possible in stands as young as 15 years old (time since fire), but that continuous crowning would not be likely at that age until fire danger conditions reached the "dry" and "extreme" level for wind speeds between 10 and 20 km/h, and for moderate fire danger conditions when wind speeds were 25 to 30 km/h. The polynomial model used to model the answers from the expert opinion survey suggested that with a 20 km/h wind speed sustained crowning was likely only in stands 25 years or older (Chapter 5, Figure 5-31). However, the results from the median analysis on the raw expert opinion survey data (Chapter 5, Figure 5-29) suggested the threshold stand age might be a few years younger than 20 years old, a stand age that concurs with the prediction of the crown fire initiation models. Although the experts predicted some crown fire activity (intermittent crown fire and torching) in stands less than 15 years old, the limit set in this project for the use of the Cruz *et al.* (2003; 2004a,b) models prevented us from exploring the potential for crown fire in younger ages. It was, however, expected that predictions made by the experts for these younger stands would be reflected in the outputs (rate of spread and intensity) of the surface fire behavior model used for stands younger than 15 years old in this project.

In general, as wind speed and fire weather/fire danger scenarios tended towards more severe burning conditions, crown fire potential increased with stand age. Otherwise model outputs generally suggested more potential crown fire activity at younger ages, especially under moister fire weather/fire danger scenarios (under all wind speeds). Instances of crowning activity in young pine stands have been reported in the literature. Cayford and McRae (1983) observed that jack pine foliage is very combustible and that trees can be killed by crown fire at any age. In fact, young jack pine forests have sometimes been reported as being more susceptible to crowning than mature stands (e.g., Brown 1975; Van Wagner 1977, 1979, 1983; Stocks 1987, 1989, Kafka *et al.* 2001).

In several instances, the crown fire initiation models predicted lower levels of crowning potential in the oldest stands of the jack pine/black spruce forest type. Interestingly, similar results were obtained through the use of geographic information systems by Kafka *et al.* (2001) in a study looking at the effects of local stand and site factors on crown fire in western Quebec.

Despite the fact that none of the fuel types represented in the FBP System (Forestry Canada Fire Danger Group 1992; De Groot 1993) corresponds exactly to the different stages of stand development in the forest type studied in this project, the results obtained from the two crown fire initiation models (Cruz *et al.* 2003; Cruz *et al.* 2004a) agreed relatively well with the predictions from the FBP System in conifer stands (Table 6-5) under similar conditions of wind speed and fire weather/fire danger scenarios.

<u>Rate of Spread</u>

The potential rate of spread, as related to each combination of time since fire and fire weather/fire danger scenario, was determined through the use of two models: 1) the BehavePlus model in the case of surface fires, and 2) the Cruz *et al.* (2004b) model in the case of intermittent and continuous crown fires. The results are presented in Table 6-6 and, for ease of comparison, in Figure 6-4.

Interestingly, the rate of spread (median of all the answers) estimated by the experts (Chapter 5) and the one obtained by the models for a 20 km/h wind speed showed a good correlation (Figure 6-5) but suggested that, on average, the experts predicted rates of spread that were approximately 60 % of those predicted by the models ($R^2 = 0.94$). The analysis of rate of spread and flame length from the expert opinion survey had already indicated the possibility that the experts may have underestimated the rate of spread in their predictions. The comparison of their estimate with the outputs from the models further supports that possibility. It is however tempered by an observation made by Cruz *et al.* (2004b) that their model over-predicted the observed spread rates with which they were compared, with most of those over-predictions occurring at the higher spread rates.

Assuming that fire spread is possible at a rate of spread faster than 0.1 m/min, the outputs from the models suggested that the forest type studied, as represented by the chronosequence used in this project, would need to be more than 5 (but less than 10) years old before it could burn again under wind speeds less than 10 km/h. The youngest age for a possible reburn was in 5 year old stands under "extreme" fire danger conditions with a 10 km/h wind speed. At higher wind speeds fire spread in these young stands becomes possible under gradually moister fire danger conditions. Similarly, the first indication of possible reburns in 3 year old stands also appears under extreme weather conditions and wind speeds of around 15 km/h. Again, at higher wind speeds fire spread becomes possible under gradually moister weather conditions in those stands. The same is true for stands 2 years after a stand-replacing fire, where the predicted rate of spread is above 0.1 m/min under "extreme" fire danger conditions and wind speeds of 25 km/h, or under lower fire danger conditions at higher wind speeds.

This predicted pattern for the possibility of reburn in young stands agrees well with that arising from the expert opinion survey (Chapter 5) and some experimental reburns conducted for this project (Chapter 4). In the first case, which considered only situations with a 20 km/h wind speed, a summary of the answers provided by the respondents for the probability of a line source fire spreading through a stand as a function of the fuel and weather scenarios indicated that they expected that under the "moderate" fire weather/fire danger scenario a stand would need to be 5 years old, while at the "dry" and "extreme" scenarios it would need to be at least 3 years old to reach that probability. Secondly, experimental fires performed in 1, 2, 3, and 4 year old stands failed to spread following line ignitions under conditions varying between those of the "moderate" and the "dry" fire weather/fire danger scenarios (with FFMC reaching 93, which is higher than the FFMC of the "dry" fire weather/fire danger scenario but lower than that of the "extreme" scenario) and an average 10-m wind speed between 9 and 13 km/h. Interestingly, those thresholds are similar to the ones reported by in Catchpole (2002) from a review of the literature for some very different vegetation types (e.g., jarrah, moorlands, heathland, mallee, eucalyp) in Oceania.

In general our results indicated that as wind speed increased and the weather scenario became drier, rates of spread increased sigmoidally as a function of time since fire until stand maturity (Figure 6-4, note the different scales on the y-axis). In the oldest stands rate of spread decreased slightly in several instances. At low wind speed or under moister weather scenarios, a peak in rate of spread was sometimes observed early during stand development. Rate of spread then decreased for a few years before increasing again with age.

We should emphasise here the fact that fire behavior predictions for stands 10 and 15 year old were done using an interpolation of the input values of younger and older stands as no stands of those ages were present in the chronosequence. Sharp discontinuities in the rate of spread (or intensity) at those ages should be interpreted with caution as they may be an artefact of 1) the estimates for the fuel conditions or 2) the use of a different fire behavior model (for a surface or a crown fire) used for the predictions. Nevertheless, a comparison of those predictions with the rate of spread observed during two experimental fires (mentioned in Weber (1985)) in a young (12 and 13 year-old) jack pine stand located in eastern Ontario showed good agreement. These two experimental fires, incorporated into the database used in the development of the FBP System for the C-4 fuel type (immature jack or lodgepole pine), were burnt under the following conditions (M.E. Alexander, personal communication): 1) calendar date - August 4, 1976 -- FFMC 89.9,

DMC 26, DC 276, ISI 11, BUI 42, FWI 22, and 10-m open wind speed 10 km/h; and 2) calendar date - May 19, 1977 -- FFMC 91.7, DMC 57, DC 107, ISI 9, BUI 57, FWI 22, and 10-m open wind speed 19 km/h. These conditions would be intermediate between the "moderate" and "dry" fire weather/fire danger scenarios defined for this project, although leaning more heavily towards the "moderate" case. The observed rate of spread for the 1976 experimental fire was 4.3 m/min and 7.6 m/min for the 1977 experimental fire.

The rates of spread obtained in this project through the use of two fire behavior models, one for surface fires and one for crown fires, were consistent to the predictions from the FBP System in conifer stands (Table 6-5) under similar conditions of wind speed and fire weather/fire danger scenarios if we consider that no fuel type in the FBP System (Forestry Canada Fire Danger Group 1992; De Groot 1993) corresponds exactly to the different stages of stand development in the forest type studied in this project .

Although the definition of flammability varies in the literature, several authors have considered the rate of spread (e.g., Brown 1975; Fogarty 2002) and/or the intensity (e.g., Brown 1975; Bond and Midgley 1995; Johnson *et al.* 1998; Fogarty 2002) of a fire as indicators of its state. Taken as such, the curves presented in Figure 6-4 or 6-6 (below) could be interpreted directly as the variation in flammability of jack pine/black spruce stands as a function of time since fire under various fire danger scenarios and wind speeds.

Fire Intensity

The potential head fire intensity of each situation (varying conditions of time since fire, fire weather/fire danger scenario) was determined through the use of two models: 1) the BehavePlus model in the case of surface fires, and 2) Byram's (1959) equation in the case of intermittent and continuous crown fires. The results are presented in Table 6-7 and, for ease of comparison, in Figure 6-6.

The potential head fire intensity varied between 0 and 95,709 kW/m, which covers almost the entire practical range (10-100 000 kW/m) for that variable (Alexander 1982; Van Wagner 1983). It is generally considered that fires tend to be self extinguishing when the head fire intensity is below 10 kW/m (Byram 1959; Alexander and De Groot 1988).

The outputs from the models suggested that the forest type studied would need to be more than 3 (but less than 10) years old before it could burn again under wind speeds less than 10 km/h. The youngest age for a possible reburn was in 3 year old stands under "dry" fire danger conditions with a 10 km/h wind speed. Similarly to what was noted for the rate of spread predictions, at higher wind speeds fire spread in young stands becomes possible under gradually moister fire danger conditions. Overall, the age for reburn as predicted from the fire intensity appeared to be slightly lower than that predicted from the rate of spread.

In general, the patterns of changing head fire intensity with stand age were similar to those for rate of spread (above). Agee and Huff (1987) also noted that their rates of spread and flame lengths (a surrogate for fireline intensity) had similar patterns, although different than the one we obtained. The curves of intensity as a function of time since fire (Figure 6-6) generally followed similar (but not identical) trends under given fire weather/fire danger and wind conditions in our forest type. A notable difference, however, was that the decrease in rate of spread observed in the oldest stands was not commonly present in the intensity curve. This was probably due to the larger amount of fuels that contributed to its calculation at those ages compared to a relatively smaller decrease in rate of spread (from equation 6.11). Other differences in the shape of the intensity and rate of spread curves were largely due to differences in the magnitude of the variation, with the exception of the head fire intensity calculated for the 71 year-old stand. Contrary to the results obtained for rate of spread, the head fire intensity calculated for that stand was often lower than for stands immediately younger or older. This appeared to be the case mainly when crown fires were predicted, which suggests that the crown fuel load used for the calculation of the intensity may be the cause for this discrepancy. In this regard, there was a greater density (and biomass) of black spruce trees in the immediately younger stands of the chronosequence that were sampled for this project. The foliage of those trees may have increased the crown fuel load enough to result in prediction of higher intensity in the stands just younger than 71 years.

An interesting aspect about the intensity curves as a function of time since fire is that they seemed to corroborate Van Wagner's (1983) statement that a recently burnt area may need a few years to acquire enough fuel to burn again, but that intense fire is possible in conifer stands younger than 10 years. More intense fires are expected, however, later during stand development.

Flammability

The first flammability index, called the Specific ISC Index, was used to locate the most flammable stage(s) of stand development for each combination of wind speed (0-30 km/h, with 5 km/h increments) and fire weather/fire danger scenarios used in this project. The second flammability index, called the Global ISC Index, was used to find the conditions over which the flammability was maximum, and how it varied under those conditions for different combinations of time since fire, wind speed, and fire weather/fire danger scenarios used in this project. Due to their different meanings, the two flammability indices developed for this project are presented separately below.

Specific ISC

The Specific ISC flammability index is presented in Figure 6-7 as a function of time since fire for each combination of fire weather/fire danger scenario and wind speed. The data points in each of the 28 sections (4 fire weather/fire danger scenarios x 7 wind speeds) of that figure show the flammability (between 0 and 1) of the jack pine/black spruce forest type as a function of stand development for specific environmental conditions of wind speed and fuel moisture based on the FWI System fuel moisture codes and can therefore be used to estimate the most flammable stage(s) of stand development for those given conditions.

Figure 6-7 offers some interesting points of discussion. The first one is related to the shape of the curve in each section of the figure as one proceeds along both the wind speed and the fire weather/fire danger scenario gradients. Under the "moist" scenario and no wind, the flammability increased almost linearly with time since fire. At the other end of the spectrum, ("extreme" weather scenario and 30 km/h winds) the relative flammability curve as a function of time since fire took a sigmoidal shape. The intermediate stages along each gradient of wind or fuel moisture (i.e., fire weather/fire danger scenario) gradually brought the changes in the curve that modified it from an almost linear relation to an S-shaped one.

Thus, the very young stage of stand development (i.e., 0-5 years) was always the least flammable one under any conditions, according the Specific ISC flammability index, while the most flammable stage of stand development varied between the immature, mature and/or senescent stage, depending on the prevailing environmental conditions. This corresponds well with observations made by several authors (e.g., Brown 1975; Martin *et al.* 1978; Heinselman 1981b) that flammability (often referred to as readiness to burn or fire potential) varies widely with stand condition and weather. It may peak one or more times before the oldest stand age and is therefore not a simple function of time since fire.

Although each of the 28 situations presented a unique curve, on average the relative flammability increased with stand age along a sigmoidal curve where the plateau was generally reached between 25-30 years after a stand-replacing fire (Figure 6-8). It is interesting to note that experienced fire control officers are of the opinion that fire hazard peaks in lodgepole pine, a species similar to jack pine, 25 years after a burn (Lyman 1945 in Brown 1975).

Global ISC

The Global ISC index is presented in Figure 6-9 as a function of time since fire for each combination of fire weather/fire danger scenario and wind speed, while Table 6-8 provides a reference as to the input values used to obtain the given ranges of the Global ISC Index. As a reference (Table 6-8), surface fires were generally predicted when the index was between 0 and 0.2, a high intensity surface fire or an intermittent crown fire was predicted for an index value between 0.2 and 0.4, and a crown fire was predicted for values of the Global ISC index larger than 0.4. With a standardisation over all the conditions of wind speed and fuel moisture scenarios used in this project, this index was used to find the conditions for which the flammability was at its maximum.

Not surprisingly, the Global ISC increased with stand age (Figure 6-9) with a sigmoidal shape, as did the average of the Specific ISC index (Figure 6-8). The maximum value reached by the index in each situation steadily increased along the gradients of both wind speed and fire weather/fire danger scenario. Consequently, the least flammable situation, as represented by the index, occurred under the "moist" fire weather/fire danger scenario with no wind while the most flammable case was obtained for the "extreme" fire weather/fire danger scenario with a 10-m open wind speed of 30 km/h (the maximum wind speed considered in this project). Various combinations of wind speed and fire weather/fire danger scenario gave similar (both in shape and in the flammability value corresponding to the asymptote) Global ICS index flammability curves as a function of time since fire (Figure 6-9).

A modelised version of the Global ISC index as a function of time since fire for situations showing an increasing gradient of fire weather/fire danger severity (as represented by wind speed and the fuel moisture scenarios) are presented in Figure 6-10. From the data presented in Figure 6-9 (more specifically the flammability level corresponding to the asymptote in each portion of the figure), an increase in the severity of the fire weather/fire danger conditions (28 situations) as related to the flammability would be, in increasing order, as presented in Table 6-9.

Horn's Flammability Model (and other considerations)

In this section we first compare our results for the flammability curve as a function of time since fire in the jack pine/black spruce stands studied with Horn's (1976) theoretical model. We then look at other similar curves presented in the literature. Finally, we discuss the implications by looking at fire return intervals and fire regime in similar stands.

The flammability curve as a function of time since fire of the jack pine/black spruce forest type in our study area, as represented by the Global ISC index, follows a sigmoidal shape similar to the one presented in Horn's (1976) theoretical model. An increase in the severity of the burning conditions (i.e., fire weather/fire danger scenario and wind speed combinations following the order presented in Table 6-9) is generally accompanied by an increase in the higher flammability limit of the curve and by a faster rate of flammability increase between approximately 3 to 5 and 25 to 30 years since fire. Accordingly, a given threshold of flammability (on the y-axis of Figure 6-10) corresponds to a gradually older time since fire for decreasing severity of the burning conditions, until a limit is reached. That limit, after which the threshold is never expected to be reached at any time during stand development, is imposed by the asymptote reached by the flammability curve in each severity condition. Taken from the time since fire aspect, at any given age, flammability increased with the severity of the burning conditions. The difference in flammability between two given levels of severity of the fire weather/fire danger conditions increases with time since fire until the flammability curves level off (at ~25-30 years). The difference then remains constant since all the curves have reached a plateau by that time. A superposition of the curves in Figure 6-10 through a standardization like the one done for the Specific ISC index would lead to a representation very much like the one presented in Figure 6-1. This was done in Figure 6-11, where we also identified some fire weather/fire danger scenarios that corresponded to a Global ISC flammability index of 0.2 before the standardisation. We can see on the figure how, like in Horn's model, more severe conditions lead to a lower flammability for a given threshold.

Although our results generally agree with the hypothesis that the flammability in the jack pine/black spruce forest type studied varies according to Horn's (1976) model, they are somewhat surprising when considering other models that have been suggested for similar coniferous forests in Canada and northwestern United States (e.g. Van Wagner 1979, 1983; Brown 1975). In those models a decrease in flammability is generally observed relatively early during stand development (after an initial peak) instead of a plateau lasting over most of the immature and mature stages. A possible reason for the plateau we observed in this study may be coming from the contribution of the black spruce understory to fire behavior during stand development. It is possible that the models (e.g., Van Wagner 1979, 1983; Brown 1975) previously published for conifer stands were developed for stands having a single canopy layer, not a multi-layered canopy like the one present in our jack pine/black spruce stands, although this has never been explicitly mentioned. In our model we also expect a decrease in the flammability curve, but suspect that it would occur later during stand development (unless a fire burns the stand and begins the sequence anew), when the stands will have entered the senescence stage. The beginning of this trend was observable in the fire behavior simulations for the 108-year-old stand under several wind speed and fire weather/fire danger scenarios, but additional stands in that stage of development would have been needed to refine the model past the mature stage and confirm that hypothesis.

The shape of the flammability curve as a function of time since fire varies widely in the literature (e.g., Muraro 1971, Brown 1975, Fahnestock 1974, Philpot 1974, 1977; Johnson 1979; Van Wagner 1978, 1979, 1983; Agee and Huff 1987; Renkin and Despain 1992; Romme 1982; Bessie and Johnson 1995; Johnson and Van Wagner 1985, Heinselman 1973; 1981a; 1981b; Romme and Knight 1981). A sigmoidal flammability function, based on biological information of the vegetation type studied (such as stand dynamics and composition of the area burning), is among those proposed by McCarthy *et al.* (2001). Li *et al.* (1997) investigated potential temporal disturbance patterns on a forest landscape with four different probability functions approximated using different parameter values for a logistic equation. Their simulation results suggested that, in theory, different fire probability functions having different parameter values could result in similar fire regimes. The fire probability function with a sigmoidal shape appeared to be the most appropriate one for their case study area located in Ontario. The model in Figure 6-10 also has the same shape as the one proposed by Schimmel and Granström (1997) for surface fires in *Vaccinium myrtillus* forests in northern Sweden, where the dominant tree species is *Pinus sylvestris*. However, their temporal divisions are different as they delineated three age class thresholds: 0-20 years - no or marginal fire spread; 20-50 years - progressive rise in potential fire intensity; and a steady state from around 50 years on. Bessie and Johnson (1995) did not find any correlation between potential fire intensity and time since fire in montane forests of southwestern Alberta for stands older than 25 years. However, they noted an initial increase in their fuel variable when five young stands 22 and 23 years old were included in the analyses. Schimmel and Granström (1997) observed that this might indicate a lower potential fire intensity earlier during stand development in the forest type studied by Bessie and Johnson (1995), but this could not be verified since the study does not include stands younger than 22 years since fire. However, it seems possible that Bessie and Johnson's (1995) results reflect the plateau reached by a sigmoidal flammability curve, where their younger stands would be located somewhere along the portion of the curve where flammability increases sharply with time. The findings of Bessie and Johnson (1995) could, in fact, correspond to those of different sections of a sigmoidal flammability curve similar to the one proposed in the present study. The sigmoidal flammability curve could also explain the frequent references to an equal flammability with time since fire in the boreal forest, which is sometimes said to occur after a brief period of low flammability (e.g., Heinselman 1981b; Rowe and Scotter 1973). A sigmoidal flammability curve was also proposed for other vegetation types around the world (e.g. Philpot 1977; McCarthy *et al.* 2001).

Reviews of the literature (e.g. Heinselman 1978, 1996; Bourgeau-Chavez *et al.* 2000) have indicated that many vegetation types in the boreal region have fire return intervals between 80 and 150 years, although mean intervals of 25-40 years have been reported. More specific to jack pine, Larsen and Macdonald (1998) obtained a mean fire return interval of 34 years using fossil pollen and charcoal records in a boreal jack pine/black spruce forest of northern Alberta. Carroll (1978) estimated that the jack pine-lichen woodlands of the Athabasca Plains Region of northeastern Alberta and northern Saskatchewan could likely burn 30-60 years after a stand-replacing fire. Accordingly, the fire return interval estimated by Carroll and Bliss (1982) was between 28 and 54 years for the same area. Vogl (1970 in Heinselman 1981a) suggested an average return interval for individual stands between 15 and 35 years based in part on pine stands located in the Northwest Territories (the other area considered was the Boundary Waters Canoe Area of Minnesota). Lynham and Stocks (1991 in Lynham *et al.* 1998) reported a fire return interval of 20-30 years in an unprotected jack pine forest of fire origin in northwestern Ontario. Heinselman (1981b, 1996) noted that young, dense conifer stands (jack pine, lodgepole pine, black spruce, and red pine) begin to support crown fires and burn well at only 15 to 20 years under proper environmental conditions. However, his observations indicated that the typical return interval for jack pine/black spruce sites in the Boundary Waters Wilderness Ecosystem of Minnesota was between 40 and 100 years (Heinselman 1996) and may have been between 50 to 75 years before European settlement. Also in the United States, Simard *et al.* (1983) reported that the average interval between major jack pine crown fires was 28 years in the Mac Lake Fire area. In Michigan's presettlement pine forests, Whitney (1986) reported return intervals of 83 years for destructive crown fires in jack pine forests.

In jack pine stands in general, as well as in the vicinity of our study area (N. Lavoie, personal observation), the main fire regime is a high intensity crown fire that kills all the trees, but surface fires that only scar trees are sometimes reported. Thus, low intensity surface fires are reported to occur, on average, at 23-40 years intervals (Heinselman 1981, 1985; Larsen 1997; Bourgeau-Chavez *et al.* 2000). In our study area, we sampled fire scars on jack pine trees in a few stands (Figure 6-12) where their presence was conspicuous. The interval between a stand-replacing crown fire and a surface fire leaving a fire scar, or between two surface fires leaving several scars on a same tree, varied between 12 and 36 years based on this limited sampling of 3-4 trees in three different stands.

The sigmoidal flammability curve obtained in this project, with its higher flammability limit reached around 25-30 years under most weather conditions, corresponds well to the fire return intervals found in the literature for jack pine stands. Interestingly, this age threshold also agrees with the age of reproductive maturity of jack pine and black spruce trees, which begins to occur when the trees reach 10 to 15 years (Roussopoulos 1978; Heinselman 1996). Those species would be eliminated from the landscape if fires occurred too frequently before the trees were able to bear cones (Cayford 1963; Roussopoulos 1978; Heinselman 1996; Weber 1985). This is not to say that young stands cannot burn before they reach their reproductive maturity. The rate of spread and intensity predictions obtained by the models showed that fire spread is possible before that time. Such fires have in fact been reported (e.g. Weber 1985, Weber 1988) in the literature and evidence of them was even found in our study area (see Chapter 5, Figure 5-32). In general, however, they probably do not occur often or they only burn as surface fires such that the trees survive. Van Wagner and Methven (1980) stated that "for each vegetation type perpetuated by fire, there will exist an optimum fire regime that best fulfils the ecological requirements of that vegetation type".

Figure 6-10 also appears to explain well the controversy about the effectiveness of recently burned patches to stop or slow the progression of a fire. The literature abounds in accounts of situations where recently burnt areas have successfully served as "firebreaks" (e.g., Philpot 1974, 1977; Despain and Sellers 1977; Sweaney 1985; Salazar and Gonzàlez-Cabàn, 1987; Alexander and Quintilio, 1990; Minnich and Chou 1997; Niklasson and Granström 2000; Amiro *et al.* 2001) and where, on the other hand, they have failed to do so (e.g., Kiil 1975; Rouse 1976; Franklin and Hemstrom 1981; Foster 1983; Agee and Huff 1987; Keeley *et al.* 1999). Although the specific results of this study cannot be generalised to other forest types, it is relatively easy to see, following one of the curves in Figure 6-10, that a fire burning in 30-80 year-old jack pine/black spruce stands would dramatically alter its behavior if it were to spread into a younger stand (say between 0 and 20 year-old). The flammability of the younger stand is less, which would translate into much lower rate of spread and fire intensity, and thus a very different fire behavior. This was observed on the site of the International Crown Fire Modelling Experiment (ICFME) located in our study area where a crown fire reached an area burned a few days previously and stopped at its boundary (see Chapter 4, Figure 4-10).

The flammability plateau reached around 25 to 30 years in jack pine/black spruce stands does not mean that all stands will burn at that age, or that the fire will be lethal if ignited, since higher flammability does not mean extreme flammability (as seen in Figure 6-10) or extreme fire behavior. The interval between fires, as reported in the literature, often starts at those ages (or slightly before) but also reaches 80 years or more in some areas. The presence of mature and overmature stands of that forest type in the study area and elsewhere also supports the notion that many stands can escape fire for long periods. Regardless of its flammability, a stand can potentially escape major disturbances for long periods of time (Kuuluvainen 2002). Disturbance by fire in a given stand depends not only on the characteristics of that stand, the terrain, the prevailing weather and drought conditions, but also on the source of ignition. The probability of ignition by lightning is generally not very high for a given stand, which is then more likely to be ignited from an advancing flame front from an adjoining area (Rowe *et al.* 1974). The time between two fires is therefore also influenced by the flammability of the adjacent areas and by the spatial arrangement of the landscape in general (Rowe *et al.* 1974; Christensen 1993; Heinselman 1996, McCarthy *et al.* 1999; Graham *et al.* 2004). Consequently, two similar sites can have different fire frequencies (Ryan 2002).

Our results also agree with comments made by several researchers (e.g., Van Wagner 1983, Heinselman 1981b) that flammability is not a simple relation with fuel load of given forest components. Several factors contribute to the flammability of a stand. However, we observed that the stand age at which flammability reaches its maximum was generally coincident with the time when a continuous layer of needles, moss, and/or lichen starts to be present on the forest floor, a process that begins around crown closure (approximately 17 years since fire in our study area). A ground layer composed of those elements in jack pine/black spruce forests respond quickly to environmental conditions and usually can burn after short droughts or dry spells (Heinselman 1996). A similar observation was also made by Schimmel and Granström (1997) in northern Sweden. They observed that an increase in rate of spread was predicted when enough time had elapsed since a surface fire so that a carpet of feathermoss was present on the forest floor. This occurred around 50 years in their *Pinus sylvestris* stands, where the overstory trees were already tall (and thus not easily killed by a surface fire) and did not have to go through the self-thinning stage, bringing more fine fuels on the forest floor earlier after a fire.

In general, however, the use of a sigmoidal equation to describe the flammability of a stand implies that it is proportional to the accumulation of standing biomass in the forest (Li *et al.* 1997), which follows a similar curve with time. In this project, the flammability curve was positively correlated with the total fine fuel load, although the relation followed a different slope before and after 15 years since fire.

Flammability was assessed for changes along two gradients. The fuel gradient was represented by time since fire and the characteristics in the fuel complex structure existing in the jack pine/black spruce forest type during stand development after a stand-replacing crown fire. The fire weather/fire danger gradient was represented by wind speed and the fire weather/fire danger scenarios. Effects of both gradients were noted on the flammability curve.

SUMMARY AND CONCLUSION

Fire behavior models, supported by experimental fires and expert opinion, were used to obtain a flammability curve for jack pine/black spruce stands in the Hay River region of the Northwest Territories (Canada). Flammability is not well defined in the literature and was therefore represented by four different quantities in this project. Direct outputs of rate of spread and head fire intensity were used at first, then two indices of flammability, the Specific ISC index and the Global ISC index were formulated.

The results obtained from the present study suggested that flammability changed in roughly a sigmoidal fashion as a function of time since fire in the forest type studied, and was similar in form to the theoretical relationship presented by Horn (1976). An increase in the severity of the burning conditions was generally accompanied by an increase in the upper flammability limit of the curve and by a higher rate increase between approximately 3 to 5 and 25 to 30 years since fire. Accordingly, a given flammability value corresponded to a gradually older time since fire for decreasing severity of the weather conditions until a limit was reached. That limit, where the flammability value is never expected to occur at any time during stand development, was imposed by the maximum reached by the flammability curve in each weather severity condition. From the perspective of time since fire, at any given age flammability increased with the severity of the burning conditions. The difference in flammability between two levels of fire weather/fire danger severity increased with time since fire until the flammability curves levelled off at about 25-30 years) after which the differences due to fire weather/fire danger conditions remained constant with further increasing stand age.

The flammability curve corresponded well to the known fire regime of jack pine or jack pine/black spruce stands reported in the literature with its fire return interval ranging from approximately 25-30 years to 80 years. This corresponds to the range of time since fire occupied by the maximum limit of the flammability curve. On the other hand, our results suggested that fire is not very likely in the first few years after a stand-replacing crown fire.

When considering all wind speeds and fuel moisture scenarios used in this project, the results from the models indicated that crown fire initiation was possible in stands as young as 15 years old (time since fire), but that continuous crowning would not be likely at that age until fuel moisture conditions reached the "dry" and "extreme" levels for wind speeds between 10 and 20 km/h or a "moderate" level of dryness for wind speeds of 25 to 30 km/h. Although fire behavior experts predicted some crown fire activity (i.e., intermittent crowning and torching) before that time, the 15-year-old limit set in this project for the use of the Cruz *et al.* (2003; 2004a,b) models prevented us from examining crown fire potential in stands younger than 15 years.

Our results are based mainly on fire behavior models, with support from a few experimental fires and expert opinion. Studies such as this one would greatly benefit in the future from case studies of wildland fires or, whenever possible, from experimental fires in stands of many ages and under various fire weather and fire danger conditions. It would also be interesting to take more advantage of research sites like the International Crown Fire Modelling Experiment (as used in this study) and other experimental burning studies (e.g., Stocks 1987) to investigate further the development of the potential fire behavior and flammability of stands as they regenerate after a stand-replacing crown fire. The infrastructures are often already present and the extra investment needed would probably not be as great as the first implementation of the original project.

At least two fire behavior phenomena, smouldering combustion (e.g. Frandsen 1987, 1991) and maximum spotting distance (e.g. Albini 1979), have been ignored in the evaluation of flammability for this project. It may be valuable to explicitly include them in further studies to assess their contribution to the flammability of a fuel complex.

It would also be pertinent to perform a similar study in other important forest types of the boreal forest. It would be premature to generalise the results from this study to all conifer stands of the boreal forest without further investigation. The more we know about the different forest types surrounding us, the better we can manage our forests to take into consideration the pervasive nature of fire. It would have been interesting to contrast our findings with those of other studies that have compared the flammability of given vegetation types with Horn's (1976) model. Unfortunately, we could not find any that were published in the literature and, to our knowledge, the applicability of his theoretical model has not been investigated elsewhere.

Finally, flammability was assessed for changes along two gradients in this study, and effects of both gradients were noted on the flammability curve as a function of time since fire. If flammability is considered the resulting effect of the fuels and weather gradients, then it might be interesting to look at its variation as a function of available fuels, a direct and combined representation of both gradients which could cover any situation.

The results from this study, supported by those of the experimental reburns and expert opinion survey, indicated that following a stand-replacing crown fire in a jack pine/black spruce stand the flammability of the area is substantially reduced. These recently burned areas can therefore act or serve as fuelbreaks for some time in the forest type studied. However, this period of low flammability under most weather and fire danger conditions appears to only last a few years, after which the flammability increases sharply with time since fire. The potential of recently burned areas to act as fuelbreaks under most conditions then appears to decrease rapidly. Our results suggested that those stands could support a wide range of fire behavior and their potential to act as a fuelbreak will vary. Finally, our model suggests that most stands of the forest type studied will have reached their maximum flammability for any given weather conditions around 25-30 years in our study area. They will then likely burn if ignited and the fire weather and fire danger conditions will determine the different aspects of fire behavior.

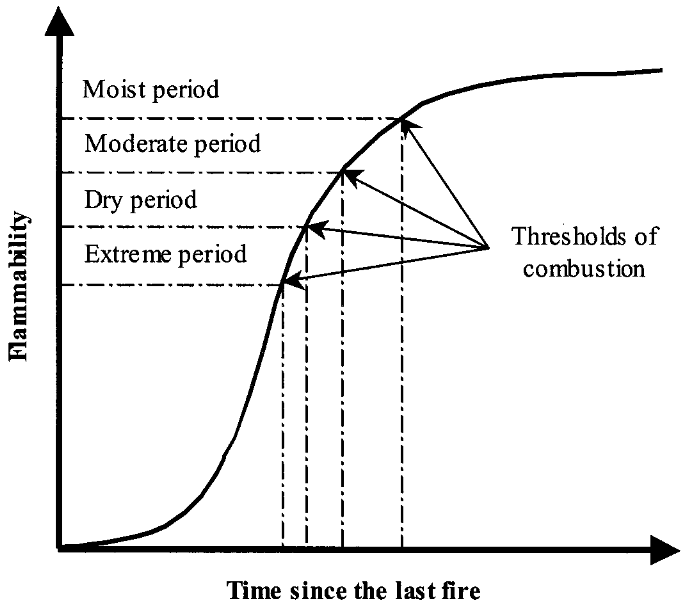

Figure 6-1. Representation of the hypothetical model presented by Horn (adapted from Horn 1976)

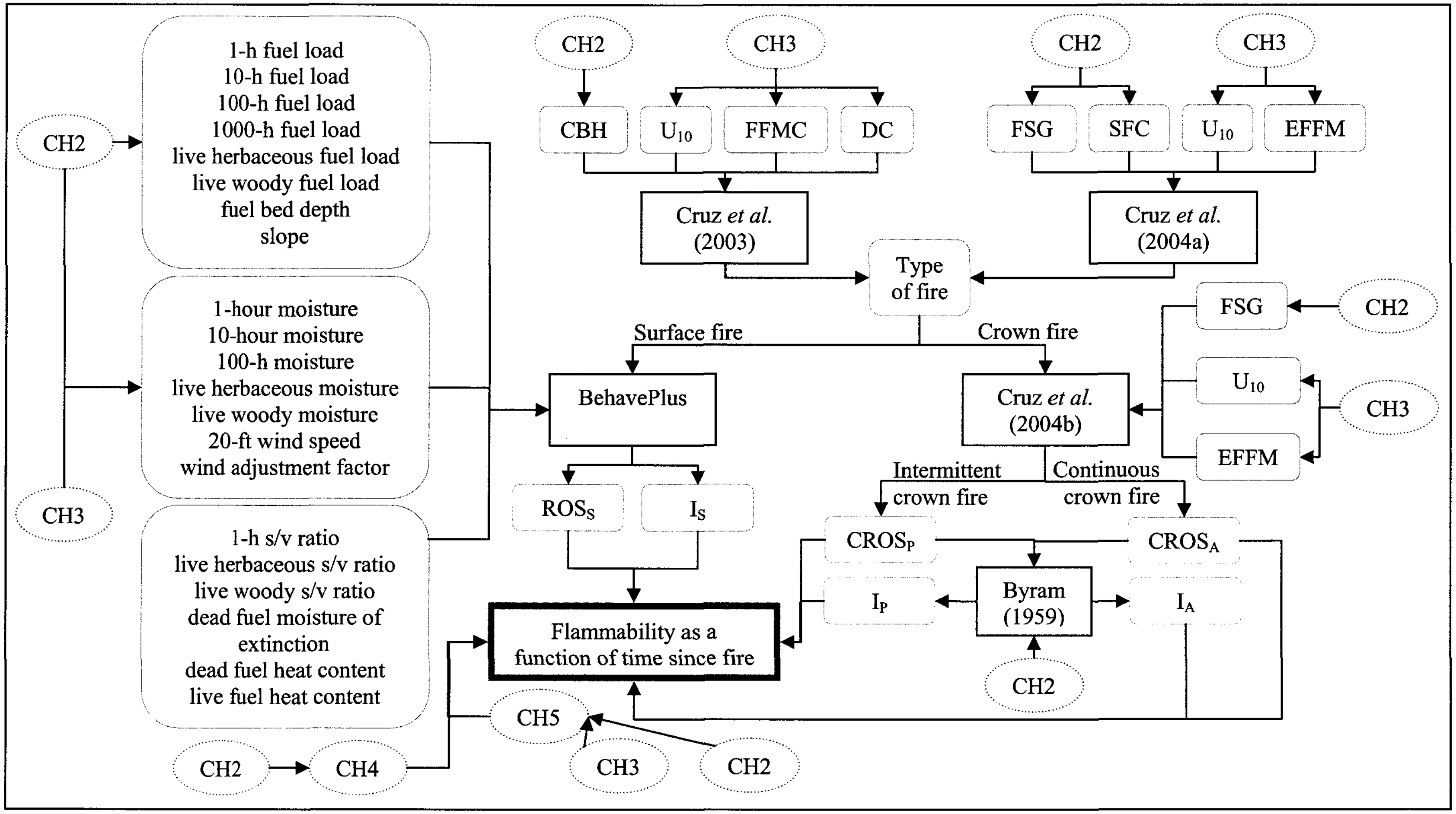

Figure 6-2. Structure of the methodology used for the fire behavior models. Inputs are in blue, outputs are in red, and complete or partial sources for the inputs are in green. CH is used as abbreviation for "chapter", ROSs and Is are surface fire rate of spread and intensity, while Ip and Ia are passive and active crown fire intensity, respectively. All other symbols were defined in the text.

Table 6-1. Conversion fraction used to convert fuel loads in American timelag fuel classes from the dead and downed woody material loads measured in the Canadian diameter classes. Stands are those in which fuels were quantified in Chapter 2.

Stand	Age	1-hour [a]		10-hour [a]		100-hour [a]				1000-hour [a]
		0.00-0.49[c] cm	0.50-0.99 cm	0.50-0.99 cm	1.00-2.99 cm	1.00-2.99 cm	3.00-4.99 cm	5.00-6.99 cm	7.00+ cm	7.00+ cm
4	1	1.000	0.278	0.722	0.796	0.204	1.000	1.000	0,058[b]	0,686[b]
9	1	1.000	0.337	0.663	0.805	0.195	1.000	1.000	0.133	0.867
7	2	1.000	0.360	0.640	0.812	0.188	1.000	1.000	0.221	0.779
8	2	1.000	0.329	0.671	0.812	0.188	1.000	1.000	0.087	0.913
5	3	1.000	0.232	0.768	0.759	0.241	1.000	1.000	0.109	0.891
6	3	1.000	0.291	0.709	0.795	0.205	1.000	1.000	0.085	0.915
14	5	1.000	0.553	0.447	0.833	0.167	1.000	1.000	0.033	0.967
12	21	1.000	0.520	0.480	0.870	0.130	1.000	1.000	0,031[b]	0,896[b]
16	56	1.000	0.533	0.467	0.872	0.128	1.000	1.000	0.115	0.885
11	57	1.000	0.360	0.640	0.896	0.104	1.000	1.000	0.020	0.980
10	71	1.000	0.504	0.496	0.851	0.149	1.000	1.000	0,093[b]	0,891[b]
13	108	1.000	0.633	0.367	0.861	0.139	1.000	1.000	0.105	0.895

a. Limits of the American time-lag fuel classes: 1-hour = 0.00-0.64 cm, 10-hour = 0.65-2.54 cm, 100-hour = 2.55-7.62 cm, and 1000-hour = 7.63-20.32 cm.

b. The total for the Canadian class is less than 1 due to dead and downed woody material larger than 20.32 cm not included in the American time-lag fuel classes.

c. Canadian diameter classes in which the dead and downed woody debris were measured in the field.

Table 6-2. Inputs used in the custom fuel models developed for the BehavePlus simulations. Plots are those in which fuels were quantified in Chapter 2.

Plot	Age	Fuel load					Fuel Bed Depth (m)	Extinction moisture content (%)	Surface/volume ratio			Heat content		Wind reduction factor[a]
		Dead			Live				Dead	Live		Dead	Live	
		1-hour (t/ha)	10-hour (t/ha)	100-hour (t/ha)	Herbs (t/ha)	Woody (t/ha)			1-hour (m^{-1})	Herbs (m^{-1})	Woody (m^{-1})	kJ/kg	kJ/kg	
4	1	0.02	1.12	6.03	0.11	0.20	0.05	20	1247	4921	4921	18700	20300	0.4
9	1	0.04	0.94	6.88	0.07	0.16	0.02	20	1247	4921	4921	18700	20300	0.4
7	2	0.02	0.61	4.15	0.04	0.09	0.05	20	1247	4921	4921	18700	20300	0.4
8	2	0.04	1.05	5.02	0.04	0.09	0.02	20	1247	4921	4921	18700	20300	0.4
5	3	0.02	0.81	8.63	0.40	0.43	0.07	20	1247	4921	4921	18700	20300	0.4
6	3	0.02	0.94	6.25	0.34	0.47	0.06	20	1247	4921	4921	18700	20300	0.4
14	5	0.52	1.26	3.41	0.69	1.21	0.25	20	1247	4921	4921	18700	20300	0.34
N/A	10	20.00	1.70	6.00	1.00	2.00	1.3	20	1247	4921	4921	18700	20300	0.22
12	21	39.07	2.13	7.15	0.07	0.52	0.25	30	5741	4921	4921	18700	20300	0.13
16	56	14.53	2.22	5.13	0.20	0.11	0.30	30	6562	4921	4921	18700	20300	0.22
11	57	14.71	3.43	4.30	0.22	0.11	0.30	30	6562	4921	4921	18700	20300	0.22
10	71	18.18	1.86	7.04	0.18	0.13	0.35	30	6562	4921	4921	18700	20300	0.28
13	108	43.85	1.10	2.73	0.18	1.08	0.35	25	6562	4921	4921	18700	20300	0.33

a. Reduction factor from the 20-ft wind speed

Table 6-3. Fuel moisture (% of dry weight) per fuel category and time since fire for the different fire weather/fire danger scenarios used in the models.

Weather Scenario	Fuel Category	Time since fire			
		Young	Immature	Mature	Senescent
Extreme	1-h	4	6	5	6
	10-h	5	7	6	7
	100-h	6	8	7	8
	Herbs	130	95	95	95
	Shrubs	125	90	90	90
Dry	1-h	7	8	8	9
	10-h	8	9	9	10
	100-h	9	10	10	11
	Herbs	150	110	110	110
	Shrubs	140	100	100	100
Moderate	1-h	12	13	13	14
	10-h	13	14	14	15
	100-h	14	15	15	16
	Herbs	190	150	150	150
	Shrubs	170	135	135	135
Moist	1-h	17	17	18	19
	10-h	18	18	19	20
	100-h	19	19	20	21
	Herbs	230	180	180	180
	Shrubs	185	150	150	150

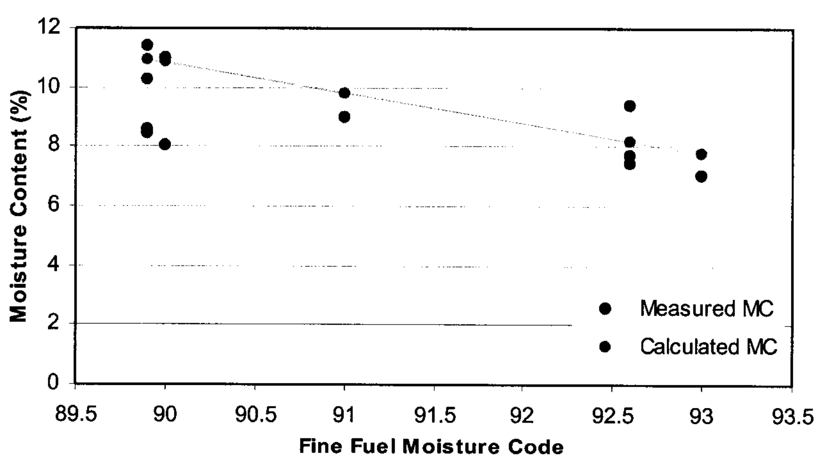

Figure 6-3. Moisture content of 10-hour timelag fuels measured in the field and moisture content calculated from the Fine Fuel Moisture Code presented as a function of the Fine Fuel Moisture Code.

Table 6-4. Type of fire (surface (S), intermittent crown (IC), or continuous crown (CC) fire) predicted with the Cruz *et al.* (2002, 2003a, 2003b) models under different wind speeds and weather scenarios in jack pine/black spruce stands of various ages (times since fire). A surface fire was assumed for stands younger than 15 years since fire.

TSF[a]	0 km/h				5 km/h				10 km/h				15 km/h				20 km/h				25 km/h				30 km/h			
	L	M	D	E	L	M	D	E	L	M	D	E	L	M	D	E	L	M	D	E	L	M	D	E	L	M	D	E
1	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
2	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
3	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
5	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
10	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
15	S	S	IC	IC	S	S	IC	IC	S	IC	CC	CC	S	IC	CC	CC	IC	IC	CC	CC	IC	CC	CC	CC	IC	CC	CC	CC
21	S	S	IC	IC	S	S	IC	IC	S	IC	IC	CC	S	IC	CC	CC	S	IC	CC	CC	IC	IC	CC	CC	IC	CC	CC	CC
57	S	S	S	IC	S	S	IC	CC	S	S	CC	CC	S	IC	CC	CC	S	CC	CC	CC	IC	CC	CC	CC	IC	CC	CC	CC
71	S	S	S	S	S	S	IC	CC	S	S	CC	CC	S	S	CC	CC	S	CC	CC	CC	S	CC	CC	CC	IC	CC	CC	CC
108	S	S	S	S	S	S	S	IC	S	S	CC	CC	S	S	CC	CC	S	CC	CC	CC	S	CC	CC	CC	S	CC	CC	CC

a. Where TSF is time since fire (years), L is "moist" fire weather/fire danger scenario, M is "moderate" fire weather/fire danger scenario, D is "dry" fire weather/fire danger scenario, E is "extreme" fire weather/fire danger scenario, S is surface fire, IC is intermittent crown fire, and CC is continuous crown fire.

Table 6-5. Rate of spread (m/min) (and type of fire) predicted by the FBP System (from Taylor *et al.* 1997) for the C-2 (Boreal Spruce), C-3 (Mature Jack or Lodgepole Pine), and C-4 (Immature Jack or Lodgepole Pine) fuel types, and rate of spread predicted by the BehavePlus or Cruz *et al.* (2004b) model for stands 21, 57, 71, and 108 years since fire.

Scenario	Wind speed (km/h)	FBP Ststem Fuel Type			Time Since Fire			
		C-2	C-3	C-4	21 years	57 years	71 years	108 years
"Moist"	0	0.9 (S)	<0.1 (S)	1 (S)	0.4 (S)	0.5 (S)	0.6 (S)	0.7 (S)
	5	0.9 (S)	<0.1 (S)	1 (S)	0.5 (S)	0.7 (S)	1.0 (S)	1.1 (S)
	10	2 (S)	0.2 (S)	2 (S)	0.6 (S)	1.1 (S)	1.6 (S)	1.8 (S)
	15	2 (S)	0.2 (S)	2 (S)	0.8 (S)	1.6 (S)	2.5 (S)	2.8 (S)
	20	3 (S)	0.3 (S)	3 (S)	1.0 (S)	2.3 (S)	3.6 (S)	4.0 (S)
	25	4 (IC)	1 (S)	5 (S)	5.0 (IC)	4.2 (IC)	4.8 (S)	5.4 (S)
	30	5 (IC)	2 (S)	7 (S)	5.4 (IC)	4.4 (IC)	6.1 (IC)	6.9 (S)
"Moderate"	0	2 (IC)	0.2 (S)	3 (S)	0.5 (S)	0.6 (S)	0.7 (S)	0.9 (S)
	5	4 (IC)	0.4 (S)	4 (IC)	0.6 (S)	0.9 (S)	1.2 (S)	1.5 (S)
	10	5 (IC)	0.8 (S)	5 (IC)	4.6 (IC)	1.3 (S)	2.0 (S)	2.5 (S)
	15	6 (IC)	1 (S)	7 (IC)	5.5 (IC)	4.8 (IC)	3.0 (S)	3.9 (S)
	20	9 (IC)	3 (S)	10 (IC)	6.0 (IC)	13.5 (CC)	13.8 (CC)	12.3 (CC)
	25	12 (CC)	5 (S)	13 (CC)	6.2 (IC)	16.5 (CC)	16.9 (CC)	15.0 (CC)
	30	17 (CC)	9 (S)	19 (CC)	18.6 (CC)	19.5 (CC)	19.9 (CC)	17.7 (CC)
"Dry"	0	8 (IC)	2 (S)	8 (IC)	0.6 (IC)	0.8 (S)	0.9 (S)	1.1 (S)
	5	10 (IC)	2 (S)	10 (IC)	5.2 (IC)	4.6 (IC)	4.2 (IC)	1.8 (S)
	10	14 (CC)	4 (IC)	13 (CC)	6.2 (IC)	16.9 (CC)	17.3 (CC)	15.4 (CC)
	15	20 (CC)	9 (IC)	19 (CC)	23.3 (CC)	24.4 (CC)	24.9 (CC)	22.2 (CC)
	20	28 (CC)	16 (CC)	28 (CC)	30.2 (CC)	31.6 (CC)	32.3 (CC)	28.7 (CC)
	25	36 (CC)	26 (CC)	36 (CC)	37 (CC)	38.6 (CC)	39.5 (CC)	35.1 (CC)
	30	52 (CC)	45 (CC)	50 (CC)	43.6 (CC)	45.5 (CC)	46.6 (CC)	41.4 (CC)
"Extreme"	0	14 (CC)	5 (IC)	14 (CC)	0.7 (IC)	1.0 (IC)	1.2 (S)	1.4 (S)
	5	18 (CC)	7 (IC)	18 (CC)	5.9 (IC)	15.1 (CC)	15.5 (CC)	3.0 (IC)
	10	25 (CC)	13 (IC)	24 (CC)	22.8 (CC)	28.2 (CC)	28.8 (CC)	25.6 (CC)
	15	33 (CC)	21 (CC)	32 (CC)	32.8 (CC)	40.6 (CC)	41.5 (CC)	36.9 (CC)
	20	43 (CC)	34 (CC)	42 (CC)	42.5 (CC)	52.6 (CC)	53.8 (CC)	47.9 (CC)
	25	62 (CC)	58 (CC)	60 (CC)	51.9 (CC)	64.3 (CC)	65.8 (CC)	58.5 (CC)
	30	70 (CC)	69 (CC)	67 (CC)	61.2 (CC)	75.8 (CC)	77.5 (CC)	68.9 (CC)

NOTE: S is surface fire, IC is intermittent crown fire, and CC is continuous crown fire.

Table 6-6. Rate of spread (m/min) predicted by the BehavePlus model for surface fires and the Cruz *et al.* (2004b) model for crown fires (the average rate of spread was used whenever more than one stand was available for a given time since fire) for different stand ages (time since fire), wind speeds and fire weather/fire danger scenarios.

TSF[a]	0 km/h				5 km/h				10 km/h				15 km/h			
	L	M	D	E	L	M	D	E	L	M	D	E	L	M	D	E
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.1	0.1	0.0	0.1	0.1	0.1
2	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.1	0.1	0.0	0.1	0.1	0.1
3	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.1	0.1	0.0	0.1	0.1	0.2
5	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.0	0.1	0.1	0.2	0.1	0.2	0.2	0.2
10[b]	0.2	0.3	0.4	0.5	1.0	1.7	2.3	2.9	1.7	3.0	4.0	5.1	2.4	4.3	5.6	7.1
15	N/A	N/A	N/A	N/A	N/A	N/A	4.6	5.0	N/A	4.2	16.9	23.7	N/A	4.8	24.3	34.1
21	0.4	0.5	0.6	0.7	0.5	0.6	5.2	5.9	0.6	4.6	6.2	22.8	0.8	5.5	23.3	32.8
57	0.5	0.6	0.8	1.0	0.7	0.9	4.6	15.1	1.1	1.3	16.9	28.2	1.6	4.8	24.4	40.6
71	0.6	0.7	0.9	1.2	1.0	1.2	4.2	15.5	1.6	2.0	17.3	28.8	2.5	3.0	24.9	41.5
108	0.7	0.9	1.1	1.4	1.1	1.5	1.8	3.0	1.8	2.5	15.4	25.6	2.8	3.9	22.2	36.9

a. Where TSF is time since fire (years), L is "moist" fire weather/fire danger scenario, M is "moderate" fire weather/fire danger scenario, D is "dry" fire weather/fire danger scenario, E is "extreme" fire weather/fire danger scenario, and N/A is "not available" (BEHAVE was not used for the stand 15 years since fire so only crown fire rates of spread are shown for that stand.

b. Inputs for BehavePlus model were obtained from interpolation of 5 and 21 years old stand inventory data.

Table 6-6. (Continued)

TSF[a]	20 km/h				25 km/h				30 km/h			
	L	M	D	E	L	M	D	E	L	M	D	E
1	0.0	0.1	0.1	0.1	0.0	0.1	0.1	0.1	0.0	0.1	0.1	0.1
2	0.0	0.1	0.1	0.1	0.0	0.1	0.1	0.2	0.0	0.1	0.2	0.2
3	0.0	0.1	0.2	0.2	0.1	0.2	0.2	0.3	0.1	0.2	0.3	0.3
5	0.1	0.2	0.3	0.3	0.1	0.3	0.3	0.4	0.1	0.3	0.4	0.5
10[b]	3.1	5.5	7.2	9.1	3.7	6.6	8.7	11.1	4.4	7.8	10.3	13.0
15	4.1	5.0	31.5	44.2	4.5	16.4	38.5	54.0	4.8	19.4	45.3	63.7
21	1.0	6.0	30.2	42.5	5.0	6.2	37.0	51.9	5.4	18.6	43.6	61.2
57	2.3	13.5	31.6	52.6	4.2	16.5	38.6	64.3	4.4	19.5	45.5	75.8
71	3.6	13.8	32.3	53.8	4.8	16.9	39.5	65.8	6.1	19.9	46.6	77.5
108	4.0	12.3	28.7	47.9	5.4	15.0	35.1	58.5	6.9	17.7	41.4	68.9

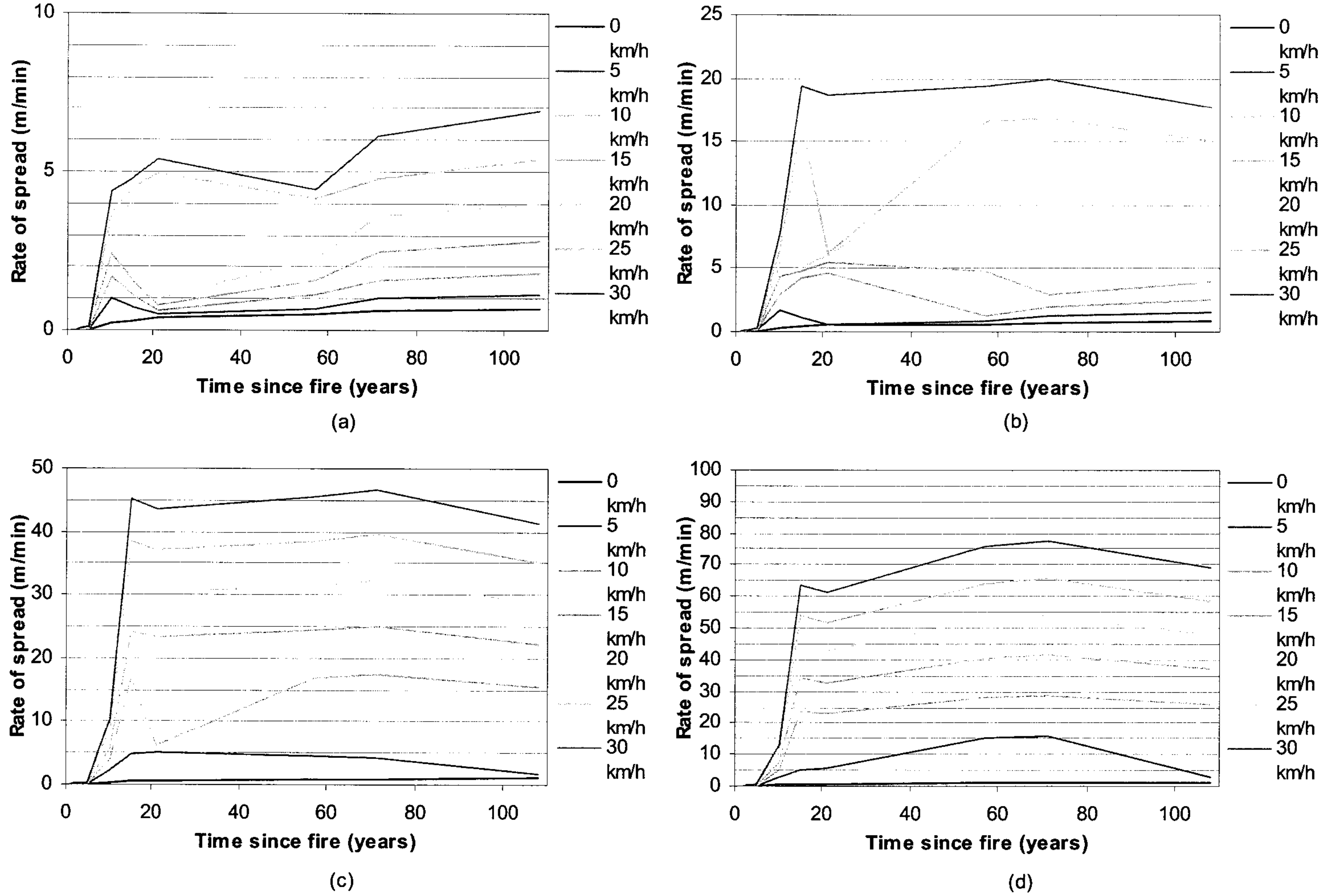

Figure 6-4. Rate of spread as a function of time since fire under different wind speed conditions for the (a) "moist", (b) "moderate", (c) "dry", and (d) "extreme" fire weather/fire danger scenarios as predicted by the Cruz *et al.* (2004b) model for crown fire and BehavePlus for surface fire. Note different scales on the y axis.

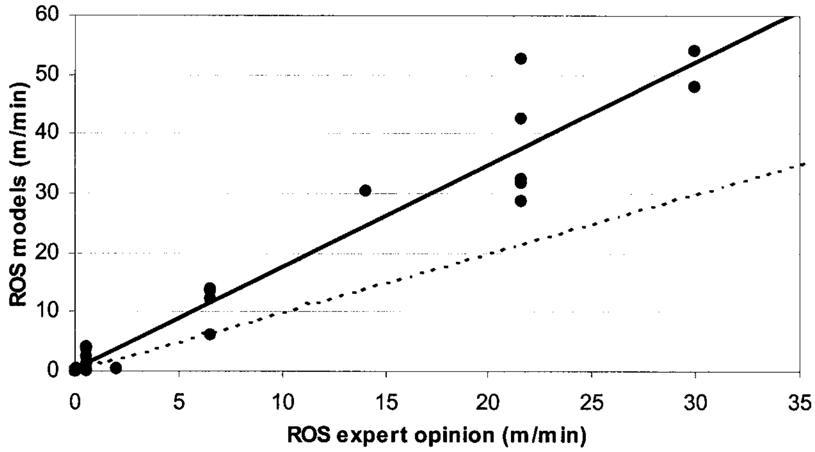

Figure 6-5. Rate of spread (m/min) predicted by fire behavior models (Cruz *et al.* 2004b for crown fire and BehavePlus for surface fires) as related to rate of spread predicted by fire behavior experts for different stand ages, weather scenarios and a 20 km/h wind.

Table 6-7. Head fire intensity (kW/m) for different stand ages, fire weather/fire danger scenarios, and wind speeds as predicted by the BehavePlus model for surface fires and Byram's (1959) equation for crown fires. The average head fire intensity was used whenever more than one stand was available for a given time since fire.

TSF[a]	0 km/h				5 km/h				10 km/h				15 km/h			
	L	M	D	E	L	M	D	E	L	M	D	E	L	M	D	E
1	0	1	1	2	0	2	3	4	1	3	5	6	1	4	6	9
2	0	1	1	2	1	3	5	6	1	5	7	9	1	6	9	12
3	0	2	3	3	1	4	6	8	1	7	10	13	1	10	15	19
5	0	1	1	1	0	2	3	4	1	4	5	7	1	5	8	11
10[b]	75	211	308	445	407	1144	1669	2408	710	1993	2907	4193	992	2786	4064	5864
15	N/A	N/A	N/A	N/A	N/A	N/A	2503	3729	N/A	1807	13560	19051	N/A	2955	19531	27440
21	154	183	258	325	179	213	3810	6091	223	2661	8465	32257	275	4675	33071	46463
57	131	163	230	332	184	231	3893	18863	286	359	21137	35199	416	4635	30446	50701
71	190	238	335	484	299	375	3722	17229	510	639	19306	32150	779	976	27808	46308
108	285	474	621	827	457	759	993	3777	788	1309	21382	35608	1212	2014	30799	51289

a. Where TSF is time since fire (years), L is "moist" fire weather/fire danger scenario, M is "moderate" fire weather/fire danger scenario, D is "dry" fire weather/fire danger scenario, E is "extreme" fire weather/fire danger scenario, and N/A is "not available" (BEHAVE was not used for the stand 15 years since fire so only crown fire rates of spread are shown for that stand.

b. Inputs for BehavePlus model were obtained from interpolation of 5 and 21 years old stand inventory data.

Table 6-7. (Continued)

TSF[a]	20 km/h				25 km/h				30 km/h			
	L	M	D	E	L	M	D	E	L	M	D	E
1	1	5	8	11	1	6	10	13	1	7	11	15
2	1	8	12	15	1	9	14	18	1	11	16	21
3	2	13	19	20	2	16	24	32	2	19	29	38
5	2	7	11	15	2	9	13	19	2	12	17	23
10[b]	1273	3576	5217	7526	1543	4332	6319	9117	1814	5093	7429	10718
15	1659	3979	25303	35550	2213	13220	30931	43457	2759	15578	36447	51206
21	337	6519	42844	60194	3376	8194	52374	73582	4262	26377	61713	86703
57	575	16859	39443	65685	2746	20608	48216	80294	3499	24283	56814	94612
71	1108	15398	36026	59993	1474	18823	44038	73337	4896	22179	51891	86414
108	1730	17054	39901	66446	2039	20847	48775	81225	2967	24565	57473	95709

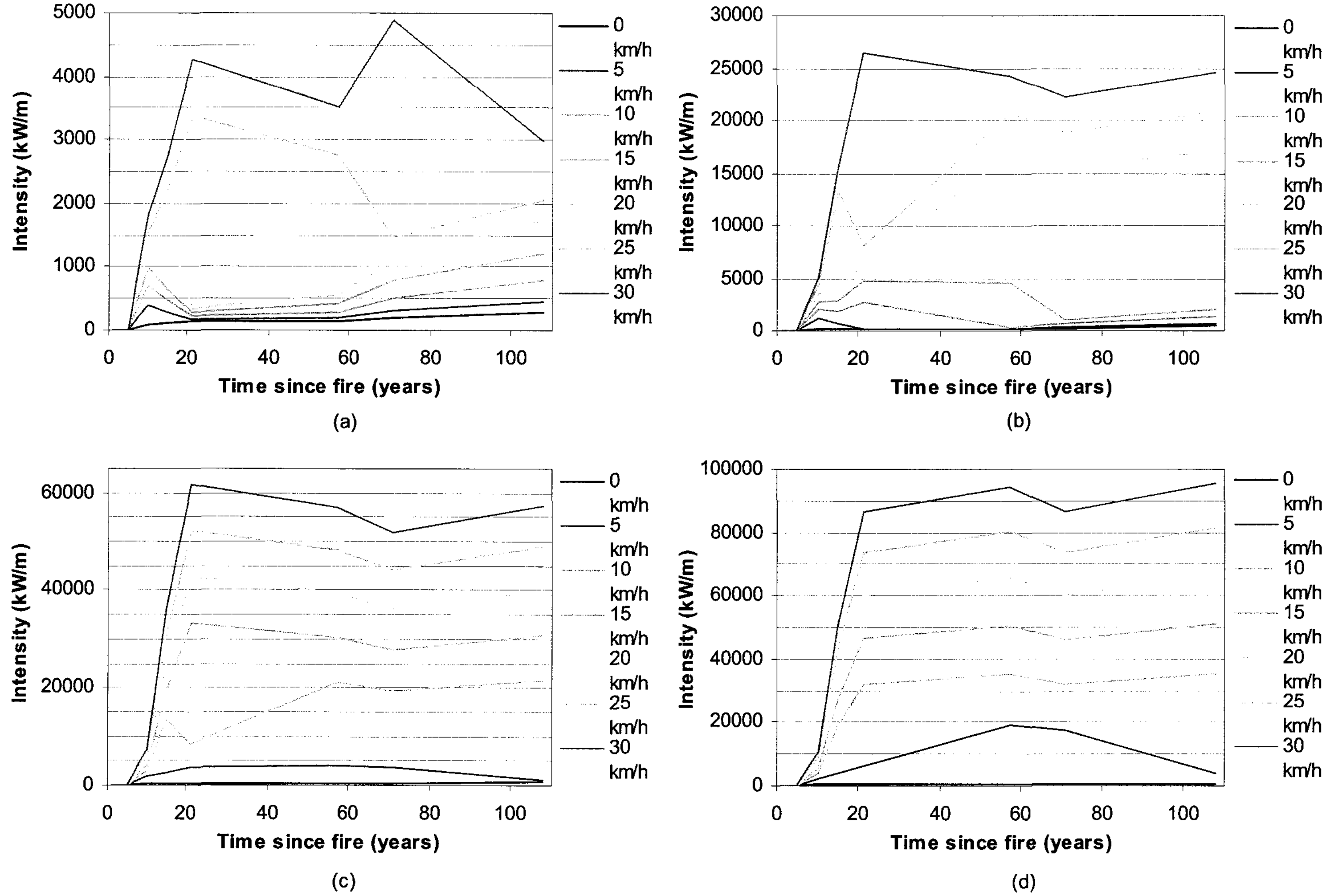

Figure 6-6. Head fire intensity (kW/m)as a function of time since fire under different wind speed conditions for the (a) "moist", (b) "moderate", (c) "dry", and (e) "extreme" fire weather/fire danger scenarios as predicted by the BehavePlus model for surface fires and Byram's (1959) equation for crown fires.

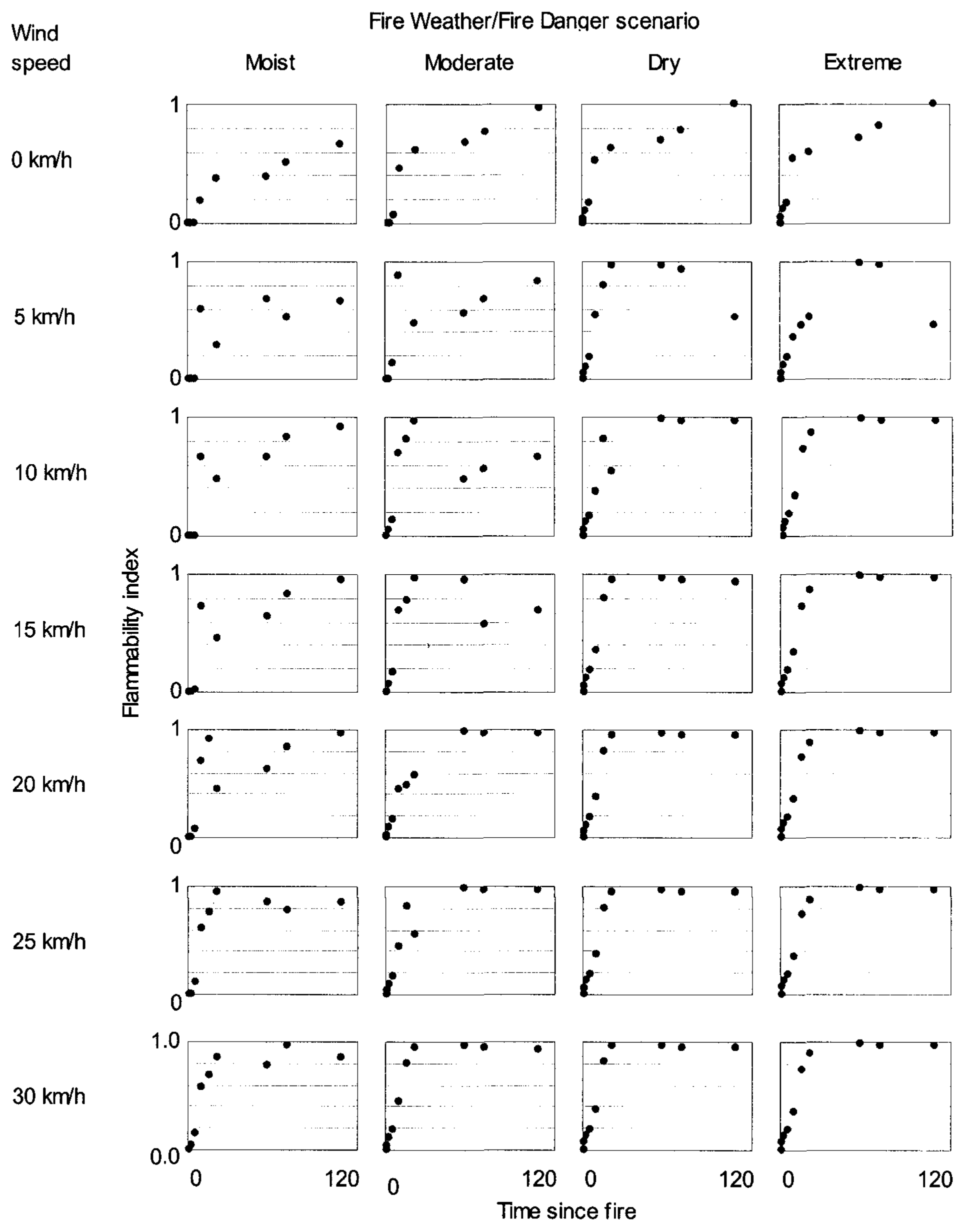

Figure 6-7. Specific ISC (ignitibility-sustainability-combustibility) flammability index as a function of time since fire for each combination of fire weather/fire danger scenario and wind speed.

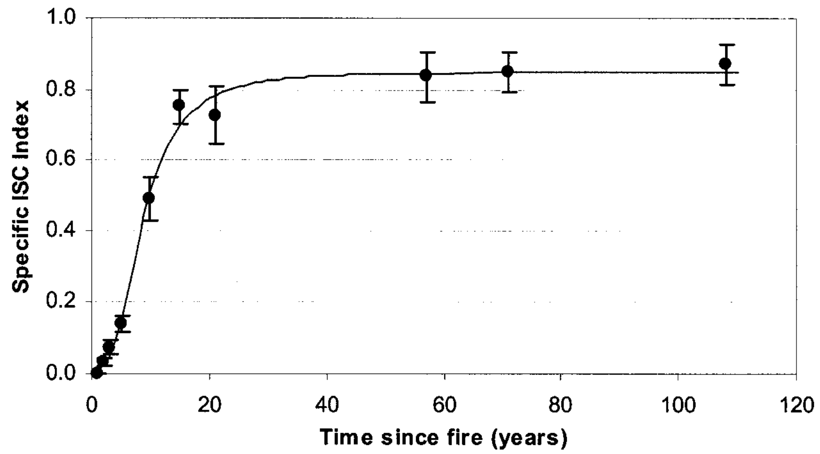

Figure 6-8. Average (and 95 % confidence interval), over all conditions of wind speed and fire weather/fire danger scenario studied in this project, of the Specific ISC (ignitibility-sustainability-combustibility) flammability index as a function of time since fire.

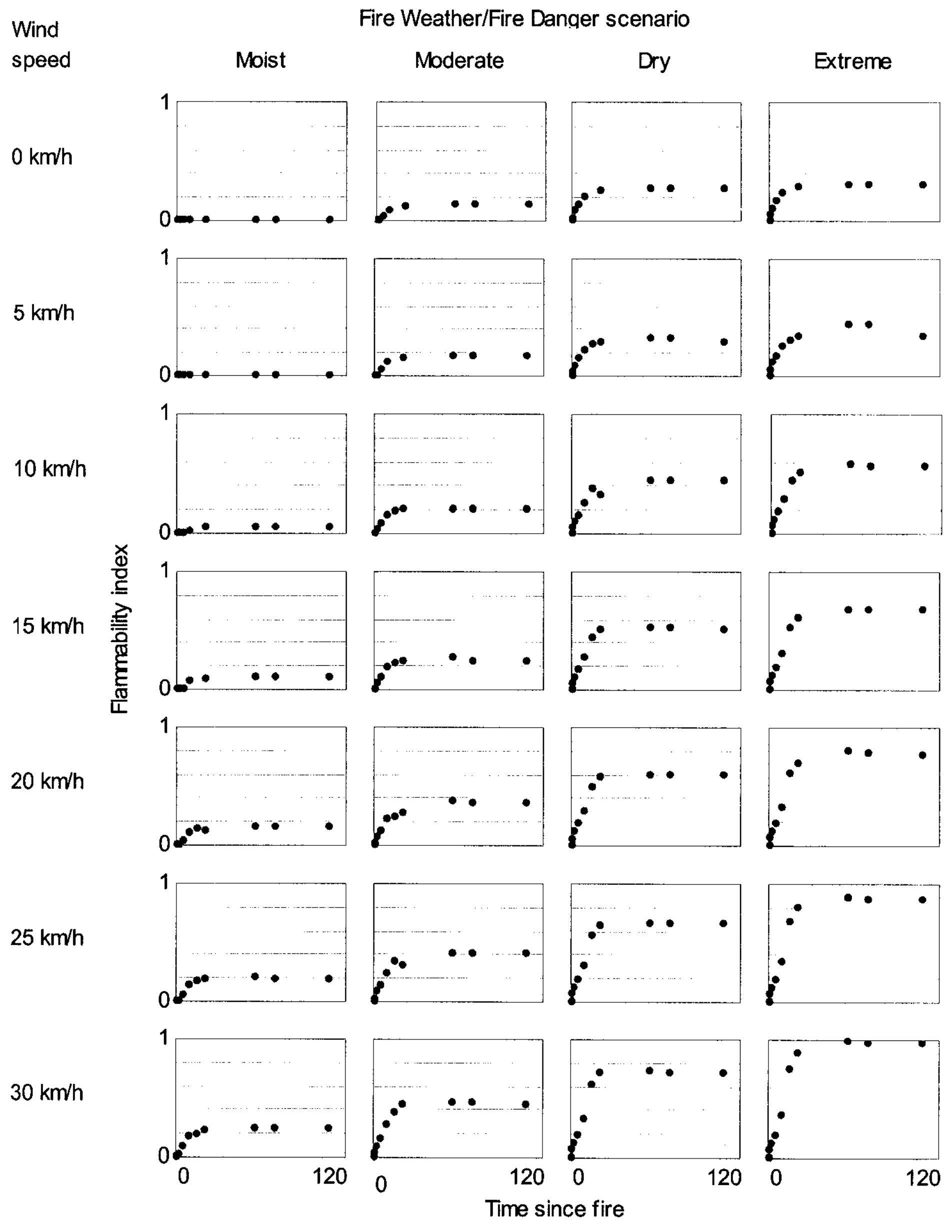

Figure 6-9. Global ISC (ignitibility-sustainability-combustibility) flammability index as a function of time since fire (years) for each combination of fire weather/fire danger scenario and wind speed.

Table 6-8. Statistics regarding the input values used to obtain given ranges of the Global ISC (ignitibility-sustainability-combustibility) Index.

Global ISC Index	Stats	Rate of spread	Intensity	Probability of ignition
0.00-0.20	Mean	0.7 ± 0.2	280 ± 98	20 ± 3
	Sample size	159	159	159
	Standard deviation	1.3	632	19
	Minimum	0.0	0	0
	Maximum	5.4	3376	57
0.21-0.40	Mean	5.7 ± 1.2	4782 ± 1170	72 ± 3
	Sample size	56	56	56
	Standard deviation	4.4	4468	10
	Minimum	0.4	230	54
	Maximum	19.4	17054	95
0.41-0.60	Mean	23.4 ± 2.4	27359 ± 2678	89 ± 2
	Sample size	29	29	29
	Standard deviation	6.6	7359	7
	Minimum	15.0	17229	78
	Maximum	38.5	42844	99
0.61-0.80	Mean	44.5 ± 3.2	52791 ± 4132	96 ± 2
	Sample size	21	21	21
	Standard deviation	7.5	9661	5
	Minimum	32.8	35550	86
	Maximum	63.7	73582	100
0.81-1.00	Mean	67.4 ± 5.3	85470 ± 5917	99 ± 1
	Sample size	7	7	7
	Standard deviation	7.1	7988	2
	Minimum	58.5	73337	95
	Maximum	77.5	95709	100

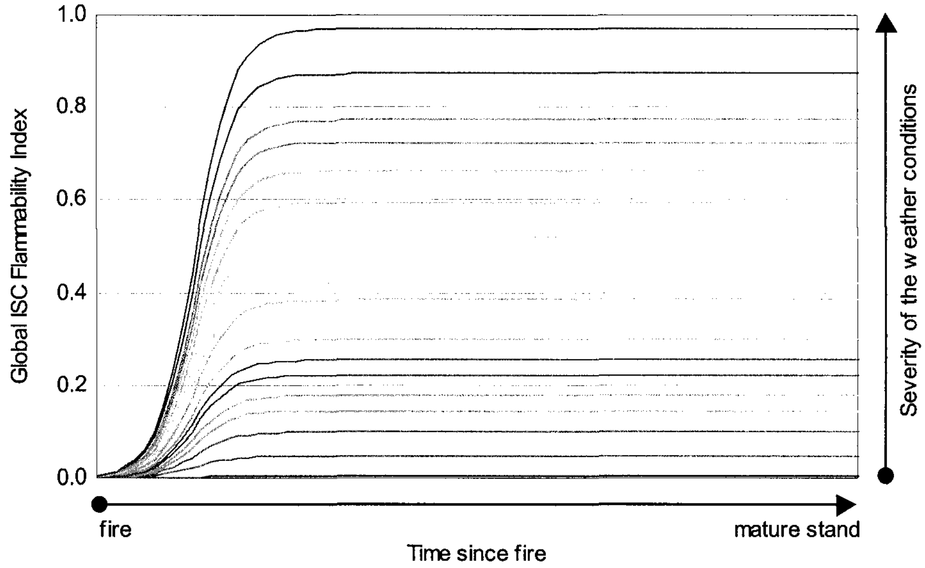

Figure 6-10. Modelised version of the Global ISC (ignitibility-sustainability-combustibility) index as a function of time since fire for situations showing an increasing gradient of fire weather/fire danger severity (as represented by wind speed and fuel moisture scenarios see Table 6-9).

Table 6-9. Combinations of fire weather/fire danger scenarios and wind speeds considered in this project ordered by increasing severity as determined by the Global ISC (ignitibility-sustainability-combustibility) flammability index.

Rank	Fire weather/fire danger scenario[a]	Wind speed (km/h)	Rank	Fire weather/fire danger scenario[a]	Wind speed (km/h)
1	L	0	15	M	20
2	L	5	16	M	25
3	L	10	17	E	5
4	L	15	18	D	10
5	M	0	19	M	30
6	L	20	20	D	15
7	M	5	21	E	10
8	L	25	22	D	20
9	M	10	23	D	25
10	L	30	24	E	15
11	M	15	25	D	30
12	D	0	26	E	20
13	E	0	27	E	25
14	D	5	28	E	30

a. Note: L = "Moist", M = "Moderate", D = "Dry", and E = "Extreme"

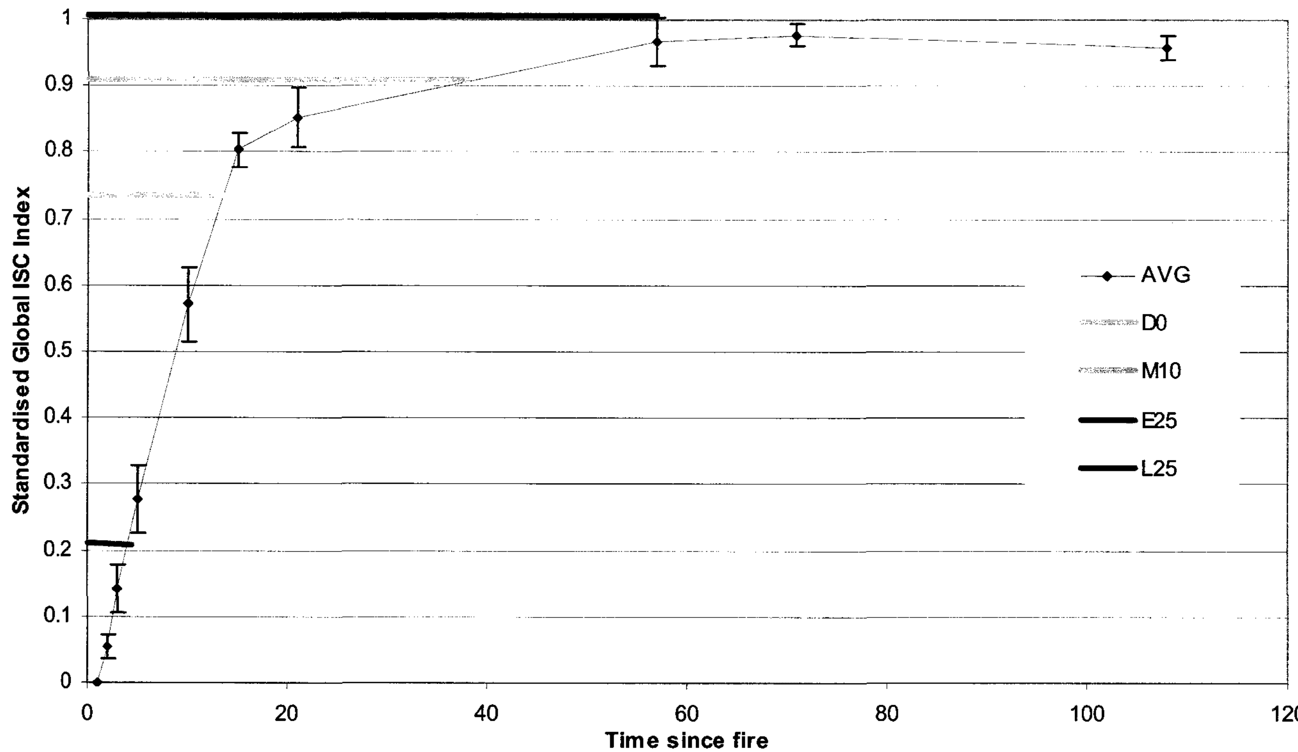

Figure 6-11. Average (and standard deviation) of the standardised curves in Figure 6-10 for comparison with Figure 6-1. We identified on the curve some fire weather/fire danger scenarios that corresponded to a Global ISC flammability index of 0.2 before the standardisation.

Figure 6-12. Photos of jack pine trees or stumps bearing a fire scar and located in our study area.

References

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NO TEXT

CHAPTER 7

Conclusion

SUMMARY OF MAIN FINDINGS

The main objective of this study was to describe the variation in flammability with time since fire in jack pine (*Pinus banksiana* Lamb.) stands exhibiting a substantial black spruce (*Picea mariana* (Mill.) B.S.P.) understory at maturity in a study area located in the Hay River district of the Northwest Territories, Canada. The hypothesis considered in this project was that the flammability of jack pine/black spruce stands in the study area varies according to the hypothetical model (Chapter 1, Figure 1-2) presented by Horn (1976). Horn's model describes an increase in flammability with time since fire during which thresholds of combustion occur at younger ages with increasingly extreme drought periods. The intrinsic shape (a sigmoidal curve was represented) of the flammability curve in that model is said to be related to vegetation development after a fire. It was of particular interest to address the validity of this model for the forest under investigation because of its complex multi-layered structure and the relatively severe fire climate in the region. In addition, there was much interest in development of a model of flammability as a function of stand age for use in landscape fire planning and operational fire management decision making.

Interestingly, in this study three very different methods (i.e., experimental fires, expert opinion survey, and fire behavior models) provided complementary results that converged towards a sigmoidal model of flammability as a function of time since fire in the forest type studied. That model, very similar in shape to the theoretical one presented by Horn (1976), shows a low flammability immediately after a stand-replacing crown fire, followed by a sharp increase between approximately 5 and 25 years after the disturbance, and a plateau thereafter where the flammability remains relatively constant as a function of time since fire for a given set of fire weather and fire danger conditions. The flammability corresponding to that plateau was further shown to vary with both wind speed and the fire weather/fire danger scenarios used in the project. Although this result agrees with our hypothesis that the flammability in the forest type studied varies according to the theoretical model presented by Horn (1976), it is somewhat surprising when considering other models that were suggested for similar forests (e.g. Van Wagner 1979, 1983; Brown 1975) where a decrease in flammability is generally observed relatively early during stand development (after an initial peak) instead of a plateau lasting over most of the immature and mature stages. Note that in our model a decrease in flammability is suspected when stands become overmature, but this could not be verified due to the scarcity of old stands in our study area.

In the development of the model, we described the dynamics in fuel composition and structure with time since a high-intensity, stand-replacing crown fire in jack pine/black spruce stands within our study area using a chronosequence covering a period of 1 to 109 years since fire. Our results suggested that stem analysis and site index data can be very helpful in the selection of the stands of a chronosequence. The detailed sampling, performed by fuel strata in each stand, showed a different progression for the ground, surface, ladder and crown fuels as a function of time since fire. This result was expected although there was much uncertainty as to what the progression of the fuels in each stratum would be. We observed that the combined load for total biomass (excluding roots and woody debris buried in the forest floor) decreased for a short period of time after a stand-replacing crown fire to reach a minimum between 20 and 40 years since fire, and then increased almost linearly with time. A similar analysis on the combined load of the fine fuels showed an initial period where those fuels loads were very low (on average 0.2 kg/m^2), followed by a gradual increase until approximately 50 years since fire where loads stabilised at around 4.3 kg/m^2.

Knowing the quantity of fuels is not sufficient to understand the potential differences in fire behavior with time since fire. Thus, we also looked at fuel structure through the use of a vertical distribution (1-m sections) of the load and bulk density of the fine fuels and total biomass (excluding roots and woody debris buried in the forest floor) of each stand. This representation had the advantage of partially solving the problem of interacting fuel layers, which was of particular importance in the forest type selected for this study. This analysis clearly showed the important contribution that the black spruce trees growing in the understory make to the ladder or "bridge" fuels in our stands. It further brought to our attention the fact that bark flakes on the stems of jack pine trees may be an underestimated source of ladder fuels. Their load and bulk density increased in importance with time since fire and by the time stands reached maturity, bark flakes had reached quantities higher than those of the jack pine needles. In fact, the ratio of bark flakes/needle fuel load in the jack pine component of our stands increased with time following a sigmoidal curve. According to that curve, the load of the bark flakes becomes more important than that of the needles approximately 65 years after a fire. Moreover, bark flake and needle fuel loads appeared to complement each other in the vertical distribution of the important fire-carrying fuels. Larger loads of needles were generally present in the top portion of the trees while bark flakes took over along the stem, when the needles started to be less abundant. Although they have sometimes been mentioned as one of several elements that can contribute to ladder fuels in a stand, bark flakes have not, to our knowledge, been quantified in such a way before in the boreal forest. Their quantity and distribution, as found in this study, may indicate that they have previously been an underestimated fuel source.

Our work towards the development of the flammability model of jack pine/black spruce stands as a function of time since fire also led us to describe the fire weather, fire danger, and fire potential climatology of our study area. Through this detailed analysis we related "moist", "moderate", "dry", and "extreme" burning conditions (representing the different periods suggested by Horn (1976) in his theoretical model) to fire weather data using archived fire weather data and the Canadian Forest Fire Danger Rating System (CFFDRS) (Alexander *et al.* 1996; Stocks *et al.* 1989). Although this analysis was performed mainly for that purpose, the results have the added benefit that they could potentially be of some use for other research and fire management activities in that region of the Northwest Territories (e.g., prescribed fires, experimental fires).

Experimental fires, ignited simultaneously in stands of different times since fire and under various fire weather and fire danger conditions, would be very useful in research on the variation of flammability as a function of time since fire. Unfortunately, they can very seldom be performed due to limited resources. Although we could not use that approach through the entire continuum of stand development, we were fortunate to have the occasion of igniting simultaneous experimental reburns in stands aged between 1 and 4 years since fire. The opportunity was provided by the presence of the well documented International Crown Fire Modelling Experiment (ICFME) (Alexander *et al.* 2004; Stocks *et al.* 2004) site in our study area. All the experimental fires we ignited in the recently burned areas showed no noticeable spread and the fires went "out" as soon as the fuel used for the ignition had been consumed. However, in one fire we observed that certain types of material (i.e., punky wood, logs, stumps) burned well, which has also been reported in the literature. The patchy vegetation present in the recently burned areas did not contribute significantly to the fire and the continuous duff layer bridging the patches did not burn. These results were somewhat surprising considering the dry conditions experienced when the experimental reburns were ignited and the presence of duff. Although we were not expecting much fire activity in those reburns, we thought that there would at least be some smouldering in the duff. The observations made during the experimental reburns indicated that under similar (or milder) weather and fuel moisture conditions, stands that show the same fuel/vegetation conditions after fire as the ICFME site are unlikely to reburn during at least the first four years following a high-intensity crown fire.

Expert judgement can provide valuable information in situations such as the one we were facing for this project, where the information needed could not readily be obtained from other sources. We used it to supplement the data obtained from experimental reburns and fire behavior models.

Of the 133 fire behavior experts we contacted, 46 answered our questionnaire. A quadratic response surface model with time since fire and Canadian Forest Fire Weather Index System (Van Wagner 1987) component values as independent variables explained between 95 and 98 % of the variation in each of the dependent variables on which the experts were questioned: 1) probability of fire spread (for a point or a line ignition), 2) rate of spread, 3) flame length, and 4) crowning or torching category. In general, the experts agreed more in their answers for situations involving older stands and drier weather conditions or younger stands and moister weather conditions. In contrast, their answers varied considerably for young stands under dry conditions and for old stands under moist conditions. Modelling of the experts' answers indicated that all dependent variables generally increased both with time since fire and with the severity of the weather conditions. However, it also suggested that under moist conditions time since fire does not much affect the dependent variables and that in very young stands, the dependent variables are not greatly affected by a change in fire weather and fire danger conditions. The data collected from the expert opinion survey generally matched well those obtained by experimental fires and fire behavior models. Although an underestimation of the rate of spread and flame length are suspected in the experts' answers, the trend in both variables with time since fire and/or the fire weather/fire danger conditions were similar to the ones obtained from experimental fires and fire behavior models.

Finally, we used fire behavior models, supported by the results from the experimental fires and expert opinion survey, to obtain a flammability curve for the forest type studied. As mentioned above, the complementary results converged towards a same model. This encourages us to believe that our approach of drawing information from a variety of sources to compensate the limitations associated with each provided the best model possible at this time in the jack pine/black spruce stands we studied. Flammability is not well defined in the literature. In this study we represented it through four different measures: first, direct outputs of rate of spread and head fire intensity were used, then two indices of flammability, the Specific ISC (Ignitibility-Sustainability-Combustibility) index and the Global ISC index were introduced. The general characteristics of the flammability curve as a function of time since fire were mentioned above. Several fuel and weather condition thresholds were identified along that curve but the main point remains that between 5 and 25 years since fire, the flammability of a stand will increase almost linearly as a function of time since fire from a period of very low flammability to one of maximum flammability under any fire weather and fire danger conditions.

Overall, this project was successful in appraising the fuels of stands having a complex multi-layered canopy as a function of time since fire. The integration of a fuel (chronosequence) and a weather (fire weather/fire danger scenarios) gradient to an approach involving a variety of sources (experimental fires, expert opinion survey, fire behavior models) provided a structured and efficient method to describe the variation in flammability of jack pine stands having a black spruce understory. The approach could potentially be used in other forest types presenting difficulties similar to the ones we encountered.

MANAGEMENT RECOMMENDATIONS

The results from this study indicated that following a stand-replacing crown fire in a jack pine/black spruce stand the flammability of the area is substantially reduced (Lavoie and Alexander 2003). These recently burned areas can therefore act or serve as fuelbreaks for some time in the forest type studied. This finding could be used in the selection of fuel treatment options such as prescribed stand-replacing crown fires (Alexander 2003) or firefighting strategies. However, this period of low flammability under most weather and fire danger conditions appears to only last a few years, after which the flammability increases sharply with time since fire.

During that period (between approximately 5 and 25 years) where our model showed a sharp increase in flammability as a function of time since fire, the potential of recently burned areas to act as a fuelbreak under most conditions appears to decrease rapidly. Although those stands have not yet reached the age where their flammability is maximum, they will likely burn if ignited and the prevailing fire weather and fire danger will contribute to determine the fire behavior experienced. Our results suggest that those stands could support a wide range of fire behavior and their potential to act as a fuelbreak will vary.

Finally, our model suggests that most stands of the forest type studied will have reached their period of maximum flammability for any given weather conditions around 25-30 years in our study area. They will then likely burn if ignited and the fire weather and fire danger conditions will determine the different aspects of fire behavior.

FUTURE RESEARCH

Although our results provide a better understanding of the temporal dynamics of fire-fuels in the jack pine/black spruce stands existing in our study area and of their variation in flammability as a function of time since a stand-replacing crown fire, they also raised several questions and aspects that require further research.

The first one is related to the contribution of bark flakes on the overstory jack pine stems to fire behavior. Although bark flakes have been reported among the fuels generally consumed in a crown fire or noted as effective ladder fuels, they have never been directly considered in the determination of the fuels consumed in a fire or in the calculation of fire intensity. They are seldom explicitly considered in the evaluation of spotting potential and their contribution to the onset of crowning and the ensuing fire behavior was, until recently (Taylor *et al.* 2004), generally considered unknown in Canada. Our study has shown that bark flake fuel loads can be as significant as the needle fuel loads in the jack pine component of our stands, and that their vertical distribution complements that of the needles in providing for a continuous vertical layer of fine fuels capable of supporting candling, torching and crowning. Future research looking at the contribution of bark flakes to fire behavior would be of value. This could be done, for example, in studies involving simultaneous experimental fires in control plots and treated plots (where the bark flakes would be removed (scraped) along a certain length of the stem of each tree). When we know more about the influence of bark flakes on the general fire behavior of jack pine stands, it would also be useful to develop fire behavior models that take them (or ladder fuels in general) into account.

Another item that needs further study is the conditions required for fire spread in the duff remaining after a stand-replacing crown fire. Our experimental fires, in stands 1 to 4 years after fire, showed that those stands do not burn even under relatively severe burning conditions despite the presence of a horizontally continuous fuelbed. Although the patchiness of the surface or ground vegetation and the ratio of fine live/dead fuels may have contributed to the lack of fire spread beyond the ignition lines or points, the duff layer left after the fire was the fuel that bridged the patches of vegetation reinvading the sites and the limited dead and downed woody material that remained. Nevertheless, this fuel layer did not burn in any of the experimental fires. To identify the properties of the duff layer that led to this result would be illuminating. We showed that the bulk density of the duff layer remaining after a high-intensity, stand-replacing crown fire was similar to the lower portion of the duff in mature stands and suggested this high bulk density may be a factor involved in the results we obtained. However, other characteristics of the duff influencing combustion, such as its inorganic content and moisture content (e.g., Frandsen 1997), should be investigated. If the bulk density was responsible for the results we obtained, then it would be interesting to investigate this further as a fuel treatment option around values-at-risk by scraping the forest floor until the portion of the forest floor layer with the higher density is exposed. This action, maybe combined with other current fuel management practices (e.g., Partners in Protection 1999), could improve in the protection of homes in forested areas.

Our difficulty, despite extended efforts, to find young jack pine stands between 6 and 20 years since fire in our study area left a gap in our chronosequence. It would be interesting to sample the fuels in such stands and, if experimental fires are not possible, to use fire behavior models to obtain fire potential and flammability data for them to verify the interpolations made in this project. In fact, the plots of the International Crown Fire Modelling Experiment could be repeatedly sampled, for example, at 5-year intervals in the next decades to provide the information needed for that purpose.

Similarly, it would also be pertinent to perform a similar study in other important forest types of the boreal forest. It would be hasty to generalise the results from this study to all conifer stands of the boreal forest without further investigation. The more we know about the different forest types surrounding us, the better we can manage our forests to take into consideration the pervasive nature of fire. It would also be interesting to use the information thus obtained in combination with the increasing number of studies looking at temporal fire disturbance patterns in the landscape, where often the variation in flammability of stands as a function of time since fire is assumed or implied (e.g., constant flammability through time, or flammability that increases linearly as a function of time since fire) (e.g., Li *et al.* 1997, McCarthy *et al.* 2001). This could result in a better understanding of landscape age dynamics and landscape fire patterns and probabilities, which would then be very valuable for fire management and forest management in general.

The results of our expert opinion survey indicated that the state of our knowledge appears to be better for situations involving older stands and drier conditions or younger stands and moister conditions than for younger stands and drier conditions or old stands and moister conditions. To provide a better understanding of flammability and fire behavior under the latter conditions it would be beneficial to document any type of fire (experimental, prescribed, wildfire) occurring under such conditions. In fact, it would be most helpful if a compendium of fire case studies from all provinces and territories was made available to Canadian fire researchers. Any fire situation (fuels, weather, topography, fire behavior, etc.) that is described has the potential to lead to a better understanding of fire behavior and more effective fire research and reduce the gap between fire (or forest) management needs and fire research products. (Alexander and Thomas 2003a, 2003b, and 2004).

It was difficult to establish values of live fuel moisture content for herbs and shrubs to be used with the four fire weather/fire danger scenarios in the BEHAVE model. This suggested that there has not been much documentation of the dynamics of moisture content in understory vegetation as a function of time of the year, stage of stand development, and fire weather/fire danger conditions in the boreal forest that can be applied in a fire management context. It could be useful to investigate those relations and maybe find predictive models for given regions.

Finally, we were unfortunately not able, despite an extended exploration of our study area and of its surroundings, to find suitable sites on which to perform simultaneous experimental fires in stands older than 4 years since fire. It would be most beneficial if such experimental fires could be performed in stands of different times since fire, under various fire weather and fire danger conditions, to test the results obtained by alternate means used in this study. Although we often complain that we don't have long-term data, we very seldom take the means to obtain them. Such a project would have to last several decades so if we don't start now, then when?

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NO TEXT

APPENDIX 1

Photoseries

Notes for the use of the photoseries:

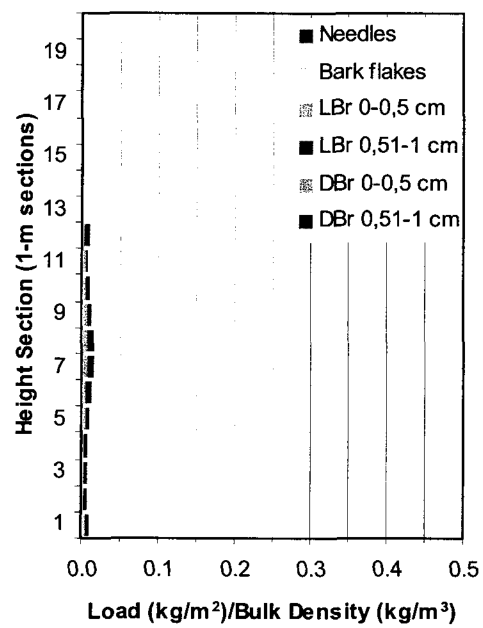
Site information:	• All the stands are part of a chronosequence. • Only the location and elevation of the stands vary in that section.
Stand information:	• The data presented for each "time since fire" was collected for the specific site identified in the field "Site ID". • The site index is the same for all the stands of the chronosequence and represents the potential height reached by the stand at 50 years. • All stands were located on flat terrain and have no slope (and no aspect).
All trees:	• The trees species used in the document are: Pj = jack pine (*Pinus banksiana*), Sb = black spruce (*Picea mariana*), and Po = *Populus* spp. • The following abbreviations were also used: L = live, and D = dead. • The density reported was the total for: trees, saplings and seedlings.
Overstory trees and understory trees:	• DBH is the average diameter at breast height (1.3 m). • The total height is for the dead and live trees taken together. • LCBH is the average live crown base height.
Forest floor:	• The bulk density (weight per unit volume) was provided for the whole forest floor profile, as well as for the first three 2-cm sections, when present. • The fuel load (weight per unit area) was provided for the whole forest floor profile, as well as for the first 2 centimetres.
Dead and downed woody material:	• The load and percent cover of the dead and downed woody material was presented for six different diameter classes. A total value was also provided.
Understory vegetation:	• Individual values were provided for load, percent cover, average height and maximum height of herbs and shrubs. • Total values provided for load and cover of understory vegetation also include other species that were not part of those two categories. Total load does not include moss and lichen but total cover does. • A percent cover of "+" for an understory species indicates a cover less than 0.5%. All values were rounded to the nearest percent.
Summary of fuel information:	• The average forest biomass (excluding roots and woody debris buried in the forest floor) load and the load of the fine fuels was presented for the three fuel strata considered in the inventory: ground fuels, surface fuels, and crown fuels.

Jack pine / black spruce stand: 1 year since fire

Site Information

Site Location:	N 61° 36', W 117° 12'
Elevation:	195 m
Prov./Territ.:	Northwest Territories
Forest Region:	Upper Mackenzie (B.23a)
Ecoregion:	Hay River Lowland (64)
Ecozone:	Taiga Plains

Vertical distribution of the crown fine fuels



Stand Information

Site ID:	P9
Main Tree Species:	*Pinus banksiana, Picea mariana*
Time Since Fire:	1 year
Crown Closure:	15 %
Site Index (50):	13.2 m
Slope:	0%

All Trees

		Pj	Sb	Po	Total
Density	L	149565	0	0	149565
(no./ha)	D	7032	4903	0	11936
Basal area	L	0.0	0.0	0.0	0.0
(m^2/ha)	D	28.2	1.2	0.0	29.3

Overstory Trees (µ 3 cm dbh)

		Pj	Sb	Po	Total
DBH	L	--	--	--	--
(cm)	D	7.4	4.2	--	7.2
Height	L	--	--	--	
(m)	D	10.5	5.8	--	
LCBH (m)	L	--	--	--	--

Understory Trees (< 3 cm dbh)

		Pj	Sb	Po	Total
Height	L	--	--	--	
(m)	D	0.6	1.4	--	1.2
LCBH (m)	L	--	--	--	--

Jack pine / black spruce stand: 1 year since fire

Forest Floor

Depth (cm)	Bulk Density (kg/m^3)	Fuel Load (kg/m^2)	Average Depth (cm)
0.0-1.99	193.2	2.3	
2.0-3.99	--		
4.0-5.99	--		
Total	189.8	2.6	1.6

Dead and Downed Woody Material

Diameter (cm)	Load (kg/m^2)	Cover (%)	Diameter (cm)	Load (kg/m^2)	Cover (%)
0.0-0.49	0.002	0.1	3.0-4.99	0.213	
0.5-0.99	0.006	0.2	5.0-6.99	0.333	
1.0-2.99	0.113	1.0	7.0+	0.912	
			Total	1.579	

Understory Vegetation

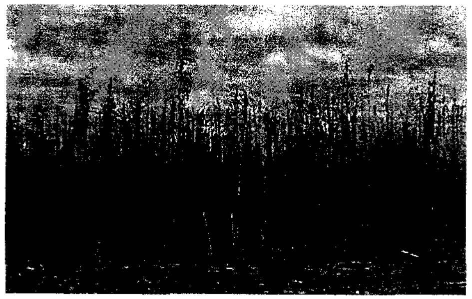
	Load (kg/m^2)	Cover (%)	Avg.Height (cm)	Max. Height (cm)
Herbs	0.006	4.7	8.7	40.0
Shrubs	0.015	6.6	18.4	35.0
Total	0.021	11.3		

Main Species (average % cover)
Rosa acicularis(3), Salix spp. (3), Geranium bicknellii (2), Linnaea borealis (1), Potentilla fruticosa (+), Galium trifidum (+)

Summary of Fuel Information

	Fine Fuels Load (kg/m^2)	Total Biomass Load (kg/m^2)
Ground Fuels	0.000	2.615
Surface Fuels	0.030	1.600
Crown Fuels	0.139	14.931
Total Fuels	0.169	19.146

Jack pine / black spruce stand: 2 years since fire



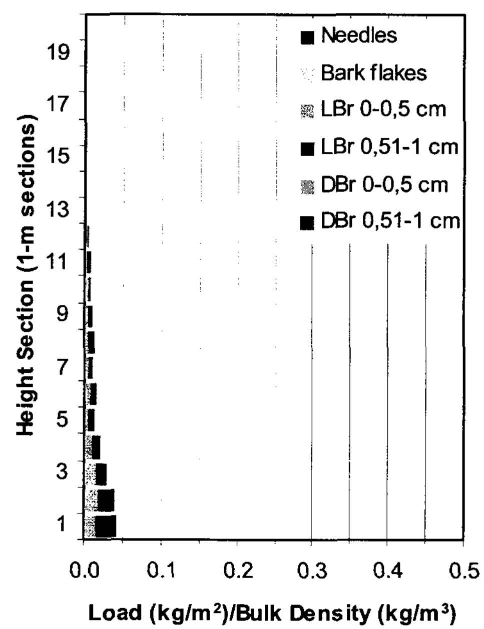
Site Information

Site Location:	N 61° 36', W 117° 12'
Elevation:	195 m
Prov./Territ.:	Northwest Territories
Forest Region:	Upper Mackenzie (B.23a)
Ecoregion:	Hay River Lowland (64)
Ecozone:	Taiga Plains

Stand Information

Site ID:	P8
Main Tree Species:	*Pinus banksiana, Picea mariana*
Time Since Fire:	2 years
Crown Closure:	19 %
Site Index (50):	13.2 m
Slope:	0%

Vertical distribution of the crown fine fuels



All Trees

		Pj	Sb	Po	Total
Density	L	84800	4000	0	88800
(no./ha)	D	4059	12600	0	16659
Basal area	L	0.0	0.0	0.0	0.0
(m^2/ha)	D	22.1	9.4	0.0	31.5

Overstory Trees (µ 3 cm dbh)

		Pj	Sb	Po	Total
DBH	L	--	--	--	--
(cm)	D	8.1	4.4	--	6.0
Height	L	--	--	--	
(m)	D	10.0	5.8	--	
LCBH (m)	L	--	--	--	--

Understory Trees (< 3 cm dbh)

		Pj	Sb	Po	Total
Height	L	--	--	--	
(m)	D	1.1	2.2	--	2.1
LCBH (m)	L	--	--	--	--

Jack pine / black spruce stand: 2 years since fire

Forest Floor

Depth (cm)	Bulk Density (kg/m^3)	Fuel Load (kg/m^2)	Average Depth (cm)
0.0-1.99	185.7	2.7	
2.0-3.99	163.9		
4.0-5.99	--		
Total	181.1	4.4	3.1

Dead and Downed Woody Material

Diameter (cm)	Load Cover (kg/m^2)	Cover (%)	Diameter (cm)	Load (kg/m^2) (%)
0.0-0.49	0.002	0.1	3.0-4.99	0.247
0.5-0.99	0.005	0.1	5.0-6.99	0.206
1.0-2.99	0.126	1.1	7.0+	0.282
			Total	0.869

Understory Vegetation

	Load (kg/m^2)	Cover (%)	Avg.Height (cm)	Max. Height (cm)
Herbs	0.005	3.0	12.7	50.0
Shrubs	0.010	6.1	21.9	35.0
Total	0.015	17.8		

Main Species (average % cover)
Ceratodon purpureus(9), Rosa acicularis (3), Salix spp. (3), Epilobium angustifolium (1), Carex spp. (+)

Summary of Fuel Information

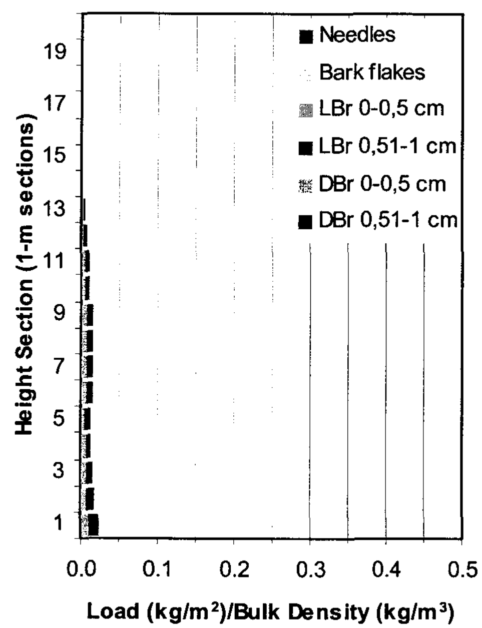
	Fine Fuels Load (kg/m^2)	Total Biomass Load (kg/m^2)
Ground Fuels	0.000	4.447
Surface Fuels	0.023	0.884
Crown Fuels	0.227	13.732
Total Fuels	0.250	19.064

Jack pine / black spruce stand: 3 years since fire

Site Information

Site Location:	N 61° 36', W 117° 12'
Elevation:	195 m
Prov./Territ.:	Northwest Territories
Forest Region:	Upper Mackenzie (B.23a)
Ecoregion:	Hay River Lowland (64)
Ecozone:	Taiga Plains

Vertical distribution of the crown fine fuels



Stand Information

Site ID:	P6
Main Tree Species:	*Pinus banksiana, Picea mariana*
Time Since Fire:	3 years
Crown Closure:	16 %
Site Index (50):	13.2 m
Slope:	0%

All Trees

		Pj	Sb	Po	Total
Density (no./ha)	L	24400	8800	0	33200
	D	7413	8776	0	16188
Basal area (m^2/ha)	L	0.0	0.0	0.0	0.0
	D	29.7	4.1	0.0	33.8

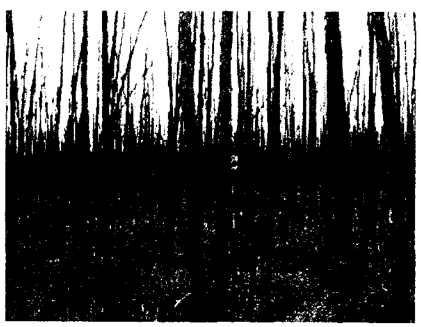
Overstory Trees (µ 3 cm dbh)

		Pj	Sb	Po	Total
DBH (cm)	L	--	--	--	--
	D	7.3	4.5	--	6.7
Height (m)	L	--	--	--	
	D	10.3	5.7	--	
LCBH (m)	L	--	--	--	--

Understory Trees (< 3 cm dbh)

		Pj	Sb	Po	Total
Height (m)	L	--	--	--	
	D	1.5	1.8	--	1.8
LCBH (m)	L	--	--	--	--

Jack pine / black spruce stand: 3 years since fire



Forest Floor

Depth (cm)	Bulk Density (kg/m^3)	Fuel Load (kg/m^2)	Average Depth (cm)
0.0-1.99	156.0	2.8	
2.0-3.99	134.1		
4.0-5.99	--		
Total	159.9	6.0	3.9

Dead and Downed Woody Material

Diameter (cm)	Load Cover (kg/m^2)	Cover (%)	Diameter (cm)	Load (kg/m^2)
(%)				
0.0-0.49	0.001	0.0	3.0-4.99	0.208
0.5-0.99	0.006	0.1	5.0-6.99	0.356
1.0-2.99	0.113	1.0	7.0+	0.441
			Total	1.124

Understory Vegetation

Height	Load (kg/m^2)	Cover (%)	Avg.Height (cm)	Max. (cm)
Herbs	0.035	15.3	10.0	60.0
Shrubs	0.047	14.2	25.2	45.0
Total	0.081	38.2		

Main Species (average % cover)

Salix spp.(10), Ceratodon purpureus (9), Carex spp. (4), Linnaea borealis (4), Rosa acicularis (3), Epilobium angustifolium (2)

Summary of Fuel Information

	Fine Fuels Load (kg/m^2)	Total Biomass Load (kg/m^2)
Ground Fuels	0.000	5.991
Surface Fuels	0.088	1.205
Crown Fuels	0.186	16.353
Total Fuels	0.274	23.549

Jack pine / black spruce stand: 5 years since fire

Site Information

Site Location:	N 61° 09', W 119° 05'
Elevation:	260 m
Prov./Territ.:	Northwest Territories
Forest Region:	Upper Mackenzie (B.23a)
Ecoregion:	Hay River Lowland (64)
Ecozone:	Taiga Plains

Stand Information

Site ID:	P14
Main Tree Species:	*Pinus banksiana, Picea mariana*
Time Since Fire:	5 years
Crown Closure:	18 %
Site Index (50):	13.2 m
Slope:	0%

All Trees

		Pj	Sb	Po	Total
Density (no./ha)	L	57637	2501	23873	84011
	D	1442	865	415	2722
Basal area (m^2/ha)	L	0.0	0.0	0.4	0.4
	D	14.9	8.0	3.5	26.5

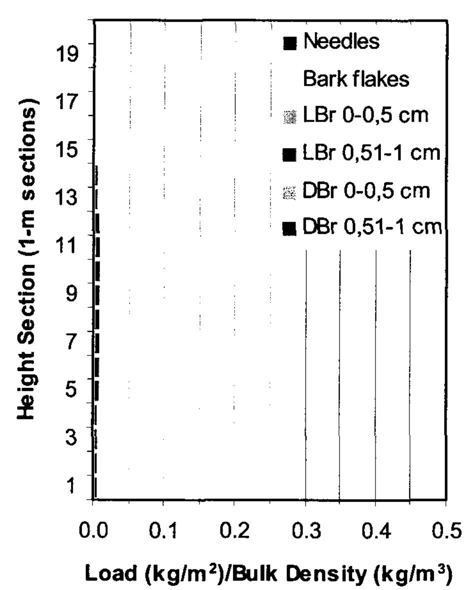
Overstory Trees (μ 3 cm dbh)

		Pj	Sb	Po	Total
DBH (cm)	L	--	--	--	--
	D	10.9	11.4	13.3	11.2
Height (m)	L	--	--	--	
	D	10.4	9.9	10.6	
LCBH (m)	L	--	--	--	--

Understory Trees (< 3 cm dbh)

		Pj	Sb	Po	Total
Height (m)	L	0.2	0.2	0.8	
	D	3.4	1.2	1.9	
LCBH (m)	L	0.0	0.0	0.5	0.1

Vertical distribution of the crown fine fuels



Jack pine / black spruce stand: 5 years since fire

Forest Floor

Depth (cm)	Bulk Density (kg/m^3)	Fuel Load (kg/m^2)	Average Depth (cm)
0.0-1.99	210.1	3.2	
2.0-3.99	209.2		
4.0-5.99	--		
Total	234.1	5.0	2.6

Dead and Downed Woody Material

Diameter (cm) (%)	Load Cover (kg/m^2)	Cover (%)	Diameter (cm)	Load (kg/m^2)
0.0-0.49	0.035	1.7	3.0-4.99	0.131
0.5-0.99	0.032	0.7	5.0-6.99	0.157
1.0-2.99	0.133	1.2	7.0+	0.928
			Total	1.416

Understory Vegetation

Height	Load (kg/m^2)	Cover (%)	Avg.Height (cm)	Max. (cm)
Herbs	0.070	35.3	13.6	100.0
Shrubs	0.121	20.0	58.4	140.0
Total	0.235	85.1		

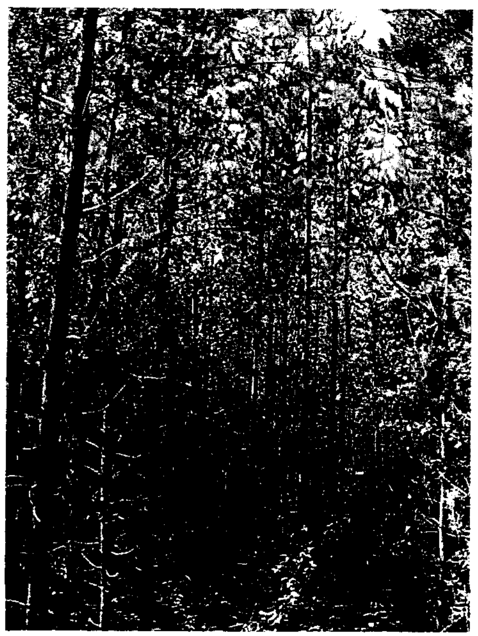
Main Species (average % cover)

Ceratodon purpureus(29), Rosa acicularis (13), Arctostaphylos uva-ursi (8), Oryzopsis asperifolia (7), Salix spp. (5)

Summary of Fuel Information

	Fine Fuels Load (kg/m^2)	Total Biomass Load (kg/m^2)
Ground Fuels	0.000	4.966
Surface Fuels	0.302	1.651
Crown Fuels	0.130	12.505
Total Fuels	0.431	19.122

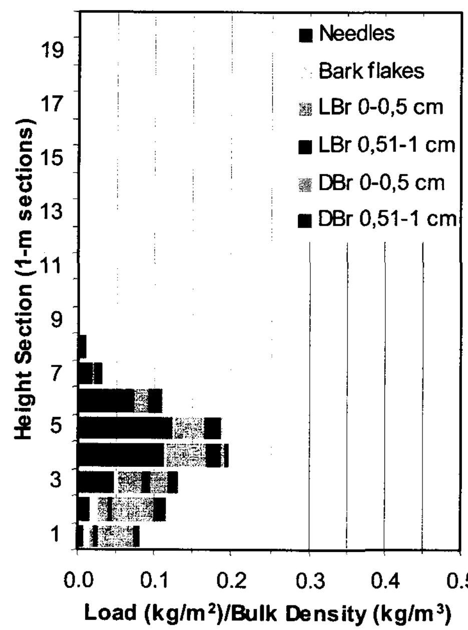
Jack pine / black spruce stand: 21 years since fire



Site Information

Site Location:	N 61° 06', W 118° 50'
Elevation:	250 m
Prov./Territ.:	Northwest Territories
Forest Region:	Upper Mackenzie (B.23a)
Ecoregion:	Hay River Lowland (64)
Ecozone:	Taiga Plains

Vertical distribution of the crown fine fuels



Stand Information

Site ID:	P12
Main Tree Species:	*Pinus banksiana, Picea mariana*
Time Since Fire:	21 years
Crown Closure:	55 %
Site Index (50):	13.2 m
Slope:	0%

All Trees

		Pj	Sb	Po	Total
Density (no./ha)	L	23242	6508	6058	35809
	D	11405	367	2999	14772
Basal area (m^2/ha)	L	15.9	0.2	1.3	17.4
	D	0.4	0.0	0.0	0.4

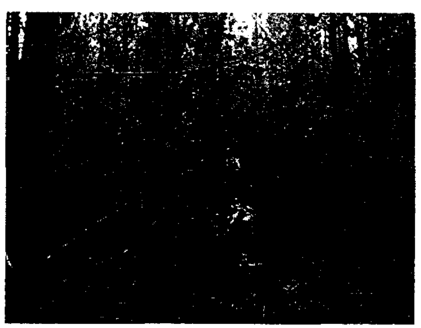
Overstory Trees (µ 3 cm dbh)

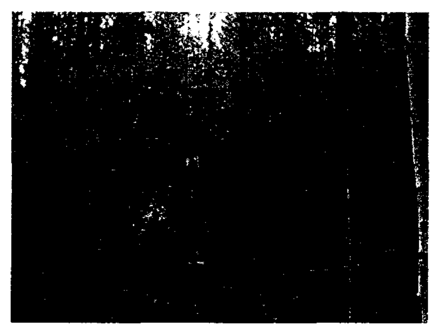
		Pj	Sb	Po	Total
DBH	L	4.3	4.5	3.9	4.3
(cm)	D	7.0	--	--	7.0
Height	L	5.1	3.6	5.2	
(m)	D	1.7	--	--	
LCBH (m)	L	2.6	0.0	3.2	2.6

Understory Trees (< 3 cm dbh)

		Pj	Sb	Po	Total
Height	L	2.9	0.5	2.9	
(m)	D	0.8	0.5	1.0	
LCBH (m)	L	2.0	0.0	1.8	1.5

Jack pine / black spruce stand: 21 years since fire





Forest Floor

Depth (cm)	Bulk Density (kg/m^3)	Fuel Load (kg/m^2)	Average Depth (cm)
0.0-1.99	90.7	1.7	
2.0-3.99	181.1		
4.0-5.99	332.0		
Total	132.4	4.8	3.6

Dead and Downed Woody Material

Diameter (cm)	Load (kg/m^2)	Cover (%)	Diameter (cm)	Load (kg/m^2)	Cover (%)
0.0-0.49	0.022	1.0	3.0-4.99	0.263	
0.5-0.99	0.037	0.9	5.0-6.99	0.370	
1.0-2.99	0.225	2.1	7.0+	1.718	
			Total	2.635	

Understory Vegetation

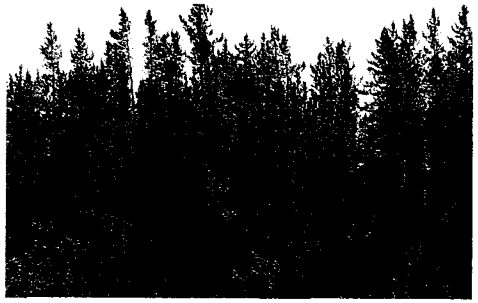
	Load (kg/m^2)	Cover (%)	Avg.Height (cm)	Max. Height (cm)
Herbs	0.008	9.3	11.3	35.0
Shrubs	0.052	13.3	64.1	200.0
Total	0.059	24.3		

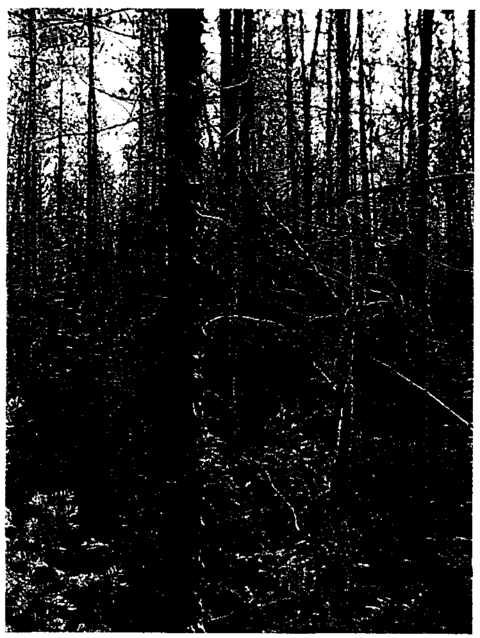
Main Species (average % cover)
Rosa acicularis(6), Salix spp. (4), Fragaria virginiana (2), Cornus canadensis (2), Ceratodon purpureus (2), Alnus crispa (2)

Summary of Fuel Information

	Fine Fuels Load (kg/m^2)	Total Biomass Load (kg/m^2)
Ground Fuels	1.689	4.775
Surface Fuels	0.118	2.694
Crown Fuels	0.873	3.809
Total Fuels	2.681	11.287

Jack pine / black spruce stand: 57 years since fire





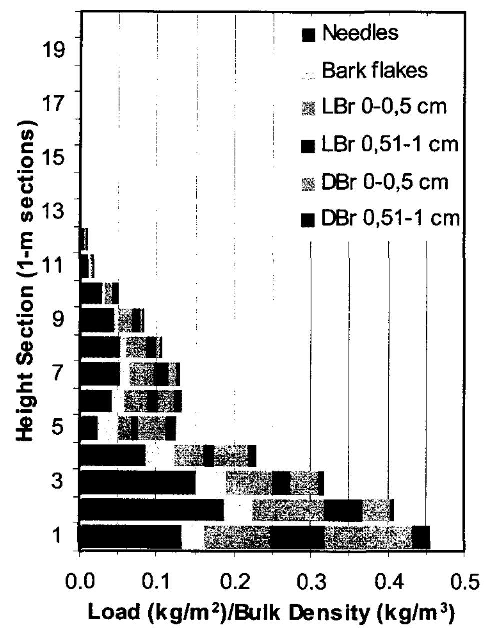
Site Information

Site Location:	N 61° 05', W 118° 44'
Elevation:	240 m
Prov./Territ.:	Northwest Territories
Forest Region:	Upper Mackenzie (B.23a)
Ecoregion:	Hay River Lowland (64)
Ecozone:	Taiga Plains

Stand Information

Site ID:	P11
Main Tree Species:	*Pinus banksiana, Picea mariana*
Time Since Fire:	57 years
Crown Closure:	47 %
Site Index (50):	13.2 m
Slope:	0%

Vertical distribution of the crown fine fuels



All Trees

		Pj	Sb	Po	Total
Density (no./ha)	L	4841	33704	66	38610
	D	2923	490	188	3601
Basal area (m^2/ha)	L	16.5	3.7	0.1	20.4
	D	1.5	0.1	0.1	1.7

Overstory Trees (μ 3 cm dbh)

		Pj	Sb	Po	Total
DBH (cm)	L	6.5	3.8	5.4	5.9
	D	4.2	--	3.7	4.1
Height (m)	L	8.0	4.5	5.0	
	D	5.3	--	4.1	
LCBH (m)	L	4.8	1.7	2.5	4.1

Understory Trees (< 3 cm dbh)

		Pj	Sb	Po	Total
Height (m)	L	4.7	1.3	--	
	D	3.3	1.4	3.6	
LCBH (m)	L	3.0	0.7	--	0.7

Jack pine / black spruce stand: 57 years since fire

Forest Floor

Depth	Bulk Density	Fuel Load	Average Depth
(cm)	(kg/m^3)	(kg/m^2)	(cm)
0.0-1.99	100.7	2.0	
2.0-3.99	115.0		
4.0-5.99	249.3		
Total	142.4	7.9	5.5

Dead and Downed Woody Material

Diameter	Load Cover	Cover	Diameter	Load
(cm) (%)	(kg/m^2)	(%)	(cm)	(kg/m^2)
0.0-0.49	0.020	1.0	3.0-4.99	0.238
0.5-0.99	0.057	1.2	5.0-6.99	0.150
1.0-2.99	0.343	3.0	7.0+	0.403
			Total	1.211

Understory Vegetation

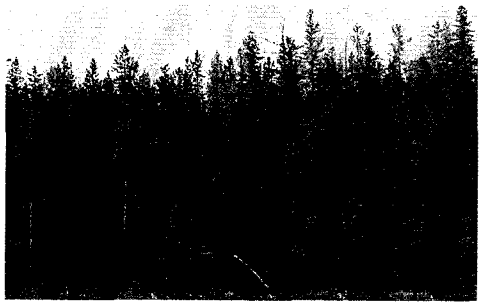
	Load	Cover	Avg.Height	Max.
Height	(kg/m^2)	(%)	(cm)	(cm)
Herbs	0.023	17.7	7.4	50.0
Shrubs	0.011	8.2	40.8	106.0
Total	0.035	50.9		

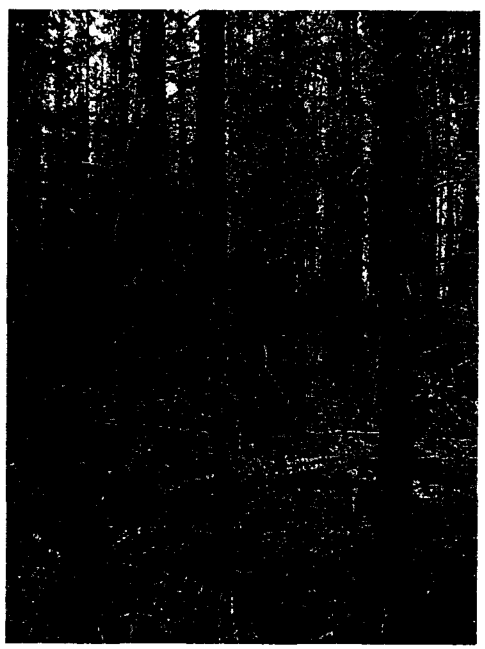
Main Species (average % cover)
Hylocomium splendens (19), Linnaea borealis (7), Rosa acicularis (5), Arctostaphylos uva-ursi (4), Cornus canadensis (3)

Summary of Fuel Information

	Fine Fuels Load (kg/m^2)	Total Biomass Load (kg/m^2)
Ground Fuels	2.014	7.892
Surface Fuels	0.112	1.245
Crown Fuels	2.036	6.914
Total Fuels	4.162	16.051

Jack pine / black spruce stand: 71 years since fire





Site Information

Site Location:	N 61° 36', W 117° 12'
Elevation:	195 m
Prov./Territ.:	Northwest Territories
Forest Region:	Upper Mackenzie (B.23a)
Ecoregion:	Hay River Lowland (64)
Ecozone:	Taiga Plains

Stand Information

Site ID:	P10
Main Tree Species:	*Pinus banksiana, Picea mariana*
Time Since Fire:	71 years
Crown Closure:	29 %
Site Index (50):	13.2 m
Slope:	0%

All Trees

		Pj	Sb	Po	Total
Density (no./ha)	L	3061	6635	0	9696
	D	2595	995	0	3589
Basal area (m^2/ha)	L	21.9	4.1	0.0	26.0
	D	4.9	0.8	0.0	5.7

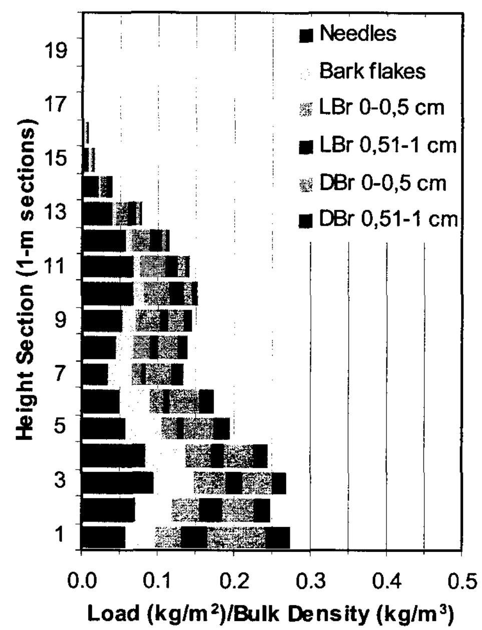
Overstory Trees (µ 3 cm dbh)

		Pj	Sb	Po	Total
DBH (cm)	L	9.6	5.2	--	8.2
	D	5.3	5.5	--	5.3
Height (m)	L	11.6	5.7	--	
	D	8.1	5.1	--	
LCBH (m)	L	7.9	1.6	--	5.9

Understory Trees (< 3 cm dbh)

		Pj	Sb	Po	Total
Height (m)	L	4.6	1.6	--	
	D	3.2	1.1	--	
LCBH (m)	L	1.9	0.6	--	0.6

Vertical distribution of the crown fine fuels



Jack pine / black spruce stand: 71 years since fire

Forest Floor

Depth (cm)	Bulk Density (kg/m^3)	Fuel Load (kg/m^2)	Average Depth (cm)
0.0-1.99	65.6	1.3	
2.0-3.99	108.9		
4.0-5.99	160.6		
Total	125.8	9.4	6.9

Dead and Downed Woody Material

Diameter (cm)	Load (kg/m^2)	Cover (%)	Diameter (cm)	Load (kg/m^2)
0.0-0.49	0.040	1.9	3.0-4.99	0.269
0.5-0.99	0.031	0.7	5.0-6.99	0.334
1.0-2.99	0.202	1.8	7.0+	0.768
			Total	1.645

Understory Vegetation

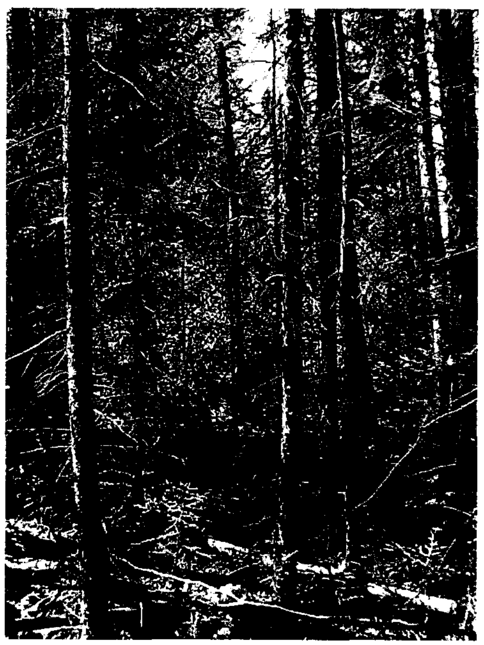
	Load (kg/m^2)	Cover (%)	Avg.Height (cm)	Max. Height (cm)
Herbs	0.018	11.9	5.1	15.0
Shrubs	0.014	7.8	29.1	50.0
Total	0.032	40.2		

Main Species (average % cover)
Hylocomium splendens (15), Arctostaphylos uva-ursi (6), Rosa acicularis (4), Linnaea borealis (4), Potentilla fruticosa (3)

Summary of Fuel Information

	Fine Fuels Load (kg/m^2)	Total Biomass Load (kg/m^2)
Ground Fuels	1.312	9.411
Surface Fuels	0.103	1.677
Crown Fuels	2.300	17.718
Total Fuels	3.715	28.806

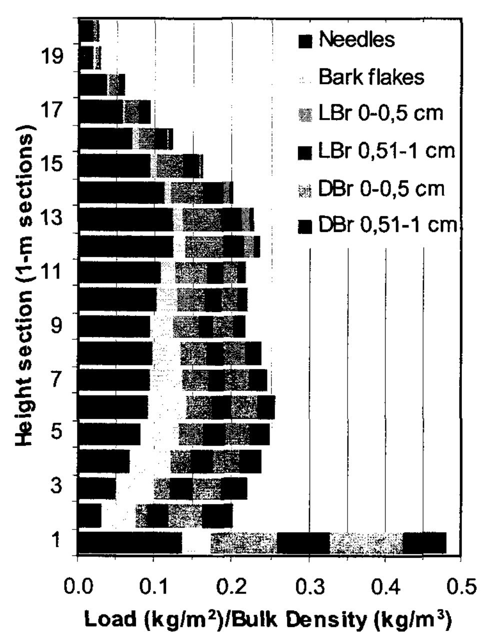
Jack pine / black spruce stand: 108 years since fire



Site Information

Site Location:	N 61° 08', W 119° 11'
Elevation:	245 m
Prov./Territ.:	Northwest Territories
Forest Region:	Upper Mackenzie (B.23a)
Ecoregion:	Hay River Lowland (64)
Ecozone:	Taiga Plains

Vertical distribution of the crown fine fuels



Stand Information

Site ID:	P13
Main Tree Species:	*Pinus banksiana*, *Picea mariana*
Time Since Fire:	108 years
Crown Closure:	52 %
Site Index (50):	13.2 m
Slope:	0%

All Trees

		Pj	Sb	Po	Total
Density	L	1066	18235	199	19500
(no./ha)	D	519	925	464	1908
Basal area	L	22.6	16.9	0.1	39.5
(m^2/ha)	D	3.9	0.5	0.0	4.4

Overstory Trees (μ 3 cm dbh)

		Pj	Sb	Po	Total
DBH	L	16.1	11.1	--	13.3
(cm)	D	10.2	6.4	--	9.4
Height	L	13.8	9.6	--	
(m)	D	10.7	5.9	--	
LCBH	L	9.6	4.4	--	6.7
(m)					

Understory Trees (< 3 cm dbh)

		Pj	Sb	Po	Total
Height	L	--	0.5	2.7	
(m)	D	0.5	0.9	0.8	
LCBH	L	--	0.1	2.1	0.1
(m)					

Jack pine / black spruce stand: 108 years since fire

Forest Floor

Depth (cm)	Bulk Density (kg/m^3)	Fuel Load (kg/m^2)	Average Depth (cm)
0.0-1.99	35.9	0.7	
2.0-3.99	37.0		
4.0-5.99	55.9		
Total	71.6	9.9	13.6

Dead and Downed Woody Material

Diameter (cm) (%)	Load Cover (kg/m^2)	Cover (%)	Diameter (cm)	Load (kg/m^2)
0.0-0.49	0.016	0.8	3.0-4.99	0.067
0.5-0.99	0.036	0.7	5.0-6.99	0.129
1.0-2.99	0.111	0.9	7.0+	0.587
			Total	0.946

Understory Vegetation

Height	Load (kg/m^2)	Cover (%)	Avg.Height (cm)	Max. (cm)
Herbs	0.018	9.3	6.5	35.0
Shrubs	0.108	17.7	80.6	220.0
Total	0.126	95.3		

Main Species (average % cover)

Hylocomium splendens (64), Alnus crispa. (7), Rosa acicularis (6), Grass *(2), Arctostaphylos uva-ursi (2),Shepherdia canadensis (2)*

Summary of Fuel Information

	Fine Fuels Load (kg/m^2)	Total Biomass Load (kg/m^2)
Ground Fuels	0.717	9.938
Surface Fuels	0.178	1.072
Crown Fuels	3.733	28.400
Total Fuels	4.628	39.410

APPENDIX 2

First contact for the expert opinion survey: prenotice letter.

Dear Mr/Ms. [name],

I am writing to ask your help in a fire behavior study conducted for a graduate research project at the University of Alberta under the supervision of Drs. Marty Alexander (Canadian Forest Service) and Ellen Macdonald (University of Alberta). This study is part of an effort to learn how the potential fire behavior varies during the development of a jack pine stand having a black spruce understory.

It is my understanding that you have a considerable amount of expertise in fire behavior observations and/or predictions in the boreal forest. I am contacting you, as part of a small group of fire behavior experts, to ask if you would be willing to answer a questionnaire that will help to complete the information already collected for the project. The questionnaire will ask you to provide assessments of potential fire behavior for a number of selected scenarios similar to the conditions you usually encounter (or have encountered) during your work. I must emphasise that there are no wrong answers and that you will be asked to complete the questionnaire to the best of your knowledge. The completion of the questionnaire should not require more than two (2) hours of your time.

Your answers will be completely confidential and will be released only as summaries. The questionnaire will be identified by a number that only myself and my supervisors (mentioned above) will be able to relate to you. The compilation of the expert judgement survey will be made into a chapter of my thesis and may potentially be published in the literature. If you want, a copy of this compilation will be mailed to you.

Your assistance in completing this questionnaire would be very much appreciated. Please contact me at the address or e-mail indicated below to confirm whether or not you are able and willing to participate. If you have any questions or comments about this study, I would be happy to talk with you.

Thank you very much for helping with this important study.

Sincerely,

Nathalie Lavoie

APPENDIX 3

Second contact for the expert opinion survey: letter sent with the questionnaire.

Dear Mr/Ms. [name],

Thank you for answering my previous letter and for accepting to participate to this fire behavior study. I am especially grateful for your help because it is only by asking experts like you to share your experiences and opinions that I can complement the data I collected in the field on how flammability changes over time in jack pine stands having a black spruce understory.

You will find enclosed a copy of the questionnaire and a stamped return envelope. The questionnaire is only identified to you by a number printed on the back cover. Your answers will therefore remain confidential and only myself and my supervisors (Drs. Marty Alexander and Ellen Macdonald) will have access to your name. It would be much appreciated if you could return the completed questionnaire within one (1) month of receiving it. The questions have been selected so that the questionnaire will take at the most two (2) hours to complete. Further instructions are given in the questionnaire, and I remain available to answer any questions or concerns you may have.

Your participation is completely voluntary. I hope that you will fill out the questionnaire soon, but if for any reason you are unable or choose not to do so, please let me know by returning a note or blank questionnaire in the enclosed stamped envelope.

Thank you for your time and consideration. It is only with the generous help of people like you that this research can be successful.

Sincerely,

Nathalie Lavoie

APPENDIX 4

Third contact for the expert opinion survey: thank you/reminder letter

Dear Mr/Ms. [name],

A few weeks ago I sent you a questionnaire for an important fire behavior research project being conducted at the University of Alberta. If you have already completed and returned it, please accept my sincere thanks. The results of this survey will help me model the relation between stand development and flammability in jack pine stands having a black spruce understory.

If you have not yet had time to complete the questionnaire, I would very much appreciate if you could do so before [date]. If for any reason you are unable to do so, please let me know by returning a note or blank questionnaire.

Thank you very much for your help with this study. I really appreciate it.

Sincerely,

Nathalie Lavoie

APPENDIX 5

Fourth contact for the expert opinion survey: thank you letter.

Dear Mr/Ms. [name],

I am writing to thank you for your participation to the expert judgement survey conducted as part of my fire behavior graduate research project at the University of Alberta. I have received your completed questionnaire and will include your answers in my analyses.

If you have indicated at the end of the questionnaire that you would like to receive a copy of the survey's compilation report, your name has already been added to my mailing list. If you have not asked for a copy of the report but would like to get one, please contact me and I will be happy to add your name to the list.

Once again I would like to thank you very much for helping with this important study on the relation between stand development and flammability in jack pine stands having a black spruce understory. Your participation contributed to complement the information already collected for the project by adding your experience and knowledge of an innumerable number of fires that were impossible to reproduce experimentally.

Sincerely,

Nathalie Lavoie

APPENDIX 6

Copy of the questionnaire used for the expert opinion survey.

The copy of the questionnaire presented in the following pages is 65% of its original size. The pages with photos were printed in color in the original questionnaire.

Fire Behavior Expert Survey

University of Alberta
2002

Please return your completed questionnaire in the enclosed envelope to:

NATHALIE LAVOIE
DEPARTMENT OF RENEWABLE RESOURCES
UNIVERSITY OF ALBERTA
751, GENERAL SERVICES BUILDING
EDMONTON, ALBERTA, T6G 2H1

INSTRUCTIONS

- The completion of this questionnaire will not take you more than two (2) hours.
- Your participation is completely voluntary. If you are unable to complete the questionnaire or choose not to do so, please let me know by returning a note or a blank questionnaire in the return envelope.
- For each stand (A to F), read over the stand description, look at the photos, and examine the stereo-pair with the stereoscope.
- Go through and answer the questions to the best of your ability. There is no wrong answer!
- The questions should be answered in their numerical order.
- When a question asks for a probability, the answer should be a percentage (%) between 0% (can never happen) and 100% (will always happen).
- Definitions of some selected terms have been placed on page 19 of this questionnaire. You may refer to them as needed.
- There are different types of bias that can influence answers provided in this type of questionnaire. One means of reducing their effect is simply to be aware of them. Try to keep the following biases in mind and to avoid their influence when answering the questions:

  Biases:

  - Omitting important hypotheses or elements of scenarios.
  - Limiting selection to only options that you have experienced.
  - Treating most recent experience/information as the most valuable.
  - Attributing too much responsibility to one condition or factor.
  - Keying your judgement on similarity to recent or vividly remembered catastrophes.
  - Failing to revise an opinion on receipt of new information.

2

ABBREVIATIONS

FFMC	Fine Fuel Moisture Code
DMC	Duff Moisture Code
DC	Drought Code
ISI	Initial Spread Index
BUI	Buildup Index
FWI	Fire Weather Index
T°	Air temperature (°C)
RH	Relative humidity (%)
Wspd	Wind speed (km/h)
Rn	Rain (mm)
ROS	Head fire equilibrium rate of spread (m/min)
FL	Flame length (m)
Avg.	Average
Dens.	Density
DBH	Diameter at breast height (cm)
CBH	Live crown base height (m)
D	Dead
L	Live
Prov./Terr.	Province/Territory

Vegetation:

Latin name	Common name	Abbreviation
Pinus banksiana	Jack pine	Pj
Picea mariana	Black spruce	Sb
Picea glauca	White spruce	Sw
Populus spp.	Poplar/Aspen	Po
Alnus crispa	Green alder	Alcr
Rosa acicularis	Prickly rose	Roac
Juniperus communis	Common juniper	Juco
Shepherdia canadensis	Canada buffaloberry	Shca
Salix spp.	Willow	Sasp
Potentilla fruticosa	Shrubby cinquefoil	Pofr
Cornus stolonifera	Red-osier dogwood	Cost
Viburnum edule	Low-bush cranberry	Vied
Note: A mix of poplar, aspen, and birch was identified as		Decid.

STAND "A" - QUESTIONS

START HERE

1 **What do you think the probability is of a fire spreading through STAND A given the following conditions:**

Date:	July 15	Time of day:	Peak burning period		
T:	25 °C	FFMC:	95	ISI:	24
RH:	33 %	DMC:	160	BUI:	180
Wspd:	20 km/h	DC:	514	FWI:	66

A. For a point ignition? (e.g. lightning, spot fire) Probability: ____ %

B. For a line ignition? (i.e., advancing fire front) Probability: ____ %

2 **For STAND A and the conditions described in Question 1, what would be:** *(see categories below)*

A. The equilibrium ROS category?

B. The flame length, in metres?

C. The torching category?

D. The crowning category?

3 **What do you think the probability is of a fire spreading through STAND A given the following conditions:**

Date:	July 15	Time of day:	Peak burning period		
T:	25 °C	FFMC:	92	ISI:	16
RH:	33 %	DMC:	93	BUI:	127
Wspd:	20 km/h	DC:	492	FWI:	46

A. For a point ignition? (e.g. lightning, spot fire) Probability: ____ %

B. For a line ignition? (i.e., advancing fire front) Probability: ____ %

4 **For STAND A and the conditions described in Question 3, what would be:** *(see categories below)*

A. The equilibrium ROS category?

B. The flame length, in metres?

C. The torching category?

D. The crowning category?

5 **What do you think the probability is of a fire spreading through STAND A given the following conditions:**

Date:	July 15	Time of day:	Peak burning period		
T:	25 °C	FFMC:	87	ISI:	8
RH:	33 %	DMC:	39	BUI:	60
Wspd:	20 km/h	DC:	325	FWI:	20

A. For a point ignition? (e.g. lightning, spot fire) Probability: ____ %

B. For a line ignition? (i.e., advancing fire front) Probability: ____ %

6 **For STAND A and the conditions described in Question 5, what would be:** *(see categories below)*

A. The equilibrium ROS category?

B. The flame length, in metres?

C. The torching category?

D. The crowning category?

7 **What do you think the probability is of a fire spreading through STAND A given the following conditions:**

Date:	July 15	Time of day:	Peak burning period		
T:	25 °C	FFMC:	83	ISI:	4
RH:	33 %	DMC:	20	BUI:	30
Wspd:	20 km/h	DC:	142	FWI:	9

A. For a point ignition? (e.g. lightning, spot fire) Probability: ____ %

B. For a line ignition? (i.e., advancing fire front) Probability: ____ %

8 **For STAND A and the conditions described in Question 7, what would be:** *(see categories below)*

A. The equilibrium ROS category?

B. The flame length, in metres?

C. The torching category?

D. The crowning category?

RATE OF SPREAD CATEGORIES

Nil	Fire cannot sustain itself
Very slow	Spread will be generally discontinuous, with maximum ROS less than 0.1 m/min.
Slow	Spread will be occasionally discontinuous, with maximum ROS 0.1 - 1.0 m/min.
Moderately slow	Spread will be continuous with maximum ROS 1.1 - 3.0 m/min.
Moderately fast	Spread will be continuous with maximum ROS 3.1 - 10.0 m/min.
Fast	Spread will be continuous with maximum ROS 10.1 - 18.0 m/min.
Very fast	Spread will be continuous with maximum ROS 18.1 - 25.0 m/min.
Extremely fast	ROS exceeds 25.0 m/min.

TORCHING CATEGORIES

Nil	No chance of torching
Low	Occasional tree may torch-out
Medium	Pole-sized understory tree likely to torch-out
High	Most understory and occasional overstory trees likely to torch-out
Extreme	Entire stand likely to torch out

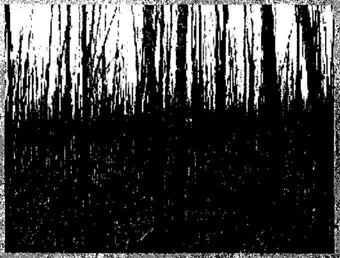
CROWNING CATEGORIES

Nil	Sustained spread in crowns will not occur
Low	Sustained spread in crowns unlikely
Medium	Some crowning likely but will not be continuous
High	Sustained crowning likely
Extreme	Sustained crowning will occur

4

STAND "A" - DESCRIPTION

Stereophotos



Data Sheet

Site Information

Site location:	N 61° 35' 00"
	W 117° 10' 00"
Elevation:	195 m
Prov./Territ.:	Northwest Territories
District:	Hay River
Ecoregion:	64. Hay River Lowland
Species:	Jack pine / Black spruce
Time since fire:	3 years
Crown closure:	19 %
Average slope:	0 %

Duff

Avg. depth: 3.9 cm

Dept (cm)	Bulk dens. (g/cm^3)
0.0-1.0	0.151
1.1-2.0	0.166
2.1-4.0	0.134
4.1-6.0	0.174

Shrubs

Main species:

Salix spp.
Rosa acicularis
Potentilla fruticosa
Shepherdia canaden.

Forest Floor

Surface material	Depth (cm)	% cover
Moss	0.6	8.7
Lichen	0.0	0.0
Needle litter	0.0	0.0

Understory

	Load		Avg. height	
Shrubs biomass	0.47	t/ha	25.2	cm
Herbs biomass	0.34	t/ha	10.2	cm
Needle litter	0.00	t/ha	0.0	cm

Dead & Downed Round-wood Fuels

Diameter class	Load (t/ha)	Cover (%)
0.0 - 0.5 (cm)	0.01	0.03
0.6 - 1.0 (cm)	0.06	0.13
1.1 - 3.0 (cm)	1.13	0.76
3.1 - 5.0 (cm)	2.09	0.97
5.1 - 7.0 (cm)	3.57	1.10
> 7.0 (cm)	3.46	0,75
Total	10.31	3.74

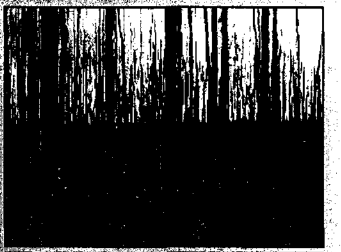
Overstory

Trees 3+ cm dbh:		Pj	Sb
Density (stems/ha)	L	0	0
	D	6372	1797
Avg. DBH (cm)	L	---	---
	D	7.3	4.5
Avg. Height (m)	L	---	---
	D	11.9	5.7
Avg. CBH (m)	L	---	---

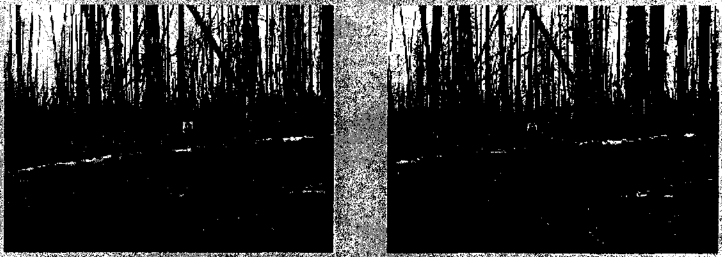
Trees <3 cm dbh:		Pj	Sb
Density (stems/ha)	L	24400	8800
	D	1041	6978
Avg. DBH (cm)	L	---	---
	D	2.5	1.8
Avg. Height (m)	L	0.05	0.05
	D	1.5	1.8
Avg. CBH (m)	L	0.0	0.0

5

STAND "B" - DESCRIPTION



Stereophotos



Data Sheet

Site Information

Site location:	N 61° 08' 39.8"
	W 119° 05' 14.1"
Elevation:	260 m
Prov/Territ.:	Northwest Territories
District:	Hay River
Ecoregion:	64. Hay River Lowland
Species:	Jack pine / Black spruce
Time since fire:	5 years
Crown closure:	21 %
Average slope:	0%

Forest Floor

Surface material	Depth (cm)	% cover
Moss	0.8	28.9
Lichen	3.4	0.9
Needle litter	0.0	0.0

Understory

	Load	Avg. height
Shrubs biomass	0.6 t/ha	58.5 cm
Herbs biomass	0,7 t/ha	13.6 cm
Needle litter	0.0 t/ha	0.0 cm

Dead & Downed Round-wood Fuels

Diameter class	Load (t/ha)	Cover (%)
0.0 - 0.5 (cm)	0.24	1,13
0.6 - 1.0 (cm)	0.62	1.40
1.1 - 3.0 (cm)	3.45	2.19
3.1 - 5.0 (cm)	1.26	0.55
5.1 - 7.0 (cm)	2.03	0.60
> 7.0 (cm)	0.39	0.12
Total	7.99	5.99

Duff

Avg. depth 2.6 cm

Bulk dens. Depth (cm)	(g/cm^3)
0.0-1.0	0.183
1.1-2.0	0.235
2.1-4.0	0.331
4.1-6.0	0.200

6

Shrubs

Main species:

Rosa acicularis
Alnus crispa
Salix spp.
Juniperus communis
Viburnum edule
Shepherdia canaden.

Overstory

Trees 3+ cm dbh:		Pj	Sb	Po
Density (stems/ha)	L	0	0	0
	D	1385	524	187
Avg. DBH (cm)	L	---	---	---
	D	10.9	11.4	13.3
Avg. Height (m)	L	---	---	---
	D	10.4	9.9	10.6
Avg. CBH (m)	L	---	---	---

Trees <3 cm dbh:		Pj	Sb	Decid
Density (stems/ha)	L	57694	3695	23873
	D	57	341	227
Avg. DBH (cm)	L	---	---	0.5
	D	2.3	1.1	1.2
Avg. Height (m)	L	0.2	0.2	0.8
	D	3.4	1.2	2.0
Avg. CBH (m)	L	0.0	0.0	---

STAND "B" - QUESTIONS

9 **What do you think the probability is of a fire spreading through STAND B given the following conditions:**

Date:	July 15	Time of day:	Peak burning period		
T:	25 °C	FFMC:	95	ISI:	24
RH:	33 %	DMC:	160	BUI:	180
Wspd:	20 km/h	DC:	514	FWI:	66

A. For a point ignition? (e.g. lightning, spot fire) Probability: %

B. For a line ignition? (i.e., advancing fire front) Probability: %

10 **For STAND B and the conditions described in Question 9, what would be:** *(see categories below)*

A. The equilibrium ROS category?

B. The flame length, in metres?

C. The torching category?

D. The crowning category?

11 **What do you think the probability is of a fire spreading through STAND B given the following conditions:**

Date:	July 15	Time of day:	Peak burning period		
T:	25 °C	FFMC:	92	ISI:	16
RH:	33 %	DMC:	93	BUI:	127
Wspd:	20 km/h	DC:	492	FWI:	46

A. For a point ignition? (e.g. lightning, spot fire) Probability: %

B. For a line ignition? (i.e., advancing fire front) Probability: %

12 **For STAND B and the conditions described in Question 11, what would be:** *(see categories below)*

A. The equilibrium ROS category?

B. The flame length, in metres?

C. The torching category?

D. The crowning category?

13 **What do you think the probability is of a fire spreading through STAND B given the following conditions:**

Date:	July 15	Time of day:	Peak burning period		
T:	25 °C	FFMC:	87	ISI:	8
RH:	33 %	DMC:	39	BUI:	60
Wspd:	20 km/h	DC:	325	FWI:	20

A. For a point ignition? (e.g. lightning, spot fire) Probability: %

B. For a line ignition? (i.e., advancing fire front) Probability: %

14 **For STAND B and the conditions described in Question 13, what would be:** *(see categories below)*

A. The equilibrium ROS category?

B. The flame length, in metres?

C. The torching category?

D. The crowning category?

15 **What do you think the probability is of a fire spreading through STAND B given the following conditions:**

Date:	July 15	Time of day:	Peak burning period		
T:	25 °C	FFMC:	83	ISI:	4
RH:	33 %	DMC:	20	BUI:	30
Wspd:	20 km/h	DC:	142	FWI:	9

A. For a point ignition? (e.g. lightning, spot fire) Probability: %

B. For a line ignition? (i.e., advancing fire front) Probability: %

16 **For STAND B and the conditions described in Question 15, what would be:** *(see categories below)*

A. The equilibrium ROS category?

B. The flame length, in metres?

C. The torching category?

D. The crowning category?

RATE OF SPREAD CATEGORIES

Nil	Fire cannot sustain itself
Very slow	Spread will be generally discontinuous, with maximum ROS less than 0.1 m/min
Slow	Spread will be occasionally discontinuous, with maximum ROS 0.1 - 1.0 m/min
Moderately slow	Spread will be continuous with maximum ROS 1.1 - 3.0 m/min
Moderately fast	Spread will be continuous with maximum ROS 3.1 - 10.0 m/min
Fast	Spread will be continuous with maximum ROS 10.1 - 18.0 m/min
Very fast	Spread will be continuous with maximum ROS 18.1 - 25.0 m/min
Extremely fast	ROS exceeds 25.0 m/min

TORCHING CATEGORIES

Nil	No chance of torching
Low	Occasional tree may torch-out
Medium	Pole-sized understory tree likely to torch-out
High	Most understory and occasional overstory trees likely to torch-out
Extreme	Entire stand likely to torch out

CROWNING CATEGORIES

Nil	Sustained spread in crowns will not occur
Low	Sustained spread in crowns unlikely
Medium	Some crowning likely but will not be continuous
High	Sustained crowning likely
Extreme	Sustained crowning will occur

7

STAND "C" - QUESTIONS

17 **What do you think the probability is of a fire spreading through STAND C given the following conditions:**

Date:	July 15	Time of day: Peak burning period			
T:	25 °C	FFMC:	95	ISI:	24
RH:	33 %	DMC:	160	BUI:	180
Wspd:	20 km/h	DC:	514	FWI:	66

A. For a point ignition? (e.g. lightning, spot fire) Probability: %

B. For a line ignition? (i.e. advancing fire front) Probability: %

18 **For STAND C and the conditions described in Question 17, what would be:** *(See categories below)*

A. The equilibrium ROS category?

B. The flame length, in metres?

C. The torching category?

D. The crowning category?

19 **What do you think the probability is of a fire spreading through STAND C given the following conditions:**

Date:	July 15	Time of day: Peak burning period			
T:	25 °C	FFMC:	92	ISI:	16
RH:	33 %	DMC:	93	BUI:	127
Wspd:	20 km/h	DC:	492	FWI:	46

A. For a point ignition? (e.g. lightning, spot fire) Probability: %

B. For a line ignition? (i.e. advancing fire front) Probability: %

20 **For STAND C and the conditions described in Question 19, what would be:** *(See categories below)*

A. The equilibrium ROS category?

B. The flame length, in metres?

C. The torching category?

D. The crowning category?

21 **What do you think the probability is of a fire spreading through STAND C given the following conditions:**

Date:	July 15	Time of day: Peak burning period			
T:	25 °C	FFMC:	87	ISI:	8
RH:	33 %	DMC:	39	BUI:	60
Wspd:	20 km/h	DC:	325	FWI:	20

A. For a point ignition? (e.g. lightning, spot fire) Probability: %

B. For a line ignition? (i.e. advancing fire front) Probability: %

22 **For STAND C and the conditions described in Question 21, what would be:** *(See categories below)*

A. The equilibrium ROS category?

B. The flame length, in metres?

C. The torching category?

D. The crowning category?

23 **What do you think the probability is of a fire spreading through STAND C given the following conditions:**

Date:	July 15	Time of day: Peak burning period			
T:	25 °C	FFMC:	83	ISI:	4
RH:	33 %	DMC:	20	BUI:	30
Wspd:	20 km/h	DC:	142	FWI:	9

A. For a point ignition? (e.g. lightning, spot fire) Probability: %

B. For a line ignition? (i.e. advancing fire front) Probability: %

24 **For STAND C and the conditions described in Question 23, what would be:** *(See categories below)*

A. The equilibrium ROS category?

B. The flame length, in metres?

C. The torching category?

D. The crowning category?

RATE OF SPREAD CATEGORIES

Nil	Fire cannot sustain itself
Very slow	Spread will be generally discontinuous, with maximum ROS less than 0.1 m/min
Slow	Spread will be occasionally discontinuous, with maximum ROS 0.1 - 1.0 m/min
Moderately slow	Spread will be continuous with maximum ROS 1.1 - 3.0 m/min
Moderately fast	Spread will be continuous with maximum ROS 3.1 - 10.0 m/min
Fast	Spread will be continuous with maximum ROS 10.1 - 18.0 m/min
Very fast	Spread will be continuous with maximum ROS 18.1 - 25.0 m/min
Extremely fast	ROS exceeds 25.0 m/min

TORCHING CATEGORIES

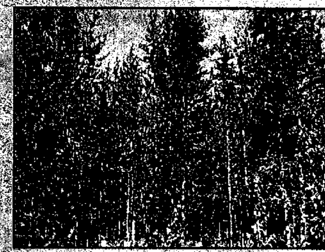
Nil	No chance of torching
Low	Occasional tree may torch-out
Medium	Pole-sized understory tree likely to torch-out
High	Most understory and occasional overstory trees likely to torch-out
Extreme	Entire stand likely to torch out

CROWNING CATEGORIES

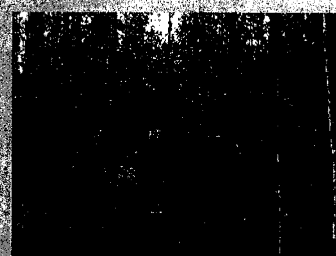
Nil	Sustained spread in crowns will not occur
Low	Sustained spread in crowns unlikely
Medium	Some crowning likely, but will not be continuous
High	Sustained crowning likely
Extreme	Sustained crowning will occur

8

STAND "C" - DESCRIPTION



Stereophotos



Data Sheet

Site Information

Site location:	N 61° 06' 07.3"
	W 118° 50' 26.2"
Elevation:	260 m
Prov/Territ.:	Northwest Territories
District:	Hay River
Ecoregion:	64. Hay River Lowland
Species:	Jack pine / Black spruce
Time since fire:	20 years
Crown closure:	58 %
Average slope:	0%

Forest Floor

Surface material	Depth (cm)	% cover
Moss	0,2	1,6
Lichen	1,7	0,2
Needle litter	3,7	74,3

Understory

	Load		Avg. height
Shrubs biomass	0,52	t/ha	64,1cm
Herbs biomass	0,08	t/ha	11,3cm
Needle litter	6,18	t/ha	3,7cm

Dead & Downed Round-wood Fuels

Diameter class	Load (t/ha)	Cover (%)
0.0 - 0.5 (cm)	0.23	1.01
0.6 - 1.0 (cm)	0.35	0.90
1.1 - 3.0 (cm)	2.17	1.54
3.1 - 5.0 (cm)	2.73	1.23
5.1 - 7.0 (cm)	3.84	1.15
> 7.0 (cm)	17.44	3.81
Total	26.76	9.64

Duff

Avg. depth 3.6 cm

Depth (cm)	Bulk dens (g/cm^3)
0.0-1.0	0.083
1.1-2.0	0.103
2.1-4.0	0.189
4.1-6.0	0.332

Shrubs

Main species:

Alnus crispa
Cornus stolonifera
Salix spp.
Rosa acicularis
Shepherdia canaden.
Potentilla fruticosa

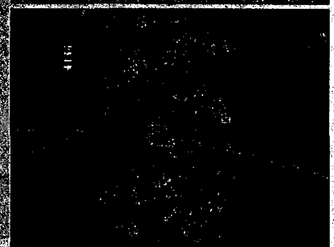
Overstory

Trees 3+ cm dbh:		Pj	Sb	Po
Density (stems/ha)	L	7694	81	243
	D	81	0	0
Avg. DBH (cm)	L	4.3	4.5	3.7
	D	7.0	---	---
Avg. Height (m)	L	5.1	3.6	5.2
	D	1.7	---	---
Avg. CBH (m)	L	2.6	0.0	3.2

Trees<3 cm dbh:		Pj	Sb	Po
Density (stems/ha)	L	15365	6427	5264
	D	11508	367	2877
Avg. DBH (cm)	L	1,7	1.0	1.2
	D	1,2	---	0,75
Avg. Height (m)	L	3.0	0,5	2,8
	D	0,8	0,5	1,0
Avg. CBH (m)	L	2.0	0,0	1,7

9

STAND "D" - DESCRIPTION



Stereophotos

Data Sheet

Site Information

Site location:	N 61° 05' 29.6
	W 118° 43' 34.5
Elevation:	240 m
Prov./Territ.:	Northwest Territories
District:	Hay River
Ecoregion:	64. Hay River Lowland
Species:	Jack pine / Black spruce
Time since fire:	56 years
Crown closure:	55 %
Average slope:	0%

Forest Floor

Surface material	Depth (cm)	% cover
Moss	2,9	23,8
Lichen	3,3	1,1
Needle litter	2,0	50,0

Understory

	Load	Avg. height
Shrubs biomass	0,11 t/ha	40,8 cm
Herbs biomass	0,23 t/ha	7,5 cm
Needle litter	2,57 t/ha	2,0 cm

Dead & Downed Round-wood Fuels

Diameter class	Load (t/ha)	Cover (%)
0.0 - 0.5 (cm)	0.21	0.97
0.6 - 1.0 (cm)	0.49	1.19
1.1 - 3.0 (cm)	3.32	2.24
3.1 - 5.0 (cm)	2.30	1.07
5.1 - 7.0 (cm)	1.46	0.45
> 7.0 (cm)	3,55	0.83
Total	11,35	6,75

Duff

Avg. depth: 5.5 cm

Depth (cm)	Bulk dens. (g/cm^3)
0.0-1.0	0.092
1.1-2.0	0.109
2.1-4.0	0.118
4.1-6.0	0.251

Shrubs

Main species:

Alnus crispa
Rosa acicularis
Juniperus communis
Potentilla fruticosa
Viburnum edule
Shepherdia canaden.

Overstory

Trees 3+ cm dbh:		Pj	Sb	Po
Density (stems/ha)	L	4412	1383	66
	D	659	0	66
Avg. DBH (cm)	L	6.5	3.8	5.4
	D	4.2	---	3.7
Avg. Height (m)	L	8.0	4.5	5.0
	D	5.3	---	4.1
Avg. CBH (m)	L	4.8	1.7	2.5

Trees <3 cm dbh:		Pj	Sb	Po
Density (stems/ha)	L	428	32321	0
	D	2265	490	122
Avg. DBH (cm)	L	2.2	1.3	---
	D	1.8	1.8	2.1
Avg. Height (m)	L	4.7	1.3	---
	D	3.3	1.4	3.6
Avg. CBH (m)	L	3.0	0.7	---

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STAND "D" - QUESTIONS

25 What do you think the probability is of a fire spreading through STAND D given the following conditions:

Date:	July 15	Time of day:	Peak burning period		
T:	25 °C	FFMC:	95	ISI:	24
RH:	33 %	DMC:	160	BUI:	180
Wspd:	20 km/h	DC:	514	FWI:	66

A. For a point ignition? (e.g. lightning spot fire) Probability: %

B. For a line ignition? (i.e., advancing fire front) Probability: %

26 For STAND D and the conditions described in Question 25, what would be: *(see categories below)*

A. The equilibrium ROS category?

B. The flame length, in metres?

C. The torching category?

D. The crowning category?

27 What do you think the probability is of a fire spreading through STAND D given the following conditions:

Date:	July 15	Time of day:	Peak burning period		
T:	25 °C	FFMC:	92	ISI:	16
RH:	33 %	DMC:	93	BUI:	121
Wspd:	20 km/h	DC:	492	FWI:	46

A. For a point ignition? (e.g. lightning spot fire) Probability: %

B. For a line ignition? (i.e., advancing fire front) Probability: %

28 For STAND D and the conditions described in Question 27, what would be: *(see categories below)*

A. The equilibrium ROS category?

B. The flame length, in metres?

C. The torching category?

D. The crowning category?

29 What do you think the probability is of a fire spreading through STAND D given the following conditions:

Date:	July 15	Time of day:	Peak burning period		
T:	25 °C	FFMC:	87	ISI:	8
RH:	33 %	DMC:	39	BUI:	60
Wspd:	20 km/h	DC:	325	FWI:	20

A. For a point ignition? (e.g. lightning spot fire) Probability: %

B. For a line ignition? (i.e., advancing fire front) Probability: %

30 For STAND D and the conditions described in Question 29, what would be: *(see categories below)*

A. The equilibrium ROS category?

B. The flame length, in metres?

C. The torching category?

D. The crowning category?

31 What do you think the probability is of a fire spreading through STAND D given the following conditions:

Date:	July 15	Time of day:	Peak burning period		
T:	25 °C	FFMC:	83	ISI:	4
RH:	33 %	DMC:	20	BUI:	30
Wspd:	20 km/h	DC:	142	FWI:	9

A. For a point ignition? (e.g. lightning spot fire) Probability: %

B. For a line ignition? (i.e., advancing fire front) Probability: %

32 For STAND D and the conditions described in Question 31, what would be: *(see categories below)*

A. The equilibrium ROS category?

B. The flame length, in metres?

C. The torching category?

D. The crowning category?

RATE OF SPREAD CATEGORIES

Nil	Fire cannot sustain itself
Very slow	Spread will be generally discontinuous, with maximum ROS less than 0.1 m/min
Slow	Spread will be occasionally discontinuous, with maximum ROS 0.1 - 1.0 m/min.
Moderately slow	Spread will be continuous with maximum ROS 1.1 - 3.0 m/min.
Moderately fast	Spread will be continuous with maximum ROS 3.1 - 10.0 m/min.
Fast	Spread will be continuous with maximum ROS 10.1 - 18.0 m/min.
Very fast	Spread will be continuous with maximum ROS 18.1 - 25.0 m/min.
Extremely fast	ROS exceeds 25.0 m/min.

TORCHING CATEGORIES

Nil	No chance of torching
Low	Occasional tree may torch-out
Medium	Pole-sized understory tree likely to torch-out
High	Most understory and occasional overstory trees likely to torch-out
Extreme	Entire stand likely to torch out

CROWNING CATEGORIES

Nil	Sustained spread in crowns will not occur
Low	Sustained spread in crowns unlikely
Medium	Some crowning likely but will not be continuous
High	Sustained crowning likely
Extreme	Sustained crowning will occur

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STAND "E" - QUESTIONS

33 What do you think the probability is of a fire spreading through STAND E given the following conditions:

Date:	July 15	Time of day:	Peak burning period		
T:	25 °C	FFMC:	95	ISI:	24
RH:	33 %	DMC:	160	BUI:	180
Wspd:	20 km/h	DC:	514	FWI:	66

A. For a point ignition? (e.g. lightning spot fire) Probability: %

B. For a line ignition? (i.e. advancing fire front) Probability: %

34 For STAND E and the conditions described in Question 33, what would be: *(see categories below)*

A. The equilibrium ROS category?

B. The flame length, in metres?

C. The torching category?

D. The crowning category?

35 What do you think the probability is of a fire spreading through STAND E given the following conditions:

Date:	July 15	Time of day:	Peak burning period		
T:	25 °C	FFMC:	92	ISI:	16
RH:	33 %	DMC:	93	BUI:	127
Wspd:	20 km/h	DC:	492	FWI:	46

A. For a point ignition? (e.g. lightning spot fire) Probability: %

B. For a line ignition? (i.e. advancing fire front) Probability: %

36 For STAND E and the conditions described in Question 35, what would be: *(see categories below)*

A. The equilibrium ROS category?

B. The flame length, in metres?

C. The torching category?

D. The crowning category?

37 What do you think the probability is of a fire spreading through STAND E given the following conditions:

Date:	July 15	Time of day:	Peak burning period		
T:	25 °C	FFMC:	87	ISI:	8
RH:	33 %	DMC:	39	BUI:	60
Wspd:	20 km/h	DC:	325	FWI:	20

A. For a point ignition? (e.g. lightning spot fire) Probability: %

B. For a line ignition? (i.e. advancing fire front) Probability: %

38 For STAND E and the conditions described in Question 37, what would be: *(see categories below)*

A. The equilibrium ROS category?

B. The flame length, in metres?

C. The torching category?

D. The crowning category?

39 What do you think the probability is of a fire spreading through STAND E given the following conditions:

Date:	July 15	Time of day:	Peak burning period		
T:	25 °C	FFMC:	83	ISI:	4
RH:	33 %	DMC:	20	BUI:	30
Wspd:	20 km/h	DC:	142	FWI:	9

A. For a point ignition? (e.g. lightning spot fire) Probability: %

B. For a line ignition? (i.e. advancing fire front) Probability: %

40 For STAND E and the conditions described in Question 39, what would be: *(see categories below)*

A. The equilibrium ROS category?

B. The flame length, in metres?

C. The torching category?

D. The crowning category?

RATE OF SPREAD CATEGORIES

Nil	Fire cannot sustain itself
Very slow	Spread will be generally discontinuous, with maximum ROS less than 0.1 m/min.
Slow	Spread will be occasionally discontinuous, with maximum ROS 0.1 - 1.0 m/min.
Moderately slow	Spread will be continuous with maximum ROS 1.1 - 3.0 m/min.
Moderately fast	Spread will be continuous with maximum ROS 3.1 - 10.0 m/min.
Fast	Spread will be continuous with maximum ROS 10.1 - 18.0 m/min.
Very fast	Spread will be continuous with maximum ROS 18.1 - 25.0 m/min.
Extremely fast	ROS exceeds 25.0 m/min.

TORCHING CATEGORIES

Nil	No chance of torching
Low	Occasional tree may torch-out
Medium	Pole-sized understory tree likely to torch-out
High	Most understory and occasional overstory trees likely to torch-out
Extreme	Entire stand likely to torch out

CROWNING CATEGORIES

Nil	Sustained spread in crowns will not occur
Low	Sustained spread in crowns unlikely
Medium	Some crowning likely but will not be continuous
High	Sustained crowning likely
Extreme	Sustained crowning will occur

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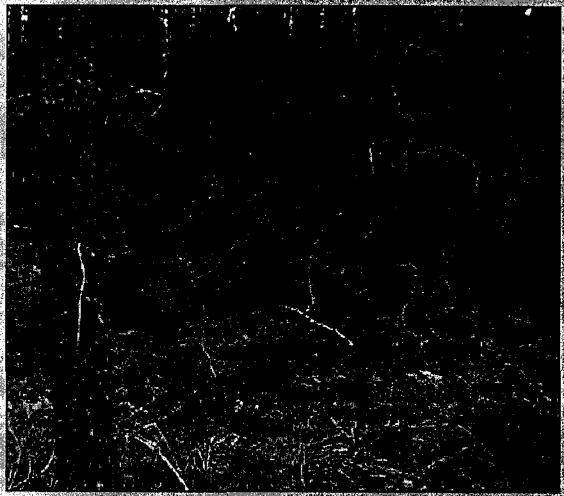
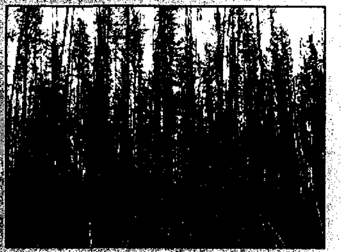
STAND "E" - DESCRIPTION





Stereophotos

Data Sheet

Site Information

Site location:	N 61° 35' 00"
	W 117° 10' 00"
Elevation:	195 m
Prov./Territ.:	Northwest Territories
District:	Hay River
Ecoregion:	64 Hay River Lowland
Species:	Jack pine / Black spruce
Time since fire:	71 years
Crown closure:	30 %
Average slope:	0%

Forest Floor

Surface material	Depth (cm)	% cover
Moss	4,7	16,1
Lichen	2,9	4,4
Needle litter	2,1	57,5

Understory

	Load		Avg. height
Shrubs biomass	0,14	t/ha	29,1 cm
Herbs biomass	0,18	t/ha	5,2 cm
Needle litter	6,46	t/ha	2,1 cm

Dead & Downed Round-wood Fuels

Diameter class	Load (t/ha)	Cover (%)
0.0 - 0.5 (cm)	0.54	2.47
0.6 - 1.0 (cm)	0.24	0.58
1.1 - 3.0 (cm)	0.90	0.59
3.1 - 5.0 (cm)	1,97	0.89
5.1 - 7.0 (cm)	3,52	1.07
> 7.0 (cm)	3,02	0,58
Total	10,19	6,17

Duff

Avg. depth: 6.9 cm

Depth (cm)	Bulk dens. (g/cm^3)
0.0-1.0	0.067
1.1-2.0	0.064
2.1-4.0	0.109
4.1-6.0	0.161

Shrubs

Main species:

Salix spp.
Potentilla fruticosa
Rosa acicularis

Overstory

Trees 3+ cm dbh:		Pj	Sb
Density (stems/ha)	L	1634	1090
	D	354	82
Avg. DBH (cm)	L	12.7	7.8
	D	7.8	5.4
Avg. Height (m)	L	14.5	9.2
	D	9.3	8.7
Avg. CBH (m)	L	9.3	2.6

Trees <3 cm dbh:		Pj	Sb
Density (stems/ha)	L	0	909
	D	57	455
Avg. DBH (cm)	L	---	1.6
	D	1.5	2.6
Avg. Height (m)	L	---	1.8
	D	2.2	1.1
Avg. CBH (m)	L	---	0.7

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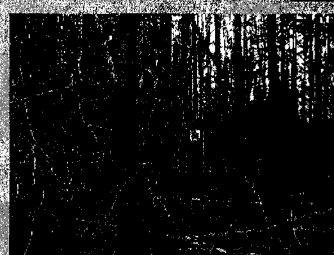
STAND "F" - DESCRIPTION

Stereophotos



Data Sheet

Site Information

Site location:	N 61° 08' 29.8"
	W 119° 11' 01.3"
Elevation:	245 m
Prov./Territ.:	Northwest Territories
District:	Hay River
Ecoregion:	64. Hay River Lowland
Species:	Jack pine / Black spruce
Time since fire:	108 years
Crown closure:	53 %
Average slope:	0%

Forest Floor

Surface material	Depth (cm)	% cover
Moss	9,6	66,7
Lichen	4,2	1,7
Needle litter	0,9	15,9

Understory

	Load	Avg. height
Shrubs biomass	1,08 t/ha	80,6 cm
Herbs biomass	0,18 t/ha	6,5 cm
Needle litter	--- t/ha	0,9 cm

Dead & Downed Round-wood Fuels

Diameter class	Load (t/ha)	Cover (%)
0.0 - 0.5 (cm)	0.16	0.77
0.6 - 1.0 (cm)	0.33	0.74
1.1 - 3.0 (cm)	1.12	0.71
3.1 - 5.0 (cm)	0.67	0.29
5.1 - 7.0 (cm)	1.30	0.38
> 7.0 (cm)	3.68	1,46
Total	7.27	4,36

Duff

Avg. depth: 13.6 cm

Depth (cm)	Bulk dens. (g/cm^3)
0.0-1.0	0.033
1.1-2.0	0.039
2.1-4.0	0.037
4.1-6.0	0.056

Shrubs

<u>Main species:</u>

Alnus crispa
Rosa acicularis
Juniperus communis
Shepherdia canaden
Salix spp.
Potentilla fruticosa

Overstory

<u>Trees 3+ cm dbh:</u>		Pj	Sb	Sw
Density (stems/ha)	L	1066	937	388
	D	432	129	0
Avg. DBH (cm)	L	16.1	10.2	13.4
	D	10.2	6.4	---
Avg. Height (m)	L	13.8	8.9	11.3
	D	10.7	5.9	---
Avg. CBH (m)	L	9.6	4.2	4.9

<u>Trees <3 cm dbh:</u>		Pj	Sb	Decid.
Density (stems/ha)	L	0	16910	199
	D	66	796	464
Avg. DBH (cm)	L	---	1.2	1.8
	D	---	0.9	1.0
Avg. Height (m)	L	---	0.5	2.7
	D	0.5	0.9	0.8
Avg. CBH (m)	L	---	0.5	2.1

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STAND "F" - QUESTIONS

41 **What do you think the probability is of a fire spreading through STAND F given the following conditions:**

Date:	July 15	Time of day: Peak burning period			
T:	25 °C	FFMC:	95	ISI:	24
RH:	33 %	DMC:	160	BUI:	180
Wspd:	20 km/h	DC:	514	FWI:	66

A. For a point ignition? (e.g. lightning spot fire) Probability: %

B. For a line ignition? (i.e., advancing fire front) Probability: %

42 **For STAND F and the conditions described in Question 41, what would be:** *(See categories below)*

A. The equilibrium ROS category?

B. The flame length, in metres?

C. The torching category?

D. The crowning category?

43 **What do you think the probability is of a fire spreading through STAND F given the following conditions:**

Date:	July 15	Time of day: Peak burning period			
T:	25 °C	FFMC:	92	ISI:	16
RH:	33 %	DMC:	93	BUI:	127
Wspd:	20 km/h	DC:	492	FWI:	46

A. For a point ignition? (e.g. lightning spot fire) Probability: %

B. For a line ignition? (i.e., advancing fire front) Probability: %

44 **For STAND F and the conditions described in Question 43, what would be:** *(See categories below)*

A. The equilibrium ROS category?

B. The flame length, in metres?

C. The torching category?

D. The crowning category?

45 **What do you think the probability is of a fire spreading through STAND F given the following conditions:**

Date:	July 15	Time of day: Peak burning period			
T:	25 °C	FFMC:	87	ISI:	8
RH:	33 %	DMC:	39	BUI:	60
Wspd:	20 km/h	DC:	325	FWI:	20

A. For a point ignition? (e.g. lightning spot fire) Probability: %

B. For a line ignition? (i.e., advancing fire front) Probability: %

46 **For STAND F and the conditions described in Question 45, what would be:** *(See categories below)*

A. The equilibrium ROS category?

B. The flame length, in metres?

C. The torching category?

D. The crowning category?

47 **What do you think the probability is of a fire spreading through STAND F given the following conditions:**

Date:	July 15	Time of day: Peak burning period			
T:	25 °C	FFMC:	83	ISI:	4
RH:	33 %	DMC:	20	BUI:	30
Wspd:	20 km/h	DC:	142	FWI:	9

A. For a point ignition? (e.g. lightning spot fire) Probability: %

B. For a line ignition? (i.e., advancing fire front) Probability: %

48 **For STAND F and the conditions described in Question 47, what would be:** *(See categories below)*

A. The equilibrium ROS category?

B. The flame length, in metres?

C. The torching category?

D. The crowning category?

RATE OF SPREAD CATEGORIES

Nil	Fire cannot sustain itself
Very slow	Spread will be generally discontinuous, with maximum ROS less than 0.1 m/min
Slow	Spread will be occasionally discontinuous, with maximum ROS 0.1 - 1.0 m/min
Moderately slow	Spread will be continuous with maximum ROS 1.1 - 3.0 m/min
Moderately fast	Spread will be continuous with maximum ROS 3.1 - 10.0 m/min
Fast	Spread will be continuous with maximum ROS 10.1 - 18.0 m/min
Very fast	Spread will be continuous with maximum ROS 18.1 - 25.0 m/min
Extremely fast	ROS exceeds 25.0 m/min

TORCHING CATEGORIES

Nil	No chance of torching
Low	Occasional tree may torch-out
Medium	Pole-sized understory tree likely to torch-out
High	Most understory and occasional overstory trees likely to torch-out
Extreme	Entire stand likely to torch out

CROWNING CATEGORIES

Nil	Sustained spread in crowns will not occur
Low	Sustained spread in crowns unlikely
Medium	Some crowning likely but will not be continuous
High	Sustained crowning likely
Extreme	Sustained crowning will occur

15

GENERAL QUESTIONS

49 **STAND A to STAND F (see photos below) illustrate the development of a jackpine/black spruce stand following high intensity crown fire.**

How soon (during stand development) after the initial crown fire would fire spread be possible under <u>each</u> of the following four (4) conditions: *Indicate the age of the stand by putting a mark on each of the scales - if your number is outside the scale, just write it down. You can show a range by putting brackets on each side of your mark (see example)*

Example: ———[—•——]—

A. T: 25°C RH: 33% Wspd: 20 km/h Rn: 10 days without rain
FFMC: 95 DMC: 160 DC: 514 ISI: 24 BUI: 180 FWI: 66

0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 80 Years

B. ________ T: 25°C RH: 33% Wspd: 20 km/h Rn: 10 days without rain
FFMC: 92 DMC: 93 DC: 492 ISI: 16 BUI: 127 FWI: 46

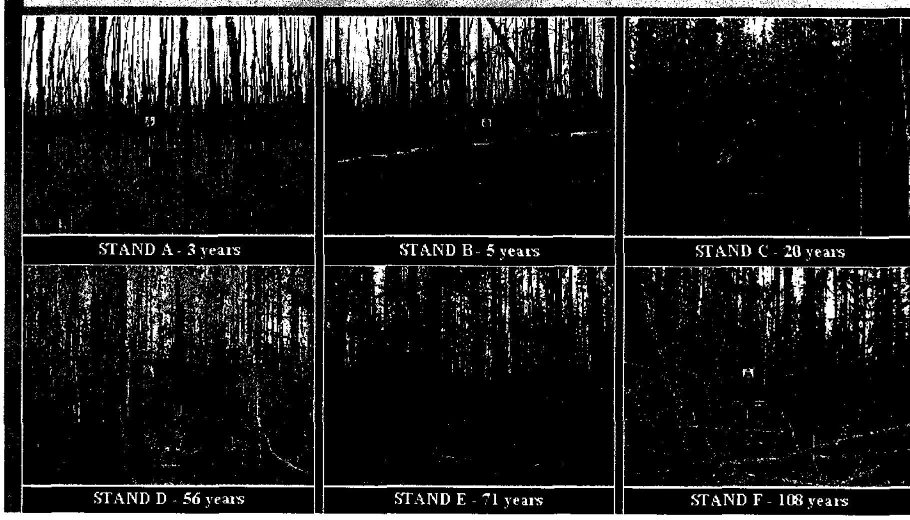
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 80 Years

C. ________ T: 25°C RH: 33% Wspd: 20 km/h Rn: 10 days without rain
FFMC: 87 DMC: 39 DC: 325 ISI: 8 BUI: 60 FWI: 20

0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 80 Years

D. ________ T: 25°C RH: 33% Wspd: 20 km/h Rn: 10 days without rain
FFMC: 83 DMC: 20 DC: 142 ISI: 4 BUI: 30 FWI: 9

0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 80 Years



STAND A - 3 years | STAND B - 5 years | STAND C - 20 years

STAND D - 56 years | STAND E - 71 years | STAND F - 108 years

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GENERAL QUESTIONS

50 Have you ever observed or heard of a young (0-15 year-old) jack pine stand, of fire origin, burning in Canada?

- ☐ Yes [go to question 51]
- ☐ No [go to question 53]

51 Has that fire been documented? *(Fire report, case study, etc.)*

- ☐ Yes → *Please provide the reference if you know it:*
- ☐ No

52 Please describe the event(s) as much as you can. *(Age of the stand, presence of black spruce or ladder fuels, FWI components, weather, carrying fuels, point/line ignition, name of the fire, location, fire behavior, etc)*

You may use the back cover of the questionnaire if you need more space, or a loose sheet of paper.

53 Have you ever observed or heard of a young (16-30 year-old) jack pine stand, of fire origin, burning in Canada?

- ☐ Yes [go to question 54]
- ☐ No [go to question 56]

54 Has that fire been documented? *(Fire report, case study, etc.)*

- ☐ Yes → *Please provide the reference if you know it:*
- ☐ No

55 Please describe the event(s) as much as you can. *(Age of the stand, presence of black spruce or ladder fuels, FWI components, weather, carrying fuels, point/line ignition, name of the fire, location, fire behavior, etc)*

You may use the back cover of the questionnaire if you need more space, or a loose sheet of paper.

PROFESSIONAL BACKGROUND

56 **About how many years of fire behavior prediction and/or observation experience (from school or work) have you had?**

Years

57 **How many of those years were <u>in the boreal forest</u>?**

Years

58 **In which province or territory have you mainly acquired your fire behavior experience?** *If more than one, please write in order of importance (time spent in each) the first two (2) and the number of years in each*

Province/Territory Years

59 **How often do you predict, observe, or document fire behavior during:**

Never	Rarely	Occasionally	Regularly	
☐	☐	☐	☐	**Wildfires?**
☐	☐	☐	☐	**Experimental Fires?**
☐	☐	☐	☐	**Prescribed Burns?**
☐	☐	☐	☐	**Others (specify)?**

60 **What percentage of your time at work is spent on fire behavior-related tasks?**

- ☐ 0 - 25 %
- ☐ 26 - 50 %
- ☐ 51 - 75 %
- ☐ 76 -100 %

61 **What category of work do you currently do?** *Please indicate the percentage of your working time related with each category.*

% Technical / Operational
% Management
% Research
% Teaching
% Engineering / Consultant
% Others (specify)

62 **Please indicate your job title, employer, and the number of years you have been in this position:**

Title
Employer
Years

63 **How did you mainly get your fire behavior training?**

64 **Have you attended and/or taught the following fire behavior courses (French or English version) in the past:**

Yes	No	
☐	☐	**Advanced Wildland Fire Behavior?**
☐	☐	**Wildland Fire Behavior Specialist?**
☐	☐	**Wildland Fire Behavior Specialist Refresher?**

65 **What is the last degree you received, and from which institution?**

Degree:
Institution:
Prov./State:
Country:

66 **What is your sex?**

- ☐ Female
- ☐ Male

67 **In what year were you born?**

Year

68 **Would you like to receive a copy of the report that will be produced from the results of this survey?**

- ☐ Yes
- ☐ No

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DEFINITIONS[2]

- **Available Fuel** - The quantity of fuel in a particular fuel type that would actually be consumed under specified burning conditions.
- **Blowup** - A somewhat sudden, and sometimes unexpected, major increase in rate of spread and frontal fire intensity sufficient to upset overall fire suppression action or plans.
- **Buildup** - The cumulative effects of those fire weather elements that cause drying of forest fuels and thereby heighten fire danger.
- **Burning Conditions** - The state of the combined components of the fire environment that influence fire behaviour and fire impact in a given fuel type.
- **Burning Period** - That part of each 24-hour day when fires are generally the most active.
- **Burn-out Time** - The duration of active flaming and smouldering combustion at a given point in the ground, surface and crown fuel layers, expressed in convenient units of time.
- **Cover Type** - The designation of a vegetation complex according to its dominant species, age, and/or form.
- **Creeping** - A fire spreading slowly over the ground, generally with a low flame.
- **Crown Fuels** - The standing and supported forest combustibles not in direct contact with the ground that are generally only consumed in crown fires (e.g. foliage, twigs, branches, cones).
- **Crowning** - A fire ascending into the crowns of trees and spreading from crown to crown.
- **Crown Scorch** - Browning of the needles or leaves in the crown of a tree or shrub caused by the heat rising above a surface fire as a result of convection.
- **Depth of Burn (DOB)** - The reduction in forest floor thickness due to consumption by the fire process.
- **Fine Fuels** - Fuels that ignite readily and are consumed rapidly by fire (e.g. cured grass, fallen leaves, needles, and small twigs). Dead fine fuels also dry very quickly.
- **Fire Behaviour** - The manner in which fuel ignites, flame develops, and fire spreads and exhibits other related phenomena as determined by the interaction of fuels, weather, and topography.

2. Source: Canadian Interagency Forest Fire Centre (CIFFC). 1999. Glossary of Forest Fire Management Terms. Winnipeg, Manitoba. On-line PDF version.

- **Fire Environment** - The surrounding conditions, influences, and modifying forces of topography, fuel, and fire weather that determine fire behaviour.
- **Fire Front** - The strip of primarily flaming combustion along the fire perimeter; a particularly active fire edge.
- **Fire Severity** - A general term most commonly describe the combined affects of both flaming combustion and smouldering combustion as manifested in various fire behaviour characteristics; this is quite inferred after-the-fact from the fire impact(s).
- **Flame Length** - The length of flames measured along their axis at the fire front; the distance between the flame height tip and the midpoint of the flame depth.
- **Flammability** - The relative ease with which a substance ignites and sustains combustion.
- **Frontal Fire Intensity** - The rate of heat energy release per unit time per unit length of fire front.
- **Fuel Arrangement** - A general term referring to the horizontal and vertical distribution of all combustible materials within a particular fuel type.
- **Fuel Bulk Density** - The dry weight of combustible materials per unit volume.
- **Fuel Load** - The dry weight of combustible materials per unit area.
- **Fuel Type** - An identifiable association of fuel elements of distinctive species, form, size, arrangement, and continuity that will exhibit characteristic fire behaviour under defined burning conditions.
- **Ladder Fuels** - Fuels that provide vertical continuity between the surface fuels and crown fuels in a forest stand, thus contributing to the ease of torching and crowning.
- **Rate of Spread (ROS)** - The speed at which a fire extends its horizontal dimensions, expressed in terms of distance per unit of time.
- **Smouldering** - A fire burning without flame and barely spreading.
- **Spotting** - A fire producing firebrands carried by the surface wind, a fire whirl, and/or convection column that fall beyond the main fire perimeter and result in spot fires.
- **Torch or Torching** - When the foliage of a single tree or a small clump of trees ignites and flares up, usually from bottom to top.

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ID: **2002**

Thank You!

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