AN ASSESSMENT OF THE REPRESENTATION OF FIRE
SEVERITY AND COARSE WOODY DEBRIS DYNAMICS IN AN
ECOSYSTEM MANAGEMENT MODEL

by

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A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE

in

THE FACULTY OF GRADUATE STUDIES
(Forestry)

THE UNIVERSITY OF BRITISH COLUMBIA
January 2008
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Abstract

Fire is the most significant natural disturbance agent in the MSdm biogeoclimatic subzone and has a determinant role in the dynamics of lodgepole pine (*Pinus contorta ssp. latifolia* Engelm.ex S.Wats.) dominated forests. Fire severity is a controversial term that usually refers to a qualitative measure of the fire effects on soil and vegetation and ultimately on ecosystem sustainability. The main objective of the thesis was to evaluate methods for quantifying and modelling the effects of fire severity on live biomass and dead organic matter and post-fire coarse woody debris (CWD) dynamics.

A review of the representation of fire in models was conducted and several of the most commonly used fire models in North America have been described in terms of fire severity representation. The potential for developing the fire severity concept as a fire effects descriptor in an ecosystem management model were assessed. Severity matrices summarizing the probabilities of occurrence for fires of varying severity were constructed for two sites in the MSdm biogeoclimatic subzone of British Columbia, using weather data and past fire records. These matrices provide information to improve fire representation in the ecosystem based model FORECAST by quantifying the effects of fire severity on dead and live biomass components. Although this represents only a preliminary step, the severity matrix approach appears to provide a viable methodology for improving the representation of fire effects in FORECAST.

Patterns of post-fire coarse woody debris (CWD) accumulation were also assessed in the context of model development. Data were collected from a chronosequence of fire affected sites in the MSdm subzone of the TFL 49 Kelowna. The ability of the FORECAST model to simulate accumulation patterns in CWD and soil organic matter and nitrogen following fire was tested by comparing model outputs with field data. The evaluation of the model against chronosequence-derived data highlighted the fact that caution needs to be taken when using such data for model testing. The very slow recruitment pattern for new CWD illustrates the need to retain sources of CWD recruitment following fire by not salvage logging all killed trees and/or surviving live trees.
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Chapter 1 Introduction

1.1 Fire, climate change and sustainable management

From the arctic tundra and boreal forests to savanna and tropical grassland, fire is the third most ubiquitous terrestrial disturbance after human urban and agricultural activities (Bond and van Wilgen 1996). Wildfires are estimated to burn over 750,000 square kilometers around the world each year (Rothermel 1993) confirming wildfire’s role as a major source of economic loss. In the tropics, an estimated 2700-6800 million tonnes of plant carbon is burned annually by savanna and shifting agriculture fires (Bond and van Wilgen 1996 and citations therein). In Canadian forests, which account for almost 10% of the total global forest, fire is one of the main agents of change with an average of about 9,500 wildfires occurring each year. Fire damages resources and destroys structures, but it also plays a significant role in creating and maintaining landscape patterns, stand structures, ecosystem processes, various measures of biodiversity, and forest health. Fire cycles influence the management of a forest and its biodiversity and productivity (CWFGM-Steering Committee 2004).

As a highly weather dependent event, fire cannot be separated from climate; it is an ecological process that is susceptible to change with shifts in climate (Swetnam and Betancourt 1998). Flannigan and Van Wagner (1991) estimated that fire will increase by 50% in response to climate change over the coming decades. Climate change will have a direct effect on many ecosystem processes, but equally important is its indirect effect through its impact on disturbance regimes such as fire, insects, diseases, and windstorms (Bhatti et al. 2003). It is even claimed that the interaction between climate change and fire regimes may have a greater impact on species, ecosystems and socioeconomic values than the direct effects of climate change (Weber and Flannigan 1997). The Intergovernmental Panel on Climate Change (IPCC) is projecting that average annual temperature in Canada will increase by 1.4–5.8°C over the present century with 0 to 0.25 mm/day increase in precipitation (Warren 2004). As a consequence, the forest area burned annually could increase in some BC and Alberta regions by 25 - 50% (Aber et al. 2001), while the severity ratings may go up to as much as 46%, and the fire season could be longer by up to 29 days (Nitschke 2006). Fires are expected to be more frequent and more intense even though their magnitude and timing are hard to predict (Johnston
et al. 2006). The amount of forest area burned could increase by 25-50% due to increased forest productivity, accompanying increases in fuel loads, and more frequent and severe droughts (Aber et al., 2001). Adaptation to this changed environmental condition and disturbance regime requires planning, which in turn requires improved ability to predict the ecosystem and value consequences of fire (Spittlehouse 2005).

Over the past half century, human population increased dramatically and so did the human-caused perturbation of global biogeochemical cycles (Kimmins 2004b). Stewardship and sustainability in the face of such change requires an understanding of and ability to predict ecosystem response to natural disturbance and management (Thompson and Harestad 2004). In this context, understanding the behaviour, propagation, and effects of wildfires on stands and landscapes is essential if emulating natural disturbance patterns is one of the objectives of sustainable forest management (CWFGM-Steering Committee 2004). Such emulation is thought to be an effective way to ensure sustainability of forest products while conserving biodiversity (Perera et al. 2004a). One way to achieve these objectives is simply to emulate the past natural disturbances and successional pathways of unmanaged forests – a “rear-view mirror driving” approach. By looking back at unmanaged ecosystem patterns and processes managers have tried to provide guidance for sustainable forest management (Kimmins 2004b). A second way is to use simulation modeling to investigate possible ecosystem processes and future successional trajectories that could be expected from different management practices or natural disturbances (Perera et al. 2004a). Management decision support tools based on a combination of experience of forest practices and an understanding of ecosystem processes could provide the best way to implement this second and more flexible approach (Messier et al. 2003).

1.2 Forest modeling

Forestry is the art, practice, science and business of managing forested landscapes to sustain a desired balance of values, and experience has in the past been the most available and dependable guide to management (Kimmins 2004b). However, considering that, in many situations, foresters have reliable records dating back only to the beginning of the last century, how can 100 years of experience or less address the much larger temporal dimension involved in the sustainability of forests and forestry? And how can experience of management systems no longer in favor guide the design of new and untested systems of management? Forecasting systems already play an important role in selection of policies and practices, and the exploration
of alternative possible and desired forest futures cannot be undertaken without this type of tool (Kimmins 2004b). However, where these tools are based solely on experience their forecasts will only be valid for futures that are the same as or very similar to the past. For futures that are significantly different, such as with altered fire regimes under climate change, such experience-based tools may not be adequate.

Forest models are becoming one of the tools that every forester should use in the process of designing new management systems and in developing management plans. Using ecologically-based, ecosystem management forecasting systems, foresters should be able to make credible analyses of the range of possible outcomes of their management plans (Messier et al. 2003).

Process simulation (PS) models, also called mechanistic models, are considered to be the “ultimate scientific approach to ecosystem modeling” (Messier et al. 2003). These models simulate key ecosystem processes, thereby overcoming the inability of experience-based (“historical bioassay”) models to represent the ecosystem in situations of changed conditions. Process-based models provide a more comprehensive description of ecosystem development. Their explanatory and descriptive capabilities increase our understanding of the system being modeled, but only if sufficient key determinants are included. The complexity of forest ecosystems requires that many determinants be represented in PS models, and this acts as an important limitation in purely process modeling. Although the more complex these models are, the higher the expected accuracy of their outputs may be, the added complexity increases the difficulty of model calibration and limits model portability. As a consequence of this complexity issue, most mechanistic models omit one or more important ecosystem processes or structures whose variation in time has important ecosystem implications. Many process models are too simple for answering complex ecological and forest management questions (Korzukhin et al. 1996). However, as our knowledge of forest ecosystem dynamics and mechanisms increases, more complex and accurate process simulation tools will undoubtedly be developed (Messier et al. 2003).

Hybrid simulation (HS) models represent a combination of the two previous approaches (historical bioassay and process-based modeling) to produce “predictions based on both experience and knowledge” (Kimmins et al. 1999). HS models employ output from, or the empirical data associated with, HB models, the growth predicted by the latter then being modified according to process-based simulations. HS models take advantage of the positive aspects of both historical bioassay and process-based models, and thereby overcome some of the
limitations of the two component approaches (inability to make accurate forecasts under changed conditions (HB); and excessive complexity in calibration and model application (PS)). This type of model has a solid foundation in empirical data but also flexibility in terms of reacting to future ecosystem change. This accounts for the increasing use and development of hybrid models (Seely et al. 2007). An example of a hybrid model is FORECAST (Kimmins et al. 1999): an ecosystem-based, stand level, forest management model. It is one of the objectives of this thesis to explore the possibility of improving its fire representation capabilities (Chapter 3) and also to test this model’s predictions against selected field data (Chapter 4).

1.3 Extending fire models capabilities

The development of fire behavior models represents an important contribution by fire scientists to our understanding and management of this complex phenomenon. The development of models that predict the behavior and effects of fire on stand level vegetation and successional dynamics in terrestrial ecosystems has received considerable attention (Andrews 1986; Finney and Andrews 1999; Keane et al. 1989; Keane et al. 1995a; Van Wagner 1987). However, there are few studies of post-fire species diversity patterns in fire affected communities (Bond and van Wilgen 1996) and even fewer models available to assess these patterns. There is also relatively little knowledge of how post-fire effects relate to pre-fire condition (forest structure and fuel), and about the degree of ecosystem change by a fire that is consistent with sustaining ecosystem structure and functions (Lentile et al. 2006).

Most of the fire behaviour models have been developed as medium to large scale landscape models. For forest managers to have a better understanding of the complexity of fire effects, tools are needed that are capable of forecasting both fire behavior and post-fire ecosystem development, and their relationships to pre-fire ecosystem state. The highly variable nature of fire behavior, the subsequent effects, the dynamic aspect of post-fire recovery, and the fact that fire is a stochastic and complex process that influences a multitude of factors make forecasting difficult. This difficulty can be reduced as we increase our understanding of the causes and consequences of fire (Morgan et al. 2001a). Appropriately complex ecological models capable of describing key ecological processes linked to fire risk and fire behavior models can make a major contribution to such forecasting. Mechanistic stand models are needed to understand the relationship between energy release in fire and post-fire ecosystem recovery (Lentile et al. 2006).
To forecast fire effects on all components of the forest ecosystem from overstory to soil surface we need quantitative predictors of post-fire effects (Morgan et al. 2001a).

Fire severity is a descriptor of the immediate effects generated by a forest fire in an ecosystem, and refers to the degree to which individuals are killed and how the ecosystem responds to fire (Johnson et al. 2003). However, there is no single accepted definition of fire severity in the fire literature, and it can be quantified in a variety of ways. Nevertheless, it is often described in terms of the post-fire appearance of vegetation, litter and soil (Lentile et al. 2006). Fire severity is explored in Chapter 2 of this thesis as a possible linkage between “true” fire behavior models and ecosystem models. The major fire behavior models developed in Canada and US are described below and the utility of each of these models in predicting post-fire effects in forest ecosystems is discussed. The possibility of improving the utility of fire behavior models by linking them to complex ecosystem process models is explored.

1.4 Coarse woody debris (CWD) and fire

Although we know that woody debris plays many roles in forests, we do not yet fully understand how important these functions are to the stability and sustainability of forest structure and function. In many British Columbia forest ecosystems more research is needed to fully understand all the roles that CWD plays (Feller 2003a; Stevens 1997). Some ecosystem functions are exclusive to snags and CWD, but little is known about the relationship between naturally occurring quantities and qualities of woody debris and healthy forest functioning - long term forest productivity, biodiversity and a variety of ecosystem processes (Caza 1993). CWD has important roles, including: preferred habitat for several animal species; effects on soil erosion and slope stability; pool and riffle formation in streams; and nutrient capture and retention. Nutrient cycling in terrestrial and aquatic ecosystems is also influenced by the characteristics of woody debris (Stevens 1997).

CWD is an important component of the ecosystem in the lodgepole pine forests of the interior of British Columbia. It affects nutrient cycling, and is especially important on nutrient poor mineral soils where the majority of nitrogen storage is in the vegetation, forest floor and CWD. (Wei and Kimmins 1998). While conserving nutrient cycling, long term accumulations of CWD, is an important fuel source, with consequences for fire risk and severity (Klinka et al. 1992). Understanding the long term consequences of fire on CWD is an important component in designing post-disturbance management practices (Remsburg and Turner 2006; Wei et al. 1997).
and also essential in predicting fire effects (Knapp et al. 2005). Thus, it could be useful to assess the CWD accumulation patterns in these fire prone lodgepole pine-dominated ecosystems.

Chapter 4 of this thesis investigates the effects that fire has on CWD and on C and N accumulation patterns in TFL 49 MSdm lodgepole pine forests. The ability of the FORECAST model to simulate these patterns is then tested against these field data.

1.5 Objectives

The thesis has three main objectives and several specific objectives. The main objectives were:
- To evaluate the advantages and disadvantages of using fire severity as a fire effects descriptor in forest ecosystems;
- To develop severity matrices based on probabilities for two weather stations in the MSdm subzone and provide the foundations and specifications of how these would be linked with the FORECAST model.
- To evaluate the ability of the FORECAST model to simulate patterns of CWD accumulation in MSdm fire-driven ecosystems.

Specific objectives were to:
- Assess the current state of fire representation in ecosystem models and the current state of ecosystem representation in fire models;
- Quantify the climatic indices necessary for the severity matrix development;
- Develop a regression model for estimating the forest floor consumption;
- Develop a methodology for estimating and quantifying the above ground biomass consumption by fire;
- Establish a chronosequence of plots to determine temporal patterns in CWD and forest floor accumulation post-fire;
- Test the capabilities of the ecologically based forest growth model FORECAST to project patterns of post-fire CWD accumulation, by comparing the model outputs with field data.

1.6 Thesis outline

Having introduced the general concepts of natural and human induced disturbances and ecosystem and fire modeling, the rest of the thesis is structured as follows.
Chapter 2 – Defining and predicting fire severity: A literature review and assessment of selected fire models

This chapter is focused on fire severity, and the use of fire severity as a fire effects descriptor is assessed. Literature definitions of fire severity are presented and the use of crown fraction burned and forest floor depth as fire severity indicators is explored. The most commonly used fire models in Canada and US are described, and their capability to represent fire severity is discussed. The possibility of linking fire behaviour models with ecosystem-based models through fire severity matrices is addressed.

Chapter 3 – Severity matrix

Severity matrices based on probabilities are constructed for C3 (mature lodgepole pine forests) and C4 (immature lodgepole pine forests) fuel types, using weather data collected from two different climatologic stations in the southern interior of B.C.. The severity matrix building algorithm developed in this chapter is intended for use in developing fire severity matrices for the ecosystem model FORECAST.

Chapter 4 – Assessing patterns of Coarse Woody Debris following fire using FORECAST. CWD and C and N accumulation patterns documented in the field in three lodgepole pine sites situated in the MSdm2 biogeoclimatic subzone are presented, and the FORECAST model’s output when calibrated for these sites is compared with the field data.

Chapter 5 – Conclusions

The thesis concludes with a summary of the findings of this study, and recommendations are made for the linkage of fire models and process-based ecosystem management models. Shortcomings of the current component models of such meta-model frameworks are summarized and recommendations made concerning future research on this topic.
Chapter 2 Defining and predicting fire severity: A literature review and assessment of selected fire models

2.1 Introduction

Fire is a major environmental factor that has almost the same importance as climate in determining the character and distribution of living organisms, including humans, other animals, plants and microbes in many terrestrial environments of the world (Odum 1997). With very few exceptions, as in very wet, very hot, very dry and very cold environments, fire has played an important role in virtually all terrestrial ecosystems and it was ecologically important long before it was utilized by humans, as evidenced by the presence of charcoal buried deeply in ancient sedimentary deposits (Kimmins 2004b).

Strong emotions will always be evoked by forest fires because of their association with great destruction, danger and un-predictability. However, the fear of fire is a Eurocentric attitude in contrast of that of first nations that used fire extensively for wildlife habitat management, to protect villages from fire, crop management, pest control, to make travel easier and for many other reasons. Fire was one of the tools that helped humans to develop a society, but large uncontrollable fires (e.g. forest wild fires) contributed over the centuries in generating a well-founded fear of this powerful phenomenon. For centuries, wild fire was considered entirely negative and to this day many people fail to recognize fire as a significant natural ecological factor that, in many forest ecosystems and under certain conditions, can have the same importance as wind or precipitation in determining the structure and species competition of the forest (Kimmins 2004b).

Forest fires vary in their severity and frequency from one region to another, and within a region, but the social and environmental impacts generated by forest fire are nearly always significant. Traditionally, forest managers have considered wildfire as being an “environmental enemy” that had to be fought and suppressed. However, many forest fires play an environmentally beneficial role or, at the very least, a non-disruptive role. There is an increasing acceptance of the fact that periodic wildfires have historically been necessary for sustaining the long term character of forest ecosystems (Kimmins 2004b).
Fire ecology has been a subject of research for more than half of a century, but understanding of its influences remains incomplete which limits our ability to develop sustainable forest management policies with respect to fire. In the face of our incomplete understanding of the natural role of fire, experience has generally been the main foundation for forest management policy and practice. However, in forestry, the time scale for determining the effects of implementing forest policy is from multiple decades to several centuries. Management experience based on the response of different forested site types and zones to various natural disturbances and management scenarios cannot form the basis, on its own, for forecasting the future because of climate change (Kimmins 2000).

As an emerging tool for the study of fire ecology, computer-based fire modeling has opened new possibilities for researchers. Many fire models have been developed in North America and around the world, modeling fire at stand or landscape levels. These models have been used to simulate fire: behavior, effects and risk. Evaluating risk, developing treatment prescriptions, comparing management options, and improving our understanding of fire effects on ecosystems are some of the benefits of fire effects modeling (Reinhardt et al. 2001). From a public perspective, the effects of fire are more important than the causes, although from a policy and management perspective they are equally important. Forest managers need to be able to predict risk but also to forecast the consequences of fire management for a variety of forest values, including growth and yield. As a consequence, it is not surprising that there is increasing interest from growth and yield modelers in the incorporation of fire effects into their models, especially for areas in which fire is a significant disturbance factor.

Fire severity is considered to be an important descriptor of fire effects on ecosystems, because it relates the effects of fire on the above and below ground components of living plants to the amount and location of organic matter losses in the ecosystem (Feller 1986; Feller 1998; Ryan and Noste 1983). Fire severity can be used to predict an ecosystems response to fire such as the effects of fire on soil, water, flora, fauna, atmosphere and society (Simard 1991).

In this chapter, the advantages and disadvantages of using fire severity as a descriptor of fire effects in ecosystems are discussed. Several landscape and stand level fire models are described, and the potential to use severity in FORECAST (FORest Environmental Change ASsessmenT)(Kimmins et al. 1999), a forest ecosystem management simulator, is explored.
2.1 Defining fire severity

Fire severity as a concept has only recently been used in the fire literature, as shown by its absence in classic forest fire texts (Feller 1988). Recent uses of fire severity in the fire ecology literature have suffered from the lack of a consistent definition. Several attempts have been made to define fire severity but none have gained general acceptance (Simard 1991). Fire severity has no single definition. It is rather a notion used to describe fire effects and is presented as a “whittling and arguing concept” among fire scientists (Jain 2004).

The Concise Oxford Dictionary of Ecology (Allaby 1994) defines severity as a code used to quantify the degree of damage by biotic (insects, disease, browsing) and abiotic (wind, snow, fire) agents. Fire severity has also been defined as the degree to which a site has been altered or disrupted by fire (Agee 1993; McPherson et al. 1990). Attempts to define fire severity quantitatively have been limited to a single attribute of behavior or consumption (e.g. fire intensity or depth of burn) thereby limiting the ability to relate fire severity to fire effects (Debano et al. 1998). From a forest management perspective, fire severity can be used as a descriptor of the impact of fire on forest ecosystems, but only in conjunction with resource management objectives. Non-technical definitions of severity do not appear to be adequate to quantify the specific fire impacts relative to resource management objectives.

Ryan (2002) reported an increase in the use of fire severity in the fire effects literature but also observed that there is still not a single standardized definition. A quantitative approach to define fire severity would involve choosing from a number of fire behavior and biomass consumption attributes that are related to specific fire effects (Agee 1993). Frequently, fire severity can be found defined as: tree mortality, heat penetration into the soil, organic matter consumption above and within the soil, the color of ash and soil, or a combination of these (Ryan 2002). Simard (1991) emphasized that fire severity needs to be defined in multiple ways in order to describe fire impacts on the affected components: ecosystem, geosystem (soil and water), atmosphere, management and society. Severity of fire varies in time and space depending on the biophysical environment, the location of the fire perimeter, and in the long term impact on the structure and species composition (Ryan 2002). Fire severity has often been used to describe the effects of fire duration and fire intensity. This is always confusing since fire intensity has a specific quantitative descriptor associated with it (i.e. $I = HWR$, where, $I =$ fire intensity (kW/m), $H =$ heat of combustion (kJ/kg), $W =$ fuel consumption (kg/m²), $R =$ rate of spread (m/s) (Alexander 1982)) while fire severity can be defined in a number of ways. This
has led to a misuse of both terms in relating fire characteristics to ecosystem effects (Feller 1988; Jain 2004; Jain and Graham 2004).

The overall effect of a fire in the forest depends on the ecosystem condition, fire behavior and specific fire effects. Fire involves combustion, a process in which heat is transferred through a material resulting in physical and chemical alterations, followed by energy release. The five stages of combustion are: pre-ignition, flaming, glowing, smoldering and extinction. During a fire, temperatures can reach 1400°C in the flame and 1000°-1200°C in the combustion zone, but these temperatures vary greatly for different locations and fuel types resulting in different fire effects (Debano et al. 1998). The heat transfer process involves convection, radiation and/or conduction, although vaporization and mass transport may also be involved. Belowground heat transfer ahead of the forest floor combustion zone is mainly by radiation and conduction. Aboveground heat transfer is mainly by radiation and convection. If heat transfer by one of these processes has adequate amounts of fuel and oxygen, the process will continue.

A considerable amount of heat is released during combustion. Surface fires, depending on their residence time, can transfer heat downwards to duff* and mineral soil, or upwards to plants and tree crowns (Ryan 2002). Belowground and/or aboveground organic matter is consumed to various degrees.

The combustion zone in duff contributes most of the downward heat to the lower layers of duff and to the mineral soil below the duff. This zone can also be supported in the combustion process by the downward heat supplied by surface woody consumption (Hawkes 1993). Fire duration is directly linked to fire severity in terms of belowground damage. Intense, fast moving fires do not transfer much heat down, but soil temperature can stay high for a few minutes to several days (Certini 2005). The most “severe” effect of this transfer is the mortality of vegetation.

Fire severity can be characterized based on above or belowground fire effects. Ryan and Noste (1983) introduced the concept of a two-dimensional fire severity matrix that quantifies the above and belowground effects of a fire, using degree of vegetation scorching and forest floor depth of burn, respectively (Ryan and Noste 1983). Usually, in fire literature, the ground

* Duff- a layer of partially and fully decomposed organic materials lying below the litter and immediately above the mineral soil. It refers to the fibrous (F) and humus (H) layers. The humus layer is organic matter decomposed to the point at which there its origin is not identifiable visually (Clayton et al 1977).
material is located below the surface litter and includes F and H layer, fine tree roots and rooting logs (Feller 2003b).

The lowest temperature that will cause plants to die is around 50-55 °C (or 122-131 F). Some species can survive for few seconds at 60 °C (140 F), but biological disruption begins at about 40ºC, involving protein degradation and plant tissue death. A soil temperature of 48-54 °C would generally kill roots whereas seed mortality occurs at temperatures of 70-90 ºC (Wright and Bailey 1982).

Some plant tissues, particularly growing points (meristems or buds) tend to be more sensitive to heat when they are actively growing and their tissue moisture is high than when tissue moisture content is low. Plant mortality depends on the percentage of tissue killed, location of dead tissue, reproductive mechanism, and species ability to recover from injury. Salt, sugars, lignin, and pectin contents are other variables that might be considered in the tolerance of plant tissues to heat. Morphological adaptations like very thick bark, cone serotiny and growth form play important roles in fire resistance. For example, for some tree species, bark can effectively protect cambium by maintaining internal temperatures at lower values (38 ºC to 82 ºC) even when external temperatures are up to 95 ºC (Debano et al. 1998).

Fire severity can be connected to the actual post fire plant effects when plants are not killed by the fire. Since fire effects can be separated into above and belowground effects it is useful to refer separately to aboveground and belowground severity (Jain and Graham 2004). Fire severity in a forest ecosystem can then be quantified as the combination of above and belowground severity and strictly related to the post fire effects on plants.

### 2.2.1 Belowground severity

Belowground fire effects and severity are determined by the duration and the amount of heat that penetrates the soil (Feller 2003b). The downward heat pulse is the result of heat released during the process of combustion in the duff during the glowing and smoldering stages. There can be a great variation in the temperature reached at different depths in the duff or mineral soil. For example, the temperature reached at the mineral soil surface in a high severity fire was recorded at 700°C, while in a moderate severity fire the temperature did not exceed 450°C (Debano et al. 1998). However, substantial consumption of organic matters begins at temperatures of 200-250 ºC and is complete at 460 ºC (Certini 2005). The combustion of soil...
organic matter generated by the downward heat pulse and sometimes supported by surface woody fuel consumption can be estimated by the forest floor depth of burn. Depth of burn, an adequate substitute for total energy release, represents the degree of reduction in organic layer thickness due to consumption by the fire process that determines post-fire organic layers and percentage of mineral soil exposure (Agee 1993). To relate depth of burn to the depth of heat penetration that exceeds the threshold for underground plant tissues survival involves consideration of pre-burn total forest floor depth (i.e. percentage of forest floor consumed and forest floor and mineral soil moisture content).

There are many attempts in the literature to quantify depth of burn and to relate it to fire severity. Authors like Tarrant (1956), Bentley and Fenner (1958) and Wells et al. (1979) have classified fire severity and downward heat transfer using visual estimations of the post-burn forest floor and soil characteristics. Others, like Trowbridge et al. (1989b) and Curran and Johnston (1991), quantified depth of burn (DOB) in different classes based on depth. Feller (1991) related depth of burn classes to relative fire severity levels as very low (DOB < 1 cm), low (DOB 1-2 cm), moderate (DOB 2-6 cm), high (DOB 6-10 cm) and very high (DOB > 10 cm). Depth of burn of the forest floor was expressed as a percentage reduction in the Prescribed Fire Predictor (PFP) (Muraro 1975). Seven classes were used here for fuel consumption and mineral soil exposure (< 20%, 21-35%, 36-50%, 57-70%, 71-90% and >90%). These depths of burn classifications are most likely applicable across BEC (Biogeoclimatic) zones but the absolute reduction classes not as much since average forest floor depth would vary from dry to wet ecosystems and warm to cool climates.

Fire can induce various changes in soil properties that can be short-term or long-term depending on severity, frequency and climatic condition; physical, chemical, and biological properties and the specific composition of the microbial community of forest soil are altered (Certini 2005). Weather history is one of the most suitable tools to be used in defining the fraction of the total fuel that is available to be consumed in a fire (Ryan 2002) and also the moisture content and combustibility of deeper organic layers and surface logs (Stocks 1986). Thus, the relationship between weather and belowground fire effects could be used to estimate a belowground fire severity.
2.2.2 Aboveground severity

Heat transfer to vegetation (the upwards heat pulse) can result in above ground vegetation mortality or scorch. Tree crown needle scorch has been used as a predictor of post-fire mortality especially in situations where reproductive and growth parts of the tree were damaged (Ryan and Noste 1983). However, generalized models of post-fire mortality that use only one severity factor like crown scorch have been found to have limited predictive ability because of their failure to adequately reflect the importance of fire behavior and the heat transfer mechanisms that can affect other fire sensitive parts of tree like fine roots (Ryan 2002).

Many studies have revealed that the degree of tree crown damage depends on fire behavior, including characteristics such as flame length and fire spread rate and intensity (Ryan 1998; Ryan and Noste 1983). In a crown fire, fuel consumption reflects the potential damage to the aboveground structure. The aboveground fire severity is related to fire intensity. Fire intensity describes the thermal energy released. A common expression used to describe fire intensity is Byram’s fireline intensity which describes the energy release at the fire front; it does not incorporate energy released later as fuel is consumed (Alexander 1982).

Cambial injury also is a factor in determining tree mortality, but there is a lack of knowledge in this area. Root injury, which is related to depth of burn, is not as reliable a predictor as foliar or stem injury in determining tree mortality (Ryan and Reinhardt 1988). Tree mortality can be predicted using a combination of the crown and root damage or using fire behavior and impact characteristics such as crown fraction burned (see FBP system) and depth of burn.

Fire line intensity is usually calculated, in Canada, using total forest floor and aboveground fuel consumption because of the difficulty in separating the portion of fuels consumed in the fire front compared to those consumed later (Alexander 1982).

To indicate the general nature of a forest fire, frontal fire intensity is best related to direct impact of fire on tree damage and mortality. Variations in topography (slope, elevation and aspect) have well-known effects on fuel moisture and on the rate of spread and intensity of fire (Morgan et al. 2001b).

Van Wagner (1983) associated above ground severity with three classes of fire intensity: fire so weak that it does not cause fire scars (<300 kW/m); fire of moderate intensity with variable tree mortality in a small area (<1500 kW/m); and fire of high intensity where all trees are dead over a large area (>1500 kW/m). Alexander (1982) described low intensity surface fires as generally less than 550 kW/m while high intensity fires as usually exceeding 4000 kW/m. Using
this classification, one can determine the probable fire intensity range from the severity class (Kafka 1997). Fire intensity may vary by 1000 fold (Alexander 1982); from 15 to exceeding 100,000 kW/m (Byram 1959). The variation in fire intensity is mainly based on influence of rate of spread (varies 100 fold) and less upon fuel consumption (varies 10 fold). The low heat of combustion varies very little from fuel to fuel (10%) which is therefore considered a constant. (Alexander 1982)

A comprehensive fire severity assessment should integrate the pre-burn ecosystem condition, the energy released during and after flaming combustion, and the effects generated in the ecosystem (Debano et al. 1998). At the stand level, the prediction of fire severity requires that the following fuels be quantified: foliage, stems, branches (for both dead and live trees), understory plants, woody debris, litter and humus. A landscape assessment involves a quantitative picture of the whole burn and how variation in topography, vegetation and fire weather creates a mosaic of different fire severity classes. Both aboveground and belowground effects can be quantified to provide an assessment of fire severity over the landscape using a combination of a scaled index that gauges the degree of ecosystem change both from the air and from ground based plots to determine stand level impacts.

There are a number of US and Canadian fire behavior and effects models that could be used to estimate above and below ground severity. Some of these fire models are reviewed in the following sections with emphasis on their ability to predict above and belowground fire severity at the stand and/or landscape scale.

2.3 Fire models

Fires are important events that disturb the forest ecosystems and generate effects that vary at different spatial and temporal scales. The complexity and difficulty in predicting wildfire has resulted in the development and use of fire behavior and effects models at the stand and landscape levels.

There are numerous types of fire models in the literature that address space, time, and process (Simard 1991); fire effects models generally involve predicting mechanism and quantitative changes of the specific indicators (e.g. fuels and vegetation) between pre-and post-fire forest ecosystem conditions (Reinhardt et al. 2001). These models can be at the stand or landscape scale involving predictions based upon theoretical, explanatory, physical, probabilistic, shape, and statistical models (Gardner et al. 1998); fire behavior models generally involve the
prediction of fire spread rate, intensity and fire type (ground, surface, passive or active crown fires) using stand information on the forest stand structure, fuel loads and local fire weather conditions. A fire growth model uses a fire behavior model, along with spatial data on topography, vegetation, and fire weather to predict fire size, shape, and severity; landscape level fire vegetation succession models incorporate fire growth and effects models, including vegetation succession models that will predict landscape vegetation changes over time (Keane et al. 2004); and minimal fire models (prey-predator equation) (Casagrandi and Rinaldi 1999). Spatial and temporal scales are important aspects in describing fire severity. Fire severity classifications split models into situational (lower scale) or extended (higher scale) models (Simard 1991).

Models that can predict fire behavior and effects over time and space can suffer from either lack of portability to other locations or require a large amount of calibration data for them to be used in a particular area. Hanel (2001) tested how some U.S. fire models predict tree mortality for Douglas-fir and lodgepole pine using data on tree diameter and species, fire severity and tree mortality from the Interior Douglas Fir (IDF) biogeoclimatic zone in B.C. The results obtained from the U.S. tree mortality model developed by Ryan and Reinhardt (1988) showed that Douglas-fir and lodgepole pine tree mortality equations predicted tree mortality for Douglas-fir poorly but correctly predicted lodgepole pine mortality (92% of the time). The model developed by Bevins (1980) that uses tree diameter at breast height and scorch height was found to overpredict tree mortality. The Regelbrugge and Conard (1993) model that uses diameter at breast height and height of bark char to predict tree mortality was found to be a poor predictor (Hanel 2001). However, as for any model, the reliability of predictions is strongly dependent on the quality of data used.

As mentioned before, fire severity is a good indicator of changes to ecosystem characteristics following a fire. Most fire behavior and effects models represent the initial state of the ecosystem in a way that allows comparisons among models, but the modeling approach and outputs vary and this renders comparisons difficult. While the overall goal of this chapter is to review how fire severity is defined in the literature and as a fire model output, this section also discusses the ability of several stand and landscape level fire behavior and effects models to predict above and belowground severity.

There are four essential components in most landscape fire simulation models (LFSMs) that represent the main processes governing the simulation of landscape fire; vegetation succession (including fuels), fire ignition, fire spread, and fire effects (Keane et al. 2004). Prediction of fire
effects in many LFSMs are rule-based (the stand burned or did not). Rarely do LFSMs incorporate fire behavior into the calculation of fire effects (Keane et al. 2004). Fire severity is a key output of the fire effects component, especially when a mechanistic approach is taken to determine fire effects. The prediction of fire severity is usually at a stand level.

The discussion of fire models is separated into stand and landscape fire models since one stand level fire model can be used in a number of different LFSMs to predict fire severity at landscape scale. Understanding the strengths and weaknesses of stand fire models to predict fire severity is important to more fully understand LFSMs abilities to predict vegetation succession, forest productivity, nutrient cycling, and carbon budgets.

### 2.3.1 Stand fire models

Fire can induce various changes in soil properties that can be short-term or long-term depending on severity, frequency and climatic condition; physical, chemical, and biological properties and the specific composition of the microbial community of forest soil are altered (Certini 2005). Weather history is one of the most suitable tools to be used in defining the fraction of the total fuel that is available to be consumed in a fire (Ryan 2002) and also the moisture content and combustibility of deeper organic layers and surface logs (Stocks 1986). Thus, the relationship between weather and belowground fire effects could be used to estimate a belowground fire severity. I have to mention that this study is focused mainly on the Canadian approach of fire behavior. The U.S. developed National Forest Fire Danger Rating System (NFFDRS) does not have a duff moisture code but only woody fuel moisture model. This has led to the DOB (depth of burn) equation in the U.S. using forest floor moisture content and other physically independent variables like bulk density and mineral content to predict DOB (Van Wagner 1975).

**Canadian Fire Weather Index (FWI)**

**Canadian Fire Weather Index (FWI)** system (Van Wagner 1987) is a major subsystem of the comprehensive Canadian Forest Fire Danger Rating System (CFFDRS) (Alexander et al. 1996; Stocks et al. 1989; Van Nest and Alexander 1999) (Fig 3.1), has been used in Canada since 1970, and was revised in 1978 and 1984. FWI system has a modular-hierarchical design
(see Fig 2.2) and it represented the first phase in the development of CFFDRS (San-Miguel-Ayanz et al. 2003). FWI has six components (see Table 2.1).

Fig 2.1 Canadian Forest Fire Danger Rating System  (source http://fire.cfs.nrcan.gc.ca/images/cffrds_e.gif, after Van Nest and Alexander (1999))
The first three components, the moisture codes, Fine Fuel Moisture Code (FFMC), Duff Moisture Code (DMC) and Drought Code (DC) represent the moisture content of the litter, shallow duff and deep duff fuel components, respectively and follow the daily changes in moisture content of the forest fuel. Higher values for these codes represent lower moisture content, and, in consequence, greater flammability and a higher impact on forest floor consumed (Van Nest and Alexander 1999). The combined effects of wind and FFMC are summarized into Initial Spread Index (ISI), while Buildup Index (BUI) is based on DMC and DC. Available fuel (live vegetation, dead woody fuel and forest floor) for consumption is represented by BUI and the rate of fire spread is represented by ISI. Duff Moisture Code, DC and BUI has been used in the development of predictive equations for depth of burn. However, fire severity (as expressed by depth of burn) has been usually predicted by using only the DMC code values (Feller 2003b).

The final component, FWI, is a compilation of the previous codes – it is obtained from ISI and BUI and represents fire intensity. Each of these components is computed based on direct weather observations. Not only FWI, the most comprehensive component, but all the intermediate codes and indices provide important information regarding different aspects of fire danger (Van Nest and Alexander 1999).
Table 2.1 Description of the FWI components

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Component</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>FFMC</td>
<td>Fine Fuel Moisture Code</td>
<td>A numerical rating of the moisture content of litter (L) and other cured fine fuels.</td>
</tr>
<tr>
<td>DMC</td>
<td>Duff Moisture Code</td>
<td>A numerical rating of the average moisture content of loosely compacted organic layers of moderate depth (the upper 5-10 cm depth in the FH layer).</td>
</tr>
<tr>
<td>DC</td>
<td>Drought Code</td>
<td>A numerical rating of the average moisture content of deep, compact, organic layers (moisture content below 10 cm to maximum of the 25 cm depth in the FH layer).</td>
</tr>
<tr>
<td>ISI</td>
<td>Initial Spread Index</td>
<td>A numerical rating of the relative spread of a fire that can be expected soon after ignition. It is the combined effect of wind and FFMC on rate of spread, without the influence of variable quantities of fuel.</td>
</tr>
<tr>
<td>BUI</td>
<td>Buildup Index</td>
<td>A numerical rating of the total amount of fuel available for combustion and is based on DMC and DC.</td>
</tr>
<tr>
<td>FWI</td>
<td>Fire Weather Index</td>
<td>A numerical rating, based on meteorological measurements, of fire intensity in a standard fuel type. It is obtained by combining ISI and BUI.</td>
</tr>
</tbody>
</table>

The FWI (Fire Weather Index) was the first step towards a comprehensive fire weather and behavior prediction system (Van Wagner 1975). More recently, the Canadian Forest Fire Behavior Prediction (FBP) system (Forestry Canada Fire Danger Group 1992) that uses FWI was developed to predict, based on standard fuel types, rate of spread and fire intensity. Fire behavior is predicted using three main inputs: fuel, weather and topography.

The FBP system (Forestry Canada Fire Danger Group 1992) is a complex, semi-empirical system that defines the two important factors in fire growth modeling: fuel types and the associated fire behavior. FBP system is a major subsystem of the comprehensive Canadian Forest Fire Danger System (CFFDRS) (Alexander et al. 1996; Stocks et al. 1989; Van Nest and Alexander 1999) which also includes the Canadian Forest Weather Index (FWI) (Van Wagner 1987). The FBP system defines and integrates many of the fuels, weather, and topographic factors that influence fire behavior. It is based on more than 500 observations of experimental and wild fires. It is considered unique as it incorporates the most extensive crown fire data set available to date (Van Nest and Alexander 1999). The FBP system has four primary fire
behavior outputs: rate of spread, fuel consumption, head fire intensity and fire description (Van Wagner et al. 1992). It also provides estimates of fire area, perimeter, perimeter growth rate, and flank and back fire behavior. FBP includes sixteen fuel types (de Groot 1993), which cover most major boreal forest fuel types in Canada. The spatial simulation of fire propagation over a landscape is provided by the FBP system through a simple, elliptical fire growth model which is used to estimate the size, shape, and flank and back fire characteristics (Lee et al. 2002). FWI is incorporated into the FBP system to predict fire behavior for the above mentioned benchmark fuel types (Van Nest and Alexander 1999). The inputs and outputs of the FBP system are presented in Figure 2.3.

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**Fig 2.3** Canadian Fire Behavior Prediction System (source: http://cwfis.cfs.nrcan.gc.ca/en/background/bi_FBP_summary_e.php), after Van Nest and Alexander (1999)
**BEHAVE and BEHAVE Plus**

BEHAVE fire behavior prediction and fuel modeling system (Andrews 1986) is a physical, stand level, surface fire behavior model developed by the U.S. Forest Service Fire Science Laboratory in Missoula, Montana. It implements Rothermel’s (1972) fire behavior model as a set of equations to estimate the rate of spread as a function of heat released and the fuel’s chemical and physical characteristics. BEHAVE was first developed on a Microsoft® DOS platform and had limited computational capabilities. BEHAVE Plus represents a redesigned, updated version of BEHAVE which was implemented in 2002 on a Windows platform. Version 3.0.2 of BEHAVE Plus, was released in 2007.

The initial BEHAVE model was composed of two subsystems composed of five programs: a Fuel Modeling subsystem (NEWMDL and TSTMDL programs) that entitles the user to create customized fuel types (Burgan and Rothermel 1984); and Fire Behavior Prediction (Burn) subsystem (FIRE1, FIRE2 and RXWINDOW programs) that provide fire behavior prediction from simple inputs (Andrews 1986). BEHAVE was mainly used for operational fire behavior predictions. The fundamental component of BEHAVE - Rothermel’s (1972) surface fire spread model - is used to predict fire spread as a function of fuel density, particle size, fuel bulk density and rate of fuel consumption (Albright and Meisner 1999). Rothermel’s model was also used as a foundation for the National Fire Danger Rating System (NFDRS)(Deeming et al. 1972) and other behavior models like FARSITE (Finney 1998). In terms of spatial representation of fire, BEHAVE does not assume the elliptical fire pattern used in Prometheus (Stephens 1997) and FARSITE, but employs a wave propagation technique and can be considered a “point system” (Albright and Meisner 1999).

BEHAVE Plus represents an update to BEHAVE incorporating models that simulate crown fire (Rothermel 1991) and large fuel burnout behind the fire front (Albini and Reinhardt 1997). Other models incorporated into BEHAVE Plus include: surface fire spread, intensity and flame length (Byram 1959; Rothermel 1972); area and perimeter of a safety point fire* (Butler and Cohen. 1998); area and perimeter of an elliptical point source fire (Anderson 1982; Andrews 1986); suppression; scorch height (Van Wagner 1973); maximum spotting distance from torching trees, burning pile or wind driven surface fire (Albini 1979); probability of mortality (Ryan and Reinhardt 1988); and ignition probability (Latham and Schlieter 1989). The

*Safety point fire- a strategic point that is used to start a fire line (Butler and Cohen 1998)
representation of crown fire and crown fire spread as well as the calculation of a wind
adjustment factor (WAF) for sheltered fuel conditions are among the latest improvements of the
BEHAVE Plus system (Andrews and Queen 2001).

Primary model outputs are: surface fire rate-of-spread and intensity, safety zone size, size of a
point source fire, fire containment, spotting distance, crown scorch height and tree mortality.
Each fuel type used in BEHAVE has a suite of burning indices that are also primary outputs of
the model. These burning indexes estimate the potential difficulty of fire containment and they
are calculated as flame length divided by 10 (Andrews et al. 2003).

Belowground severity in BEHAVE is quantified at a spatial level by the total heat per unit
area (Van Nest and Alexander 1999). Probability of tree mortality is the most important
BEHAVE Plus output for estimating aboveground fire severity. The tree mortality module in
BEHAVE Plus predicts the probability of a tree dying when it is exposed to fire. The inputs
used for this module are bark thickness, diameter at breast height (DBH), crown ratio, shrub
height and percent crown volume scorched. Percent crown volume scorched is calculated from
scorch height which is also dependent on flame length, ambient air temperature and midflame
wind speed. Flame length can be calculated by the scorch module or introduced by the user.
Indirect estimates of aboveground fire severity can be approximated using crown height scorch
or crown volume scorch (Andrews et al. 2003). Crown scorch height (Bevins 1980; Peterson
1985) and crown volume scorch (crown consumption volume) (Peterson 1985; Ryan et al. 1988)
are two parameters that are comparable in predicting mortality through direct tissue damage
measurements (Fowler and Sieg 2004). Crown scorch height implies the maximum or mean
height of foliage scorch and thus leafs/needles kill (Bevins 1980; Ryan et al. 1988). Crown
scorch volume is referring to foliage scorch but can include bud kill and consumption (Fowler
and Sieg 2004; Peterson 1985).

Forest floor consumption is not predicted by BEHAVE Plus so that belowground severity
cannot be estimated directly. However, some components of forest floor consumption might be
estimated because in the ignition module, duff and litter depth are input variables along with
fuel type. Components of fuel consumption can be determined through the CONSUME 3.0
model and FEPS (Fire Emission Production Simulator) model.

BEHAVE Plus can be considered a useful modeling system that can be adapted for a wide
range of conditions (e.g. the model can recognize 206 tree species). Most of the inputs are
determined by the user and each calculation represents a uniform set of conditions. It does not
have spatial representation capabilities as the outputs are presented in the form of tables, graphs
and simple diagrams (Andrews et al. 2003) but when incorporated into FARSITE, fire severity can be represented spatially.

Comparison of BEHAVE and FBP System As two of the most comprehensive fire behavior prediction systems used in North America, BEHAVE and FBP have similarities and differences. Fire environment (slope, aspects, wind speed and direction) are represented in BEHAVE but they are assumed to be constant through a particular model simulation (Trevis 2005). BEHAVE, like FBP has pre-established fuel types, but also allows the user to create a customized fuel model starting with the description of a standard fuel type and then allowing the user to change fuel loading and other standard parameters (Anderson 1982). The FBP system predicts forest floor and surface woody fuel consumption while in BEHAVE, litter, surface woody fuels and herbaceous vegetation consumption is predicted. BEHAVE is based on physical theory and laboratory experiments while FBP system is an empirically derived model that used fire behavior data from documented wildfires and from experimental fires (Van Nest and Alexander 1999). The FWI moisture codes are based on drying characteristics of forest floor material (litter, shallow and deep duff), while in the US National Forest Fire Danger Rating System (NFFDRS), surface fuel moisture contents are directly estimated and are based on different size classes of woody fuels in a range of size classes based on their time lag. These differences in the Canadian and US fire weather systems make comparison in fire weather conditions between these two systems difficult and are not considered compatible (Van Nest and Alexander 1999). Surface fire spread and intensity is predicted by BEHAVE but, at least in the initial versions, crown fire initiation and spread, as well as, the ability to incorporate non homogenous surface fuel loading was not available. The FBP system predicts surface and crown fire intensity and spread as a continuous function for each fuel type, except grass and slash fuels (Trevis 2005). As mentioned, BEHAVE does not predict forest floor consumption while the FBP system combines forest floor and surface woody fuel consumption into the surface fuel consumption. Belowground fire severity as expressed by forest floor consumption cannot be directly represented by FBP except in the slash fuel types. However, the First Order Fire Effects Model (FOFEM) (Reinhardt 2003) does allow prediction of forest floor consumption. As well, the Canadian fire effects model BORFIRE allows separate prediction of forest floor and surface woody fuel consumption and is linked to the FBP system by the standard FBP fuel types (de Groot 2006; de Groot et al. 2003).
NEXUS

NEXUS (Scott 1999; Scott and Reinhard 2001) is an Excel spreadsheet-based application that was developed to simulate crown fire potential behavior in forest stands. Predictions of surface and crown fire behavior are based on models developed by Rothermel (1972; 1991). The model is able to simulate changes in fire behaviour and can be used to compute surface, transitional and crown fire behavior and two indices of crown fire hazard.

Linkages are established between surface and crown fire predictions using Van Wagner’s (Van Wagner 1977) equations (Scott 1999). Surface versus crown fires are estimated using the crown fraction burned transition function (Van Wagner 1993). NEXUS is a combination of the crown fire modeling concepts used by the Canadian FBP system and the BEHAVE surface fire behavior models and uses the same fuel sub-models that are used by BEHAVE, and also has a similar tabular output, involving charts and graphs. However, NEXUS also has a wind reduction factor (that ranges from open to within-stand) and fine dead fuel moisture for fire behavior prediction.

Six different fuel scenarios can be simultaneously simulated using NEXUS, each scenario being defined by a combination of fuel model, fuel moistures, crown fuel characteristics, site characteristics and multipliers (Scott 1999). The primary inputs are: fuel model (Anderson 1982); canopy closure(%), stand height, crown base height, bulk density; surface dead wood fuel loading; litter, dead wood and crown live needle moisture; wind direction from uphill; wind speed and slope. Among the outputs produced by NEXUS are: crown fraction burned (%), smoke emission and particulate production, and torching and crown fire indices (Scott 1999).

Fire severity is not explicitly computed by NEXUS, although aboveground severity can be estimated using crown fraction burned or flame length. Belowground fire severity cannot be estimated using NEXUS. An extended, spatial scale version of NEXUS is under development and will allow fire effects information to be implemented in the landscape planning.

FOFEM

A first order fire effects model (FOFEM) (Reinhardt 2003) was developed as an easy-to-use simulation tool to help managers, planners and analysts to make better fire management decisions with respect to prescribed or wildfire effects. Like NEXUS, FOFEM is a stand level model. FOFEM predicts first order fire effects, (i.e. effects with an immediate impact on forest ecosystems), but also long-term fire effects such as tree regeneration, vegetation succession or site productivity changes (Reinhardt 2003).
The current version, FOFEM 5.2.1, provides quantitative predictions of tree mortality, fuel consumption by size class, mineral soil exposure, smoke emissions and soil heating. The consumption of woody fuel is predicted using the BURNUP model (Albini and Reinhardt 1997). Empirical equations are used to simulate consumption for the other fuel categories (litter, duff, shrubs, herbs and crown). Tree mortality is predicted using the surface flame length, scorch height, species and tree size (Reinhardt and Ryan 1988). FOFEM 5.2.1 uses flaming and smoldering combustion to determine smoke emissions and emission rates. The soil heating component, which is part of FOFEM 5.2.1, predicts soil temperature at different soil depths over time since ignition.

It can be concluded that FOFEM, a model that uses predictions from several other models and subsystems, represents an important step in the modeling of fire effects even though it is not capable of simulating long-term fire effects. Aboveground severity can be estimated using crown fraction burned or scorch height; belowground severity can be estimated using the soil heating output or depth of burn.

**FFE-FVS**

The fire and fuels extension to the forest vegetation simulator (FFE-FVS) is a modeling tool that creates a linkage between stand dynamics and fuel management by incorporating models of fuel dynamics, fire behavior and fire effects into a model of forest stand development (Crookston et al. 2000). As the name implies, the fire and fuels extension FFE is an addition to the Forest Vegetation Simulator (FVS) (Stage 1973; Wykoff et al. 1982), also known as PrognosisBC, a simulation tool capable of representing tree growth and mortality and also ecosystem response to various management scenarios (Reukema et al. 1997). Fire effects like tree mortality, fuel consumption and smoke production can be simulated over several decades, thereby exceeding the temporal capabilities of FOFEM. The fuel models that are used in FFE-FVS are similar to those used by FOFEM and BEHAVE (Reinhardt and Crookston 2003). FFE-FVS is classified by the Landscape Fire Succession Models (LFSM) classification system as a spatial simulation model of fire and vegetation dynamics, in the category of succession models.

The input variables include forest stand and management data (specific to FVS), and fuel loading and moisture content and other weather parameters specific to FFE. The model produces output tables for fuel consumption, potential fire intensity and spread rate, smoke
production/emissions, tree mortality, as well as fire effects on the stand. Indices of crowning potential can also be produced. Output variables can be displayed for any future year. Fire intensity is predicted using variables such as slope, mid-flame wind speed and fuel moisture content. Crown fire potential is determined using a crowning and torching index (a function of wind speed) which determines if a crown fire is active or passive. Probability of mortality is calculated based on crown scorch height, crown length, tree diameter and species (Reinhardt and Crookston 2003). Equations from FOFEM (Reinhardt 2003) are used to predict tree mortality.

The FFE-FVS model is capable of representing the actual and potential effects of fire in a stand but does not have any capabilities to represent fire spread or fire likelihood (Reinhardt and Crookston 2003). Thus, the model can predict aboveground and belowground fire severity and long-term fire effects such as regeneration and future development of the forest stand. The capabilities of FFE-FVS can be extended visually by linkage to the Stand Visualization Simulator (SVS) program (http://forsys.cfr.washington.edu/svs.html, accessed May 2007). FFE-FVS operates on yearly steps so that live fuels (e.g. herbs and shrubs) are poorly represented in terms of seasonal changes in fuel and phenology. However, FFE-FVS represents a successful integration of fire behavior elements into a forest management model.

**FIRESUM**

The fire succession model (FIRESUM) (Keane et al. 1989) is a deterministic, stand level, process-based model developed to simulate the effects of fire regimes on tree composition, stand structure and fuel loading as related to the availability of moisture, light and nutrients. Fire is simulated as a stochastic event, through Monte-Carlo simulations, and it affects the ecosystem by reducing the available fuel (litter, duff, down woody fuels) (Keane et al. 1989). Forest stand dynamics like tree growth, woody fuel accumulation and litter fall are modeled deterministically on annual time steps. The model predicts fire effects such as tree mortality, establishment, regeneration, changes in species composition for periods that can be extended to several centuries. FIRESUM outputs have been used to estimate fire hazard, and also fire effects on forest stands, including wildlife habitat (Rothermel 1972). A surface fire behavior model is used to predict fire behavior.

The model was initially calibrated for the Northern Rocky Mountains. FIRESUM requires as inputs stand information, weather data, and site characteristics such as topography and soil type.
Firesum produces various outputs that include basal area for each species, fuel availability and some fire behavior parameters (Keane et al. 1989). Scorch height and tree crown characteristics are estimated in a single value for the whole stand in Firesum. The model’s advantages include the ability to incorporate climate change effects and to determine long-term changes in vegetation dynamics.

**Borfire**

Borfire (Boreal Fire Effects Model) is a compilation of Canadian fire behavior models to determine first-order fire effects on stand attribute and estimate ecological effects (mortality, regeneration) (de Groot 2006). The model is incorporated as a submodel in the Canadian Wildland Fire Information System (CWFIS) to estimate carbon emissions. CWFIS is a system that applies both Canadian Forest Fire Danger Rating System (Stocks et al. 1989) and the Fire Monitoring, Mapping and Modelling (FireM3) at the national level in Canada. CWFIS provides daily spatial FWI system data to drive Borfire and is also linked with Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) (Kurz and Apps 1999) to convert carbon pool data into fuel data for Borfire (de Groot 2006). Through CBM-CFS3, the components of carbon pool are matched with the fuel consumption algorithm from Borfire at individual stand levels. The data are integrated in the CBM-CFS3 as disturbance matrices (de Groot et al. 2007).

Borfire is a stand level model that simulates fire effects on boreal species as Pinus banksiana, Picea glauca, Picea mariana, Populus tremuloides, Betula papyrifera and Abies balsamea. The model calculates fuel consumption on stand components like live tree material (roots fine and coarse, stemwood, branchwood and foliage) coarse and medium woody debris and forest floor organic matter. Pre-burn fuel load can be adjusted by species (de Groot 2006). Fuel consumption algorithm is different for each component. E.g. surface litter material is assumed to be consumed as long as fire is capable of spreading. Consumption of CWD follows Mcrae (1980) equations derived from Buildup Index (BUI) (indicator of total fuel available) with adjustments to ensure a gradual decrease to zero. The Montreal Lake fire experiment showed that almost half of total fuel consumption occurred in the coarse and medium dead woody debris components of forest floor (de Groot et al. 2007).
determine yield equation for burned species and consequently affect fuel load distribution in stand components (de Groot et al. 2007).

Fire severity is directly calculated in this model in the fuel consumption component. This severity is a result of combining fire weather with the prefire components of the forest stand and determines the amounts of carbon release to the atmosphere from fire.

2.3.2 Landscape fire models

Prometheus

The Prometheus Canadian Wildland Fire Growth Model (CWFGM-Steering Committee 2004) is a physically-based, deterministic fire growth model that is capable of representing spatial fire behavior at the landscape level. It was developed to utilize and improve key features from a number of existing models in order to create a “state-of-the-art” wildland fire growth model capable of simulating fire spread across different landscapes with heterogeneous fuels and topography based on daily or hourly fire weather data. Prometheus is a stand alone application and has an interactive, user friendly interface with GIS compatible input and output data formats. Prometheus is based on the Canadian Forest Fire Behavior Prediction (FBP) System and on Huygens' principle of wave propagation that uses differential spread equations derived by Dr. Gwynfor Richards at Brandon University (Richards 1990;1995;1999).

The Prometheus model incorporates the FBP calculations and the weather indices obtained from FWI as well as GIS data. The main inputs to Prometheus are: FBP fuel type grid (ASCII grid); FBP fuel type lookup table (ASCII text); FBP fuel type projection file; fire ignition data as point, line or polygon (shape file); and weather stream data (ASCII text). Besides these mandatory files, the user can use optional files that include: digital elevation model (DEM), slope and aspect maps (grid); wind speed and direction files (grid); fuel breaks data (shape file) and the corresponding attribute files(CWFGM-Steering Committee 2004). Other inputs can be foliar moisture content (determined from elevation, latitude, longitude and date) and the type and duration of prediction. The model is also dependent on the date and time of the ignition as well as on the geographic location. Based on all of this information, multiple scenarios can be
simulated, as the model first generates future diurnal weather values that are then combined with FWI and FBP Systems to simulate rate of spread across the landscape.

*Prometheus* produces as primary outputs: rate of spread (two dimensional views as a function of time), fuel (forest floor, surface woody and crown foliage) consumption, fire intensity and the type of fire and all these components can be exported as ASCII grid files (CWFGM-Steering Committee 2004). Fire intensity values are predicted by the built-in fuel consumption component of the FBP system and are calculated, as previously described, from fireline intensity (Feller 2003b; Van Wagner et al. 1992) by using only the total surface fuel consumption that occurs in the fire front. Since the FWI system considers only dead fuel, the seasonal changes in the vegetation are not sufficiently developed in Prometheus. Also, fire growth simulations in Prometheus do not consider precipitation directly, but do so indirectly through the moisture code; this limits the spatial representation of the model.

The severity of a particular fire is quantified by the Danger Severity Rating (DSR). DSR ultimately represents the fire control efficiency, a fire weather severity, derived based on the FWI values and can be used to compare one fire season to another. However, it does not account for fire load that is a function of fire size and intensity and is used mainly to compare one fire season with other (Harvey et al. 1986).

In terms of belowground severity, forest floor consumption is predicted in *Prometheus* using FBP, but is combined with woody fuel consumption so that its individual contribution cannot be distinguished (Van Wagner et al. 1992), although the BORFIRE (de Groot 2006) does allow separate prediction of forest floor and woody fuel consumption.

Crown Fraction Burned (CFB) is defined as the predicted fraction of the tree crowns consumed by the fire (Feller 2003b; Van Wagner 1977) and can be considered a reliable measure for the aboveground severity. The FBP System considers a gradual transition from surface fire to crown fire that depends on how much the predicted surface fire intensity exceeds the critical fire intensity. There is more easily handled as a rate of spread at which the crown will become involved in a fire, where rate of spread is a function of fine fuel moisture content, wind speed, and surface fuel consumption (Van Wagner et al. 1992). The fire type can be

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* Crown fraction burned is described by a two equations model which determines the extent of crowning (Van Wagner 1977). The model takes into account the foliar moisture content and the height to live crown to define the amount of energy required for canopy ignition and fire intensity (Byram 1959) to measure heat source (Cruz et al. 2003).
described by CFB classes as surface, intermittent crowning or continuous crown and used as measure of aboveground fire severity.

Prometheus has a Microsoft® COM (Component Object Model) interface that allow users to alter or integrate parts of Prometheus COM with other Microsoft application.

FARSITE

FARSITE (Fire Area Simulator) (Finney 1998) is a deterministic (mechanistic) spatial and temporal fire growth simulation model developed by a group of researchers from The System for Environmental Management and United States (US) Forest Service, Fire Sciences Laboratory in Missoula, Montana. FARSITE incorporates five models of fire behavior: surface fire (Albini 1976; Rothermel 1972), crown fire (Rothermel 1991; Van Wagner 1977; 1993), point-source fire acceleration, spotting from torching trees (Albini 1979) and fuel moisture (Rothermel et al. 1986). The model simulates fire growth patterns for various weather scenarios by integrating the above mentioned models using a vector propagation technique (based on Huygens principle of wave propagation). FARSITE produces spatial and temporal representations of fire behavior and growth over the landscape in a form of “vector fire perimeters” (polygons) at specific time intervals (Finney and Andrews 1999). Each vertex of these polygons contains information about fire spread and intensity which are then interpolated to produce fire behavior raster maps (Finney 1998). These two-dimensional raster maps are in the form of an ellipsoidal fire shape (Van Wagner 1973).

FARSITE requires as spatial inputs - ASCII files for the fuels (obtained from the Rothermel-based fuel models (Anderson 1982; Rothermel 1972), fuel models also used in BEHAVE), vegetation and topography (elevation, slope and aspect); and as tabular inputs - weather data (temperature, relative humidity, wind speed and direction, and precipitation). The model generates vector and raster maps that can be used to spatially analyze fire effects or suppression options (Albright and Meisner 1999). These maps can also be exported to GIS software (e.g. ArcView or ArcGIS) and are useful in the analysis of fire effects over different landscapes for which past, current and potential future fires can be simulated (Finney and Andrews 1999).

There are three parameters that are used to control the spatial and temporal resolutions of the simulations: time step, distance resolution and perimeter resolution. These parameters control the amount of data used and the details that are going to be simulated (Finney 1998).
FARSITE has proven to be a complex but dynamic mechanistic model capable of representing fire behavior for a wide range of conditions. Used for simple simulations of individual fires, the model can be used to represent how individual environmental factors are affecting fire behavior and growth and how they contribute to certain fire effects (Finney and Andrews 1999).

FARSITE can be also used to simulate forest dynamics over centuries as spatially explicit processes. The model has capabilities to represent variable weather and fuel conditions that will result in heterogeneous fire behaviour. Time of arrival, fire line intensity, rate of spread, flame length and heat per unit area are some of the variables that can be analyzed using FARSITE outputs (Opperman et al. 2006). FARSITE can dynamically represent the linkages between the environmental factors, fire growth and behavior and fire effects. The variable fire behavior is translated in variable fire effects (Finney 1999). These components can be further extrapolated to express fire severity at various spatial and temporal scales. Among the fire effects that can be simulated with this model are: the level of crown damage represented by crown scorch fraction as the combined effects of fireline intensity and crown height; and the percentage of crown kill (calculated from fireline intensity and crown dimensions of individual trees) which is a strong predictor of tree mortality along with bark thickness and tree size (Finney 1999). Crown scorch fraction can be used to estimate aboveground severity. All these fire effects, depending on data availability, can be represented at various spatial and temporal scales.

FARSITE can be considered a useful model as it explores the complex spatial and temporal relationship between environment, fire growth and behavior and fire effects. An example of this is the ability of FARSITE to predict smoke emissions (Finney 1999b). It also explores the potential linkages between different existing fire behaviour models. The model extrapolates the advantages of each of these models and is also useful in identifying different shortcomings or missing components. These vector or wave type models are considered to avoid the problems generally encountered by cellular-based models in dealing with spatial and temporal heterogeneity (Finney 1998). The model has been successfully tested against field experiments and data. As for all mechanistic models, data availability is the chief disadvantage. However, with the improved remote sensing and computation capabilities data availability is becoming less an impediment for mechanistic simulations.

Like Prometheus, FARSITE is a fire growth model that has good potential for investigations of fire behavior at the landscape level in an interactive manner (Opperman et al. 2006).
The fire-biogeochemical model (FIRE-BGC) (Keane et al. 1996) is a mechanistic, biogeochemical vegetation succession model that simulates fire and climate long-term landscape dynamics. It is based on a hierarchical design (landscape-site-stand-species-tree) and represents an important step in scaling up fire effects from an individual tree level to the ecosystem and up to the landscape level, which is simulated as homogenous stands (He and Mladenoff 1999). However, the scaling up and/or down processes are not spatially explicit. It is a highly complex model that was created by merging several models. It uses FIRESUM (Keane et al. 1989), a gap, stand level model to simulate all individual trees from the plots and FARSITE (Finney 1998), a mechanistic fire behavior model to predict fire behavior and growth. The mechanistic ecosystem biogeochemical process approach of FOREST-BGC (Running and Gower 1991) is used to simulate tree growth by representing the amount of carbon that is fixed daily by forest canopy photosynthesis at the stand level (Keane et al. 1996).

The model has a complex architecture with mixed temporal and spatial scales. It has two spatial scales as ecosystem processes are represented at a landscape scale (using raster data layers) whereas processes as tree growth and regeneration are modeled at a stand level scale. The inputs required by the model are: weather variables (precipitation, temperature, relative humidity, and solar radiation); fire variables (fire intensity, fire severity, and rate of spread all produced by FARSITE); fuel (woody fuel, litter and duff) structural and physical characteristics; structural and physiological tree variables (growth, mortality, regeneration, stomatal conductance, carbon and nitrogen availability, insects and diseases); and spatial landscape characteristics (e.g. digital elevation models) (Keane et al. 1995b). FIRE-BGC calculates individual tree growth and mortality, seedling development, organic matter accumulation and decomposition on daily and annually steps. It also produces spatial data layers of ecosystem processes such as evapotranspiration and net primary production, species cover maps and fire behavior parameters. Landscape variables are generally represented on annual steps. Fire-caused tree mortality is produced empirically as derived from logistic regression probability functions (Keane et al. 2004; Keane et al. 1995b).

FIRE-BGC can be used to estimate fire effects over a short or long-term basis and at the landscape level (e.g. fire effects produced in different climate conditions can be compared). It is possible to obtain fire severity estimations using the model outputs: e.g. forest floor
consumption can be estimated from the model output values for fuel consumption if soil data are available (Keane et al. 1996). The model is limited to the geographic area that was calibrated for (e.g. Glacier National Park, U.S.), requires over a thousand input parameters, and is computationally intensive (Keane et al. 1995b). Nonetheless, one of its strongest points is its ability to use climatic data, including climate change prediction.

2.4 Discussion

Fire severity is a controversial term that has been defined in many ways and usually refers to a qualitative measure of fire effects on soil and site resources that influence ecosystem functioning and sustainability. Fire severity has also been defined in terms of negative impacts on ecosystem function, and also changes to the geosystem and atmosphere (Simard 1991). Other definitions of fire severity are: an ecological parameter which loosely reflects the effects of fire (Agee 1993); a measure of the heat transmitted into litter, duff and soil layers (Debano et al. 1998).

The selected stand and landscape fire models reviewed previously in this chapter represent a range of approaches to the prediction of fire behavior and effects at different scales. Some of the stand level fire models predict only first-order fire effects (BEHAVE, FOEM, FBP, BORFIRE) while others are able to predict fire effects over a the long-term (FIRESUM, Fire-BGC, FFE-FVS). However, only FIRESUM and Fire-BGC are able to predict the impacts of fire severity over a long time period and allow interactions with future climate change. Prometheus, FARSITE, and Fire-BGC can predict fire behavior at a landscape scale, while only FARSITE and Fire-BGC can predict fire effects. Table 3.2 summarizes the spatial and temporal characteristics of these models, the scale fire severity is predicted, type of fire effects predicted for ecosystems, fuel consumption, and the model’s capability to integrate with FORECAST.
Table 2.2 Summary, for selected fire models, of their scale; ability to predict fire severity and other ecosystem effects, and compatibility with the FORECAST model.

<table>
<thead>
<tr>
<th>Fire Model</th>
<th>Scale</th>
<th>Multiyear simulation</th>
<th>Type of fire*</th>
<th>Spatial fire severity</th>
<th>Fire effects on ecosystem</th>
<th>Compatibility of fire model with FORECAST</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>First order fire effects</td>
<td>Vegetation Succession</td>
</tr>
<tr>
<td>BEHAVE</td>
<td>Stand</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>NEXUS</td>
<td>Stand and watershed</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>FOFEM</td>
<td>Stand and watershed</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>FFE-FVS</td>
<td>Stand</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>FIRESUM</td>
<td>Stand</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>BORFIRE</td>
<td>Stand</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Prometheus</td>
<td>Landscape</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>-</td>
</tr>
<tr>
<td>FARSITE</td>
<td>Landscape</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Fire-BGC</td>
<td>Landscape/individual tree</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>-</td>
</tr>
</tbody>
</table>

*Ground, surface and crown fire
Most of these fire models do not predict fire severity directly but can be derived from other model outputs. Among the most common methodologies used to predict post-fire tree mortality are mathematical approaches like discriminate analysis (Jain and Graham 2004) or logistic regression techniques (Cruz et al. 2003). Although these models can predict with a low error, they usually are only applicable for a narrow range of ecosystems. Other more complex approaches might be necessary to simulate fire effects over a wide range of slope, aspect, and site productivity. Linking fire models with growth and yield or stand dynamics models could be a feasible and practical way to represent fire effects, especially over long time periods. Developing ecosystem models that are able to predict fire effects could be another solution, although incorporating fire severity prediction capabilities into ecosystem models cannot occur unless a suitable fire behavior model is incorporated along with fire weather predictive capability.

Forest managers need both short and long-term fire effects predictions, at both stand and landscape scales. Fire severity prediction represents an important component of fire effects modeling. Since forest ecosystem models are developing capabilities to represent short and long-term disturbance effects, fire severity is a key factor in these simulation models.

Ideally, the flexibility of process-based simulation models should be combined with stochastic or empirical based models (Kimmins 2000). However, “historical dynamics of any real landscape are only one realization of stochastic processes” (Lertzman and Fall 1998). The variability of fire regimes makes it almost impossible to predict fire regimes using empirical methods (Perrera et al. 2003). Some growth and yield models that incorporate fire effects on dead or live components can provide the understanding of stand development patterns and autecological responses to fire. However, this is a capability that requires a level of complexity that is generally found only in process-based models (Agee 1993). However, while such process-based models are capable of representing fire effects to some extent, they have limited potential to simulate complex fire-generated impacts like fire severity. Hard or soft linkages between ecological and fire behavior and effects models appears to be necessary.

Based on the review above, fire severity can really only be assessed by ecosystem-level process-based models. Most of the models that were reviewed in this study use an empirical modelling approach, e.g. linking measures of fire to tree mortality. Also, very few of the selected models reviewed are dealing with post-fire stand development and succession, and none deals with differential effects on trees and minor vegetation which can have a big effect on
succession – sometimes assisting tree regeneration and sometimes the reverse. Seedbeds, seed sources, vegetative reproduction from buried bud banks, and competing vegetation – all play a role in regeneration that is not considered in these models. On the other hand, to be useful from a fire perspective, a complex ecosystem management model should incorporate fire and be capable of simulating various interactive effects derived from the frequency and severity of fire events: an allogenic succession factor that in many types of forest ecosystem is a component of long term sustainability (Kimmins 2004a). A dynamic ecosystem-level assessment of fire severity impacts should be defined in terms of the time scales of succession, stand dynamics, and forest harvest rotations. The main focus of this assessment should be tree mortality as a first order fire effect, although other factors should be considered that would influence succession such as the incorporation of spatial scale since it affects available seed sources for regeneration and the consequences of different levels of fire severity and its impact on nutrient cycling that influence the rate and pattern of succession. One cannot consider fire severity in isolation from the initial ecosystem condition and frequency of fire disturbance (e.g. a particular fire behavior may produce different fire severities depending on the type of ecosystem that burns). Fire frequency also interacts with fire severity (Kimmins 2004a; Kimmins 2004b).

Since severity is defined as effects on the ecosystem and most of the fire models are focusing only on fire behavior and tree mortality, a more dynamic ecological assessment in terms of ecosystem resilience, successional dynamics and ecology of natural disturbance is needed. This is increasingly necessary to meet the public’s expectations for stewardship and sustainable ecosystem management. The capabilities that many of the present fire models lack could be addressed by linking them with process-based ecosystem management models.

2.5 Fire representation in FORECAST

This literature review and critical assessment of selected fire models in terms of their ability to predict both above and below ground fire severity provides critical information and direction in terms of designing and developing a fire sub-model in FORECAST.

FORECAST (FORest and Environment Change ASsessmenT) is a decision support tool tool developed for evaluating long-term sustainability and value tradeoffs related to stand-level management in forest ecosystems (Kimmins et al. 1999). Developed as an advanced Windows®-based interface version of the FORCYTE 11 (FORest nutrient Cycling and Yield
FORECAST represents the outcome of 32 years of ecological modeling research at UBC. The models of the FORCYTE series are described by the authors as hybrid, stand level simulation models capable of making predictions of the effects of management and natural disturbance on biomass and nutrient accumulation in different forest ecosystems over time (Kimmins 1993). The scientific foundation of FORECAST is represented by a hybrid simulation approach: “experience + knowledge = prediction”. The models using this approach are driven by empirical equations or empirical growth data from which rates of key ecosystem processes are calculated in conjunction with other field measurements or the published literature. This type of model was developed with the objective of being both portable and simple enough to calibrate and use in forest management applications, yet have sufficient complexity to represent the key ecosystem structures and processes that determine the outcome of management and the effects of disturbances such as fire (Kimmins et al. 1990). The use of the process-based simulation increases the flexibility of the model, and the constraints imposed by the empirical data used increase its accuracy and reality. The model has been developed as a modeling framework that has to be locally calibrated and tested. It has been calibrated for many different ecosystem types, and tests have shown that, depending on the quality of the calibration data, the model can produce accurate representations of the ecosystem processes on a yearly time scale. The model can be used to simulate ecosystems at different levels of representations. The lower the representation level is needed, the less the amount of input data (Kimmins et al. 1999) but the less reliable the predictions for futures that are not a duplicate of the past. For a more detailed FORECAST description see (Kimmins et al. 1999).

Fire is one of the disturbances that can be represented in FORECAST. It is simulated as a user defined event in the fire sub-model. The user can choose different settings to represent fire either as a site preparation or fire hazard reduction activity or as a wildfire by deterministically simulating slashburning, stand underburning or wildfire. The fire sub-model has different settings that enable the user to determine how fire will affect the growth-determining process and the resultant productivity of the stand. Fire is a stand event that in short term interrupts the growth process of the stand and sometimes destroys the stand partially or totally. The fire representation involves simulation of a pre-fire vegetation community and soil condition (including soil organic matter, forest floor and fuel loading, determining when a fire will occur, and defining the degree of mortality of each tree and minor vegetation species being simulated and the extent of combustion of different fuel components. The model then simulates
ecosystem function and stand evolution over time as a function of the fire impacts that have been defined. Ecosystem organic components in FORECAST are separated into live and dead and also into aboveground and belowground components. Live components are trees, plants and bryophytes. Dead parts are forest floor organic matter, coarse woody debris and litter (Fig 2.4).

FORECAST can represent different fire types – ground, surface, and crown and fire or any combination thereof - by means of burning codes that define the impacts of the fire type on ecosystem components (i.e. the burn severity) as defined above. For each represented tree species, the effects of fire represented are percentages of killed and burned components (e.g. % killed and % burned of each component of each tree - stemwood, bark, branches, foliage and roots). The consumption of soil organic matter and dead plants material is simulated based on
definitions of the different components removed under the different burning codes (see Figures 2.5 and 2.6).

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**Fig 2.5** Screen capture with FORECAST interface for Section 3 (fire submodule). There are three possible fire type settings represented by the Burning codes values (1, 2, 3). There are default settings for each burning code, but the users can set their own settings. “Kill” represents the percentage of the live biomass component to be killed by the fire, and “Burn” represents the percentage of the kill biomass that will be decomposed to ash (see the figure insets).

The biomass components for the threes are: SW=stemwood, BK=bark, BN=branches, FL=foliage, RL=large roots, RM=medium roots, RS=small roots, FR=fruit, and for the understory plants: SH=aerial shoots, FL=foliage, RT=roots, TU=tubers and FR=fruit.
Fig 2.6 Screen capture with FORECAST interface representing the management file. The picture inset represents the Burning setup section. In this example, a fire described by Burn code 1 is simulated at year 75 and another fire described by Burn code 2 is simulated at year 150 of the simulation cycle.

The main advantage of this approach to defining fire severity is the potential to model long term fire effects. The burning severity code settings represent potential fire effects on different ecosystem components and they need to be somehow logically connected. Currently, it is the user’s responsibility to define these burning codes at appropriate values. Currently, FORECAST does not have full capabilities to represent fuel moisture content and fire weather and climate variations but they are in the advanced development phase. FORECAST can produce estimates of the total fuel load available on the simulated ecosystem but dead biomass consumption
cannot be directly simulated by the fire module in FORECAST. Burning of dead components will be simulated as either an accelerated decomposition process or as an organic material removal. The fire sub-model in FORECAST currently does not predict consumption by a fire of different live ecosystem components but they can be directly manipulated. The hydrology model FORWADY (Seely and Kimmins 2003), which implementation in FORECAST is in an advanced development phase, will offer the possibility to simulate the forest floor layers and their moisture content.

The decomposing material is separated in the actual version of the model in 40 decomposition classes described for each type of nutrients (Figure 2.7). For each class, at every time step of a simulation, FORECAST represents the decomposition of litter in humus as determined by the nutrient concentration, weight loss rates, and the temporal pattern of change in nutrient concentration. These classes are based on the empirical input data that describe each biomass component, so the number of classes may vary for each data set, as the user can combine several classes with similar properties in one class. Microbial immobilization and mineralization are represented as an increase and a decrease in nutrients content respectively.

![Fig 2.7 Screen capture with FORECAST interface for Soil Section which describes the 40 types of the decomposition components available. In this example, depicting a CWDdm data setting, only 20 types are used.](image)
In a case of a fire, each of the decomposition classes (representing ecosystem components) is converted into ash based on the user specification (Figure 2.8). Each decomposition type is split in ten deciles. Thus, these specifications are described by the percentage of deciles that is transformed into ash for each of the 40 each decomposition classes described above.

At the current stage of development in FORECAST, implementation of a stand level fire behavior model in FORECAST is not feasible. The user can simulate fuel consumption of above and belowground ecosystem components using the burning codes that are already functioning in the model. However, this current approach is both simplistic and complex since there are an infinite number of potential different combinations of fuel consumption by ecosystem component. To obtain reliable FORECAST simulation results using this method of defining fire
severity, the user needs to have an advanced knowledge of fire behavior or to have the ability to run an appropriate fire model.

Each model, at the end of the day should be considered “good” or “bad” based on its usability. To improve the usability of FORECAST in terms of representing fire at the ecosystem scale, severity matrices based on probabilities will be built to be used in the process of model calibration. At this initial stage, these matrices would not improve the overall capabilities of FORECAST but will improve the “functionality” of the model. Thus, the user would have the possibility of selecting a limited number of reliable fire scenarios. These fire scenarios represent the compilation of the historical weather condition, fire weather indexes and fire data collected from the field. For each individual data set, a probability severity matrix is intended to be developed and will allow user to select the most reliable type of fire for that particular data set.

The most commonly used fire models in Canada and US were described here and their capability to represent fire severity was discussed as well as literature definitions of fire severity. The use of crown fraction burned and forest floor depth as fire severity indicators is feasible and it can be concluded that the use of fire severity as a fire effects descriptor the ecosystem models is feasible in. The possibility of linking fire behaviour models with ecosystem-based models through fire severity matrices is addressed in the next chapter where the development of an algorithm to develop these severity matrices is presented.
Chapter 3 Severity matrix

3.1 Introduction

3.1.1 Fire effects on forest ecosystems

Fire plays an important role in forest ecosystems, with implications for most ecosystem components (Agee 1993). It also influences many forest ecosystem processes, including mortality, succession, fuel accumulation and nutrient cycling. Prediction of the ecological effects of fires of varying severity is complex, but general trends can be identified. The severity of fire in forest ecosystems refers mainly to the extent of its effects on vegetation and soil organic matter (see Chapter 2).

The ecosystem component most affected by fire is vegetation. There is a strong interaction between fire and vegetation: fire affects vegetation, but vegetation can also influence fire behavior through its direct relationship to the accumulation of different types of fuels (Agee 1993). Fire kills vegetation directly by heating the tissues and indirectly by exposure to smoke and gases. The post-fire recovery of vegetation communities depends on the proportion of different types of vegetation (growth forms, species, and age classes) killed and the quantity of organic matter consumed, both of which are affected by fire severity. Aboveground severity is typically expressed as the crown fraction burned as it is a relatively efficient measure of fire effects (Ryan 2002). Improving our understanding of the interactions between vegetation and fire will assist forest managers in developing ecologically appropriate fire strategies.

Fire effects on soils constitute the second major impact of fire in forest ecosystems. The effects of fire on forest soils can be grouped into two main categories: 1) effects on forest floor organic matter and 2) effects on mineral soil physical properties. The consumption of organic matter including litter and humus has short and long-term implications for nutrient availability. In the short term, the conversion of nutrient rich forest floor materials to ash acts to release mineral nutrients in plant-available forms and to increase nutrient cycling through its long-term effects on soil pH and temperature. However, the export of easily volatilized nutrients (such as N, S and B) contained in smoke and gases during burning can reduce long-term ecosystem productivity through reductions in ecosystem nutrient capital (Neary et al. 1999). Large woody material, which represents an important source of fuel but also has a variety of ecological roles
in many ecosystems (Wei et al. 2003), is only consumed in the most severe fires. The proportion of large surface fuels that are burned is an important indicator of fire severity and therefore of fire effects.

Fire can also affect mineral soil physical properties by altering soil structure, bulk density, organic matter content and through its effects on hydrological properties of the mineral soil surface (Smithwich et al. 2005). Soil structure, the arrangement of particles in the soil which reflects the influence of soil organisms, roots, and certain chemical processes, can be adversely affected by even moderate burn severity (Agee 1993). Extremely severe fires are likely to be highly detrimental to forest soils (Brown et al. 2003).

3.1.2 Fire regimes in lodgepole pine forests in the southern interior of British Columbia.

A particular fire regime greatly affects forest succession; age, stocking, and species composition of trees and minor vegetation; and the incidence of insects and diseases. British Columbia’s southern interior is characterized by diverse climates, which range from very dry to very wet, and from very warm to very cold, which in turn determines radically different fire regimes and vegetation types (Wong et al. 2003). These various conditions and the non-deterministic nature of processes that are involved in fire regimes make any prediction very difficult (Perera et al. 2004b). Fire frequency can range in these type of forests anywhere from 12 to over 800 years (Nitschke 2006).

Fires, stand development, mortality influences and fuel accumulation interact in a complex manner (Gara et al., 1985), especially because fires vary greatly in frequency, intensity, size, and other characteristics. Fires in lodgepole pine forests can be low intensity, creeping, surface fires, but high intensity crown fires during severe weather burn vast areas (Lotan et al. 1985). Lodgepole pine forms a self-replacing “fire climax” community over large areas in the central interior of British Columbia, where frequent, large-scale fire disturbance is a characteristic feature. Stand-replacing wildfire has historically been the major allogenic disturbance in the study area, with a fire return interval of approximately 100–125 years (Pojar 1985). Reed (1998) conducted a study in both MS and ESSF zones and estimated that a historical probability for a stand replacing fire based on the current age distribution was 51 years with a 95% confidence interval of 35–101 years. However, on drier MS sites, low-severity fires (24–76 years) are believe to occur in addition to high-severity fires (107–243 years) (Johnson and Fryer 1989). Over the centuries, it appears that fire frequency varied continuously throughout the Holocene.
(past 11,000 years) and for the last 500 years ranged from 200 to 250 years (Reed 1998). However, this is somehow different than the 60- to 130-year fire cycles reported for Kootenay National Park by Masters (1990) and is probably a result of the limited temporal resolution of charcoal records (Nitschke 2006). Others, like Pollack et al. (1997) used corrected forest inventory age data and statistical techniques to estimate stand replacement intervals and their modeling scenarios estimate replacement intervals of 108–124 years for MSdk and, 107–123 years for the MSdm1. In another study, Gray et al. (2002) emphasized that aspect and neighboring fire regimes appear to be influential in the severity of the dominant fire regime in the MS zone. South aspects were characterized by frequent, mixed-severity fire regimes of point mean fire intervals of 14–39 years in elevational transects in the following variants and subzones: the IDFdm2 and MSdk in the Cranbrook Forest District; the MSdm1 in the Invermere Forest District; and the IDFxh2, the IDFdk1, and the very dry cool subzone of the Montane spruce (MSxk) near Ashcroft in the Kamloops Forest District. The influence of aspect on disturbance regime is also supported by Holt et al. (2001), who sampled 38 MSdk stands in the Nelson Forest Region to develop old-growth definitions based on structural attributes.

For the particular case of TFL 49, Table 3.1 shows an average of the fire characteristics for the area.

<table>
<thead>
<tr>
<th>BEC</th>
<th>Fire Type</th>
<th>Mean Fire Return Interval Range (yrs)</th>
<th>Minimum Fire Size (ha)</th>
<th>Mean Fire Size (ha)</th>
<th>Maximum Fire Size (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MS</td>
<td>Stand Replacement</td>
<td>35 – 150</td>
<td>0.1</td>
<td>1069</td>
<td>5000</td>
</tr>
</tbody>
</table>

**Table 3.1 Average historical wild fire characteristics on MS zone**

### 3.1.3 Fire severity in the MS zone

Fire severity varies in lodgepole pine dominated MSdm forests, where the multi-aged structure of the forest was attributed to episodic moderate-severity disturbances and subsequent gap-phase pine regeneration pulses (Wong et al. 2003). Barrett et al. (1991) also found a mixed-severity fire regime in the western larch–lodgepole pine forests on the west side of Montana’s Glacier National Park (Jain and Graham 2004).
Besides aspect and neighboring fire regimes species composition appear to influence the severity of fire regimes that dominate MS stands. Johnson and Fryer (1989) examined the population dynamics of 13 lodgepole pine–Engelmann spruce stands in the MS-like forests of the Kananaskis Valley, Alberta. Their results provide evidence for long-term coexistence of both species across the landscape, even though lodgepole pine is considered early successional. The authors suggest that coexistence is facilitated due to the average fire return interval being shorter than the lifespan of lodgepole pine: less than 2% of the stands in the Kananaskis survive to 300 years (Johnson and Fryer 1989).

In conclusion, most studies and analyses consistently indicate that natural disturbances were likely complex and not in equilibrium in the MS lodgepole pine forests, creating changing patterns over space and time in both stand structure and landscape conditions (Nitschke 2006).

### 3.1.4 Other disturbances in MS zone

Biogenic disturbance agents such as insects and diseases are also common. The well known mountain pine beetle (*Dendroctonus ponderosae*) periodically kills lodgepole pine forests over large areas (e.g. during the 1980’s, much of the logging in the MS zone concentrated on removing beetle-affected timber), and such insect attacks are often a prologue to fire. Lodgepole pine, pine bark beetle and fire have an intricate relationship (Agee 1993). When these pines are about 80-160 years old, they become very susceptible to mountain pine beetles. Trees killed recently by beetles and those later that have fallen down have been shown to increase the potential for crown fire initiation (Turner et al. 1999).

The current mountain pine beetle epidemic is the worst in the recorded history in BC (Arsenault 2004).

Another biotic factor is represented by the dwarf mistletoe (*Arceuthobium americanum* Nutt. ex Engelm.) which is reducing the vigor of lodgepole pine, but has historically been kept in check by stand-replacing wildfires (Gara et al. 1985).

In addition, timber harvesting has affected much of the dry forest types in the Southern Interior Forest Region, and shaped stand structure for over a century. Managers should be very cautious in selecting harvest treatments to reduce fire severity based on a model of fuel build up in the absence of fire. These artificially created unburned areas are generally exhibiting the lowest fire severity (Odion et al. 2004).

It can be concluded that several interacting factors, including climate, harvesting, fire suppression, and patterns of insect pest attack, are key drivers in creating and maintaining
today’s conditions. Stand-replacing wildfires and severe mountain pine beetle outbreaks are the two main agents that maintain forests of lodgepole pine in various successional stages across MS landscapes.

3.1.4 Representation of fire severity in FORECAST

As mentioned in Chapter 2, FORECAST (Kimmins 1999) is a stand level ecosystem management simulation tool that has the ability to represent fire effects. However, the model representation of fire severity is dependent on the user’s knowledge of fire aspects in a particular ecosystem. The model can be calibrated for ecosystems in different biogeoclimatic zones, sub-zones and ecosystem associations.

In FORECAST, the user must define a desired level of severity in order to obtain reliable predictions in terms of ecosystem development after a fire. This “setup” operation requires advanced knowledge of fire severity levels for the particular ecosystem being simulated, which is not always possible. Therefore, it would be useful for the model user to have the ability to choose from a set of realistic fire severities for the area of interest. These could be developed as part of the FORECAST calibration process using local fire weather and fuel consumption algorithms. A two-dimensional fire severity matrix could be created that would contain a grid of probabilities reflecting the frequency of different combinations of above and belowground fuel consumption classes.

Given the dynamic relationships between lodgepole pine-dominated forest ecosystems and natural disturbance regimes, the prediction of fire effects on ecosystem structure and function clearly requires a consideration of its impacts on both vegetation and soil. In this chapter, fire severity will be expressed in terms of live crown consumption, and soil organic layer and coarse woody debris reduction. The impact on structure and function of the forest ecosystem and the utility of fire severity in predicting these effects will be explored. A fire severity matrix is developed and its potential linkage to the ecosystem management model FORECAST is investigated.

3.1.2 Objectives

The overall objective of the work presented in this chapter is to develop probability-based severity matrices for two representative locations (with local climate data) in the MSdm2
biogeoclimatic subzone in the southern interior of B.C. and to investigate the linkage of such matrices with the FORECAST ecosystem management model.

Specific objectives include:

1. To quantify the climate indices necessary for severity matrix development,
2. To develop a regression model for estimating forest floor consumption using a database from past fires, and
3. To develop a methodology for estimating and quantifying the above ground biomass consumption following a fire.

3.2 Methods

3.2.1 Description of the study area

3.2.1.1 Climate and soils

The study area is located in Tree Farm License (TFL) 49 near Kelowna on the western side of the Okanagan Lake in the south central interior of British Columbia. TFL 49 is administrated by Tolko Industries Ltd. according to BC Ministry of Forests and Range regulations and specifications for Pilot Projects (BCMoFR 2005). The study area falls within the South Thompson variant of the MSdm (Montane Spruce Dry Mild) subzone (Meidinger et al. 1991) and may be characterized as a gently rolling plateau at 1300-1500m elevation in the rain shadow of the Coast Mountains. It is subject to cold air drainage and pooling from the ice and snow fields in these mountains, and to cold, dry continental air from the Canadian boreal region during the winter. The mean annual temperature is less than 2 ºC, but the summer is warm and relatively dry (mean annual precipitation of 400–700 mm) (Steen and Coupé 1997). Most of the zone is under snow for 4–5 months, from November to March. In summers, frequent thunderstorms create the potential for wildfire when fuels are dry.

Soils within the study area are characteristically well-drained, represented mostly by Orthic and Eluviated Dystric Brunisols, Orthic Humo-Ferric Podzols, or Brunisolic Gray Luvisols, and developed on thick morainal deposits composed primarily of volcanic materials. Humus forms are moderately thick (5-10 cm) hemimors or hemihumimors.
3.2.1.2 Vegetation

The MS zone has strong floristic affinities with the ESSF, such as climax stands of spruce and subalpine fir, and prominence of *Vaccinium membranaceum* (black huckleberry) in zonal ecosystems, as well as some affinity with the IDF as indicated by the abundance of *Calamagrostis rubescens* (pinegrass), *Paxistima myrsinites* (falsebox), and occasionally Douglas-fir in zonal ecosystems. However, the MS lacks many species characteristic of both the IDF and ESSF. Thus, even though the MS is characterized as a transitional zone, it does have its own unique combination of species because of its intermediate nature. Hybrid white spruce (*Picea engelmannii x glauca*) is more common than Engelmann spruce (*Picea engelmannii* Parry ex Engelm. 1863). Characteristic understory species in addition to the three listed above are *Lonicera utahensis* (Utah honeysuckle) and *Vaccinium scoparium* (grouseberry).

One of the most distinctive features of the MS landscape is the extensive young and maturing seral stands of lodgepole pine (*Pinus contorta ssp. latifolia* Engelm.ex S.Wats.) that have formed following wildfire (Wong et al. 2003). Lodgepole pine plays an important role in the forest industry and environment in British Columbia. Wildfire is one of the most important factors involved in the establishment, development and renewal of lodgepole pine forests in Northern America (Lotan et al. 1985). On most sites where lodgepole pine grows, fire is necessary for the species’ continued dominance (Fisher and Bradley 1987). Lodgepole pine’s frost tolerance, resistance to drought, and serotinous cones all favor its establishment after fire. Thus this species requires high intensity fires to open their serotinous cones. These stands may burn every 35-100 years, but can be relatively resistant to fire until there is enough fuel to generate crown fires (Gara et al. 1985). Under the lodgepole pine canopy, frost and surface drying are reduced, and hybrid white spruce and subalpine fir can regenerate. In wetter subzones, and on wet sites in all areas, maturing seral stands contain mixtures of lodgepole pine, hybrid white spruce, and subalpine fir.

The *Hybrid spruce — Falsebox — Feathermoss* zonal site series of the MSdm2 variant (very common in TFL 49) was selected as the focal site type for field sampling and model analysis. Lodgepole pine, hybrid white spruce, and subalpine fir form mixed, maturing seral stands. Douglas-fir also can be a component of these stands. The shrub layer is moderately to well
developed, consisting primarily of *Paxistima myrsinites* (falsebox), *Vaccinium membranaceum*, and a low cover of *Lonicera utahensis*.

### 3.2.2 Rationale for developing a probability-based severity matrix

Fire severity is a multi-faceted issue, and there have been several attempts described in the literature to express severity as a combination of different factors. One of the first methodologies that classified fire severity was developed and described by Ryan and Noste (1983). They combined five flame length classes and four classes for the depth of forest floor charring, obtaining a two-dimensional fire severity matrix that could be used as an index of fire severity and also as a method to compare fire effects on different fires. Flame length and char classes were derived from postburn observations (e.g. flame lengths were calculated from the observed crown scorch (Van Wagner 1972)). However, fire severity should be linked to a good understanding of stand history, vegetation phenology and vigor, and soil (Ryan and Noste 1983).

Jain and Graham (2004) studied fires in the Rocky Mountains over three consecutive years (2000, 2001, and 2002), focusing on pre-wildfire forest structure and describing ways to classify fire severity. They produced a system to evaluate fire severity in relation to forest structure by developing a two-dimensional matrix that uses four classes of tree crowns and four classes of soil components (only three of them considered to be relevant). The four classes of fire severity used for tree crown were: no fire (1), green crowns (2), brown crowns (3), and black crowns (4); the four for soil were: unburned (1), light char (2), moderate char (3) and deep char (4). This is a modification of past fire severity classifications (e.g. Ryan and Noste (1983), Key and Benson (2002)). The matrix described in their study provides an empirical probability distribution giving an estimate of risk or certainty for a particular fire severity within the stand (Jain and Graham 2004).

One of the goals of the thesis is to improve the fire representation in the FORECAST model. As mentioned, most of the fire models described in Chapter 2 do not simulate long-term fire effects on ecosystems, but FORECAST is capable of doing that. However, FORECAST is not capable of simulating fire behavior. Rather, it uses a deterministic approach to parameterize fire severity in a fire submodel. By using a fire severity matrix to parameterize fire severity, a more accurate simulation of a particular fire type for a specific climate-vegetation combination should be obtained.
Based on the above rationale it was determined that a generic “fire severity matrix” with 3 levels of live biomass consumption on one axis and 3 levels of dead biomass consumption on the other would be suitable to characterize the probability of different fire severity classes occurring for a given forest type and climate (see Fig 3.5). The fire severity matrices and cell probabilities were used to guide the parameterization of the fire submodel within FORECAST.

Dead biomass consumption was determined using surface large (>=7cm diameter) woody fuel consumption (SFC) and forest floor (L, F and H layers) consumption (FFC). Since fine fuels (less than 7 cm diameter) are considered to be consumed in a high percentage (between 74-95%) during a fire (DeGroot 2006) they are not considered here.

The live biomass component is represented only by the fraction burned in the tree crowns. Severity matrices were created for the MSdm2 biogeoclimatic subzone of the TFL 49, Tolko, with fire weather data obtained from two selected Ministry of Forests and Range fire weather stations: Brenda Mine and Spruce.

3.2.3 Representation of aboveground fire severity

3.2.3.1 Crown fraction burned (CFB) as a measure of aboveground severity

Aboveground severity of a given fire can be described by estimating the crown fraction burned during a specific fire event (Van Wagner 1977). Among the factors that affect crown fire initiation and spread are the scrown base height and fuel load, canopy bulk density, and foliar moisture content. However, crown fires generally consume the foliage and fine branches so their spread is limited by the crown biomass and moisture content (Van Wagner 1977).

Crown fraction burned (CFB) is a primary output of the Fire Behavior Prediction (FBP) system and is classified in terms of the type of fire (Forestry Canada Fire Danger Group 1992). Thus, a fire type can be described as ground, surface or crown. For the purpose of developing the severity matrices, the fraction of live crown biomass burned in a specific fire event was calculated using an algorithm used in the FBP system (Hirsch 1996). Three levels of aboveground fire severity were described for use in the severity matrix (Table 3.2). These three levels are subsequently combined with three belowground severity classes for the final severity matrix formulation (see Section 3.2.3).
<table>
<thead>
<tr>
<th>CFB (%)</th>
<th>Fire type</th>
<th>Fire severity</th>
</tr>
</thead>
<tbody>
<tr>
<td>=&lt;10</td>
<td>Ground fire</td>
<td>Low</td>
</tr>
<tr>
<td>10&gt;and =&lt; 50</td>
<td>Surface fire</td>
<td>Medium</td>
</tr>
<tr>
<td>&gt;50</td>
<td>Crown fire</td>
<td>High</td>
</tr>
</tbody>
</table>

### 3.2.3.2 Calculation of CFB for probability matrix

There are three main factors which affect fire behavior and ultimately CFB: topography, fuel, and weather (Feller 2003b). CFB was calculated using the FBP system algorithms that were implemented using SAS ® software (SAS Institute Inc. 2003) with programming in SAS done by Dr. Steve Taylor, Pacific Forestry Centre, Victoria, BC. The original SAS program was adapted to meet the analysis requirements in this thesis. The SAS programming code and input variables used are presented in Appendix 1. The program calculates the potential daily CFB values (at 1600 hrs Pacific Standard Time) using the fuel type, and topographic and weather parameters. Fuel type and topographic variables are considered constants for a particular run as they represent a specific fuel type-weather station combination. Weather parameters determine the variability in estimating severity and they were derived here from two weather stations using records collected over a ten year period. Using the frequency of the simulated fire events falling into each of the CFB classes described above, a probability for each aboveground severity class was calculated for each of two FBP fuel types (C3 and C4, mature and immature lodgepole or jack pine) and weather station combinations. Details on the values used for topography, fuel and weather variables are provided in the following sections.

#### Topography

Topographic variables used to calculate CFB were slope, aspect and elevation. These variables generally do not change with time, but vary spatially (Feller 2003b). Variation in topography can cause important changes in fire behavior but this change is not the focus of this study as topographic features are considered uniform for the simulated area. Nonetheless, topography does have a significant role in determining fire severity.

Slope influences fire direction and spread, and combined with solar radiation and wind makes it more difficult to predict the dimensions of a fire. Aspect and elevation are other factors that
influence fire severity indirectly through their effects on ambient temperature and ambient foliar (Van Wagner 1972).

The topographic variables (slope, aspect and elevation) and their values used to calculate CFB for the creation of the aboveground fire severity matrices are presented in Table 3.3.

**Table 3.3** Topographic parameters used in the calculation CFB for the fire severity matrices.

<table>
<thead>
<tr>
<th>Fuel type</th>
<th>Weather station</th>
<th>Topographic features</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Slope</td>
</tr>
<tr>
<td>Mature (C3) Brenda</td>
<td>25%</td>
<td>S-SW</td>
</tr>
<tr>
<td>Mature (C3) Spruce</td>
<td>25%</td>
<td>S-SW</td>
</tr>
<tr>
<td>Immature (C4) Brenda</td>
<td>25%</td>
<td>S-SW</td>
</tr>
<tr>
<td>Immature (C4) Spruce</td>
<td>25%</td>
<td>S-SW</td>
</tr>
</tbody>
</table>

**Fuel type**

Fuel type is one of the key variables in the FBP system, and is defined as “an identifiable association of fuel elements of distinctive species, form, size, arrangement and continuity that will exhibit characteristic fire behavior under defined burning conditions” (Forestry Canada Fire Danger Group 1992). Fuel is considered “the source of thermal energy and the driving force behind the phenomena of fire behavior” (Feller 2003b). Fuel type is an important criterion describing the potential burning materials represented by vegetation and decomposing organic layers. Fuels are classified based on their vertical distribution as ground, surface and aerial fuels. The FBP system recognizes 16 different fuel types, and each type is represented as a relatively homogenous fuel complex that is extended over a sufficient area such that it and is capable of maintaining a certain fire behavior over a considerable period of time (Forestry Canada Fire Danger Group 1992).

Fuel characteristics (including compactness, moisture content, vertical and horizontal continuity and piece size) affects fire intensity and residence time, therefore above and belowground fire severity. The lack of vertical continuity from the surface to crown fuels will typically reduce the probability of a crown fire developing. Horizontal discontinuity in surface fuels can stop a fire if there is no spotting ahead of the fire front and the radiant energy from the fire front is low enough to prevent ignition of nearby fuels. The size, shape and moisture content
of fuel elements can also influence fuel consumption and burnout time (e.g. large diameter woody debris, if dry enough, can continue to burn and generate heat and re-ignite the adjacent vegetation). Moisture content and chemical composition of fuel can have a strong influence on fire behavior. The higher the fuel moisture content, the more heat is required to evaporate the water and raise the fuel temperature to the point of ignition, thus reducing the combustion rate and amount. Fuel chemistry (e.g. presence of any volatile organic compounds or other substances that may increase flammability) may also influence fuel ignition and fire intensity (Forestry Canada Fire Danger Group 1992).

For the purposes of this study only C3 (mature lodgepole and jack pine) and C4 (immature lodgepole and jack pine) fuel types (Hirsch 1996) were used as they were representative of forest cover within TFL 49 (C3 and C4 fuel types occupy 33.5% and 2.5% of TFL 49, respectively). The mature pine fuel type is characterized by pure, fully stocked (1000–2000 stems/ha) lodgepole pine (*Pinus contorta* Dougl. ex Loud.) stands that have grown to the stage of almost complete crown closure. The base of the live crown is well above the ground and dead surface fuels are light and scattered. Ground cover is composed mostly of feather moss (*Pleurozium schreberi*) over a moderately deep (approximately 10 cm), compacted organic layer. A sparse conifer understory may be present (de Groot 1993). The immature pine fuel type is characterized by pure, dense jack pine (*Pinus banksiana* Lamb.) or lodgepole pine (*Pinus contorta* Dougl. ex Loud.) stands (10 000–30 000 stems/ha) in which natural thinning mortality results in a large quantity of standing dead stems and dead downed woody fuel. Vertical and horizontal fuel continuity is characteristic of this fuel type. Surface fuel loadings are greater than in the mature (C3) fuel type, and organic layers are shallower and less compact. Ground cover is mainly needle litter suspended within a low shrub layer (*Vaccinium spp.*) (de Groot 1993).

**Climate**

Climate is perhaps the single most important factor determining fire occurrence and behavior (Kimmins 2004b). Climate also influences fire occurrence indirectly through its impact on the development of vegetation communities (fuel types) and on decomposition rates of dead organic matter. Climate acts to regulate wildfire through fuel moisture content and lightning strikes, one of the most common causes of fire ignition (Oliver and Larson 1990). Both fire behavior and severity are significantly affected by variation in climate patterns.
Temperature and precipitation have a direct effect during a fire as high temperatures raise fuel temperature and reduces moisture content making ignition and spread easier while precipitation, depending on the amount, can increase fuel moisture content where ignition can no longer occur or fires are extinguished. Wind speed and direction influences the propagation rate and spread direction. Wind can also speed the drying of fuels, sustain the oxygen need for combustion and cause fires to spot ahead of the fire front. For the purpose of calculating CFB to determine cell probabilities in the fire severity matrices, fire weather data were obtained from two Ministry of Forests and Range, Protection Program weather stations, Brenda Mine and Spruce Station, located within the MSdm2 biogeoclimatic subzone in or near TFL 49 (see Figure 3.1).

**Figure 3.1** Location of the selected weather stations
“Brenda Mine” weather station (called Brenda Mine in the rest of this thesis) is situated in the south western part of the TFL 49 in the MSdm2 biogeoclimatic subzone at 1493 m elevation. Daily weather data were available for this station beginning in 1977. However, continuous records for FWI codes and indices were only available for 17 years. Two large fires took place in 1920 and 1930 in the proximity of this weather station (partially represented in Figure 3.1) (Lindgren 2001).

“Spruce” weather station (called Spruce in the rest of this thesis) is located in the middle of TFL 49 at 1462 m elevation. Daily fire weather data and FWI codes and indices were available for 13 years, starting in 1970, with only a period of 10 years overlap with Brenda Mine. For analysis purposes, only this 10-year overlap period (1987-1997) was used to create the fire severity matrices. Only fire weather during the active fire season (April through October) was used for the CFB calculations. Further detail for climate stations is provided in Table 3.4.

Table 3.4 Relative humidity, FWI codes and indices, elevation and location of Brenda Mine and Spruce fire weather stations. Fire weather was for the period 1987 to 1997.

<table>
<thead>
<tr>
<th>Weather Station</th>
<th>Brenda Mine</th>
<th>Spruce Station</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevation (m)</td>
<td>1493</td>
<td>1462</td>
</tr>
<tr>
<td>Latitude</td>
<td>49º 52’ 06” N</td>
<td>50º 24’ 48” N</td>
</tr>
<tr>
<td>Longitude</td>
<td>119º 59’ 36” W</td>
<td>119º 59’ 48” W</td>
</tr>
<tr>
<td>RH (%)</td>
<td>Min 0 Max 99 Average 64.5</td>
<td>Min 0 Max 99 Average 59</td>
</tr>
<tr>
<td>FFMC</td>
<td>0 100 64</td>
<td>0 96.4 68</td>
</tr>
<tr>
<td>DMC</td>
<td>1 176 18</td>
<td>1 108 23</td>
</tr>
<tr>
<td>DC</td>
<td>1 581 234</td>
<td>1 791 261</td>
</tr>
<tr>
<td>BUI</td>
<td>1 219 28</td>
<td>1 134 35</td>
</tr>
<tr>
<td>FWI</td>
<td>0 50 6</td>
<td>0 58 8</td>
</tr>
</tbody>
</table>

Where: RH = relative humidity; FFMC = Fine Fuel Moisture Code; DMC = Duff Moisture Code; DC = Drought Code; BUI = Buildup Index; FWI = Fire Weather Index.
3.2.4 Representation of dead biomass severity

Dead biomass consumption, one of the two axes used in the computation of the severity matrix was quantified both as forest floor consumption (FFC) and as surface fuel consumption (SFC). FFC was estimated using a regression analysis while SFC was calculated using the equations provided by Stocks (1986; 1989).

3.2.4.1 Development of FFC equations

To calculate FFC for use in populating the severity matrix it was necessary to develop a regression model in which FFC is the dependent variable and a series of FWI codes and index and descriptive variables (FFD-Forest Floor Depth, FFL-Forest Floor Load*, BD-Bulk Density, BUI- Buildup Index, DMC-Duff Moisture Code; DC-Drought Code) as independent variables. A relationship developed from untransformed variables was considered to be more desirable for improving model precision (Neter et al. 1996). The procedures used here to develop an appropriate model included both transformed and non-transformed variables, but emphasis was put on the non-transformed variables.

Data used in the regression were obtained from four fire experiments conducted in the mature and immature Jack Pine and Lodgepole pine forests across Canada in the last decade (Lawson 1973; Quintilio et al. 1977; Stocks 1986; Stocks 1989). A total of 36 observations were used to develop regression models for the aforementioned fuel types.

Data description - the fire experiments

Mature pine fuel data were obtained from three fire experiments conducted in Ontario, Alberta and British Columbia. The first experiment (Kenshou Lake) was conducted at Kenshou Lake site, situated 37 km from White River, Ontario by the Fire Research Unit of the Great Lakes Forestry Centre (GLFC) in cooperation with the Ontario Ministry of Natural Resources (OMNR) (Stocks 1987). Here the forest cover reflects the impact of multiple periodic fires. In 1972, a series of 24 burn plots were established, 12 of which were successfully burned over a ten year period: four in 1973, two in 1975, two in 1976, one in 1979 and three in 1983. All fires were set up in the same period between late May and early July. In each burn plot, a complete

* Forest Floor Load – a dry weight of combustible material organic surface component of the soil supporting forest vegetation (combined duff and litter layers) per unit area (kg/m² or t/ha) (Feller 2003b).
inventory of crown, surface and ground fuel components was conducted before and after the each fire to determine the amount of fuel consumed. Fire weather conditions were recorded for the experimental burns with on-site weather stations and FWI codes and indices calculated.

The second experiment was conducted mature jack pine stand near Darwin Lake, located in northeastern Alberta (Quintilio et al. 1977). The experiment took place during the summer of 1974 with the objective of studying fire behavior at various levels of fire danger. Pre-burn measurements of the vegetation and fuel loading were recorded as well as the fire weather. Seven experimental fires were lit, but precipitation terminated two of fires so that fuel consumption and fire behavior were only available for 5 burns.

The third experiment was conducted in mature lodgepole pine stand 40 miles north of Prince George in the interior of British Columbia. The experiment consisted of three experimental fires that were lit in three consecutive years (1968, 1969 and 1970). Fire Weather codes and indices were calculated from an on-site weather station. Fuel consumption and fire behavior was documented for each of the tree experimental burns.

Data for the immature jack pine fuel type were obtained from one experimental site and conducted by Brian Stocks, Canadian Forest Service, in 1973 near Sharpsand Creek, 60 km north of Sault Ste. Marie, Ontario (Stocks 1987). Eighteen experimental fires were lit a range of fire weather conditions to determine fuel consumption and fire behavior. Live and dead vegetation samples were inventoried pre- and post-fire in all experimental fires. For the purpose of this thesis, data were limited to 12 experimental fires for which no thinning or other treatments were conducted prior to burning.

In all the experimental fires, quantitative values of depth of burn (DOB), pre-burn forest floor depth (FFD), forest floor consumption (FFC) and FWI codes and indices: Build-up index (BUI), Drought Code (DC), Duff Moisture Code (DMC), and Fire Weather Index (FWI) were recorded.

Three categories of dead biomass fire severity (low, medium and high) were described for use in the fire severity matrix (Table 3.5). FFC was expressed as a percentage of the initial FFD. The frequency of FFC for each fire severity class was calculated by determining the proportion of the total number of days in the fire weather record that had predicted FFC values within the range of each FFC fire severity class. The frequencies of the three FFC fire severity classes were subsequently combined with the frequency of CFB classes as part of the fire severity matrix assembly process.
Table 3.5 Fire severity classifications for Forest Floor Consumption (FFC).

<table>
<thead>
<tr>
<th>FFC (%)</th>
<th>Fire severity</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;= 33</td>
<td>Low</td>
</tr>
<tr>
<td>33 &gt;and =&lt; 66</td>
<td>Medium</td>
</tr>
<tr>
<td>&gt; 66</td>
<td>High</td>
</tr>
</tbody>
</table>

To determine the frequency of FFC fire severity classes, a significant statistical relationship was required between the FFC (the dependent variable) and at least two independent variables: one of them being a FWI code or index and the other a forest floor parameter such as pre-burn depth or bulk density. Empirical statistical models that appeared in published papers on FFC were also evaluated. The statistical analyses were computed using procedures from SAS 9.0 software package (SAS Institute Inc. 2003). The model selected to estimate the forest floor consumption for the severity matrix construction is:

$$ FFC = 1.28 \times 0.040 \times (BD) + 0.0036 \times (DC) $$

where FFC [kg/m²] = forest floor consumption, BD [g/cm³]=bulk density and DC=drought code. The steps followed in selecting the best statistical model are presented in Appendix 2.

3.2.4.2 Surface fire consumption equations

Dead biomass consumption was estimated using surface fuel consumption (SFC) which was defined as the percentage of the pre-burn surface fuel load (SFL) that was consumed by fire. It was represented only by large woody debris (diameter ≥7cm). As mentioned, I assumed that all fine woody fine fuels are consumed by fire. Regression equations developed by Stocks (1987) for C4 fuel types and by Stocks (1989) for C3 fuel type were used to estimate the SFC. The regression equations were based on experimental fires conducted in the Sharpsand Creek (C4) and Kenshou Lake (C3) experimental areas. Two different regression equations were used for each fuel type (table 3.6). Therefore, eight fire severity matrices were constructed using SFC one of the dead biomass consumption components.
The main goal of this chapter was to develop fire severity matrices using FWI codes and indices calculated from daily weather observations recorded at the two chosen weather stations in the MSdm2 subzone: Brenda Mine and Spruce. The generic form for a fire severity matrix would use a combination of aboveground live biomass consumption and surface/belowground dead biomass consumption resulting in a 3x3 grid (9 cells) (B. Hawkes, 2003, Pers. Comm.) (see Figure 3.2). Separate fire severity matrices were created for each fuel type (C3 and C4) and fire weather station (Brenda Mine and Spruce). The surface/belowground dead biomass component of the fire severity matrix is composed of FFC and SFC while the aboveground live biomass component is represented by CFB. Therefore, of the fire severity matrices had two separate dead biomass components; one for each of the dead biomass fuel components, FFC and SFC.

<table>
<thead>
<tr>
<th>Fuel type</th>
<th>SFC regression equation</th>
<th>SSE</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C3</td>
<td>SFC = -0.1988+0.0081 DMC</td>
<td>0.045</td>
<td>0.60</td>
</tr>
<tr>
<td>C3</td>
<td>SFC = -0.1915-0.0119 SFL +0.0081 DMC</td>
<td>0.047</td>
<td>0.60</td>
</tr>
<tr>
<td>C4</td>
<td>SFC = -0.174 +0.0076 BUI</td>
<td>0.1</td>
<td>0.64</td>
</tr>
<tr>
<td>C4</td>
<td>SFC =-0.2145+0.0359 SFL +0.0070 BUI</td>
<td>0.096</td>
<td>0.70</td>
</tr>
</tbody>
</table>

Where, SFC [kg/m2] = surface fuel consumption, BD [g/cm3] = bulk density, SFL [kg/m2] = surface fuel load, DMC= duff moisture code, BUI = buildup index.

### 3.2.5 Fire severity matrix development

The main goal of this chapter was to develop fire severity matrices using FWI codes and indices calculated from daily weather observations recorded at the two chosen weather stations in the MSdm2 subzone: Brenda Mine and Spruce. The generic form for a fire severity matrix would use a combination of aboveground live biomass consumption and surface/belowground dead biomass consumption resulting in a 3x3 grid (9 cells) (B. Hawkes, 2003, Pers. Comm.) (see Figure 3.2). Separate fire severity matrices were created for each fuel type (C3 and C4) and fire weather station (Brenda Mine and Spruce). The surface/belowground dead biomass component of the fire severity matrix is composed of FFC and SFC while the aboveground live biomass component is represented by CFB. Therefore, of the fire severity matrices had two separate dead biomass components; one for each of the dead biomass fuel components, FFC and SFC.
<table>
<thead>
<tr>
<th>Aboveground Fire Severity</th>
<th>Low (CFB)</th>
<th>Medium (CFB)</th>
<th>High (CFB)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Low (FFC)</strong></td>
<td>Low*Low</td>
<td>Med*Low</td>
<td>High*Low</td>
</tr>
<tr>
<td></td>
<td>e.g. a spring surface fire with high forest floor moisture content</td>
<td>e.g. passive crown fire with high forest floor moisture content</td>
<td>e.g. an active crown fire in early spring in boreal forest with high forest floor moisture content and frozen</td>
</tr>
<tr>
<td><strong>Medium (FFC)</strong></td>
<td>Low*High</td>
<td>Med*Med</td>
<td>High*Med</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cell probabilities based on frequency of occurrence for all days in the 10 year period during the fire season using FWI codes and indices from representative fire weather station</td>
<td></td>
</tr>
<tr>
<td><strong>High (FFC)</strong></td>
<td>Low*High</td>
<td>Med*High</td>
<td>High*High</td>
</tr>
<tr>
<td></td>
<td>e.g. a low intensity surface fire with very dry low forest floor moisture content.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Fig 3.2** Generic fire severity matrix using FFC and CFB and descriptions of fire behavior and fuel consumption conditions that might illustrate a FFC and CFB combination in some selected cells.

When FFC and SFC were combined with CFB, the fire severity matrices became a 3x6 grid with FFC and SFC having separate frequencies of occurrence (probabilities) when combined with CFB but contained in one illustration (see Figure 3.3 as example).
<table>
<thead>
<tr>
<th>Aboveground Live Biomass Fire Severity</th>
<th>_</th>
<th>Low (CBF)</th>
<th>Medium (CBF)</th>
<th>High (CFB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>_</td>
<td>_</td>
<td>Low</td>
<td>Med * Low</td>
<td>High * Low</td>
</tr>
<tr>
<td>_</td>
<td>_</td>
<td>Cell probabilities based on frequency of occurrence for all days in the 10 year period during the fire season using FWI codes and indices from representative fire weather station</td>
<td>_</td>
<td>_</td>
</tr>
<tr>
<td>_</td>
<td>_</td>
<td>Low * High</td>
<td>Med * High</td>
<td>High * High</td>
</tr>
<tr>
<td>_</td>
<td>_</td>
<td>_</td>
<td>_</td>
<td>_</td>
</tr>
<tr>
<td>Belowground Dead Biomass Fire Severity</td>
<td>Low (FFC)</td>
<td>Low * Low</td>
<td>Med * Low</td>
<td>High * Low</td>
</tr>
<tr>
<td>Surface Fuel Consumption</td>
<td>High (FFC)</td>
<td>Low * High</td>
<td>Med * High</td>
<td>High * High</td>
</tr>
<tr>
<td>Surface Fuel Consumption</td>
<td>Low (SFC)</td>
<td>Low * Low</td>
<td>Med * Low</td>
<td>High * Low</td>
</tr>
<tr>
<td>Surface Fuel Consumption</td>
<td>High (SFC)</td>
<td>Low * High</td>
<td>Med * High</td>
<td>High * High</td>
</tr>
</tbody>
</table>

Fig 3.3 An example of a 3x6 fire severity matrix with FFC and SFC as distinct and separate matrices but on the same illustration.

By combining the aboveground and belowground and surface fire severities in one illustration or figure, eight fire severity matrices were built for the study area. Two sets of 8 fire severity
matrices were developed for each of the two fire weather stations and fuel type combinations. Since both SFC regression equations, presented in Table 3.6, were used to estimate SFC, additional sets of fire severity matrices were created. However, only the matrices determined using equations C32 and C42 (Table 3.6) are presented here. The other additional matrices using the other two SFC regression equations are presented in the Appendix 3.

Some differences were evident in the fire severity matrices cell probabilities when using the two different fire weather data sets. A comparison of some selected weather data parameters between the two weather stations seemed warranted. For a 10 year period, graphical comparisons were constructed between Brenda Mine and Spruce. Monthly and daily weather parameter averages as well as FWI codes and indices are presented in the results section.

3.3 Results

3.3.1 Matrix results

Figures 3.4-3.7 represent the four 3x6 matrices obtained using the methodology described above. The actual matrix probabilities are presented in tabular form in Tables 3.7 and 3.8. Even though the initial 3x3 matrices were expanded to 3x6 matrices (or, more precisely, (3x3) x2), the two components of the dead biomass are discussed separately.
Fig 3.4 Fire severity matrix with cell probabilities as percentages for Brenda weather station in a mature lodgepole pine dominated forest (C3). Dead biomass consumption is separated into forest floor fuel consumption (FFC) and surface fuel consumption (SFC). SFC was estimated using equation C32 (Table 3.6). Live crown biomass consumption is represented by CFB.
Fig 3.5 Fire severity matrix with cell probabilities as percentages for Spruce weather station in a mature lodgepole pine dominated forest (C3). Dead biomass consumption is separated into forest floor fuel consumption (FFC) and surface fuel consumption (SFC). SFC was estimated using equation C32 (Table 3.6). Live crown biomass consumption is represented by CFB.
Fig 3.6 Fire severity matrix with cell probabilities as percentages for Brenda weather station in an immature lodgepole pine dominated forest (C4). Dead biomass consumption is separated into forest floor fuel consumption (FFC) and surface fuel consumption (SFC). SFC was estimated using equation C42 (Table 3.6). Live crown biomass consumption is represented by CFB.
Fig 3.7 Fire severity matrix with cell probabilities as percentages for Spruce weather station in an immature lodgepole pine dominated forest (C4). Dead biomass consumption is separated into forest floor fuel consumption (FFC) and surface fuel consumption (SFC). SFC was estimated using equation C42 (Table 3.6). Live crown biomass consumption is represented by CFB.
Table 3.7 Fire severity matrix with cell probabilities as percentages for Brenda and Spruce weather station in a mature lodgepole pine dominated forest (C3). Dead biomass consumption is separated into forest floor fuel consumption (FFC) and surface fuel consumption (SFC). SFC was estimated using equation C32 (Table 3.6). Live crown biomass consumption is represented by CFB.

<table>
<thead>
<tr>
<th>Fuel Type C3</th>
<th>Weather Station</th>
<th>Dead biomass</th>
<th>Live biomass (CFB)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Brenda</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>FFC</td>
<td>Low</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>74.2</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>13.3</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>SFC</td>
<td>Low</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>15.6</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>1.9</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Spruce</td>
<td>Low</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>FFC</td>
<td>Medium</td>
<td>53.4</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>43.7</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>SFC</td>
<td>Low</td>
<td>84.8</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>10.3</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>2.6</td>
<td>0</td>
</tr>
</tbody>
</table>
Table 3.8 Fire severity matrix with cell probabilities as percentages for Brenda and Spruce weather station in an immature lodgepole pine dominated forest (C4). Dead biomass consumption is separated into forest floor fuel consumption (FFC) and surface fuel consumption (SFC). SFC was estimated using equation C42 (Table 3.6). Live crown biomass consumption is represented by CFB.

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>Weather Station</th>
<th>Dead biomass</th>
<th>Live biomass (CFB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C4</td>
<td></td>
<td></td>
<td>Low</td>
</tr>
<tr>
<td>Brenda</td>
<td>FFC</td>
<td>Low</td>
<td>22.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Medium</td>
<td>48.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>SFC</td>
<td>Low</td>
<td>58</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Medium</td>
<td>13.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High</td>
<td>1.5</td>
</tr>
<tr>
<td>Spruce</td>
<td>FFC</td>
<td>Low</td>
<td>5.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Medium</td>
<td>56.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High</td>
<td>35.3</td>
</tr>
<tr>
<td></td>
<td>SFC</td>
<td>Low</td>
<td>62.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Medium</td>
<td>7.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High</td>
<td>1.1</td>
</tr>
</tbody>
</table>

**FFC fire severity probabilities**

In the mature pine (C3) fuel type (Figures 3.4 and 3.5), the fire severity matrices show a greater than 50 % frequency of occurrence (probability) for a medium FFC and low CFB. Low CFB indicates that only surface and ground fires would occur, although a medium amount of FFC was predicted. A similar trend was found for immature pine (C4) fuel type (Figures 3.6 and
3.7) but with a higher frequency of occurrence of high CFB, especially when using Brenda weather station data. However, there is a difference between the predictions obtained using the two weather data sets, and the difference is greater for immature (C4) than for mature (C3) fuel types (the sum of the absolute differences between the corresponding matrix cells is 165 for C4 vs. 115 for C3).

**SFC fire severity probabilities**

The highest frequency of occurrence of CFB and SFC was a low CFB and SFC for both C3 and C4 fuel types (Figures 3.4, 3.5, 3.6, and 3.7). However, a low CFB and a medium SFC was the next highest frequency of occurrence for C3 and C4 fuel types for both weather stations. For the C3 fuel type fire severity matrices, a high CFB and low SFC occurred for both fire weather stations (Figures 3.4 and 3.5). The differences between the Brenda and Spruce matrices were smaller than for the FFC matrices. Thus, the sums of absolute difference between the corresponding cell values were 22 for the mature (C3) and 32 for the immature (C4) fuel types.

**3.3.2 Comparison of weather parameters and FWI codes and indexes between Brenda and Spruce weather stations**

A comparison of weather parameters and FWI codes and index between Brenda and Spruce weather stations is shown in Figures 3.11-3.14. These figures illustrate monthly averages of temperature, relative humidity, wind speed and precipitation for Brenda and Spruce weather stations during the fire season for the period 1987-1997.
Fig 3.8 Comparison between the monthly average daily temperature obtained at Brenda and Spruce weather stations.

Fig 3.9 Comparison between the monthly average daily wind speeds obtained at Brenda and Spruce weather stations.
Fig 3.10 Comparison between the monthly average precipitation obtained at Brenda and Spruce weather stations.

Fig 3.11 Comparison between the monthly averages of daily relative humidity obtained at Brenda and Spruce weather stations.
Average monthly fire season temperature, wind speed, and precipitation were found to be higher for Brenda weather station than Spruce (Figures 3.8, 3.9 and 3.10). Average monthly fire season relative humidity exhibited a high variation from month to month, although Spruce weather station had a slightly higher relative humidity than Brenda, especially during the summer months (Fig 3.11).

Figures 3.12-3.15 show a comparison between the average of the noon standard time daily readings for the weather variables (temperature, maximum wind speed, precipitation and relative humidity) between Brenda and Spruce weather stations. As was found in the previous comparison, higher daily temperature and wind speed were observed for Brenda. Except for a few exceptions in July, the Spruce weather station had higher daily precipitation than for Brenda (Fig 3.14). In addition, relative humidity was higher for the Spruce weather station than Brenda (Fig 3.15).

**Fig 3.12** Comparison between the average daily temperature values obtained at Brenda and Spruce weather stations.
Fig 3.13 Comparison between the average daily wind speeds obtained at Brenda and Spruce weather stations.

Figure 3.14 Comparison between the average daily precipitation amounts obtained at Brenda and Spruce weather stations.
Figure 3.15 Comparison between the average daily relative humidity values obtained at Brenda and Spruce weather stations.

FWI codes and indices were calculated from weather observations recorded at Brenda and Spruce fire weather stations (see figures 3.16-3.). Comparisons among DC, DMC and BUI values between the two weather stations indicated that there was slightly higher values for Brenda than for Spruce, especially for DC which represents the forest floor moisture content in the organic layers occurring below 7 cm in depth (from the top of the litter layer). The DC has been found to be correlated to smoldering combustion, seasonal drought and total woody fuel consumption, and helps to determine long-term drought conditions (Feller 2003b).
Figure 3.16 Comparison between the average daily DC values calculated at Brenda and Spruce weather stations.

Figure 3.17 Comparison between the average daily DMC values calculated at Brenda and Spruce weather stations.
3.4 Discussion

The main objective of the work presented in this chapter was to develop probability-based fire severity matrices for FBP fuel types, C3 and C4, the MSdm biogeoclimatic subzone of the TFL 49, in the southern interior of B.C. A total of eight matrices were constructed based on combinations of live and dead biomass consumption using two local fire weather stations. Live biomass consumption was represented by CFB, while dead biomass was represented by both FFC and SFC. However, only the four fire severity matrices presented in this chapter are discussed in this section. The other four matrices are presented in the Appendix 2, which represent variations of SFC based on different equations available from the literature.

Figure 3.18 Comparison between the average daily BUI values calculated at Brenda and Spruce weather stations.
3.4.1 Fire severity matrices: C3 fuel type (mature lodgepole pine forests)

**Fire severity matrix: CFB x FFC**

Since the soil variables used in developing the matrices were based on the same data for both Brenda and Spruce weather data sets, the only variables contributing to differences in the severity matrices are the weather variables. For both weather stations, the fire severity matrix for CFB and FFC (C3 fuel type) indicated a high probability of a low CFB and medium FFC (74.2%) (Figure 3.4, Table 3.7). This high probability of a low CFB is partly because the fire weather conditions for large fast spreading crown fires in the MSdm biogeoclimatic subzone occur infrequently, as the fire return estimates in the literature illustrate (e.g. Pollack et al. 1997). The limited 10 year period of the fire weather available for both weather stations resulted in a relatively reduced number of severe fires. However, if a longer period of weather records was used that included more drought years, the fire severity matrix results might change, especially in the combinations of high CFB and high FFC and SFC.

The high probability of a medium FFC is partly because of the FFC consumption ranges used for the FFC severity classes. A low intensity surface fire will consume at least the litter layer of the forest floor. There would not have to be much additional drying of the lower forest floor layers to have some additional consumption to bring the FFC into the medium class. The probability for a low CFB and high FFC was greater (43.7% vs. 13.3%) for the Spruce weather station than for Brenda in spite of Spruce having a slightly lower DC over an average fire season (except for July) than Brenda (Figure 3.16), although monthly average precipitation was lower for Spruce except for July where Brenda station was higher. There are some large clearcuts near Brenda weather station. This could explain why there are higher wind speeds recorded at Brenda compared to Spruce since the presence of clearcuts can increase local turbulence (Lindgren 2001). The presence of a clearcut may also lower the relative humidity through “the clothesline effect” (Oke 1987) and cause some bias in the weather observations for Brenda weather station.

**Fire severity matrix: CFB x SFC**

The fire severity matrices for CFB and SFC for C3 fuel type overall showed less variation (<5%) in probabilities between Brenda and Spruce weather stations than CFB and FFC fire severity matrices (e.g. 20% for the Low and Med combination for C3; Figures 3.4-3.5, Table 3.6). The highest probability in the matrices was low CFB and low SFC (80% Brenda, 84.8% Spruce). The high probability of a low SFC was because that the coarse woody debris (>7cm), is
not easily consumed by fire since, in moist biogeoclimatic zones like MS, internal log moisture content tend to be high throughout the fire season which limits consumption to the drier outside regions of the log (Lawson and Hawkes 1989). The probability of a low CFB and medium SFC (15.6% Brenda, 10.3% Spruce) was the second highest with all other matrix combinations having negligible probabilities. This again reflects the generally low consumption of coarse woody debris in fire, both surface and crown fires.

In conclusion, based on the 10 year data period examined, a wildfire starting in a C3 FBP fuel type (mature lodgepole pine forest) would, on most days of an average fire season, be a surface fire with a low fire severity (low CFB, medium FFC, and low SFC). The probability of a crown fire with high fire severity is much more rare but does occur since most of the mature lodgepole pine stands in the study area resulted from this type of fire behavior and severity.

3.4.2 Fire severity matrices C4 fuel type (immature lodgepole pine forests)

The matrices developed for the immature lodgepole pine C4 FBP fuel type were different compared to the C3 fuel type, especially in terms of CFB. This is because C4 compared to C3 has a higher probability of crowning due to a lower average crown-based height (4.0 and 12.0 m, respectively) and higher canopy bulk density (0.23 kg/m$^3$ and 0.12 kg/m$^3$, respectively) (Alexander et al. 2004) (see Figures 3.6, 3.7 and Table 3.8).

**Fire severity matrix: CFB x FFC**

The C4 fuel type fire severity matrices had the highest probability occurring for a low CFB and medium FFC fire severity for both Brenda (48.1%) and Spruce (56.3%) weather stations. This was similar to what was also found for the C3 fuel type. The next highest probability that occurred was for the low CFB and low FFC severity (22.2%) using the Brenda weather station, while Spruce had a low CFB and high FFC (35.5%) severity. The largest difference between the two weather stations was found to be for the high CFB and low FFC combination (Brenda (14%); Spruce (1.3%)) and for the low CFB and high FFC (Brenda (2.4%); Spruce (35.5%)).

These differences in fire severity probabilities between the two weather stations are assumed to be generated only by differences in the weather records (Figures 3.8-3.15). The slightly drier, and windier conditions observed at Brenda weather station compared to Spruce probably resulted in a higher CFB probability.

The monthly average precipitation was lower for Spruce except for July where Brenda station was higher (Figures 3.10, 3.14) which probably contributed to the higher FFC at Spruce, although Spruce had lower DC values up until the end of July than Brenda. Thus, a higher
probability of a surface fire is predicted by the Spruce based matrix while the weather records collected at Brenda station determined a higher occurrence of crown fires.

**Fire severity matrix: CFB x SFC**

Probabilities for CFB and SFC for C4 immature forests did not differ much between the fire severity matrices for Brenda and Spruce weather stations (Figures 3.6-3.7, Table 3.8).

The highest probability was for the low CFB and low SFC severity (Brenda (58%), Spruce (62.7%)), that was similar to the C3 fuel type. Again, it was obvious that the C4 fuel type had a higher CFB probability than C3, with the second high probability for a high CFB and a low FFC (Brenda (16.9 %), Spruce (18.7%)) severity. This again reflects the generally low consumption of coarse woody debris in fire, both surface and crown fires.

The results presented in this chapter should be treated cautiously since the equations developed for FFC and used for SFC originated from experimental fires from different locations in Ontario, Alberta and British Columbia in jack and lodgepole pine forests. The differences in fire weather between Brenda and Spruce stations could have been partly explained by the proximity of large clearcuts near to Brenda station which might have influenced the weather readings. As well, the FFC final equation was based on only bulk density and DC as independent variables. The coefficient for DC as compared to bulk density was a small number so that most of the differences in FFC between C3 and C4 fuel types was probably more because of differences in the bulk densities than fire weather as represented by the two weather stations used.

### 3.4.3 Fire severity matrix development and climatology

The development of fire severity matrices presented in this chapter should be considered a preliminary step toward quantifying fire severity in northern temperate forests and a potential model to link with stand ecosystem models like FORECAST. A key new feature presented in this chapter, as compared to previous fire matrix severity approaches (e.g. Ryan and Noste 1983) and first order fire effects models like FOFEM, is the fire severity matrix to fire weather data in order to create a fire severity climatology. Wildfire severity could be monitored in a number of different forest ecosystem and fire climate zones, with the results compared to fire severity matrices built with existing fuel consumption algorithms and fire weather records to test if new fuel consumption models need to be developed.
If a simulation of ecosystem dynamics is done, then there needs to be an understanding of the frequency of occurrence of different levels of fire severity for the area of interest. This fire severity climatology is similar to the approach developed in Taylor et al. (1998) to examine the changes in southern dry BC forests in terms of predicting the impact on potential fire behaviour of stand structure changes because of the lack of fire. In addition, if fuel consumption equations used to develop the fire severity matrices have independent variables that could be estimated under future climates, then changes in fire severity with climate change could be determined.

Further research is necessary on fuel consumption equation development and interpretation. More FFC, SFC and CFB data are needed for BC wildfires in a number of different biogeoclimatic zones and subzones so that fire severity matrices could be constructed for a number of key ecosystems where modeling of the impacts disturbances and forest management activities is to being done.

3.4.4 Improving fire representation in FORECAST using severity matrices

The initial objective of the thesis was to explore approaches to the improvement of the fire-module (Section 3) of the FORECAST model by developing fire severity matrices to assist in the calibration of this module. The fire severity concept is already represented in FORECAST in a deterministic manner, but only at a low extent as the model user must establish the desired “fire severity” levels for each individual component when simulating a fire (See Figure 2.5 and 2.6 in Chapter 2).

It has to be mentioned that for a non-fire expert using the model could be difficult to know how to calibrate these input files. The fire severity matrices developed external to the model for the type of forest being simulated provides a basis for this calibration. Figure 3.22 shows a proposed upgrade of the FORECAST fire codes by using the severity matrices results. The matrices results that have developed in this chapter can be used to calibrate Section 3 – the fire codes, by using the probability results for the fire severity and then provide the user with the code settings that would generate the desired type of fire severity.
### Burning code #1

**Weather data:** Brenda STN  

**Fire Severity specifications**

- **Probability of occurrence:** 74%
- **Fire severity types:**
  - **CFB:** Low (<0.1)
  - **FFC:** Medium (33-66%)
- **Fire description:** Late spring or early fall fire

### Burning code #2

**Weather data:** Brenda STN  

**Fire Severity specifications**

- **Probability of occurrence:** 13%
- **Fire severity types:**
  - **CFB:** Low (<0.1)
  - **FFC:** High (>66%)
- **Fire description:**

### Burning code #3

**Weather data:** Brenda STN  

**Fire Severity specifications**

- **Probability of occurrence:** 10%
- **Fire severity types:**
  - **CFB:** Low (<0.1)
  - **FFC:** Low (<33%)
- **Fire description:** Early spring or late fall fire

### Existent settings

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<th>BN</th>
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<th>RM</th>
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### Proposed additions

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</table>

**Fig 3.19** An example of the proposed upgrade of the Section 3 (Fire sub-module) in FORECAST using the fire severity specifications obtained from the severity matrix developed for Brenda station in mature lodgepole pine forest. The settings are presented only for one tree species.
Originally the intention was to automate this process, so that the user would enter a risk probability matrix related to the weather input data file in CLIMATE-FORECAST (Figure 3.20).

The model would then institute fire in accordance with this risk matrix and the climate data to start a fire, and the model would look at the stand structure and fuel loading to determine what severity of fire should be simulated. However, this level of complexity was beyond the possibilities of the thesis – and is not necessarily useful – since it may be better to keep the models simpler by making these calculations externally and soft link them through the input files (e.g. as described in Figure 3.22). The matrix development algorithm can be used as guidance when setting a fire and could be easily implemented as a help file.
Chapter 4 Assessing patterns of coarse woody debris following fire using FORECAST

4.1 Introduction

4.1.1 What is CWD and why do we care about it?

Coarse woody debris (CWD) is usually defined in British Columbia as non-self supporting, dead woody material that is located above the soil and is in various stages of decomposition, including above-ground logs and large fallen branches (B.C.MoF 2003). There are some controversies regarding the inclusion of self supported stumps and snags as well as regarding the underground component which can account to up to 20% of the total decaying wood at a site (Stevens 1997). Until the 1980’s CWD was generally neglected as a component of forest ecosystem because of sampling difficulties (requiring longer periods of observations over large areas) related to its wide variability in space and time (Feller 2003a). Usually, only pieces bigger than 7.5cm in diameter are considered CWD and they are represented by a large variety of types: logs, snags, chunks of wood, larger branches and coarse roots (Harmon et al. 1986). However, in this thesis the definition of CWD will be limited to decaying pieces of wood larger than 7.5 cm diameter and situated above the soil surface. Since standing snags were not measured, they are not included as CWD here, though references to snags are made later in this chapter.

CWD plays many important roles in forest ecosystems including the following: it may influence regeneration patterns of forest trees by providing substrate for seedling establishment; adds a significant amount of organic matter to the soil; provides habitat and a primary energy source for many decomposer organisms (Caza 1993); retains moisture through dry periods providing a refuge for ectomycorrhizal roots and their associated soil organisms; it provides a site for asymbiotic or associative nitrogen-fixing bacteria; represents a long-term, slow release pool of nutrients for the ecosystem (Franklin 1992; Harmon et al. 1986; Stevens 1997); provides habitat and structure to maintain biological diversity in both terrestrial and aquatic ecosystems (Caza 1993); affects the geomorphology of streams and slopes by maintaining slope stability, preventing erosion and storm surface runoff. Finally, CWD often represents a significant pool
for long-term carbon storage in forest ecosystems (Stevens 1997 and citations thereon). CWD also act as a fire fuel along with the other surface fuels (twigs, branches, logs, litter, and duff) (Knapp et al. 2005). CWD loading and condition influence fire severity, fire persistence and burn time. When excessive accumulations of CWD are ignited they can contribute to extreme or severe fire behaviour which ultimately might be detrimental for the ecosystem (Brown et al. 2003). The risk of both fire and bark beetle infestation are influenced by the amount of CWD present in the ecosystem (Duvall and Grigall 1999).

The main agents that determine CWD accumulation in terrestrial ecosystems are generally the same agents that cause tree mortality: fire, insects, diseases, suppression and competition. In the aquatic ecosystems, besides the above mentioned agents, there are additional processes that contribute to the input of CWD like mass movement of soil on hill slopes, transport by flood, snow avalanches and bank undercutting. CWD accumulation in an ecosystem occurs both at the level of transfer from the living wood to dead wood and also at the level of the transfer between components of the CWD (e.g. from snags to logs; (Harmon et al. 1986).

4.1.2 CWD and stand dynamics

There is a close interrelation between live and dead trees in the forest ecosystems (Brassard and Chen 2006). Dead trees are eventually added to the CWD pool in the forest ecosystem (Hely et al. 2000). Following mortality a dead tree or snag goes through stages of decay including loss of foliage, loss of twigs and small branches, loss of large branches, bark and finally fragmentation or falling to become downed log (Storaunet and Rolstad 2002). Depending on a number of factors (see Sectoin 4.1.3), the log and other CWD components will gradually decompose (Suntervant et al. 1997) and will be incorporated into the soil. Large branches, tree tops and whole trees that fall to the forest floor are all sources of CWD (Arsenault 2004).

There many agents that generate CWD directly or indirectly: wind, fire, diseases, suppression and competition, slope failure, aging (Harmon et al. 1986). These agents might act alone or in concert (Stevens 1997). While the majority of CWD in forests originates from disturbances (fire, wind, insects and diseases) (Harmon et al. 1986), the CWD produced during stand development processes (e.g. injuries, self pruning, stem exclusion) should not be neglected (Suntervant et al. 1997). Thus, it can be concluded that CWD could be produced in the forests by large-stand replacing disturbance events, smaller more frequent endemic disturbances and natural stand development processes.
There is increasing acknowledgement of the importance of age-dependent change in the composition and structure of the forest and the accompanying pattern of CWD accumulation (Pickett and White 1985). Hely et al. (2000) related the temporal patterns of CWD accumulation to stand development and demonstrated how factors such as site conditions and disturbance may influence these temporal patterns. Stand development has been described as having four main phases: stand initiation, stem exclusion, understory re-initiation and old growth (Oliver and Larson 1990). Each phase is associated with a set of key determinants (Figure 4.1). The transition between the first and last stages involves processes that generate increase of biomass, and horizontal and vertical diversification of the canopy, and accumulation of coarse woody debris (Franklin 1992). Thus, CWD may be considered as an indicator of the structural stage of stand development. In the lodgepole pine forests within the study area, where fire is the main disturbance factor, CWD (particularly in younger stands) is predominantly a reflection of the time since the last stand replacing fire. However, from a management perspective where much of the population of mature trees is removed during harvesting, understanding the rate of production of ‘new’ CWD from stand development and endemic disturbance agents is important. One of the goals of this chapter is to explore the temporal dynamics and patterns CWD accumulation lodgepole pine forests following fire and or harvesting.
4.1.3 Decomposition of CWD

Decay and material transfer are the two main processes that affect the dynamics of the CWD mass on a given site (Stevens 1997). There are several types of decay processes: leaching (the loss of soluble materials as water percolates through a log); fragmentation or the breaking up of snags and logs into smaller pieces (caused physical or biological processes), the transport of material out of the ecosystem (falling down the hill, or carried away by water); collapse and settling following structural strength decline; seasoning (e.g. moisture and temperature changes); respiration or biological transformation (metabolic transformations caused by fungi or invertebrates) (Harmon et al. 1986; Stevens 1997).

Decay rates may be influenced by the position, diameter, decay stage, climatic variable, structural and chemical characteristics of wood (Pittman 2005). Different tree species typically decompose at different rates (e.g. softwood faster than hardwood, low density wood species faster than denser species). Also smaller pieces tend to decompose more quickly than larger pieces (Stevens 1997). Climatic variable as temperature, moisture, oxygen, carbon dioxide tend...
to be among the most influential factors affecting the rate of decomposition (Harmon et al. 1986). For example, temperature can affect the distribution and activity of the fungi and insects in decomposing wood through its effects on relative humidity, moisture oxygen and carbon dioxide levels. In general CWD decomposes faster in warmer and wetter climates (Pittman 2005). The position of CWD can also influence its rate of decomposition. Elevated CWD has been shown to have slower decomposition rates than CWD in contact with the ground (Remsburg and Turner 2006).

4.1.4 Efforts to model CWD

The complexity of forest ecosystem management requires prediction systems – models – that can explicitly account for key ecosystem determinants, and the effects of fire thereon (Kimmins et al. 2007). Appropriate models can help to evaluate which is the best way to manage such a complex system such as a forest in new and untested ways to achieve a new set of objectives.

As described above, CWD has many important roles in the forest ecosystems. In the large areas of extensively managed forests throughout British Columbia, which are subject to many different natural disturbance agents, CWD is often abundant and has been identified as an indicator of forest structure and habitat quality in the development and application of sustainable forest management plans (Feller 2003a). Questions regarding the optimum levels of CWD in maintaining the productivity and diversity in the forests and how these levels can be maintained through multiple rotations are of high importance (Stevens 1997). Maintaining the natural levels of CWD appear to be the reasonable targets in most cases but these levels might not always be the optimum ones (Prescott and Weetman 1994). Management recommendations for CWD should address not only the mass and volume issues but also the finer-scale processes. Since models are useful tools for understanding and projecting CWD dynamics, they can be used to increase the knowledge regarding CWD and also to supply the inevitable lack of information (Stevens 1997). There are many models that simulate CWD but most of them are focused on the riparian recruitment of CWD and their impact on stream ecosystems (Wei 2004). There are, however, several models that address the dynamics of decaying wood in the terrestrial ecosystems like: SRS1 (The Snag Recruitment Simulator) (Marcot 1992), The Snag Dynamics Projection Program (McComb and Ohmann 1996), DecAID (Decayed Wood Advisory Model) (Mellen et al. 2002), a spatially explicit snag accounting model (DeLong et al. 2004) developed
within the SELES (Spatially Explicit Landscape Event Simulator) modelling framework (Fall and Fall 2001). FFE-FVS (Fire and Fuels Extension to the Forest Vegetation Simulator) (Crookston et al. 2000) also possesses a snag submodel (see Chapter 2). CWD is sometimes included as an output of growth and yield models. An example is the TIPSY-Snag Model which is a submodel of TIPSY (Table Interpolation Program for Stand Yields) model (http://www.for.gov.bc.ca/hre/gymodels/Tipsy/). TIPSY is a growth and yield model based upon the interpolation of a set of yield tables from TASS, a British Columbia Ministry of Forests and Range individual tree growth and yield model. It is widely used in silvicultural decisions and timber supply analysis in British Columbia. The snag submodel of TIPSY estimates the number of standing dead trees by using a logistic model that apply the dead tree fall probability obtained from stand variables by estimates the number of standing dead trees stratified by diameter classes (http://www.for.gov.bc.ca/hre/gymodels/Tipsy/).

Empirical growth and yield models such as TASS/TIPSY are the most frequently used models by forest managers and they are relatively easy to use. These statistical or mathematical models represent an abstraction of the natural dynamics of a forest stand (Vanclay 1994). Though quite accurate for future environmental conditions and management regimes that resemble those of the past, they are less useful for changed future environments and management systems because they generally lack any representation of the process of growth and stand development, and the ecological processes that are affected by disturbance. Simple population models of timber or wildlife are easier to develop and use than the more complex ecosystem-level models, but are unlikely to provide accurate forecasts in ecosystems that are implicitly complex. This is also the case with the CWD, which is not explicitly represented by the aforementioned models.

Representing the results of almost 30 years of research and model development, FORECAST (Kimmins 1993, 2001; Kimmins et al. 1999), LLEMS (Local Landscape Ecosystem Management Simulator) (Kimmins et al. 2001) and POSSIBLE FOREST FUTURES (PFF) (Kimmins et al. 2001; Kimmins 2004) are ecologically-based forest management models that are receiving increasing attention from companies and government agencies in Canada and internationally. However, use of these models as both management and educational tools requires further software development, calibration and testing. In Chapter 3, a methodology was developed to improve the representation of fire severity on biomass and dead organic matter in
the FORECAST model. In this chapter, the FORECAST will be used to project CWD accumulation patterns following fire and the model’s predictions are tested against field data.

4.1.5 Objectives

The main objective of this chapter is to evaluate the patterns of CWD accumulation in these fire-driven lodgepole pine dominated ecosystems.

Specific objectives are to:

1. Establish a chronosequence of plots in the field to document temporal patterns in CWD and forest floor accumulation post-fire.
2. Use the ecologically-based forest growth model FORECAST to project patterns of CWD accumulation post-fire.
3. Test model predictions of CWD against the chronosequence measurements.

4.2 Methods

4.2.1 Field sampling

A combination of field and analytical methods were employed to address the objectives outlined above. Field work was conducted in July and August 2004 in the MSdm2 subzone of the Tolko’s Tree Farm License (TFL) 49 located due east on Kelowna and Okanagan Lake in British Columbia. The purpose of the field work was to establish of a chronosequence of plots to describe temporal patterns in CWD and forest floor accumulation post fire and to collect other data needed for testing the FORECAST model’s ability to represent long term dynamics of CWD. The field trip was also undertaken to provide general information on the effects of fire in lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm.) dominated stands in the MSdm2 subzone.

Time and financial considerations restricted the field data collection to CWD, soil pit samples and soil organic horizons. Because the fire-affected sites of the MSdm2 subzone extend across the large area of the TFL, the following sampling strategy was adopted. GIS layers provided by Tolko industries (Riverside Forest Products Ltd., Kelowna at the time of data collection) and by Pacific Forestry Research Center, Victoria (for the fire data base) were used in conjunction with ArcGIS 9.x and Arc View 3.x. (ESRI 2005) software. The procedure consisted of overlaying aerial photographs (at 1x 1m²-resolution) with forest cover information, and then with coverage
files representing fire locations obtained from the fire database. Additional data were obtained from Tolko staff. All the information was compiled to identify a population of potential stands for use in developing a chronosequence fire-origin stands (Section 4.2.2). Lodgepole pine dominated stands in the MSdm2 are nearly always fire-initiated (Wong et al. 2003), but the fire database only contained data from 1915, thereby limiting the length of the chronosequence. Because of the funding restrictions, only stands growing in medium productivity site were considered.

A stand was selected only when the following conditions were met:

- site index to be between 15-20 for lodgepole pine, which represent a medium site;
- slope to be in the range of 15-30 %;
- mid-slope, medium stands -stands on ridges or lower slopes were excluded;
- slope aspect, predominantly W-SW-S;
- dominated by lodgepole pine with only small % of “interior” (hybrid) spruce and subalpine fir;
- plant associations classified as Hybrid spruce-Falsebox – Feathermosss (Meidinger et al. 1991);
- total burned area >10ha in size and fire to be classified as severe fire;
- stands to be situated in areas with similar climatic conditions (this condition was imposed because the precipitation regime, even within a biogeoclimatic subzone, can vary significantly).

Taking all the above criteria into consideration, only four sites were found that qualified. While there were other suitable stands, other factors such as accessibility excluded them. The final step in stand selection was to confirm the locations and stand history with experienced Riverside personnel. The selected stands were located in the southern part of the TFL, with one exception: the site burned in 1986 that is located 30 km to the north (see Fig 4.2).

The four selected sites are characterized as fire-initiated stands in which fires occurred respectively in 1920, 1930, 1952, and 1986 (Table 4.1). To meet the criteria of a chronosequence, it was assumed that these four stands varied only in time since fire.
Fig 4.2 Location of the chronosequence field sites within the MSdm2 variant of TFL 49.

For statistical analysis, the population was considered to be stratified by age, and the number of samples necessary to collect from each stratum was estimated. The population of interest in this case is represented by the totality of 0.094ha circular plots that satisfy the above assumptions. Each of the four selected site represents a strata (Table 4.1).
Table 4.1 Strata description

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<tr>
<td>Total</td>
<td>-</td>
<td>17.14</td>
<td>N=180</td>
</tr>
</tbody>
</table>

4.2.1.1 Calculating the sample size

Formulae and notations I used here were according to Cochran (1977) and the sampling is considered as without replacement:

The suffix \( h \) denotes number of stratum and \( i \) the element (unit) within the stratum.

\( N \) – total number of elements (units) in population

\( N_h \) – number of units in stratum \( h \)

\( Y_{hi} \) – value obtained for stratum \( h \)

\( W_h = N_h/N \) – stratum weight

\( L \)-number of strata

\( n_h \)-number of samples on stratum \( h \),

\( n \)-number of samples for the entire population.

We have the stratified mean of population

\[
\bar{y}_{ST} = \frac{1}{L} \sum_{h=1}^{L} \bar{y}_h W_h
\]

Variance of stratum mean

\[
s^2_{\bar{y}_h} = \frac{s^2_h}{n_h} \left( \frac{N_h - n_h}{N_h} \right)
\]

Where \( s^2_h \) is variance of stratum \( h \)

\[
s^2_h = \frac{\sum_{i=1}^{n_h} (y_{hi} - \bar{y}_h)^2}{n_h - 1}
\]
And then **variance of the mean:**

\[ s_{y_{ST}}^2 = \sum_{h=1}^{L} W_h^2 s_{y_h}^2 \]

Confidence interval for the mean:

\[ \bar{y}_{ST} \pm t_{EDF,1-\alpha/2} S_{y_{ST}} \]

where \( EDF \)-effective degrees of freedom

\[ EDF = \frac{\left( s_{y_{ST}}^2 \right)^2}{\sum_{h=1}^{L} W_h^2 s_{y_h}^2} \frac{1}{n_h - 1} \]

The minimum sample size will be calculated based on three methods as follows:

Using **proportional allocation** without replacement, the total sample size can be calculated using:

\[ n = \frac{N \times t^2 \times \sum N_h s_{y_h}^2}{N^2 \times AE^2 + t^2 \times \sum N_h s_{y_h}^2} \]

Sample size for each stratum can be then calculated as

\[ n_h = \frac{N_h \times n}{N} = W_h \times n \]

Using **Neyman allocation** without replacement, the total sample size can be calculated using:

\[ n = \frac{t^2 \times \left( \sum N_h s_{y_h} \right)^2}{N^2 \times AE^2 + t^2 \times \sum N_h s_{y_h}^2} \]

and sample size for each stratum can be calculated as

\[ n_h = \frac{N_h s_{y_h}}{\sum N_h s_{y_h}} \times n = \frac{W_h s_{y_h}}{\sum W_h s_{y_h}} \times n \]

Using **equal allocation** without replacement, the total sample size can be calculated using:

\[ n = \frac{L \times t^2 \times \sum N_h^2 s_{y_h}^2}{N^2 \times AE^2 + t^2 \times \sum N_h s_{y_h}^2} \]

and sample size for each stratum can be calculated as

\[ n_h = \frac{n}{L} \]

As observed, for calculating \( n \) and \( n_h \), the values of variances \( s_{y_h}^2 \) for each stratum and the allowable error \( AE \) must be known or needs to be estimated. The values for variances and \( AE \) were computed using data from literature. Data sets were selected to be as accurate as possible and to be from sites characterized by conditions similar to those assumed in this project.

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However, the literature is rather poor in information about CWD data in younger stands, especially for the MSdm2 subzone. There is plenty of information (including those provided by Tolko for MSdm2) but only for older age classes (stands older than 100 years). Because more than one variable was collected from each sample unit, separate computations were made for volume and pieces of CWD per hectare.

CWD data were obtained from the “Coarse Woody Debris database for unmanaged stands in British Columbia” (B.C.MoF 2003). Based on these data, variances were computed for volume and pieces per hectare basis for each of the four strata. The $AE$ is usually considered to be equal to half of the width of the widest confidence interval that one is willing to accept (Marshall and LeMay 1990). In this case the $AE$ values were computed based on the literature information for PE (percentage error) as

$$PE = \frac{AE \times 100}{y}, \quad \text{or} \quad AE = \frac{PE \times y}{100}.$$ \quad \text{Where } y \text{ is the population mean}

For this study, I have considered percentage error as +/- 30% of the mean, with a 95% confidence interval. Parminter (1998) recommended values for PE around +/-20% of the mean value, but he also considers that the field conditions might lead researchers to use a higher PE.

Using the BCMoF-CWD database, the most appropriate values were selected for each of the corresponding ages. The resultant variances and allowable errors are presented in Table 4.2.

**Table 4.2** Variances and allowable error values that were used in sample size computations

<table>
<thead>
<tr>
<th>Strata</th>
<th>Variance (m$^3$/ha)</th>
<th>Pieces/ha (no/ha)</th>
<th>Volume/ha</th>
<th>Pieces/ha</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>43.5</td>
<td>587.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L2</td>
<td>64.6</td>
<td>524.4</td>
<td>32.7</td>
<td>294.0</td>
</tr>
<tr>
<td>L3</td>
<td>68.5</td>
<td>524.4*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L4</td>
<td>64.6</td>
<td>629.6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Since no data were available, data from L2 have been used*
Using these results, the minimum sample size values, based on the three allocation methods, are presented in Table 4.3 (optimal allocation is not used because I considered that the cost of measuring any plot is the same):

**Table 4.3 Minimum sample size allocation (n)**

<table>
<thead>
<tr>
<th>Allocation method</th>
<th>Based on volume data</th>
<th>Based on number of pieces data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( n )</td>
<td>( n_1 )</td>
</tr>
<tr>
<td>Proportional</td>
<td>15</td>
<td>6</td>
</tr>
<tr>
<td>Equal</td>
<td>16</td>
<td>4</td>
</tr>
<tr>
<td>Neyman</td>
<td>14</td>
<td>4</td>
</tr>
</tbody>
</table>

The values obtained for the first two allocation procedures are the same as are values for both variables (volume and number of pieces). The Neyman allocation gave only slightly different results. It is assumed that a proportional allocation would provide a good estimation of the population except for strata L3. This would have only two plots which might prove to be insufficient. On the other hand, the six plots suggested for strata L1 or L2 might be unnecessarily high. Thus, I selected four plots for each stratum, which is also the average for all strata given by the equal allocation method. This was materialized on the field by four plots being sampled for each of the four sites (S17, S52, S73 and S83). These sites are described in Table 4.4 (Section 4.2.3.3).

### 4.2.1.2 Plot installation

The line intersect method is usually the most efficient way of assessing the amount CWD on a site (Taylor 1997; Van Wagner 1968). This method was compared with a complete census sampling scheme by Clark et al. (1995b) who concluded that both yield similar results and show no evidence of systematic bias. The line transect system was preferred because it is less subjective and considerably faster (Parminter 1998). Several line intersect sampling procedures have been used in North America. The plot design used in this thesis is based on the method proposed by McRae et al. (1979) and described by Trowbridge et al. (1989a) for estimating logging slash fuel loads in British Columbia. It employs an equilateral triangle with 30m lines (a 90m long transect). It is the most common design used for fuel measurements, being recommended by several government agencies, including the B.C. Ministry of Forests (Trowbridge et al. 1989a). The area potentially covered by this type of transects is represented
by a circle with a radius equal 17 m, and having a surface area of 0.094ha. Each circular plot in this study represents a population unit (see Fig 4.3).

Fig 4.3 The triangle plot layout

A random selection of the plots was made for each stratum. The triangle orientation was established based on a randomly selected compass bearing as suggested by Trowbridge et al. (1989), so each triangle had a different, randomly chosen orientation.

In two cases the terrain conditions were unsuitable for the plot conditions; one was too close to the road and another one near a camping site. These two plots were moved 34m in a randomized direction until the desired layout was achieved.

4.2.1.3 CWD dimensions and measurements

For this project, CWD was defined as dead woody material greater than 7.5 cm in diameter, in any stage of decay, and consisting of aboveground logs, exposed roots and large fallen branches. The dimension of the minimum diameter was the only difference from the methodology described in Marshall et al. (2000) where the minimum diameter is 10 cm. The CWD pieces were classified on the ground by decay class, as for the further necessities more data might be available for the modeling. The classification was based on the description made by Sollins
and updated in "The Field Manual for Describing Terrestrial Ecosystems" (Meidinger 1999) as follows:

Decay class 1 = solid wood, recently fallen, bark and twigs present.
Decay class 2 = solid wood, significant weathering, branches present.
Decay class 3 = wood not solid, may be sloughing but nail still must be pounded into tree.
Decay class 4 = wood sloughing and/or friable, nails may be forcibly pushed into log.
Decay class 5 = wood friable, barely holding shape; nails may be easily pushed into log.

4.2.1.4 Calculation of CWD variables

CWD mass was estimated using CWD volume (measured using field data) and CWD density values suggested by Krankina and Harmon (1995). They assumed a linear relationship between CWD decay and the variables influencing the decomposition process (Graham and Cromack 1982). The considered that density values vary between 0.16 Mg/m³ for decay class 5 and 0.35 Mg/m³ for decay class 1. However, the mass estimations must only be regarded as rough estimates, since no CWD density measurements were done in this study. Moreover, Krankina and Harmon’s (1995) study area had a more southerly location, where tree growth and decay could differ.

4.2.1.5 Criteria for separating CWD pieces in previous and current

In assessing and modelling the temporal dynamics of CWD in forest stands it is important to identify the nature and timing of recruitment events. As described Section 4.1.2, CWD recruitment is closely linked to the various phases in stand development and associated disturbance events. Stand replacing fires tend to generate abundant snags and CWD while also creating conditions for the growth of new cohorts (Passovoy and Fule 2006). The CWD present within a stand at any given time will often include pre-disturbance debris, disturbance-generated debris and residual standing trees (which subsequently die and become snags), depending on stand history and on previous stand structure (Spies and Franklin 1989). The temporal dynamics of CWD can thus be summarized in two phases: the decay of predisturbance and disturbance-generated debris, and the accumulation of debris produced by stand development processes and endemic disturbance agents in the new stand (Harmon et al. 1986; Spies et al. 1988). The proportion of CWD derived from the original stand-replacing disturbance event will decline relative to that generated from the current stand with increasing time since disturbance. When
comparing modelled with field measured CWD accumulations it is important to distinguish between these two types of CWD.

For the purpose of model testing, CWD in the present analysis was categorized as either “previous” – derived from the pre-disturbance stand, or “current” - derived from stand development processes after the original fire. Pre-disturbance and disturbance generated CWD were considered to be old CWD since they were produced from the previous stand. Each piece measured in the field was classified as new or old. Decay class and diameter were the main criteria used for classifying the CWD within old and new categories. The species of some CWD pieces was easy to identify, but in many cases this was not possible due to advanced decay. Identification varied by decay class. There is obviously more certainty in the species identification of a freshly fallen (decay class one) CWD piece than in the identification of a partially rotten (decay class four) CWD piece.

The following criteria were applied in the classification process:

1. if piece diameter was bigger than the average dbh (breast height diameter) of the actual stand, then the piece was considered to be from the previous stand;
2. if decay class is greater than 3 and the stand initiation date is older than 1952, then the piece was judged to be from the previous stand.

However, specific rules and criteria were applied to each site individually as follows:

- For the 1986 site all CWD pieces were considered as part of the previous stand.
- In the 1952 site, CWD pieces were considered to be from the previous stand only when the decay class was 3 or greater and the diameter was larger than 15cm.
- For the 1930 site, CWD were considered “previous” when decay class was 4 or greater and the diameter was greater than 20cm.
- For the 1920 site, CWD were considered as to be “previous” when the decay class was 5 and the diameter was greater than 35cm.

4.2.1.6 Soil variables measured in the field

In addition to CWD variables, soil variables were measured or estimated for the purpose of model calibration. On each circular plot determined by the triangle layout for the CWD (see Fig 4.2) a soil pit was dug as close as possible to the center of the plot. Another nine locations were randomly selected across the three 120º sectors determined by the CWD transects (by
randomized compass bearing and randomized distance using random generator function of the hand calculator). Thus, three locations were selected on each of the three quadrants. At one location for each quadrant, samples of the organic soil layers were taken. On all nine locations, the LFH layer depth was measured. Beside the LFH depth, bulk density for each layer and C (carbon) and N (nitrogen) were assessed. Each soil sample was dried at room temperature and sieved. C and N contents were measured on a LECO –CN 2000 analyzer. The precision of this instrument was RSD = 0.4% for Carbon, and RSD = 0.3% for Nitrogen.

4.2.2 The chronosequence approach

The chronosequence approach is often employed in ecosystem analysis to examine a temporal trend in a developmental process or condition by studying different aged sites within a specific forest type. The method can help to reveal trends in stand development or plant succession, or to generate hypotheses about patterns and mechanisms. The approach, though controversial, is still used in many natural sciences, including forestry. Its main advantage is the opportunity to study ecological processes over time periods that are longer than direct observation would permit. The chronosequence approach assumes that all the sites that make up the chronosequence are ecologically similar, have had the same histories, and that the only difference between them is time. It is often difficult to find sites that meet these strict criteria and compromises are frequently made in practice. Opinion continues to be split on whether or not the benefits of the chronosequence outweigh its limitations. However, the extended periods of time involved in stand and ecosystem development generally make direct empirical observation of these processes and their products impractical, and, consequently, despite the problems in the method (Yarie et al. 1989), chronosequence research is often the only choice available in model evaluation and in understanding long term ecosystem dynamics (Bardgett et al. 2005).

One of the most effective methods by which to assess whether or not a chronosequence is valid is to re-measure over time the component stands of the chronosequence. If re-measurement shows the same temporal development pattern for each plot as implied by the original chronosequence data, confidence in the method is increased. However, chronosequence studies should be complimented wherever possible with long-term studies that track the respective ecosystem over time (Bardgett et al. 2005; Martin et al. 2002).
In this study, the chronosequence approach was used to assess the long term interaction between disturbance and ecosystem dynamics and to compare it with model output and findings from literature. As described above, four sites mostly similar in terms of soil, vegetation, climatic and topographic conditions were selected to study the effects of fire on certain soil properties and CWD accumulations.

4.2.3 Using FORECAST to simulate CWD accumulation patterns

4.2.3.1 The FORECAST model

FORECAST is a management-oriented, stand-level forest growth and ecosystem dynamics simulator. A detailed description of the FORECAST model can be found in Kimmins et al. (1999) and a summary description was provided in Chapter 2. The model was designed to accommodate a wide variety of harvesting and silvicultural systems in order to compare and contrast their effect on forest productivity, stand dynamics and a series of biophysical indicators of non-timber values. Projection of stand growth and ecosystem dynamics is based upon a representation of the rates of the key ecological processes that are regulating the availability of, and competition for, light and nutrient resources.

The FORECAST model was used to simulate CWD accumulation patterns in the MSdm2 subzone and the results were compared with the field data. Dead stems and branches are represented in FORECAST through a snag submodel. A data set calibrated by Brad Seely at UBC for the MSdm2 biogeoclimatic subzone was used.

4.2.3.2 Model calibration and initialization

Because an existing FORECAST calibration dataset for the MSdm2 subzone set was used for the modelling work, only a brief description of the calibration process is provided (a more detailed description of the calibration process is available in Seely (2004)). The dataset was developed using regional growth and yield data for lodgepole pine, Douglas-fir, and hybrid spruce. Data were either from previous field studies or derived from TIPSY (see www.for.gov.bc.ca/hre/gymodels/TIPSY). These data were transformed into biomass using species-specific allometric biomass equations (Standish et al. 1985). Other data describing the ecosystem processes, including decomposition rates, nutrient concentrations, photosynthetic light response curves, minor vegetation, and canopy light interception, were derived from
various literature sources (see Seely 2004). As suggested in Blanco et al. (2007), FORECAST
data sets developed for a regional applications (e.g. a biogeoclimatic sub-zone (Meidinger et al.
1991)), while not as accurate as site-specific calibrations, provide a reasonable level of accuracy
for most applications.

The simulation process in FORECAST must start with the description of the initial ecosystem
conditions. This is contained in a state of the ecosystem or ECOSTATE file. An ECOSTATE
file represents the starting condition for every simulation run in which the ecosystem condition
at a given time is described in terms of levels of organic matter resources (which defines in part
nutrient inventories) and vegetation characteristics (which in turn define light conditions within
the vegetation canopy and several components of nutrient inventories and dynamics). During the
runs, the ECOSTATE file is modified according to the treatments applied and the simulated
process rates.

An initial blank file (INISTATE) is created by the Soil Setup program at the beginning of a
simulation activity. The INISTATE file’s characteristics reflects the decisions the user has made
concerning what species and what decomposition classes are to be included in the simulation.
INISTATE is then populated with data that describe the desired starting condition for the future
runs by switching off the nutritional feedback on growth, and running FORECAST to simulate
the known or assumed history of ecosystem disturbance. Having the nutrient feedback switched
off forces the simulation to replicate the historical bioassay input data and use the ecosystem
process rates that have been calculated there from. The model builds the ecosystem state from
scratch based on the historical data. It may be necessary for the user to run the model several
times to emulate the length of time over which the present ecosystem condition developed and
achieve the observed field levels of various variables. The user should carefully observe the
pattern of certain indicators (e.g. total humus mass, humus nutrient accumulation, humus
organic matter) that would indicate whether the ECOSTATE has reached the desired starting
conditions for subsequent runs. Experience with FORECAST shows that appropriate
ECOSTATE file preparation has almost the same importance as the calibration of the model
(Blanco et al. 2007; Kimmins et al. 1999).

4.2.3.3 Preparation of starting condition files (ECOSTATE)

As mentioned above, a generically calibrated MSdm2 biogeoclimatic subzone ECOSTATE file
was used to simulate the general conditions of the measured sites (Table 4.4).
Table 4.4 Description of the four selected sites.

<table>
<thead>
<tr>
<th>Site</th>
<th>Year of disturbance</th>
<th>Time since disturbance</th>
<th>Site index</th>
<th>SOM (t/ha)</th>
<th>Densities (Sph)</th>
<th>Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>S17</td>
<td>1986</td>
<td>17</td>
<td>17</td>
<td>84.4</td>
<td>1600</td>
<td>70P130Sp</td>
</tr>
<tr>
<td>S51</td>
<td>1952</td>
<td>55</td>
<td>15</td>
<td>103.1</td>
<td>1180</td>
<td>80P120Sp</td>
</tr>
<tr>
<td>S73</td>
<td>1930</td>
<td>73</td>
<td>16</td>
<td>112.7</td>
<td>1200</td>
<td>90P110Sp</td>
</tr>
<tr>
<td>S83</td>
<td>1920</td>
<td>83</td>
<td>18</td>
<td>74.7</td>
<td>1030</td>
<td>90P110Sp</td>
</tr>
</tbody>
</table>

SOM-Soil organic matter

For modeling purposes and to have a better representation of the initial field conditions four initial state files were prepared, one for each of the selected sites, by simulating the stand disturbance history. The runs conducted for each site are almost similar but differ in terms of SOM (soil organic matter) and SI (site index). Based on the literature findings, the fire frequency was estimated at 100-125 years (Nitschke 2006; Wong et al. 2003). The starting conditions of the initial ecostate simulations were based on a mixture of lodgepole pine (initial density of 2000 sph), spruce and Douglas-fir (initial densities of 1000sph each). The three tree species were simulated as to naturally regenerate in years 1, 3 and 6 after the disturbance, respectively (see Table 4.5). Douglas-fir was simulated into the ecostate at year 6 to represent the very few individuals of this species found alive on the field.
Table 4.5 Descriptions of the simulation settings for four selected sites

<table>
<thead>
<tr>
<th>Site index</th>
<th>Site index</th>
<th>Site index</th>
<th>Site index</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>15</td>
<td>16</td>
<td>18</td>
</tr>
</tbody>
</table>

**Tree species settings**

<table>
<thead>
<tr>
<th>Tree#1 Lodgepole pine (Pl)</th>
<th>Densities (Sph)</th>
<th>Year of regeneration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2000Pl</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>2000Pl</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>2000Pl</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>2000Pl</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tree#2 Hybrid spruce (Sp)</th>
<th>Densities (Sph)</th>
<th>Year of regeneration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1000Sp</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>1000Sp</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>1000Sp</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>1000Sp</td>
<td>3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tree#3 Douglas-fir (Fd)</th>
<th>Densities (Sph)</th>
<th>Year of regeneration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1000Fd</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>1000Fd</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>1000Fd</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>1000Fd</td>
<td>6</td>
</tr>
</tbody>
</table>

**Runs**

<table>
<thead>
<tr>
<th>ECOSTATE preparation</th>
<th>Duration (years)</th>
<th>Nutrients feedback</th>
<th>Fire at year*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>400(4x100)</td>
<td>Off</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>400(4x100)</td>
<td>Off</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>400(4x100)</td>
<td>Off</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>400(4x100)</td>
<td>Off</td>
<td>100</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ECOSTATE simulation</th>
<th>Duration (years)</th>
<th>Nutrients feedback</th>
<th>Fire at year</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>200(2x100)</td>
<td>On</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>200(2x100)</td>
<td>On</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>200(2x100)</td>
<td>On</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>200(2x100)</td>
<td>On</td>
<td>100</td>
</tr>
</tbody>
</table>

| Data collected at year (of second cycle) | 17 | 51 | 73 | 83 |

*A fire was simulated at the end of each 100 years cycle

The model was run for four cycles of 100 years with a low severity fire simulated at each 100 years interval. Nitrogen feedback was set at off, meaning the model to build up an ecosystem similar with the actual one defined by the calibration data in terms of humus and litter accumulation as well as nutrients (see Seely et al (1999) for more details about the calibration and ECOSTATE preparation). At the end of these 400 years of simulation, humus mass had leveled off and there was no further nitrogen accumulation in the ecosystem. At this point, the simulated ecosystem is considered to have the same biological, chemical and physical characteristics with the field ecosystems.

**4.2.3.4 Simulation of the current stands within the chronosequence**

The scope of the above described ECOSTATE preparation phase was to obtain the four ECOFILES which represent the initial ecosystem conditions before stand initiation (Table 4.5).
The nutrients feedback option was switched on and the pre-fire conditions were simulated for each site by growing up a forest for two cycles of 100 years with a high severity fire simulated at the end of the first cycle at year 100. The first simulated cycle basically represented the pre-fire stand, called “previous” here, while the second cycle represented the post-fire conditions, or the “actual” or measured stand. Thus, each of the actual forests (S83, S73, S51 and S17) was simulated as starting after the first cycle of the simulation. For a better representation, all four sites are simulated up to year 100 but the information regarding the actual stand conditions were collected at year 17, 51, 73 and 83 for the S17, S51, S73 and S83 respectively. It has to be mentioned that

4.2.4 Testing FORECAST using field data

FORECAST model has been successfully used as management tool in several projects in Canada, Europe and China. The capabilities of the model have also been tested against field data and other similar models with favorable results(Bi et al. 2007; Binkley 1986; Blanco et al. 2007; Boldor 2007; Comeau and Sachs 1992; Morris et al. 1997; Sachs 1996; Sachs and Trofymow 1991; Seely et al. 1999; Seely et al. 2002; Wei et al. 2003; Wei et al. 2000; Welham et al. 2002; Yarie 1986).

One of the most common methodologies used to assess model performance is the simple graphical comparison between model predictions and field data. This widely used technique, does not provide a rigorous test but is nonetheless useful in testing time series type models against small data sets, and is considered a measure of model adequacy (Haefner 2005). Graphical comparisons between data and model outputs were done in this study for the CWD and soil variables. Snags were not measured in the field and therefore only model results are presented here.

There is a great diversity of opinions with respect to statistical methods for model validation-evaluation (Yang et al. 2004). Especially with complex ecosystem models, there are many statistical procedures that can be used, but none has been adopted universally because of the specificity of each model. Still, error estimation tests and procedures like those proposed by Freese (1960) and Reynolds (1984) are widely used. Useful methodologies for model evaluation were proposed by authors like Power (1993), Brown and Kulasiri (1996), West (1995) and
Hasenauer et al. (1997). In this thesis, two statistical tests have been used to compare FORECAST outputs with field data values, reflecting the particularities of the field data.

The bias of a model can be assessed using the predictive bias, the mean error of a prediction series (Power 1993). A summary of measured data and the corresponding model simulation values are prepared for each variable averaged across all three site indices (SI36, SI39 and SI43). The differences between predicted and observed values for each SI and age, for each of the four variables analyzed, were calculated and the overall mean difference, standard error and mean absolute difference were determined. The model bias (the mean error) has been calculated using the following formula as given in Power (1993):

\[
Bias = \bar{e} = \frac{\sum_{i=1}^{m} e_{i+1}}{m},
\]

where \( n \) is the number of observed values, \( m \) the number of predicted values, \( e \) the difference observed – predicted. In our case \( n = m \).

One of the most common tests in the literature, goodness-of-fit, can be computed both for continuous and categorical data (Snedecor and Cochram 1980). This explores the similarity between observed and predicted data populations, and various methodologies that compute goodness-of-fit have been developed. Having the reduced amount of data points, tests were computed only for CWD mass data, where eight pairs (model-field) of data were available. Two tests have been selected to evaluate the similarity between FORECAST predictions and field values.

The first index used was Theil’s inequality coefficient (\( U \)), as used in Power (1993) and Blanco et al. (2007). This coefficient is calculated as follows:

\[
U = \sqrt{\frac{\sum_{i=1}^{n} D_i}{\sum_{i=1}^{n} Observed_i^2}},
\]

where \( D_i = \text{Observed}_i – \text{Predicted}_i \), \( n \) represents the number of data pairs, and \( i^{th} \) is a particular pair. The \( U \) coefficient is bounded between 0 and \( \infty \). For values of \( U = 0 \), the model is assumed to produce perfect predictions. For \( U = 1 \), the model would produce predictions of a system behaviour that might not be any better (thought they can be less cost effective) than a zero change prediction. If \( U > 1 \), then the predictive power of the model is worse that the no-change prediction (Power 1993).
The modelling efficiency index \((EF)\) (Vanclay and Skovsgaard 1997), is another way of estimating the goodness-of-fit, a test somehow equivalent with the coefficient of determination \((R^2)\), and is given by the following formula:

\[
EF = 1 - \frac{\sum_{i=1}^{n} D_i^2}{\sum_{i=1}^{n} (\text{Observed}_i - (\text{Avgpred}))^2}
\]

where \(D_i = \text{Observed}_i - \text{Predicted}_i\) and \(n\) represents the number of data pairs, \(\text{Avgpred}\) is the average of the predicted value, and \(i^{th}\) is a particular pair. This statistic provides a simple index of model performance on a relative scale, partially similar to the \(R^2\) scale (that has only positive values), where \(EF = 1\) indicates a perfect fit, \(EF = 0\) suggests that the model predictions are no better than a simple average, and a negative value would indicate an eventually poor model performance.

4.3 Results

4.3.1 Initial soil conditions

The comparison between the model outputs and the field data are presented for all soil selected variables in Figures 4.4-4.5. The chronosequence indicates a gradual accumulation of soil C and N content with increasing time since stand replacing fire with the exception of the S83 site (1920) which showed a slight decline in total soil C content relative to the . A comparison of total soil C and N measured in the chronosequence field plots against those accumulated in the model during the setup runs (see Sections 4.2.3.2 – 4.2.3.3) is shown in Figures 4.4 and 4.5, respectively. As indicated by this comparison, the initial model conditions for total soil C and N were similar to the field measured values for all sites.
Fig 4.4 Comparison between the recorded (Field) and simulated (Model) average mass values for C (soil Carbon (C)) for the four sites sampled in the TFL 49. Bars represent standard error of the mean.

Fig 4.5 Comparison between the recorded (Field) and simulated (Model) average mass values for the soil Nitrogen (N) for the four sites sampled in TFL 49. Bars represent standard error of the mean.
4.3.2 CWD dynamics

A comparison of the average field-measured values for ‘previous’ and ‘current’ stand CWD mass against those simulated by the model for each of the chronosequence sites is presented in Figure 4.6. While the model shows a clear temporal pattern of accumulation of ‘previous’ CWD after the stand-replacing fire followed by a gradual but steady decline resulting from decomposition, the pattern from the field chronosequence values is much less distinct with only a small decline in previous CWD potentially indicating a longer residence time. The temporal pattern of accumulation of CWD from the current stand (from stand-self thinning and endemic disturbance agents) is more consistent between the model and the field measurements.

![Graph showing comparison between model and field measurements of CWD mass over years since fire](image)

**Fig 4.6** Comparison between the measured (dots) and simulated (lines) average mass of CWD (logs only) in the four selected sites of TFL 49. Disturbance year is showed besides each field data point. Bars represent standard errors.
Figures 4.7 and 4.8 depict the previous and current CWD accumulation (volume per hectare) stratified by diameter classes for each of the four measured site.

![Graphs showing CWD accumulation](image)

**Fig 4.7** Previous CWD accumulation (in volumes per hectares) for each of the four measured site, stratified by diameter classes. The piece diameter classes are as follows 1: <10cm, 2: 10-15cm, 3: 15-20 cm, 4: 20-25 cm, 5: 25-30 cm, 6: 30-35 cm, 7: 35-40 cm, 8: 40-45 cm, 9: 45-50 cm, 10: 50-55 cm. Bars represent standard errors.
Figure 4.8 Current CWD accumulation (in volumes per hectares) for each of the four measured site, stratified by diameter classes. The piece diameter classes are as follows: 1: <10cm, 2: 10-15cm, 3: 15-20 cm, 4: 20-25 cm, 5: 25-30 cm, 6: 30-35 cm, 7: 35-40 cm, 8: 40-45 cm, 9: 45-50 cm, 10: 50-55 cm. Bars represent standard errors.

Figure 4.9 presents the snag mass as simulated by FORECAST using the same settings as for the other variables. Snags were not measured in the field, but no snags from the initial stand disturbance appeared to be standing in any of the field sites including the 1986 fire. The modelled pattern of snag mass (for both previous and current stand snags) is consistent with the modelled patterns of CWD accumulation and the snags in the model eventually fall down to become logs based on a size and species dependent decay function.
Fig 4.9 The average mass values for snags as simulated by FORECAST model using the settings for the four selected sites in the TFL 49.

The results of the statistical tests computed to test the fit between the accuracy of the model predictions are presented in table 4.6. Tests were conducted for current and previous CWD mass values as well as for the total CWD.
Table 4.6 Statistics and tests that were used to compare the field results obtained from the four selected sites in TFL 49 with the FORECAST model outputs’ for CWD mass. (Sample number n = 4 for previous and old CWD and n=8 for the total)

<table>
<thead>
<tr>
<th>Statistic tests</th>
<th>Variable</th>
<th>CWD mass (t/ha)</th>
<th>Current CWD mass (t/ha)</th>
<th>Previous CWD mass (t/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bias indicators</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean difference bias</td>
<td>-2.7</td>
<td>-3.2</td>
<td>-2.4</td>
<td></td>
</tr>
<tr>
<td>Goodness of fit tests</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Theil’s coefficient (U)</td>
<td>0.69</td>
<td>0.72</td>
<td>0.69</td>
<td></td>
</tr>
<tr>
<td>Conclusion-prediction</td>
<td>Average</td>
<td>Average</td>
<td>Average</td>
<td></td>
</tr>
<tr>
<td>Modelling efficiency (EF)</td>
<td>0.28</td>
<td>-1.03</td>
<td>0.24</td>
<td></td>
</tr>
<tr>
<td>Conclusion-prediction</td>
<td>Average</td>
<td>Poor</td>
<td>Average</td>
<td></td>
</tr>
</tbody>
</table>

4.4 Discussion

The objectives of this chapter were to investigate patterns of CWD accumulation following stand replacing fire based upon a chronosequence of fire initiated lodgepole pine dominated stands from the MSdm subzone. In addition the capability of the FORECAST model to project CWD dynamics following stand initiating fire was evaluated.

4.4.1 Chronosequence study of CWD dynamics

There are two components in the temporal dynamics of CWD: the decay of pre-disturbance and disturbance-generated debris, and the accumulation of debris from the development of the subsequent stand (Harmon et al. 1986; Spies et al. 1988). As previously mentioned in section 4.2.1, the measured pieces of CWD were separated in “previous” and “current” based on their stand of origin. It was hypothesized that the temporal pattern of CWD accumulation resulting from the chronosequence would show the “U” shaped trend described by Feller (2003) as the most frequent pattern in many B.C. ecosystems. The initial peak in CWD in this general model is explained by the large input of CWD from dead trees of the previous stand killed by the fire. As the snags fall and the logs and woody debris decompose, the quantity of CWD declines to a minimum when the loss of the ‘previous’ CWD has not yet been replaced by the accumulation.
of new snags and logs derived from the current stand. Eventually, with the onset of stand self-thinning and the cumulative effect of endemic disturbance agents, the quantity of CWD begins to increase towards a second but generally smaller peak.

The field-measured temporal pattern of CWD did in fact show a weak “U” shape but there were some unexpected results (Figure 4.6). Firstly, assuming that all the stands prior the stand-initiating fire were similar in age and biomass at the time of the fire it was expected that there would be more ‘previous’ CWD in the 1986 fire site (S86) than what was measured. One potential explanation for this ‘missing’ CWD was that there had been some salvage harvesting following the fire as indicated by the presence of some cut stumps. While salvage harvesting was a criterion for avoiding sites for inclusion in the chronosequence, it was difficult to find sites with relatively recent fires that had not been salvaged. The second unexpected pattern in the chronosequence CWD data was that the oldest site originating from the 1920 fire (S83) had greater amounts of CWD classified as ‘previous’ than both the younger S73 and S51 sites (Figure 4.6). Possible explanations include that some of the CWD in this site was derived from large Douglas-fir trees that may have survived the initial fire (there was charcoal present on the logs) but died later after the initiation of the current stand. I would estimate that about 30% of the largest pieces were Douglas-fir logs. Alternatively, the stand present prior to the 1920 fire may have contained significantly more biomass than the other stands or at least a greater proportion of Douglas-fir. In any case, these results demonstrate the difficulty of constructing chronosequences as a tool for the analysis of long-term ecosystem patterns and processes. Despite these difficulties, chronosequences constitute the only possible source of validation data in the absence of long term studies.

The patterns of new or ‘current’ CWD accumulation followed those expected by the general model. This very slow recruitment pattern for new CWD illustrates the need to preserve existing CWD where possible and leave mature trees for the recruitment of new CWD in managed landscapes.

4.4.2 Evaluation of model performance

4.4.2.1 Initial soil conditions

The general temporal trend observed in the field chronosequence (Figure 4.4) is an increase with age in SOM as indicated by C contents. However, a drop is seen for the S83 site. Total soil
nitrogen also shows a gradual increase with the stand age (time since fire), with slightly smaller quantities for site S51 (Figure 4.5). The decomposition of dead wood is among the major controls of carbon retention in the forest ecosystem (Yatskov et al. 2003). There is also a relationship between heterogeneous CWD spatial dispersal on a site and the forest floor characteristics (Maser and Trappe 1984). This might explain why the SOM and C patterns differ from the CWD patterns. N soil content shows a similar pattern to that of CWD with an initial decrease followed by an increase in N content for the oldest site (S83).

The fact the initial soil N and C conditions derived from the setup runs of the model were similar to the field measured values (Figures 4.4 – 4.5) illustrates that the method of using the model to generate initial soil conditions based on an approximation of historical disturbance regimes and estimates of site productivity works reasonably well. Factors that can cause deviations from expected organic matter accumulations include variations in the intensity of past disturbance events such as fire severity.

4.4.2.2 CWD dynamics

A fair comparison of modelled patterns of CWD accumulation to those observed in the field requires the CWD to be separated into two classes based on its origin: ‘previous’ and ‘current’. A graphical analysis of modelled ‘previous’ CWD relative to field observations indicates that the model over predicted CWD in the young site (S17) and under predicted it in the oldest sites. FORECAST was consistent with the general “U” shape model (Feller 2003a; Van Wagner 1983) if you account for the fact that snags were not included as a component of CWD (causes reduced levels early on in stand development).

The statistics presented in Table 4.6 show different results for the current and old CWD mass. Theil’s coefficient predicted an average fit between the field data and model outputs for both variables. The modelling efficiency estimated a poor model data fit for the current and an average fit for the previous accumulated CWD mass. This is somehow in contradiction with the graphical comparisons where smaller differences field-model values were observed for the current CWD. These results should be then cautiously considered having so few field observations. If the tests were conducted for both current and previous CWD variable together a better fit is obtained between model and field data and both tests would estimate average fit between model and data.
Variance in model predictions from the field measured values could be explained by either poor model performance, violated assumptions in the construction of the chronosequence, or some combination of the two. Given the relatively small number of sites included in the chronosequence and the fact that there was no replication of fires by age, the results presented here should be interpreted carefully. Differences in between-site relationships are certain to vary between different ages of the chronosequence as not all the chronosequence sites are physically identical nor do they have identical histories. When comparing the field data with the model results, it can be concluded that the model predictions are producing an average fit with the field data. By considering the current and previous quantities of CWD a single variable, the statistical tests showed a better fit for both Theil’s and Modelling Efficiency indicators.

It has to be mentioned again that the model was only generically calibrated for an average mesic MSdm site. The settings used for the simulation of the previous stand were estimated based on map records the accuracy of which could not be verified. In this case the simulation of previous CWD quantities depends only on the previous stand variables. Thus, the pre-fire characteristics are of major importance for the modelling experiment. Any difference between my estimations and the actual stand characteristics are to be represented by the model simulations. No model can be more accurate than the input data.

Time since fire (along with stand canopy composition) is one of the two significant factors in CWD changes. It also affects the soil organic content as well as nutrients. Age influences decomposition of fallen logs within the stand and the ecological processes associated with nutrient cycling (Lambert et al. 1980). The modeling experiment conducted here was undertaken to test the ability of FORECAST to replicate the pattern of CWD and soil biomass accumulation. Since a chronosequence of sites was used, the year since disturbance was assumed to be the only variable factor. The model’s output were adequate in illustrating this aspect for the mentioned conditions, proving the usefulness of such models that allow users to produce and compare in a short period of time processes and treatments that would otherwise need decades to occur in natural conditions.
Chapter 5 Synthesis

Disturbances can be defined as temporally discrete events that alter ecosystems, communities or population structures (Pickett and White 1985). They may also be categorized as events that accelerate or retard successional development more than expected from autogenic processes characteristic of the ecosystem in question (Kimmins 2004a). Understanding natural disturbance regimes and stand development processes is necessary as a foundation for sustainable forest management, but this understanding is not enough. Achieving complex economic, ecological and social goals requires complex and flexible forest management practices and tools that incorporate this understanding in predictions of how best to adapt to changing environmental conditions and social pressures. Both the forest industry and environmental organizations support the use of ecosystem models in the design of systems and plans for the management of forest ecosystems. The use of models provides a method for evaluating the long-term of impacts of disturbances on stand dynamics.

Fire is the most significant natural disturbance agent in the MSdm biogeoclimatic subzone and has a determinant role in the dynamics of lodgepole pine (Pinus contorta ssp. latifolia Engelm.ex S.Wats.) dominated forests. The frequency of fire in these ecosystems is likely to increase with climate change (Nitschke 2006). One means of characterizing the effect of fire on forest ecosystems is through the concept of fire severity. Defined in several ways, fire severity is a controversial term that usually refers to a qualitative measure of the fire effects on soil and vegetation and ultimately on ecosystem sustainability. There are many definitions of fire severity in literature, most of them relating it to negative impacts on the ecosystem. One of the objectives of the thesis was to explore the possibility of quantifying fire severity in terms of short and long term effects on ecosystem structures and processes. Severity matrices based on probabilities were constructed for climate data sets from two weather stations and for two fuel types in the MSdm biogeoclimatic subzone of B.C. The application of this concept in the FORECAST ecosystem management simulation model (Kimmins et al. 1999) was then assessed. Another objective was to test the ability of the FORECAST model to simulate accumulation patterns in CWD and soil organic matter and nitrogen following fire by comparing model outputs with field data.

Chapter 2 of the thesis addressed the fire severity issue and the potential for its representation in an ecosystem management model. Crown fraction burned (live biomass) and forest floor
consumption and surface fuels (dead biomass) were discussed as possible fire severity representations. Also, a literature review was presented of the stand and landscape-level fire models most frequently used in North America. The representation of fire severity in these models was explored, as was the possibility of linking fire behavior models with ecosystem management models by using fire severity calculated in the former as a fire effects parameter in the latter. Most of the fire models described do not explicitly represent fire severity or fire effects, but an assessment of the most useful outputs from these model produce was presented. Mortality is one of the main first order fire effects in many of the models, but a dynamic ecosystem-level assessment of severity should be defined in terms of the time scales of succession and stand dynamics as important secondary fire effects. A conclusion of this chapter was that the ecosystem representation capabilities of the present fire models could be improved by linking them with process-based ecosystem management models through the medium of fire severity. Fire severity is a complex term and it cannot be considered in isolation from the initial ecosystem conditions and from the frequency of disturbance.

Chapter 3 addressed the complex problem of representing the fire severity concept as a fire severity matrix for use in a soft link between fire behavior models and FORECAST. Although the link itself needs further work, the goal was to provide an algorithm to parameterize fire severity that would be consistent with the input file of FORECAST that defines fire severity. Using weather data and past fire literature records, live and dead biomass severity were estimated for two fuel types and two different climatologic stations in the MSdm subzone in TFL 49 near Kelowna in the southern interior of B.C. Eight combinations of matrices that represent the potential aboveground biomass and dead organic matter severity were produced. The matrices differed between the two different climate data sets, illustrating the sensitivity of the estimated severity to climatic inputs. These matrices may be used to provide information to improve the representation of live and dead biomass fire severity levels in the FORECAST model. However, it has to be mentioned that the fire weather variables were used for a limited 10 year period of time and resulted in a relatively reduced number of severe fires. If a longer period of weather records was used that included more drought years, the fire severity matrix results might change, especially in the combinations of high CFB and high FFC and SFC. Also, the probability matrices are representative for a general mesic MSdm ecosystem.

This study represents only a preliminary step in the process of improving FORECAST fire representation. However, an important outcome of the study is the conclusion that the severity
matrix concept can be used in FORECAST as it is, at least for the MSdm zone, as guidance for the fire settings in the fire sub-module (Section 3). The matrices enable the user to pick the most probable combination of live and dead biomass fire severity and to use this information to calibrate the severity codes in FORECAST.

The severity matrix approach developed here provides an example of the development of such matrices for other biogeoclimatic subzones. The *sine qua non* for such development would be fire data availability, but is expected that such data would be available for most of the fire-prone biogeoclimatic subzones of B.C. Libraries of severity matrices could be developed for each biogeoclimatic zone in B.C. As the climate module in FORECAST is further developed, a dynamic link between the fire severity matrix concept presented here and the FORECAST model could be established. However, an analysis of the usefulness of such an upgrade is necessary.

In Chapter 4, field and simulation methods were used to investigate the accumulation patterns of CWD following fire into a chronosequence of sites in the MSdm subzone. FORECAST was used to simulate these accumulation patterns and the model outputs were compared with the field data. It is often difficult to find sites that meet the strict criteria of a chronosequence, and compromises are frequently made in practice. Initial densities of lodgepole pine are notoriously variable and it was assumed that the stand densities obtained from TOLKO were accurate and some of the assumed age effects could be, in fact stand effects. Any differences between the previous stand age (i.e. the age of which the fire did occur) and the fire behaviour could have implications in the CWD accumulation. Also, no snags were measured on the field. But these are inevitable risks with any chronosequence study. Repeated measurements over time might be necessary to validate a chronosequence.

However, the measured patterns of CWD accumulation following fire were generally in agreement with model predictions. The very slow recruitment pattern for new CWD illustrates the need to retain sources of CWD recruitment following fire by not salvage logging all killed trees and/or surviving live trees. Where possible, live and dead mature trees should be retained to provide recruitment of new CWD in managed landscapes.

The ability of FORECAST to assess the CWD accumulation patterns was evaluated using graphical and statistical tests. Soil variables (soil organic matter, carbon and nitrogen content) were also collected from the field and compared with the model outputs. Generally, the model outputs were in the same range as the field averages. However, the statistical test presented here
must be carefully interpreted since only a limited number of data points were available from the field, and the model was only calibrated for a zonal (mesic) MSdm site. The settings used for the simulation of the previous stand were estimated based on map records, the accuracy of which could not be verified. The simulation of previous CWD quantities depends on the previous stand variables and any difference between my estimation of and the actual pre-fire stand characteristics will have had important implications for the comparisons I made. No model can be more accurate than the input data, and it must be emphasized again that the accuracy of model performances will reflect the availability of appropriate calibration data sets.

An additional factor in model performance, one that is ignored in most other models, is the definition of the state of the ecosystem at the start of the simulation (the ECOSTATE file in the case of FORECAST). In my study the ECOSTATE file was prepared to reflect the known history of the study sites. The performance of the model gives confidence in its ability to do this. Experiments with changing the ECOSTATE file to represent a different history have produced very different results that do not accurately mimic the field data.

The confidence into the model might have been improved with more data points available from the field. Also, having the particularities of the fire phenomenon, better data might be provided by fire experiments. But maybe only because the model performed adequately in the actual conditions gives user confidence into the model capabilities. Many previous studies with FORECAST have shown significant improvement of the model predictions when better field data and calibration data were used (e.g. Bi et al. 2007, Blanco et al. 2007, Boldor 2007, Sachs and Trofimow 1990, etc.)

From this study I conclude that FORECAST is capable of simulating the patterns of soil biomass and CWD accumulations following fire. However, the question remains as to how useful it is to have ecosystem models that can accurately represent the fire effects? Is the added model complexity justified by an improved accuracy of representation? Since few of the most commonly used fire models accurately represent fire effects, what are the alternatives? One alternative would be the meta-modelling concept (Kimmins 2004b; Messier et al. 2003; Urban et al. 1999). Meta-models essentially incorporate the strengths of multiple models into a framework where the outputs of one model become the inputs of another. This approach has been applied in many of the fire models described in the second chapter of the thesis (e.g. FARSITE, BEHAVE, FOFEM, Fire-BGC).
Study of the complexity of fire requires complex and powerful tools. But, as mentioned, though accurate and complex in terms of fire behavior, most fire models need a better representation of key ecosystem processes if we are to understand and be able to predict the long term ecosystem consequences of fires of different severity, and the consequences of different fuel and fire management policies. A linkage between fire models and ecosystem models like FORECAST would make possible the incorporation of multiple and complex scenario analyses into a strategic decision-making process capable of addressing forest wildfires in a broader temporal, spatial and value context than is usually possible with the fire models that are generally used. However, the usefulness and cost-effectiveness of metamodeling and linking fire models to ecosystem models remains to be explored. What other alternatives would be more cost-effective? Improving the capabilities of fire models to represent ecosystem processes or the opposite: to improve the fire representation capabilities of forest ecosystems?

In this thesis, I have investigated the possibility of improving the fire representation capabilities of an ecosystem management model, FORECAST by introducing the live and dead biomass fire severity concepts through severity matrices. This could constitute a first step toward a more complex linkage between fire models and ecosystem models. The performance of FORECAST has now been established in several studies. However, fire representation in FORECAST is still limited since stochasticity or landscape representations are not possible. But successfully test of the FORECAST model in several experiments gives confidence in using it as the driver of landscape-level simulations. The severity matrix approach presented here is easy to apply in the model and could certainly improve the usefulness of the model in conditions of actual complex management systems, where the natural and human resources are limited. This suggests that complex ecosystem models will become increasingly appropriate for decision support in forest management in the future.
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Appendix 1

*---------------------------------------------------------------*
NAME: FBPPRIME.SAS
PURPOSE: CALCULATE PRIMARY FBP VALUES FROM AN FWI DATA LISTING

USAGE: ADJUST INFILE STATEMENT TO DATA AND SET SITE AND FUEL
TYPE VARIABLES FOLLOWING THE 'USER DEFINED' STATEMENTS
REFERENCE: FORESTRY CANADA FIRE DANGER GROUP 1992. DEVELOPMENT
AND STRUCTURE OF THE CANADIAN FOREST FIRE BEHAVIOR
PREDICTION SYSTEM. INFO REPORT ST-X-3, SCIENCE AND
SUSTAINABLE DEVELOPMENT DIRECTORATE, OTTAWA. 63 PP
CONVENTION - VARIABLE NAMES AND COMMENTS ARE IN CAPS
*---------------------------------------------------------------*
/*This is the order and name of the excel file that HAVE to be maintained!

PROC IMPORT OUT= WORK.Brenda
   DATAFILE= "D:\FWI_BR_SP\Spruce.xls"
   DBMS=EXCEL REPLACE;
   SHEET="Sheet1$";
   GETNAMES=YES;
   MIXED=NO;
   SCANTEXT=YES;
   USEDATE=YES;
   SCANTIME=YES;
RUN;

data temp1;

/* INITIALIZE VARIABLES */

GS = 0 ;   * PERCENT GROUND SLOPE ;
SAZ = 0 ;   * SLOPE AZIMUTH, UPSLOPE (OPPOSITE OF ASPECT) ;
SF = 0 ;   * SLOPE FACTOR, UPSLOPE ;

WAZ = 0 ;   * WIND AZIMUTH, DEGREES;
WS = 0 ;   * OBSERVED WIND SPEED ;
WSE = 0 ;   * SLOPE EQUIVALENT WIND SPEED ;
WSV = 0 ;   * NEW VECTORED WIND SPEED ;
WSX = 0 ; * NET-VECTORED WIND SPEED IN X - DIRECTION;
WSY = 0 ; * NET-VECTORED WIND SPEED IN Y - DIRECTION;

BfW = 0 ; * BACK FIRE WIND FUNCTION;
BISI = 0 ; * BACKFIRE ISI;
FF = 0 ; * FINE FUEL MOISTURE FUNCTION IN THE ISI;
FW = 0 ; * WIND FUNCTION IN THE ISI;
ISF = 0 ; * SLOPE ADJUSTED ZERO WIND ISI;
ISI = 0 ; * FINAL ISI, ACCOUNTING FOR WIND AND SLOPE;
ISZ = 0 ; * ZERO WIND, ZERO SLOPE ISIS;

a = 0 ; * RATE OF SPREAD COEFFICIENT;
b = 0 ; * RATE OF SPREAD COEFFICIENT;
c = 0 ; * RATE OF SPREAD COEFFICIENT;
BROS = 0 ; * BACKFIRE RATE OF SPREAD;
CF = 0 ; * CURING FRACTION, GRASS FUEL TYPES;
FRS = 0 ; * FLANK FIRE RATE OF SPREAD;
RAZ = 0 ; * SPREAD DIRECTION AZIMUTH;
ROS = 0 ; * FINAL RATE OF SPREAD;
RSC = 0 ; * CROWN FIRE SPRATE, PLANTATION TYPE;
RSF = 0 ; * SURFACE FIRE SPREAD RATE WITH ZERO WIND, UPSLOPE;
RSI = 0 ; * INITIAL SPREAD RATE WITHOUT BUILDUP EFFECT;
RSZ = 0 ; * CRITICAL SPREAD RATE FOR CROWNING;
RSS = 0 ; * SURFACE FIRE SPREAD RATE IN PLANTATION TYPE;
RSZ = 0 ; * SURFACE FIRE SPREAD RATE WITH ZERO WIND, LEVEL GROUND;

CFC = 0 ; * CROWN FUEL CONSUMPTION;
FFC = 0 ; * FOREST FLOOR CONSUMPTION;
SFC = 0 ; * SURFACE FUEL CONSUMPTION;
TFC = 0 ; * TOTAL FUEL CONSUMPTION;
WFC = 0 ; * WOODY FUEL CONSUMPTION;

CSI = 0 ; * CRITICAL SURFACE FIRE INTENSITY FOR CROWNING;
FFI = 0 ; * FLANK FIRE INTENSITY;
HFI = 0 ; * HEAD FIRE INTENSITY;
RFI = 0 ; * BACKFIRE INTENSITY;
SFI = 0 ; * SURFACE FIRE INTENSITY;

Dj = 0 ; * JULIAN DATE;
Do = 0 ; * JULIAN DATE OF MINIMUM FMC;
ELV = 0 ; * ELEVATION;
FMC = 0 ; * FOLIAR MOISTURE CONTENT;
LAT = 0 ; * LATITUDE (DEGREES);
LATN = 0;  * NORMALIZE LATITUDE (DEGREES);
LON = 0;  * LONGITUDE (DEGREES);
ND = 0;  * NUMBER OF DAYS BETWEEN CURRENT DATE AND Do;

CBH = 0;  * CROWN BASE HEIGHT (m);
CFB = 0;  * CROWN FRACTION BURNED;
CFL = 0;  * CROWN FUEL LOAD (kg/m2);
FME = 0;  * FUEL MOISTURE EFFECT;

BE = 0;  * BUILDUP EFFECT;
BEmax = 0;  * MAXIMUM VALUE OF BUILDUP EFFECT;
BUI = 0;  * BUILDUP INDEX;
BUIo = 0;  * FUEL TYPE SPECIFIC AVERAGE BUI;
q = 0;  * PROPORTION OF MAXIMUM SPREAD AT BUI EQUAL TO 50;

CR = 0;  * DEGREE OF CURING (%), GRASS TYPES;
FFMC = 0;  * FINE FUEL MOISTURE CODE;
GFL = 0;  * GRASS FUEL LOAD (KG/M2);
M = 0;  * MOISTURE CONTENT EQUIVALENT OF FFMC (%);
PC = 0;  * PERCENT CONIFER, MIXEDWOOD TYPES;
PDF = 0;  * PERCENT DEAD FIR, MIXEDWOOD TYPES;
PH = 0;  * PERCENT HARDWOOD, MIXEDWOOD TYPES;

set Brenda;

/* START USER DEFINED*/

/* INPUT PROJECT SPECIFIC WX DATA
infile 'C:\AngiTh\MAtrixWork\brenda.dat' missover;
*/
infile mo dayyr temp rh ws rain ffmc dmc dc bui oldisi fwi dsr;
*drop temp rh rain dmc dc fwi dsr;  *

wd = 270;

/* Angi: If there are not separate fields for the day and yr, use the following two lines: */
/* day = int (dayyr / 100) ;
yr = mod (dayyr, 100) ; */

stn = 'Br';
/*DATA trees;
infile file1;
input species crowncls age dbh height volume;
run;*/

/*END USER DEFINED*/

if oldisi = . then
do;

/* INITIAL SPREAD INDEX */

M = 147.2*(101-FFMC)/(59.5+FFMC);  * (eqn.1) ;
Fw = exp(0.05039 * WS);  * (eqn. 24) ;
Ff = 19.115 * exp(0.1386*M)*(1.0+(M**5.31)/4.93e07);  * (eqn. 25) ;
oldisi = 0.208 * Fw * Ff;  * (eqn. 26) ;
end;

if bui = . then
do;

/* BUILDUP INDEX (BUI) */

if DMC = 0 and DC =0 then BUI = 0;
if DMC < = 0.4 * DC then
BUI = 0.8* DMC * DC / (DMC + 0.4 * DC);  *
* (eqn. 27a) ;
else BUI = DMC - (1 - 0.8 * DC / (DMC + 0.4 * DC)) * (0.92 + (0.0114 * DMC)**1.7);  * (eqn. 27b) ;
end;

/* file sasuser.missing ;

if bui = . or ffmc = . or oldisi = . or ws = . then put
   stn year mo day ffmc dmc de oldisi bui ;

*/
/* START USER DEFINED*/

/* SET PROJECT & SITE SPECIFIC VARIABLES */

if stn = 'Sp' then
  do;
    LAT = 50.48;   * LATITUDE IN DEGREES ;
    LON = 119.99;  * LONGITUDE IN DEGREES ;
    ELV = 1462;   * ELEVATION ABOVE MSL IN METRES ;
  end;
else ;
  LAT = 50.4;   * LATITUDE IN DEGREES ;
  LON = 119.99;  * LONGITUDE IN DEGREES ;
  ELV = 1462;   * ELEVATION ABOVE MSL IN METRES ;

GS = 20;   * GROUND SLOPE IN PERCENT ;
AS = 170;   * SITE ASPECT IN DEGREES ;
CR = 90;   * CURING RATIO FOR GRASS TYPES ;
PC = 60;   * PERCENT CONIFER FOR MIXEDWOOD TYPES ;
PH = 40;   * PERCENT HARDWOOD FOR MIXEDWOOD TYPES ;
PDF = 30;   * PERCENT DEAD FIR FOR DEAD BALSAM FIR TYPES ;

/* END USER DEFINED*/

/* CALCULATE JULIAN DAY WHERE DAY IS THE DATE OF A PARTICULAR MONTH */

if mo = 1 then Dj = day ;
if mo = 2 then Dj = 31 + day ;
if mo = 3 then Dj = 59 + day ;
if mo = 4 then Dj = 90 + day ;
if mo = 5 then Dj = 120 + day ;
if mo = 6 then Dj = 150 + day ;
if mo = 7 then Dj = 181 + day ;
if mo = 8 then Dj = 212 + day ;
if mo = 9 then Dj = 243 + day ;
if mo = 10 then Dj = 273 + day ;
if mo = 11 then Dj = 304 + day ;
if mo = 12 then Dj = 334 + day ;
if Dj < 121 or Dj > 273 then delete ;

/* 6.0 FOLIAR MOISTURE CONTENT */
LATN = 43 + 33.7 \times \text{exp}(-0.0351 \times (150 - \text{LON})) \quad \text{(eqn 3)};

D0 = 142.1 \times (\text{LAT}/\text{LATN}) + 0.0172 \times \text{ELV} \quad \text{(eqn 4)};

ND = \text{abs}(\text{Dj} - \text{D0}) \quad \text{(eqn 5)};

\text{if ND < 30 then FMC = 85 + 0.0189 \times ND^2} \quad \text{(eqn 6)};

\text{if ND >= 30 and ND < 50 then FMC = 85 + 0.0189 \times ND^2} \quad \text{(eqn 7)};

\text{if ND >= 50 then FMC = 120} \quad \text{(eqn 8)};

/* FUEL TYPE DEFINITIONS - AFTER SECTION 4.0, TABLE 2

<table>
<thead>
<tr>
<th>ft</th>
<th>IDENTIFIER</th>
<th>DESCRIPTIVE NAME</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>C-1</td>
<td>SPRUCE-LICHEN WOODLAND</td>
</tr>
<tr>
<td>2</td>
<td>C-2</td>
<td>BOREAL SPRUCE</td>
</tr>
<tr>
<td>3</td>
<td>C-3</td>
<td>MATURE JACK OR LODGEPOLE PINE</td>
</tr>
<tr>
<td>4</td>
<td>C-4</td>
<td>IMMATURE JACK OR LODGEPOLE PINE</td>
</tr>
<tr>
<td>5</td>
<td>C-5</td>
<td>RED AND WHITE PINE</td>
</tr>
<tr>
<td>6</td>
<td>C-6</td>
<td>CONIFER PLANTATION</td>
</tr>
<tr>
<td>7</td>
<td>C-7</td>
<td>PONDEROSA PINE - DOUGLAS-FIR</td>
</tr>
<tr>
<td>8</td>
<td>D-1</td>
<td>LEAFLESS ASPEN</td>
</tr>
<tr>
<td>9</td>
<td>M-1</td>
<td>BOREAL MIXEDWOOD - LEAFLESS</td>
</tr>
<tr>
<td>10</td>
<td>M-2</td>
<td>BOREAL MIXEDWOOD - GREEN</td>
</tr>
<tr>
<td>11</td>
<td>M-3</td>
<td>DEAD BALSAM FIR MIXED WOOD - LEAFLESS</td>
</tr>
<tr>
<td>12</td>
<td>M-4</td>
<td>DEAD BALSAM FIR MIXED WOOD - GREEN</td>
</tr>
<tr>
<td>13</td>
<td>S-1</td>
<td>JACK OR LODGEPOLE PINE SLASH</td>
</tr>
<tr>
<td>14</td>
<td>S-2</td>
<td>WHITE SPRUCE - BALSAM SLASH</td>
</tr>
<tr>
<td>15</td>
<td>S-3</td>
<td>COASTAL CEDAR - HEMLOCK - DOUGLAS-FIR SLASH</td>
</tr>
<tr>
<td>16</td>
<td>0-J-1a</td>
<td>MATTED GRASS</td>
</tr>
<tr>
<td>17</td>
<td>0-J-1b</td>
<td>STANDING GRASS</td>
</tr>
</tbody>
</table>

/*SELECT FUEL TYPES (ft) VIA DO STATEMENT
SET FUEL TYPE SPECIFIC PARAMETER VALUES: TABLES 6,7,8
(THE COULD BE DONE MORE EFFICIENTLY WITH ARRAYS)

/* START USER DEFINED*/

do ft = 3,4 ;

148
/* END USER DEFINED*/

* C-1 PARAMETERS;

    if ft = 1 then
        do ;
            FTYPE = 'C-1' ;
            a = 90 ;
            b = 0.0649 ;
            c = 4.5 ;
            q = 0.90 ;
            BUI0 = 72 ;
            BEmax = 1.076 ;
            CBH = 2.0 ;
            CFL = 0.75 ;
        end ;

* C-2 PARAMETERS ;

    if ft = 2 then
        do ;
            FTYPE = 'C-2' ;
            a = 110 ;
            b = 0.0282 ;
            c = 1.5 ;
            q = 0.70 ;
            BUI0 = 64 ;
            BEmax = 1.321 ;
            CBH = 3.0 ;
            CFL = 0.80 ;
        end ;

* C-3 PARAMETERS ;

    if ft = 3 then
        do ;
            FTYPE = 'C-3' ;
            a = 110 ;
            b = 0.0444 ;
            c = 3.0 ;
            q = 0.75 ;
            BUI0 = 62 ;
\[ \text{BEmax} = 1.261; \]
\[ \text{CBH} = 8.0; \]
\[ \text{CFL} = 1.15; \]

\text{end ;}

* C-4 PARAMETERS ;

if ft = 4 then
  do ;
    \text{FTYPE} = 'C-4';
    \text{a} = 110 ;
    \text{b} = 0.0293 ;
    \text{c} = 1.5 ;
    \text{q} = 0.80 ;
    \text{BU10} = 66 ;
    \text{BEmax} = 1.184 ;
    \text{CBH} = 4.0 ;
    \text{CFL} = 1.20 ;
  end ;

* C-5 PARAMETERS ;

if ft = 5 then
  do ;
    \text{FTYPE} = 'C-5';
    \text{a} = 30 ;
    \text{b} = 0.0697 ;
    \text{c} = 4.0 ;
    \text{q} = 0.80 ;
    \text{BU10} = 56 ;
    \text{BEmax} = 1.220 ;
    \text{CBH} = 18.0 ;
    \text{CFL} = 1.20 ;
  end ;

* C-6 PARAMETERS ;

if ft = 6 then
  do ;
    \text{FTYPE} = 'C-6';
    \text{a} = 30 ;
    \text{b} = 0.0800 ;
    \text{c} = 3.0 ;

q = 0.80 ; 
BU10 = 62 ; 
BEmax = 1.197 ; 
CBH = 7.0 ; 
CFL = 1.80 ; 
end ;

* C-7 PARAMETERS ;

if ft = 7 then 
do ; 
   FTYPE = 'C-7' ; 
   a = 45 ; 
   b = 0.0305 ; 
   c = 2.0 ; 
   q = 0.85 ; 
   BU10 = 106 ; 
   BEmax = 1.134 ; 
   CBH = 10.0 ; 
   CFL = 0.50 ; 
end ;

* D-1 PARAMETERS ;

if ft = 8 then 
do ; 
   FTYPE = 'D-1' ; 
   a = 30 ; 
   b = 0.0232 ; 
   c = 1.6 ; 
   q = 0.90 ; 
   BU10 = 32 ; 
   BEmax = 1.179 ; 
end ;

* M-1 PARAMETERS ;

if ft = 9 then 
do ; 
   FTYPE = 'M-1' ; 
   q = 0.80 ; 
   BU10 = 50 ;
BEmax = 1.25 ;
CBH = 6.0 ;
CFL = 8.0 ;
end ;

* M-2 PARAMETERS ;

if ft = 10 then
  do ;
    FTYPE = 'M-2' ;
    q = 0.80 ;
    BUl0 = 50 ;
    BEmax = 1.25 ;
    CBH = 6.0 ;
    CFL = 8.0 ;
  end ;

* M-3 PARAMETERS ;

if ft = 11 then
  do ;
    FTYPE = 'M-3' ;
    q = 0.80 ;
    BUl0 = 50 ;
    BEmax = 1.25 ;
    CBH = 6.0 ;
    CFL = 8.0 ;
  end ;

* M-4 PARAMETERS ;

if ft = 12 then
  do ;
    FTYPE = 'M-4' ;
    q = 0.80 ;
    BUl0 = 50 ;
    BEmax = 1.25 ;
    CBH = 6.0 ;
    CFL = 8.0 ;
  end ;

* S-1 PARAMETERS ;
if ft = 13 then
    do;
        FTYPE = 'S-J1';
        a = 75;
        b = 0.0297;
        c = 1.3;
        q = 0.75;
        BU10 = 38;
        BEmax = 1.460;
    end;

* SJ2 PARAMETERS;

if ft = 14 then
    do;
        FTYPE = 'S-J2';
        a = 40;
        b = 0.0438;
        c = 1.7;
        q = 0.75;
        BU10 = 63;
        BEmax = 1.256;
    end;

* SJ3 PARAMETERS;

if ft = 15 then
    do;
        FTYPE = 'S-J3';
        a = 55;
        b = 0.0829;
        c = 3.2;
        q = 0.75;
        BU10 = 31;
        BEmax = 1.590;
    end;

* OJ1a PARAMETERS;

if ft = 16 then
    do;
        FTYPE = 'O-J1a';
        a = 190;
    end;
b = 0.0310;
c = 1.4;
q = 1.0;
BU10 = 1.0;
BEmax = 1.0;
GFL = 0.3;

end;

* 0-1b PARAMETERS;

if ft = 17 then
  do;
    FTYPE = 'O-1b';
    a = 250;
    b = 0.0350;
    c = 1.7;
    q = 1.0;
    BU10 = 1.0;
    BEmax = 1.0;
    GFL = 0.3;
  end;

/* 7.0 PRIMARY COMPONENTS

7.1 INITIAL SURFACE FUEL CONSUMPTION (BY FUEL TYPE)
(NB 100% fuel consumption assumed for 0-1 */

if BU1 = 0 then SFC = 0;
else;
    select (ft);

* C-1;

when (1)
  do;
    SFC = 1.5 * (1 - exp(0.230 * (FFMC - 81))); * (eqn 9);
    if SFC < 0 then SFC = 0;
  end;
when (2,11,12)
  SFC = 5 * (1 - exp(-0.0115 * BUI))**1.00 ; * (eqn 10) ;

when (3,4)
  SFC = 5 * (1 - exp(-0.0164 * BUI))**2.24 ; * (eqn 11) ;

when (5,6)
  SFC = 5 * (1 - exp(-0.0149 * BUI))**2.48 ; * (eqn 12) ;

when (7)
  do ;
    FFC = 2 * (1 - exp(-0.104 * (FFMC - 70))) ; * (eqn 13) ;
    if FFC < 0 then FFC = 0 ;
    WFC = 1.5 * (1 - exp(-0.0201 * BUI)) ; * (eqn 14) ;
  SFC = FFC + WFC ; * (eqn 15) ;
  end;

when (8)
  SFC = 1.5 * (1 - exp(-0.0183 * BUI)) ; * (eqn 16) ;

when (9,10)
  SFC = ((PC/100)*5*(1Jexp(J0.0115*BUI)))+
       ((PH/100)*1.5*(1JEXP(J0.0183*BUI))); * (eqn 17) ;

when (13)
  do ;
    FFC = 4.0 * (1 - exp(-0.025 * BUI)) ; * (eqn 19) ;
    WFC = 4.0 * (1 - exp(-0.034 * BUI)) ; * (eqn 20) ;

SFC = FFC + WFC ; * (eqn 15) ;
\[ SFC = FFC + WFC; \quad * \text{(eqn 25)}; \]

\* S-2;

* when (14) do ;
\[ FFC = 10.0 * (1 - \exp(-0.013 \times BUI)); \quad * \text{(eqn 21)}; \]
\[ WFC = 6.0 * (1 - \exp(-0.060 \times BUI)); \quad * \text{(eqn 22)}; \]
\[ SFC = FFC + WFC; \quad * \text{(eqn 25)}; \]
end;

\* S-3;

* when (15) do ;
\[ FFC = 12.0 * (1 - \exp(-0.0166 \times BUI)); \quad * \text{(eqn 23)}; \]
\[ WFC = 20.0 * (1 - \exp(-0.0210 \times BUI)); \quad * \text{(eqn 24)}; \]
\[ SFC = FFC + WFC; \quad * \text{(eqn 25)}; \]
end;

* when (16,17) do ;
\[ SFC = GFL; \quad * \text{(eqn 18)}; \]
end ;

/* 7.2 RATE OF SPREAD

7.2.2 SLOPE EFFECT ON FIRE SPREAD
CONVERSION TO WIND SPEED EQUIVALENT

ISZ CALCULATIONS - ZERO WIND ISI */

\[ m = \frac{(147.2 \times (101 - FMFC))}{(59.5 + FMFC)}; \quad * \text{(eqn 46)}; \]
\[ fF = (91.9 \times \exp(-0.1386 \times m)) \times (1 + ((m^{5.3})/4930000)); \quad * \text{(eqn 45)}; \]
\[ ISZ = (0.208 \times fF); \quad * \text{(eqn 52)}; \]

/* RSZ - ZERO WIND RATE OF SPREAD BY FUEL TYPE;

NATURAL AND CUTOVER FUEL TYPES AFTER 7.2.1

C-1, C-2, C-3, C-4, C-5, C-7, D-1, S-1, S-2, S-3 */
select (b);
when (1,2,3,4,5,7,8,13,14,15)
  RSZ = a *(1-exp(-b * ISZ))*c ; * (modified eqn 26) ;
* M-1 ;
when (9)
  RSZ = ((PC/100)*((110*(1-exp(-0.0282*ISZ))**1.5)))+
       ((PH/100)*((1-exp(-0.0332*ISZ))**1.6)));
* (modified eqn 27) ;
* M-2 ;
when (10)
  RSZ = ((PC/100)*((110*(1-exp(-0.0282*ISZ))**1.5)))+
       0.2 * ((PH/100)*((1-exp(-0.0332*ISZ))**1.6)));
* (modified eqn 28) ;
* M-3;
when (11)
  do ;
  a = (170*exp(-35.0/PDF)); * (eqn 29) ;
  b = (0.082*exp(-36.0/PDF)); * (eqn 30) ;
  c = (1.698*(0.00303*PDF)); * (eqn 31) ;
  RSZ = a *(1-exp(-b * ISZ))*c ; * (eqn 26) ;
  end ;
* M-4 ;
when (12)
  do ;
  a = 140*exp(-33.5/PDF); * (eqn 32) ;
  b = 0.0404; * (eqn 33) ;
  c = 3.02*exp(-0.00714*PDF)); * (eqn 34) ;
  RSZ = a *(1-exp(-b * ISZ))*c ; * (eqn 26) ;
  end ;
* C-6  PLANTATION FUEL TYPES AFTER 7.2.1.2 ;
when (6)
  RSZ = 30*(1-exp(-0.08*ISZ))**3.0); * (modified eqn 62) ;
* 0-1  GRASS FUEL TYPES AFTER 7.2.1.3 ;
when (16, 17)
  do ;
CF = (0.02 * CR)-1;                        * (eqn 35);
if CR <= 50 then CF = 0;
RSZ = (a*(1- exp(-b * ISZ))**c)* CF;        * (eqn 36);
end;
end;

/* 7.2.2 SLOPE EFFECT ON FIRE SPREAD 
CALCULATION OF ADJUSTED ISI */

* SLOPE FACTOR :
  SF = exp(3.533*(GS/100)**1.2);                           * (eqn 39);

* SLOPE ADJUSTED ZERO WIND RATE OF SPREAD :
  RSF = RSZ * SF;                                              * (eqn 40);

* ISF - ISI WITH SLOPE INFLUENCE AND ZERO WIND :

c1 = 1/c;  * for convenience in ISF calex;

select (ft);
  when (9,10,11,16,17)
    do;
      if ft = 9 or ft = 10 then
        ISF = log(1-((100*RSF)/(PC*A))**c1))/Jb;   * (eqn 42 MJ1, MJ2) ;
      else
        do;
          if RSF >= a * CF then ISF = 4.605/b ;
          else ISF= log(1-(RSF/(CF*a))**c1)/Jb;  *(eqn 43 OJ1) ;
        end;
      end;
  end;

otherwise
  do;
    if RSF >= a then ISF = 4.605/b ;                           *check this ;
    else ISF = log(1-(RSF/a)**c1)/-b ;                       *(eqn 41);   
  end;
end;
* SLOPE EQUIVALENT WIND SPEED 

\[ WSE = \frac{\log(ISF/(0.208*{fF}))}{0.05039} \]  
* (eqn 44);

/* NET EFFECTIVE WINDSPEED - ADDITION OF WIND AND SLOPE VECTORS

NOTES: 1. CONVERSIONS ARE REQUIRED BECAUSE SAS USES RADIANS FOR TRIG FUNCTIONS
2. DEG = RAD * 180/Pi; RAD = DEG * Pi/180 *
3. EQNS 45 AND 46 WERE USED ABOVE TO CALCULATE ISZ
4. WIND AZIMUTH IS THE BEARING THAT THE WIND IS BLOWING, OPPOSITE OF WIND DIRECTION
5. SLOPE AZIMUTH IS THE UPSLOPE BEARING, OPPOSITE OF ASPECT */

```
if WD < 180 then WAZ = WD + 180 ;
if WD >= 180 then WAZ = WD - 180 ;
if AS < 180 then SAZ = AS + 180 ;
if AS >= 180 then SAZ = AS - 180 ;
```

```
WSX = (WS * sin(3.14159/180*WAZ)) + (WSE * sin(3.14159/180*SAZ)) ;  * (eqn 47);
WSY = (WS * cos(3.14159/180*WAZ)) + (WSE * cos(3.14159/180*SAZ)) ;  * (eqn 48);
WSV = sqrt (WSX**2 + WSY**2) ;  * (eqn 49);
```

```
if WSV = 0 then RAZ = WAZ ;
else RAZ =180/3.14159 * arcos (WSY/WSV) ;  * (eqn 50);
```

```
if WSV < 0 then RAZ = 360 - RAZ ;  * (eqn 51);
```

*p FINAL ISI *

```
if  WSV > 40 then
   fW = 12 * (1- exp(-0.0818 * (WSV -28))) ;  * (eqn 53a);
else fW = exp(0.05039 * WSV ) ;  * (eqn 53);
```

/* NOTE fW = 0 when WSV = 0 */

```
ISI = (0.208 * fW * {fF}) ;  * (eqn 52);
```

/* 7.2.1 BASIC RATE OF SPREAD EQUATIONS

7.2.1.1 NATURAL AND CUTOVER FUEL TYPES

159"
(C-1, C-2, C-3, C-4, C-5, C-7, D-1, S-1, S-2, S-3) */

```plaintext
select (8);
when (1,2,3,4,5,7,8,9,13,14,15)
RSI = a *(1-exp(-b * ISI))**c ; * (eqn 26) ;

* M-1 ;

when (9)
RSI = ((PC/100)*(110*(1-exp(-0.0282*ISI)**1.5)))+
     ((PH/100)*(30*(1-exp(-0.0232*ISI)**1.6))) ; * (eqn 27) ;

* M-2 ;

when (10)
RSI = ((PC/100)*(110*(1-exp(-0.0282*ISI)**1.5)))+
     0.2 * ((PH/100)*(30*(1-exp(-0.0232*ISI)**1.6))) ; * (eqn 28) ;

* M-3 ;

when (11)
do ;
    a = (170*exp(-35.0/PDF)); * (eqn 29) ;
b = (0.082*exp(-36.0/PDF)); * (eqn 30) ;
c = (1.698*(0.00303*PDF)); * (eqn 31) ;
    RSI= a*(1-exp(-b*ISI))**c ;  * (eqn 26) ;
end ;

* M-4 ;

when (12)
do ;
    a = 140*exp(-33.5/PDF); * (eqn 32) ;
b = 0.0404; * (eqn 32) ;
c = 3.02*(exp(-0.00714*PDF)); * (eqn 33) ;
    RSI = a*(1-exp(-b*ISI))**c ;  * (eqn 26) ;
end ;

* 7.2.1.2 PLANTATION FUEL TYPES - TREATED IN 7.2.4 ;

* 7.2.1.3 GRASS FUEL TYPES - 0-1 ;

when (16,17)
do ;
    CF = (0.02 * CR)-1; * (eqn 35) ;
    if CR <= 50 then CF = 0;
```

160
\[ RSI = (a^1 \cdot \exp(-b \cdot ISI)^c) \cdot CF; \] 
* (eqn 36) ;

end ;

otherwise ;

end ;

/* 7.2.3 BUI EFFECT ON SURFACE FIRE RATE OF SPREAD */

if BUI = 0 then BE = 0 ;
/* WHEN BUI IS ZERO AND SFC = 0 THEN ROS = 0 */
else BE = \exp(50 \cdot \log(q) \cdot (1/BUI - 1/BUI0)) ;
* (eqn 54) ;

if BE < BEmax then
  ROS = BE \cdot RSI; 
* (eqn 55) ;
else ROS = BEmax \cdot RSI ;

/* 7.2.4 CROWNING EFFECT ON SPREAD RATE */

7.2.4.1 TRANSITION FROM SURFACE FIRE TO CROWN FIRE - TIMBER TYPES */

if ft <= 12 then
  do ;

  * CRITICAL SURFACE FIRE INTENSITY FOR CROWNING ;
  CSI = 0.001 \cdot CBH**1.5 \cdot (460 + 25.9 \cdot FMC)**1.5 ; 
  * (eqn 56) ;

  * CRITICAL SURFACE FIRE SPREAD RATE ;
  SFC2 = SFC ;
  /* INCLUDED TO PREVENT DIVIDE BY ZERO ERRORS */
  SFC2 = SFC ;
  /* INCLUDED TO PREVENT DIVIDE BY ZERO ERRORS */
  if SFC2 = 0 then SFC2 = 1 ;
  RSO = CSI / (300 \cdot SFC2) ; 
  * (eqn 57) ;

  if ft ne 6 then

  /* C-6 TREATED SEPARATELY */
  do ;

161
if ROS < RSO then CFB = 0;
else CFB = 1 - exp(-0.23 * (ROS-RSO)); * (eqn 58); if CFB < 0 then CFB = 0;
end;

end;

/* 7.2.5 CONIFER PLANTATION - FUEL TYPE C-6 */

if ft = 6 then do;

* 7.2.5.1 FOLIAR MOISTURE EFFECT ON CROWN FIRE SPREAD;

H = 460 + (25.9 *FMC); * (eqn 60);
FME = (((1.5*(0.00275*FMC))**4.0)/(H))*1000; * (eqn 61);

* 7.2.5.2 CONIFER PLANTATION SPREAD RATE;

* INTERMEDIATE SURFACE FIRE SPREAD RATE;

RSI = 30*((1-exp(-0.08*ISI))**3.0); * (eqn 62);

* SURFACE FIRE SPREAD RATE;

if BE < BEmax then

    RSS = RSI * BE; * (eqn 63);
else RSS = RSI * BEmax;

* CROWN FIRE SPREAD RATE;

RSC = 60*((1-exp(-0.0497*ISI))**1.00)*(FME/0.778); * (eqn 64);

* AFTER 7.2.4.1 CRITICAL SURFACE FIRE INTENSITY FOR CROWNING;

if RSS < RSO then CFB = 0;
else CFB = (1-exp(-0.23*(RSS-RSO)))); * (after eqn 58);
if CFB < 0 then CFB = 0;
ROS = RSS+(CFB *(RSC-RSS)); * (eqn 65);
end;
/* 7.3 FINAL FUEL CONSUMPTION */

if ft = 8 or ft >= 13 then do;
    TFC = SFC;
    CFB = 0;  * Added 8.3.05 by ST;
end;

else
    CFC = CFL * CFB;  * (eqn 66);
    TFC = SFC + CFC;  * (eqn 67);
end;

/* 7.4 FIRE INTENSITY */

FI = 300 * TFC * ROS;  * (eqn 68);
FINT =int (FI);

* FIRE INTENSITY CLASS (codified FIC);

if FI <= 10 then FIC = 1;
if FI > 10 and FI <= 500 then FIC = 2;
if FI > 500 and FI <= 2000 then FIC = 3;
if FI > 2000 and FI <= 4000 then FIC = 4;
if FI > 4000 and FI <= 10000 then FIC = 5;
if FI > 10000 then FIC = 6;

/* 7.5 FIRE DESCRIPTION */

if ft = 8 or ft >= 12 then crwn = 'S';
else
    do;
        if CFB < = 0.1 then crwn = 'aS';
        if CFB > 0.1 and CFB < = 0.5 then crwn = 'bIC';
        if CFB > 0.5 then crwn = 'cCC';
    end;
output;
end;

proc sort data = temp1 ;
by stn ftype yr mo day ;

/* OUTPUT RESULTS TO FILE */

data temp2 ;
    set temp1;

/*START USER DEFINED*/

    file fileout ;

/*END USER DEFINED*/

    put stn $ 1-2 ftype $ 4-6 day 8-10 mo 12-14 yr 16-17 fmc 19-22 .1
        ffmc 24-25 ws 27-28 oldisi 30-31 bui 33-35 ros 37-40 .1 cfb 42-45 .1
        fint 47-51 fic 53;

/*:Export Temp 2 as an excel file*/
PROC EXPORT DATA= WORK.TEMP2
    OUTFILE= "D:\FWI_BR_SP\Temp_Spruce.xls"
    DBMS=EXCEL REPLACE;
    SHEET="temp2";
RUN;

Appendix 2

Model selection

Several models were evaluated to determine the relationship between FFC and a selected number of potential independent variables using different statistical techniques and tests for significance. The general format of hypothesis tested, for all models, was:

Ho: There is no difference in forest floor consumption with different levels of FWI codes and indices and forest floor physical characteristics;

Ha: There is a difference in forest floor consumption with different levels of FWI codes and indices and forest floor physical characteristics.

All hypotheses were tested using the F test, under the required assumptions of: homoscedasticity, normal distribution of the errors, and independent errors to be met (Neter et al. 1996). The significance level (alpha) was established at \( \alpha = 0.05 \). To facilitate extrapolation to the FORECAST model, a single regression equation was desired for both pine fuel types (C3 and C4). Accordingly, a new variable: Ftype (fuel type) was introduced as categorical variable with values 0 and 1 for the fuel types C3 and C4, respectively. Models were tested with and without Ftype. Plots of FFC against the potential independent variables are presented in Figure A2.1.
Fig A2.1 Graphical relationship between forest floor consumption (FFC), expressed as absolute depth reduction, and potential independent variables including Drought Code (DC), forest floor bulk density (BD), pre-burn forest floor depth (FFD), Build-Up Index (BUI) and Duff Moisture Code (DMC), and forest floor load (FFL).
The evaluated models along with the tests results are presented in Table A2.1. A nonlinear model, a linear model with FFC transformed with Arcsin transformation and several linear models with and without Ftype categorical independent variable and no forest floor physical characteristics are shown. The computations were made using the SAS System software (SAS Institute Inc. 2003). Among the models tested for FFC, it was decided that a final selection would be done between the two linear models for ease of use in FORECAST and with only a couple of independent variables. Theoretical criteria were also taken in consideration when selecting the models (e.g. intercept vs. non-intercept, or if the results are bound to the expected values of the variables and they make biological sense).

**Table A2.1** The models that were selected to be tested for significance. All models contain the variable Ftype.

<table>
<thead>
<tr>
<th>Model</th>
<th>Description</th>
<th>Equation</th>
<th>$p$</th>
<th>MSE</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Non-linear</td>
<td>FFC=$a$(FFD$^b$)*(BUI$^c$)</td>
<td>0.003</td>
<td>0.054</td>
<td>0.002</td>
</tr>
<tr>
<td>B</td>
<td>Dependent variable transformed with Arcsin. No forced xy intercept</td>
<td>Arcsin (FFC%)=-4.6(FFL)+0.74(BD)+3.26(FFD)+1.03(DMC)+0.118(DC)+0.90(BUI)</td>
<td>0.004</td>
<td>0.05</td>
<td>0.017</td>
</tr>
<tr>
<td>C</td>
<td>Linear-No fuel type categorical variable</td>
<td>FFC=1.058 -0.034BD -0.015FFD +0.002DC</td>
<td>0.006</td>
<td>0.288</td>
<td>0.415</td>
</tr>
<tr>
<td>D</td>
<td>Linear-No forest floor physical characteristics independent variables</td>
<td>FFC=0.94-0.034BD+0.003DC</td>
<td>0.002</td>
<td>0.284</td>
<td>0.411</td>
</tr>
</tbody>
</table>

The models shown in Table 3.6 are further described as:

- **Model A**, is a non-linear regression that has a very low coefficient of determination ($R^2=0.002$).
- **Model B**, is a linear regression that uses an Arcsin transformation of FFC (%). Due to data particularities, the transformation of FFC generates bias in the estimator. The lack of an zero interception by the regression equation makes biological sense (FFC cannot
be zero in these conditions since will be always some forest fuel consumed during the fire) but, in most cases, this can generate bias in a model (Kozak and Kozak 1995). This seems to be case here in Model B.

• Model C, is a linear regression that has a moderate coefficient of determination reasonable ($R^2 = 0.41$). The estimator was found to be bias, and the regression equation, when used with recorded forest floor depths in the study area produced unrealistic estimates of FFC(%). The regression equation was bias for the fuel type C4.

• Model D (linear) is similar to model C but does not include FFD. As was the case for Model C, coefficient of determination was moderate but the estimator for C4 fuel type was biased.

The last two models, obtained using the stepwise selection (Neter et al. 1996), suggested the use of the categorical variable Ftype to improve model fit and eliminate bias. The use of the categorical Ftype variable increased the model fit to $R^2 = 0.70$. Similar models were developed by Stocks (1987; 1989) using data from a single study site which limited the results to a relatively homogeneous forest type. The objective of the present study is to create a more general FFC consumption model that would be suitable for forest floor consumption purposes over a variety of jack and lodgepole pine forest types and ages. Therefore, all independent variables used in Models C and D including the Ftype categorical variable were combined into one multiple regression analysis. The independent variable coefficients and their significance are presented in Table A2.2. The Ftype categorical independent variable and BD were strongly significant.
**Table A2.2** Independent variables coefficients and their significance from the initial step in the backward elimination process

| Independent variable | Estimate | Standard Error | t Value | Pr > |t|
|----------------------|----------|----------------|---------|------|
| Intercept            | 0.842    | 0.324          | 2.60    | 0.0148 |
| FFD                  | -0.031   | 0.031          | -1.03   | 0.3134 |
| FFL                  | 0.258    | 0.149          | 1.73    | 0.0947 |
| BUI                  | 0.013    | 0.007          | 1.82    | 0.0795 |
| DMC                  | -0.009   | 0.005          | -1.91   | 0.0660 |
| BD                   | -0.031   | 0.012          | -2.72   | 0.0111 |
| DC                   | 0.002    | 0.001          | 1.79    | 0.0847 |
| Ftype 0              | -0.361   | 0.111          | -3.26   | 0.0029 |

**Independent variable selection**

To select the most significant among the 6 independent variables, a stepwise regression procedure (Barrett and Gray 1994) was performed. The stepwise regression procedure consisted of three parts: forward selection; forward stepwise regression, and backward elimination. This procedure is one of the most common techniques used in selecting a suitable model (Barrett and Gray 1994; Rencher 1995).

The backward elimination method used here begins with all independent variables included in the model and deletes one variable at a time using a partial F value. The first step involves the calculation of the partial F value for each independent variable. The variable with largest partial F statistic that exceeds the predetermined threshold value is deleted. The second step involves the calculation of a partial F value for each of the q-1 remaining variables with the least important variable, in the presence of the others, is eliminated (Al-Subaih 2002). This process continues until a step is reached at which the largest partial F is “significant” (i.e., does not exceed the predetermined value), indicating that the corresponding variable is not redundant in the presence of the other variables in the model (Barrett and Gray 1994). The backward elimination procedure usually determines a “best” combination of the significant independent variables in the model. The following variables; FFD, FFL, BUI, DMC were eliminated through this elimination process. This procedure indicated that the “best” equation was the one with BD and DC as independent variables. A summary of the elimination process is presented in Table A2.3 and Table A2.4. The first variable eliminated was FFD, based on its significance, followed
by FFL, BUI and DMC. The three assumptions that have to be met in this procedure for the regression equation are; errors are normally distributed, errors show homoscedasticity, and the observations are independent. Figure A2.2 illustrates the summary of the final model which is: FFC = 1.28-0.040(BD) + 0.0036(DC) (1) after outliers were removed, as discussed below. Where FFC [kg/m²] = forest floor consumption, BD [g/cm³] = bulk density and DC = drought code.

**Table A2.3** Stepwise procedure –variables selection based on R-square

<table>
<thead>
<tr>
<th>Equations</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>FFC=0.842-0.0315(FFD)+0.0257(FFL)+0.013(BUI)-0.009(DMC)-0.0314(BD)+0.0021(DC)</td>
<td>0.70</td>
</tr>
<tr>
<td>FFC=0.68+0.193(FFL)+0.0122(BUI)-0.009(DMC)-0.0286(BD)+0.0027(DC)</td>
<td>0.69</td>
</tr>
<tr>
<td>FFC=0.954+0.0108(BUI)-0.0105(DMC)-0.0275(BD)+0.0029(DC)</td>
<td>0.67</td>
</tr>
<tr>
<td>FFC=1.080-0.0059(DMC)-0.026(BD)+0.0041(DC)</td>
<td>0.6446</td>
</tr>
<tr>
<td>FFC=1.25-0.040(BD)+0.0036(DC)</td>
<td>0.619</td>
</tr>
</tbody>
</table>

**Table A2.4** Significance and summary statistics (including Mallow’s Cp) of the independent variables eliminated in the stepwise procedure.

<table>
<thead>
<tr>
<th>Step</th>
<th>Variable removed</th>
<th>Number of variables</th>
<th>Partial R²</th>
<th>Model R²</th>
<th>C(p)</th>
<th>F value</th>
<th>Pr &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>FFD</td>
<td>6</td>
<td>0.0112</td>
<td>0.6918</td>
<td>7.0537</td>
<td>1.05</td>
<td>0.3134</td>
</tr>
<tr>
<td>2</td>
<td>FFL</td>
<td>5</td>
<td>0.0218</td>
<td>0.026700</td>
<td>7.1049</td>
<td>2.05</td>
<td>0.1632</td>
</tr>
<tr>
<td>3</td>
<td>BUI</td>
<td>4</td>
<td>0.0254</td>
<td>0.6447</td>
<td>7.4951</td>
<td>2.31</td>
<td>0.1394</td>
</tr>
<tr>
<td>4</td>
<td>DMC</td>
<td>3</td>
<td>0.0248</td>
<td>0.6199</td>
<td>7.8323</td>
<td>2.16</td>
<td>0.1514</td>
</tr>
</tbody>
</table>
Data outliers

At this stage in the development of the final FFC regression equation, it is appropriate to test for outliers and influential observations. These particular observations have to be studied individually, so that a decision can be made as to whether they should be retained or eliminated from the analysis (Neter et al. 1996).

A test based on the distribution of the Durbin-Watson statistic, $d$. Durbin-Watson bounds was done that are dependent on the level of significance (already established at $\alpha=0.05$), the number of observations and the number of independent variables. If calculated $d$ is larger than the upper
Durbin-Watson bound, then the errors are independent, if \( d \) is smaller than the lower bound then the errors can be correlated and if \( d \) is between the upper and lower bounds the test is inconclusive (Neter et al. 1996). Two FFC observations were determined as being outliers and eliminated from the FFC data set. Without the two outliers, the independent variable coefficients showed higher coefficient of determination (Table A2.5, A2.6). The chosen FFC model was:

\[
\text{FFC} = 1.28 - 0.040(BD) + 0.0036(DC) \tag{1}
\]

The model fit is R-square = 0.69, and this is the final version of the equation used for the estimation of the Forest Floor Consumption.

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Sum of Squares</th>
<th>Mean Square</th>
<th>F value</th>
<th>Pr &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>3</td>
<td>2.932</td>
<td>0.977</td>
<td>21.05</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Error</td>
<td>30</td>
<td>1.393</td>
<td>0.046</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total Corrected</td>
<td>33</td>
<td>4.325</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

**Table A2.6** Intercept and independent variable estimates and their significance in the final FFC regression model (after the elimination of two outliers).

| Parameter | Estimate | Standard Error | t value | Pr > |t| |
|-----------|----------|----------------|---------|-------|-----|
| Intercept | 1.287    | 0.154          | 8.33    | <.0001|
| BD        | -0.041   | 0.006          | -6.49   | <.0001|
| DC        | 0.004    | 0.001          | 5.92    | <.0001|

**Modeling interaction**

Since there is more than one independent variable in the final FFC regression equation and one of those is a categorical variable, then there is a possibility that the variables interact with each other. Interaction of the independent variables refers to the manner of which explanatory variables combine to affect the response variable (Belsley et al. 1980). If the independent variables interact, there is a possibility to use this aspect to improve the model fit. A linear
model was used to detect the potential interactions between the independent variables and the potential benefits for model performance.

Transformations usually express more powerfully the interactions between the independent variables. In order to identify these potential transformations of the variables, two difficulties have to be overcome: the identification of the association of the variables that makes the correlation strong; and the identification of the function that links the selected variables.

Usually, combinations of variables are dependent on the function that connects them and information regarding the association between the variables can be drawn from the literature. Another approach is based on information provided by plotting the variables on scatter graphs. Building a new composite variable consisting of a combination of other variables is one of the most difficult actions in modeling and involves the assumptions of normal distribution, homoscedasticity and absence of correlation errors (Aiken and West 1991; Curran et al. 2004).

For this particular case, based on information from the literature and from the data scatter plots, the following transformations were considered:

\[
X_1 = BD \times F_{type}
\]
\[
X_2 = DC \times F_{type}
\]
\[
X_3 = BD \times DC \times F_{type}
\]
\[
X_4 = BD \times DC
\]

Where,
\[
F_{type} = 0 \text{ for C3, } F_{type} = 1 \text{ for C4.}
\]

Using the transformed variables, a linear model was used that utilized the same backward elimination procedure, with the results presented in Tables A2.7, A2.8, and A2.9 and Figure A2.3.

**Table A2.7** ANOVA summary for the interaction model

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Sum of Squares</th>
<th>Mean Square</th>
<th>F Value</th>
<th>Pr &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>4</td>
<td>3.26469</td>
<td>0.81617</td>
<td>19.92</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Error</td>
<td>31</td>
<td>1.26985</td>
<td>0.04096</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corrected Total</td>
<td>35</td>
<td>4.53453</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Table A2.8 Summary statistics for the variables used in the interaction model

<table>
<thead>
<tr>
<th>Variable</th>
<th>Parameter Estimate</th>
<th>Standard Error</th>
<th>Type II SS</th>
<th>F Value</th>
<th>Pr &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>0.18982</td>
<td>0.10799</td>
<td>0.12656</td>
<td>3.09</td>
<td>0.0887</td>
</tr>
<tr>
<td>Ftype</td>
<td>-2.55216</td>
<td>0.93766</td>
<td>0.30347</td>
<td>7.41</td>
<td>0.0106</td>
</tr>
<tr>
<td>DC</td>
<td>0.00714</td>
<td>0.00104</td>
<td>1.94165</td>
<td>47.40</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>X1</td>
<td>0.11579</td>
<td>0.03789</td>
<td>0.38259</td>
<td>9.34</td>
<td>0.0046</td>
</tr>
<tr>
<td>X4</td>
<td>-0.00020</td>
<td>0.00003</td>
<td>2.02364</td>
<td>49.40</td>
<td>&lt;.0001</td>
</tr>
</tbody>
</table>

### Table A2.9 Summary of backward elimination procedure results for the interaction model

<table>
<thead>
<tr>
<th>Step</th>
<th>Variable Removed</th>
<th>Label</th>
<th>Number of Variables</th>
<th>Partial R-Square</th>
<th>Model R-Square</th>
<th>C(p)</th>
<th>F Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>X3</td>
<td>X3</td>
<td>6</td>
<td>0.0001</td>
<td>0.7417</td>
<td>6.0111</td>
<td>0.01</td>
</tr>
<tr>
<td>2</td>
<td>BD</td>
<td>BD</td>
<td>5</td>
<td>0.0020</td>
<td>0.7397</td>
<td>4.2287</td>
<td>0.23</td>
</tr>
<tr>
<td>3</td>
<td>X2</td>
<td>X2</td>
<td>4</td>
<td>0.0197</td>
<td>0.7200</td>
<td>4.3689</td>
<td>2.27</td>
</tr>
</tbody>
</table>
Fig A2.3 Residual plots for the interaction model

After replacing the variables the model became:

\[ FFC = 0.18982 + 2.55216(F\text{type}) + 0.00714(DC) + 0.11579(BD \times F\text{type}) - 0.00019817(BD \times DC) \]  
(2)

And after replacing the categorical dependent variable the models are:

\[ FFC = 0.19 + 0.007(DC) - 0.0002(BD \times DC) \] (C3-fuel type)

\[ FFC = -2.363 + 0.007(DC) + 0.1158(BD) - 0.0002(BD \times DC) \] (C4-fuel type)

The model (2) fit is slightly better than model (1) with \( R^2 = 0.72 \). However, the estimates produced by model (2) became bias when the model was applied to extreme values of the FWI codes and indices (e.g. DC, see Fig 3.4). Combining this with the fact that model (2) is a 3rd degree polynomial function, I decided to use model (1): \( (FFC = 1.28 - 0.040\text{ (BD)} + 0.0036\text{ (DC)}) \) for the fire severity matrix construction. Where FFC [kg/m²] = forest floor consumption, BD[g/cm³]=bulk density and DC=drought code.
Appendix 3

Severity matrices developed using equations C31 and C41

Fig A3.1 Fire severity matrix with cell probabilities as percentages for Brenda weather station in a mature lodgepole pine dominated forest (C3). Dead biomass consumption is separated into forest floor fuel consumption (FFC) and surface fuel consumption (SFC). SFC was estimated using equation C31 (Table 3.6). Live crown biomass consumption is represented by CFB.
Figure A3.2 Fire severity matrix with cell probabilities as percentages for Spruce weather station in a mature lodgepole pine dominated forest (C3). Dead biomass consumption is separated into forest floor fuel consumption (FFC) and surface fuel consumption (SFC). SFC was estimated using equation C31 (Table 3.6). Live crown biomass consumption is represented by CFB.
Figure A3.3 Fire severity matrix with cell probabilities as percentages for Brenda weather station in an immature lodgepole pine dominated forest (C4). Dead biomass consumption is separated into forest floor fuel consumption (FFC) and surface fuel consumption (SFC). SFC was estimated using equation C41 (Table 3.6). Live crown biomass consumption is represented by CFB.
Figure A3.4 Fire severity matrix with cell probabilities as percentages for Spruce weather station in an immature lodgepole pine dominated forest (C4). Dead biomass consumption is separated into forest floor fuel consumption (FFC) and surface fuel consumption (SFC). SFC was estimated using equation C41 (Table 3.6). Live crown biomass consumption is represented by CFB.
Table A3.1 Fire severity matrix with cell probabilities as percentages for Brenda and Spruce weather station in a mature lodgepole pine dominated forest (C3). Dead biomass consumption is separated into forest floor fuel consumption (FFC) and surface fuel consumption (SFC). SFC was estimated using equation C31 (Table 3.6). Live crown biomass consumption is represented by CFB.

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>Weather Station</th>
<th>Dead biomass</th>
<th>Live biomass</th>
</tr>
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Table A3.2 Fire severity matrix with cell probabilities as percentages for Brenda and Spruce weather station in an immature lodgepole pine dominated forest (C4). Dead biomass consumption is separated into forest floor fuel consumption (FFC) and surface fuel consumption (SFC). SFC was estimated using equation C41 (Table 3.6). Live crown biomass consumption is represented by CFB.

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