University of Alberta

The occurrence of splits and insects in fire-killed trees

by

Nobutaka Nakamura ©

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Abstract

The occurrence of splits and insects in fire-killed trees in Alberta was studied by calculating frequency of trees with splits and insect damages at the time of about one year after fire. The frequency of splits was greater in black spruce (*Picea mariana* (Mill.) B.S.P.) than in lodgepole pine (*Pinus contorta* Dougl. ex Loud.). Frequency of splits decreased with size of tree in lodgepole pine. The white-spotted sawyer beetle *(Monochamus scutellatus* [Say]) was the insect most commonly observed in the fire-killed trees sampled. Moisture content in fire-killed white spruce trees (*Picea glauca* [Moench] Voss) was measured at the time of 1.5, 2.5 and 3.5 months after fire to determine the moisture content change in the tree boles. The moisture content decreased with time after fire; and it was higher in large trees than small trees. Splits were first observed 3.5 months after fire in the fire-killed trees.

Acknowledgement

First of all, I must thank my supervisors Dr. Lars Bach, a wood scientist, and Dr. Paul M. Woodard, a fire scientist, for their great guidance and support throughout my graduate program. I should also mention that Dr. Bach was particularly generous with financial support during the early stages of my academic program. In addition, he provided me the opportunity to work at the Alberta Research Council on some of his NSERC supported research.

This thesis research would not have started without the vision of my supervisors who introduced me to the need for such work. They also arranged for me to visit Millar Western Forest Product Ltd.'s salvage operations after the Virginia Hills Fire of 1998. This fire, near Whitecourt, Alberta was extremely large and it was at that time I became aware of the need for understanding the post-burn deterioration in trees. I must also thank Mr. Bruce West and many other people at Millar Western Forest Product Ltd. for supporting my work while I did field research in their Forest Management Agreement area.

In the process of developing this thesis research, I got many useful ideas and suggestions from the other members of my supervisory committee: Dr. Peter Blenis, a forest pathologist in the Department of Renewable Resources, Dr. John Spence, an entomologist in the Department of Biological Sciences in the Faculty of Science, and Dr. Uldis Silins, a forest hydrologist in the Department of Renewable Resources. I thank all of them for their time and support for my thesis work. Lastly, I thank Dr. Grant Hauer, a forester/economist in the Department of Rural Economy, who read the thesis and participated in the defense of the thesis because Dr. Spence had to depart on sabbatical.

The data collections were done with the generous supports from many organisations and individuals. The Millar Western Forest Products Ltd. provided me with maps of the fire, information on how to access the burned sites and a radio during the field samplings around Whitecourt, Alberta. During field sampling they served as my lifeline. Satoshi Tamai helped me with the field sampling in Whitecourt area. The Christina River Catering of Lac La Biche, Alberta provided me with discounted yet comfortable accommodation during my filed sampling of the fires in the Lac La Biche

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Chapter 1. INTRODUCTION

1.1 Introduction

Fire is a natural disturbance in the Boreal Forest Biome of the world. Fires in this forest area are generally characterized as high intensity (Byram 1953), stand replacing (high severity) and large in area (Johnson 1992). In Canada, fires are commonly greater than 100,000 ha in size, and fire return intervals average 100 years (Johnson 1992). Hence, it is widely known that forest fire plays an important role in the plant and animal diversity of this circumpolar biome (Lutz 1956, Slaughter et al. 1971, Rowe and Scotter 1973, Kelsall et al. 1977, Johnson 1992, Schimmel and Granstrom 1996).

There have been many severe fire years in Canada. However, the year "*1995*", stands out as one of the most notable fire years in history of this country (Natural Resources Canada 1997). During that year over 6,570,000 ha of forest were burned, and of this area over 1,240,000 ha were fully stocked and highly productive. It is interesting to note the area disturbed by fire in 1995 was greater than the 1,011,000 ha of the land area that was timber harvested in that year (Natural Resources Canada 1997). Due to the exceptional fire season of 1995, the damages in merchantable timber and future impact on annual harvest caused by the fires became issues of concern for the forest companies and governments in western Canada (FREIC 1997).

Fire-killed trees are commonly "salvage" logged. Salvage cutting is the harvest of dead, dying, damaged, or deteriorating trees to recover merchantable wood after such natural disturbances as windstorm, insect infestation, disease outbreaks or wildfire (Wenger 1984). To efficiently salvage log an area, a forester needs information on: (1) the locations of the damaged timber, (2) the volume and value of the timber, and (3) the rate and nature of deterioration in the affected trees (Wright et al. 1956). Of the information needed, the location, volume and value of the damaged timber can be readily obtained by inventorying the affected stands. The rate and nature of deterioration in damaged trees may be estimated from the past studies if they exist. However, this information is often lacking.

During May and June in 1998, more than 370,000 ha of forested land in the Whitecourt Forest District in the Province of Alberta (FERIC 1998) were burned or disturbed by a wildfire. Stands of white spruce (*Picea glauca* [Moench] Voss), black spruce (*P. mariana* [Mill.] BSP), lodgepole pine (*Pinus contorta* Dougl. Ex Loud.) and popular (*Populus tremuloides* Michx. and *P. balsamifera* L.) were burned. This fire was named the Virginia Hills Fire. Following the fire, local logging companies immediately commenced salvage logging operations. They felt obligated to do this in an attempt to reduce the losses to their annual allowable cut (AAC). In reality they had little knowledge of how this fire-killed wood would deteriorate over time.

The goal of this study was to investigate the rate and type of deterioration in fire-killed trees in Alberta. Specifically, I looked at how fire-killed spruce and pine trees are deteriorated by checks/splits and by insects. In Alberta, checking (splitting) is known to be one of the dominant factors in the deterioration of fire-killed trees (Szabo and Kasper 1971); but the rate and nature of physical deterioration by checks/splits is not well understood. This information will help forest managers to efficiently harvest merchantable wood before it's volume and the values associated with it are lost due to checking and splitting.

1.2 Objectives

The objectives of this study were:

O_1. To determine if aspect of slope, tree species, tree size influenced frequency of splits in fire-killed trees,

O_2. To document the change of stem moisture content in fire-killed trees, and

O_3. To record the frequency of insect damage in fire-killed trees.

Specifically, since there is little information available on the formation of splits in standing fire-killed white spruce, black spruce and lodgepole pine trees in Alberta, I observed split formation in fire-killed trees in an attempt to answer the following questions.

- How frequently do fire-killed trees of these species split within one field season after burning?
- What is the type and height of splits in these fire-killed trees?

- In which orientation (N, NE, E, SE, S, SW, W, NW) do splits occur in fire-killed trees?

The first objective (O_1) was to determine the factors influencing on frequency of splits within the two species (black spruce, lodgepole pine). Specifically, three factors (aspect of slope, species of tree, size of tree) were selected in an attempt to answer the following questions:

- Does aspect of slope influence on frequency of splits in fire-killed trees?
- Does species of tree influence on frequency of splits in fire-killed trees?
- Does size of tree influence on frequency of splits in fire-killed trees?

The second objective (O_2) was to determine when splits occur as a result of rapid dehydration and the associated shrinkages in fire-killed trees. Since there is little information on moisture content change and moisture gradient in fire-killed trees, the specific objective was to know how moisture content changes in fire-killed trees with time after fire. The following questions were asked:

- Are there any significant differences in moisture content among trees sampled at different times after fire?
- Are there any significant differences in moisture content among trees of different sizes?
- Are there any significant differences in moisture content among orientations (north, east, south, west) of tree?

The third objective (O_3.) was to assess the onset of insect damage. Although the focused in this study was the physical degradation in fire-killed trees, the biological degradation by insects was also studied. The specific objective of this minor phase of the study was to observe the occurrence of insects in fire-killed trees. I did this by asking the following question.

- Are there any factors (aspect of slope, species of tree, size of tree) related to frequency of insect damage?

Chapter 2. LITERATURE REVIEW

2.1 Salvage logging and utilisation of fire-killed tree

Salvage logging for the purpose of utilizing the fire-killed trees is important when a large fire occurs in an area that contains a large amount of merchantable wood (Bradner and Anderson 1930, Baumgartner 1987, Henly 1988). This fire-killed wood can be extremely valuable (Kemp 1967) and the loss of merchantable volume can significantly affect the annual allowable cut (AAC) for the area (Van Wagner, 1983, Montgomery et al. 1986, Singh 1990, Martell 1994, Boychuk and Martell 1996).

One of the important concerns relative to utilising fire-killed trees centers around the direct effects of fire on wood properties. It is known that high temperature affects the structure of wood cells and decreases mechanical properties of wood (Kollmann and Sachs 1967, Knudson and Williamson 1971, Knudson and Schniewind 1975, Schaffer 1977, Gerhards 1982). Specifically, when the thermal environment surrounding or adjacent to the tree exceeds 100°C, dehydration within the wood is accelerated. At temperatures between 130°C and 190°C, lignin and hemicellulose begin to degrade. At temperatures between 200°C and 280°C, cellulose undergoes chemical dehydration (Pyne et al. 1996). The degradation of the principal wood components results in a decrease in the mechanical properties of wood.

Pyrolysis is a chemical decomposition occurring as a result of high temperature wherein the chemical components of wood decompose into gases such as carbon dioxide and hydrocarbons (Goldstein 1973). These are the gases that contribute most to the combustion processes. The production of pyrolysates is accelerated at temperatures around 250°C and 280°C. At temperatures between 280°C to 320°C, exothermic reactions dominate and at the upper temperature levels large quantities of flammable gases are produced. Hot gases may appear as flames when temperatures reach or exceed 425°C to 480°C (Pyne et al. 1996).

Although few studies have documented the effects of heat from a wildfire on wood properties in a standing live tree during and after natural fires, it is generally considered that fire has little effect on wood tissue because of the protection afforded by bark (Fahenstock and Hare 1964, Hare 1965, Vines 1968, Ryan and Reinhardst 1988, Hengst and Dawson 1994) and the high moisture content of the wood. Onodera et al. (1971) found that only about 10 layers of cells from the surface of tree trunk were deformed by heat. Wood from fire-killed trees can have the same mechanical properties and pulp strength properties as those of wood from green trees (Knapp 1912; Onodera et al. 1971; Lowe 1996). However, it is well known that charcoal on bark and wood causes problems in the pulping process and difficulties with the debarking (Lowe 1996; Krilov and Ingate 1984).

Quality and market value of fire-killed trees are another important concern for utilising fire-killed trees. The quality and market value of dead trees had been studied in insect-killed trees (Snellgrove and Fahey 1977, Dobie and Wright 1978, Sinclair and Ifju 1979, Lowery and Pellerin 1982), wind-blown trees (Peralta et al.1993, Faust 1994), and fire-killed trees (Willits and Sampson 1988). These studies provide information of how defects in dead trees influenced the merchantable values of these stems and how long this value is maintained. Willits and Sampson (1988) stated that checking, damage from wood borers, blue stain, and spiral grain in combination with the checking were the defects commonly found in fire-killed trees. They reported all of these outcomes could significantly reduce the value of the wood in these trees.

2.2 Deterioration of fire-killed tree

Weathering, insects, and fungus are the main causes of deterioration of fire-killed trees. The deterioration of fire-killed trees has been studied in the different regions of the world. Specifically, Lowell et al. (1992) reviews the work done in North America. Whereas, Wright and Grose (1970) report on work done in Australia and Onodera et al. (1971) discusses work in Japan. Interestingly, most studies have found that the same species of organisms are responsible for the deterioration commonly found in fire-killed trees regardless of location. However, the rates of deterioration are different among the regions due mostly to variation in climate and forest types. In the following sections, the physical and biological deterioration of dead or dying trees are reviewed based on literature pertaining to studies preformed in North America.

Physical deterioration

The physical deterioration in fire-killed trees is caused by weather checks/splits. Weather checks/splits are lengthwise separations of wood that occur due to rapid drying and the associated shrinkage in wood tissue. Weather checks/splits significantly reduce the merchantable value of fire-killed tree for saw logs. However, the magnitude of the effects depends greatly on the length and depth of checks/splits in the tree bole. Szabo and Kasper (1971) studied checking and splitting in fire-killed lodgepole pine and white spruce in Alberta. They found that spiral check caused more damage than straight check; maximum check depth occurred in the top portion of the first log and/or the bottom portion of the second log. Although weather checks/splits are believed to be caused by rapid dehydration in fire-killed trees, I found few studies on the relationship between the change of moisture content and the formation of weather checks/splits.

Biological deterioration

Knapp (1912) reported bark beetles were often the first agents to begin the deterioration process. Bark beetles feed mainly on cambium and shallow sapwood; thus their effect is relatively minor. Wood borers often cause greater damage because they penetrate deeper in sapwood tissue. The white-spotted sawyer beetle (*Monochamus scutellatus* [Say]) is one of the most common wood borers known to use fire-killed trees (Richmond and Lejeune 1945, Gardiner 1957). Their period of attraction to fire-injured trees can last up to three field seasons; but the highest concentration of beetles are commonly found within the first season after the fire (Miller and Patterson 1927).

Blue stain fungi (*Ophiostoma spps.* Syd. & P. Syd.) is often found in fire disturbed trees because it is generally carried by the various bark beetles (*Dendroctonus* and *Ips* species), which are know to attack fire-weakened trees (Furniss 1965, Geiszler et al. 1984, Rasmussen et al. 1996). Blue stain seems to be most prevalent during the first year after burning, and it degrades the value of merchantable wood because of the colour of the stain (Leach and Orr 1934, Lowell and Cahill 1996, Hood and Ramsden 1997). Wood decay fungi colonize in fire-killed trees through infection courts such as insect holes and weather checks or splits (Basham 1957). Commonly, they appear in the second year as sap rot and progresses to heart rot by third year (Wallis et al. 1974, Lowell and

Cahill 1996). Red belt fungus (*Fomitopsis pinicola*) is one of the most common wood decay fungi found in fire-killed trees (Basham 1957, Wallis et al. 1971).

The moisture content of a tree after a disturbance directly influences fungal and insect activities. The growth of fungi in wood is retarded when the average moisture content is between 25% and 30% and is arrested when it reaches 20% (Kimmey 1955, Panshin and de Zeeuw 1980). Blue stain occurs when the sapwood dries to 100-110% of moisture content (Hood and Ramsden 1997); and it develops best when the wood contained between 45% and 70% of moisture content (Wright and Grose 1970). Skolko (1947) found extremely dry fire-killed spruce trees did not exhibit fungal activities on sites that had been severely burned. Few insect attacks were observed in fire-killed trees, which maintained high moisture content after they were defoliated during the fire (Miller and Patterson 1927, Prebble and Gardiner 1958). In effect, the loss of the transpiration surface area caused the bole or stem moisture to be trapped for longer periods within the tree.

2.3 Split formation in wood logs

Splits (or cracks) occur in the boles of living and dead trees. Frost cracks, and drought cracks as well as cracks caused by lightning are known to be common stem cracks in living trees (Dietrichson et al. 1985). Frost cracks occur as a result of tension stress in the tangential direction of wood during long periods of low temperatures. Kubler (1983) stated that main cause of the tension stress was shrinkage due to freezing-out of cell wall moisture into lumens of wood cells. Sano (1996) suggested ice segregation in the internal shakes (separations between the rings of annual growth) strongly contributed to the occurrence of frost cracks. Drought cracks occur when trees have a water shortage and have false annual ring with abnormal cell division, enlargement and cell wall thickening (Dietrichson et al. 1985).

Splits occur in dead trees or logs when moisture is lost from the wood. As green wood dries, it first loses "free water", which is the water found in the lumens of wood cells. If drying continues, the wood will reach what is known as the fiber saturation point (FSP) (Haygreen and Bowyer 1996). The FSP is the moisture content at which no "free water" exists in the cell lumens, but the walls of wood cells are saturated with "bound water", which is chemically bounded with wood components (Haygreen and Bowyer 1996). The FSP of wood averages about 30%, but it can range from 20% and 35% depending on species and the difference in their structure and chemical compositions (Kollmann and Côté 1968, USFPL 1999).

The removal of free water above the FSP does not cause shrinkage of wood. However, wood starts shrinking once its moisture content is below the FSP. Wood shrinkage is the result of shrinkage in the cell walls in which wood fibers move close together after the water molecules between the cells are removed. The amount of shrinkage is proportional to the amount of water removed from the cell wall (Haygreen and Bowyer 1996). The shrinkage causes stress in wood, which is called drying stress (Panshin and de Zeeuw 1980). The greatest drying stress is encountered when the moisture gradient is the largest; and the smallest stress is encountered when the moisture content is uniformly distributed (Tauchert and Hsu 1977).

Splits in wood occur when the tensile stresses become greater than the cross-grain fracture strength (Hsu and Tang 1974). Hsu and Tang (1974) classify the drying stresses causing checks/splits as:

(1) drying stress caused by differential (anisotropic) shrinkage of wood;
(2) surface stress in drying wood surface whose shrinkage is restricted by moist layers underneath;
(3) drying stress related to the cylindrical anisotropy of wood.

The differential (anisotropic) shrinkage of wood is related to many of the common seasoning defects of wood, and the shrinkage behaviour of wood has been studied extensively by many researchers (Ylinen and Jumppanen 1967, Barrett et al. 1972). The dimensional change of wood are in the order of 0.1% to 0.3% longitudinally, 3% to 6% radially, and 6 to 12% tangentially as wood dries from fiber saturation to the completely dry condition (Skaar 1988). The differential shrinkage is caused by four dominant factors: (1) variations in lignification intensity between the radial and tangential walls of cells, (2) variations in cells wall thickness and shape of cell cross-sections between earlywood and latewood, (3) changes in microfibril angle between radial and tangential walls of cells, and (4) extractive contents of heartwood (Boyd 1974). The differential shrinkage causes tension stresses around the circumference of wood (tangential face of wood) because of difference between shrinkage ratio in the circumference and radius of the log.

The surface stress is a drying stress, which develops in the drying surface of wood. At the beginning of drying, the surface layers of the bole wood lose moisture and contract, but the shrinkage of the layer is restricted by moist wood underlying it (Hsu and Tang 1974). Specifically, the outer wood cells are stressed in tension and the inner cells are stressed in compression (Hsu and Tang 1974).

The stress related to the cylindrical anisotropy of wood has rarely been investigated, but Hsu and Tang (1974) stated "... the three orthogonal symmetry axes (longitudinal, radial, and tangential axes of the cylindrical wood log) are not all fixed in space but rotated with respect to the cylindrical axis. Because of this peculiar anisotropy, large drying stresses are produced even if the material is homogeneous and the moisture content is the same throughout". As well as the drying stresses mentioned above, growth stress also can be a cause of splits in tree boles particularly in trees with large growth stress (Kubler 1974, Panshin and de Zeeuw 1980). Growth stress develops in most trees as result of a deposition and polymerization of lignin within the secondary wall during the maturation of fibrous cells (Panshin and de Zeeuw 1980).

2.4 Moisture content in wood

Moisture content (gravimetric) in wood is defined as the weight of water contained in the wood relative to the ovendry weight of wood. It is expressed as a ratio of the weight of water to the weight of the oven-dry wood. In wood technology terminology, it is customary to describe moisture content as percentage of moisture based on the dry weights (Kollmann and Côté 1968). The moisture content of green wood varies among species, within species and by locations within a single tree.

The variation of moisture content among species can be found in the average moisture content of green wood by species as listed in the Wood Handbook (USFPL 1999). The average moisture content of softwood species ranges from 31% for longleaf pine to 121% for baldcypress in heartwood. In the sapwood, moisture can range from 98% for Port-Orford cedar to 249% for western red cedar. In hardwood species, the average moisture content in heartwood ranges from 44% for rock elm to 162% for cottonwood. For sapwood the range varies from 44% for white ash to 146% for cottonwood. Generally, the moisture content of sapwood in softwood species is greater than that for the heartwood. In hardwood species, differences in moisture content between heartwood and sapwood depends on the species (USFPL 1999). The variation of moisture content within species depends on where the trees are grown, their age, and their volume (Haygreen and Bowyer 1996). Softwood species tend to have a lower overall moisture content as they age because the percent of sapwood volume declines (Haygreen and Bowyer 1996). The most significant variation of moisture content within a single tree is found between sapwood and heartwood. This variation is caused by accumulation of a variety of polyphenolic substances (extractives) in cell walls and lumens of the heartwood. These extractives tend to occupy the place of water molecules (Haygreen and Bowyer 1996). The stem moisture content within a single tree will also vary by height and within and among growing seasons (Skaar 1972).

When a tree is cut, girdled or killed, wood starts losing its moisture because translocation of water from the roots to leaves is interrupted. The moisture content of wood decreases as it approaches the equilibrium moisture content (EMC) at which point the wood neither gains nor losses moisture (USFPL 1999). The EMC of wood is determined based on the relative humidity, temperature, and whether wood is adsorbing or desorbing moisture (Kollmann and Côté 1968). The EMC of wood in desorption is higher than it in adsorption, and the ratio of adsorption EMC to desorption EMC is constant at 0.85 (USFPL 1999). The difference of EMC between in adsorption and desorption is called hysteresis, and this phenomenon has been well investigated by many researchers (Stamm 1964, Kollmann and Côté 1968). For practical uses, the EMC of wood is estimated under any given temperature and relative humidity as in Figure 1 (USFPL 1999).

2.5 Movement of water in wood

In the drying process, water in wood moves through such passages as the pit chambers, pit membranes of bordered pits, or through cell walls. The movement of water depends on whether the moisture content is above or below the fiber-saturation point (FSP) (Stamm 1964; Kollmann and Côté 1968; Hunter 1995). Above the FSP, water moves as a result of surface drying and capillary forces (Haygreen and Bowyer 1996). The capillary forces are caused by the differences of capillary pressures (capillary tensions) within the capillaries of wood (Kollmann and Côté 1968). In a capillary with internal radius r (m), the capillary pressure T (Pa) is given by the capillary-pressure equation as follows:

$$T = \frac{2\beta}{r} \tag{1}$$

where: β (kg/m) = surface tension of the water (Kollmann and Côté 1968, Skaar 1972). The different capillary pressures occur in capillaries of wood (tracheids and rays for softwood; vessels, fibers, and rays for hardwood) due to evaporation of water from one side of capillaries and different sizes of capillaries. Evaporation on wood surface causes tensile forces on the water beneath the surface, which pulls the water from the interior of wood (Mullins and McKnight 1981). The narrow capillaries draw water from the wide ones because tension force is stronger in narrow capillaries than wide ones (Kollmann and Côté 1968). The capillary flow continues to the surface as long as the rate of flow can equal the rate of loss of water by evaporation (Mullins and McKnight 1981).

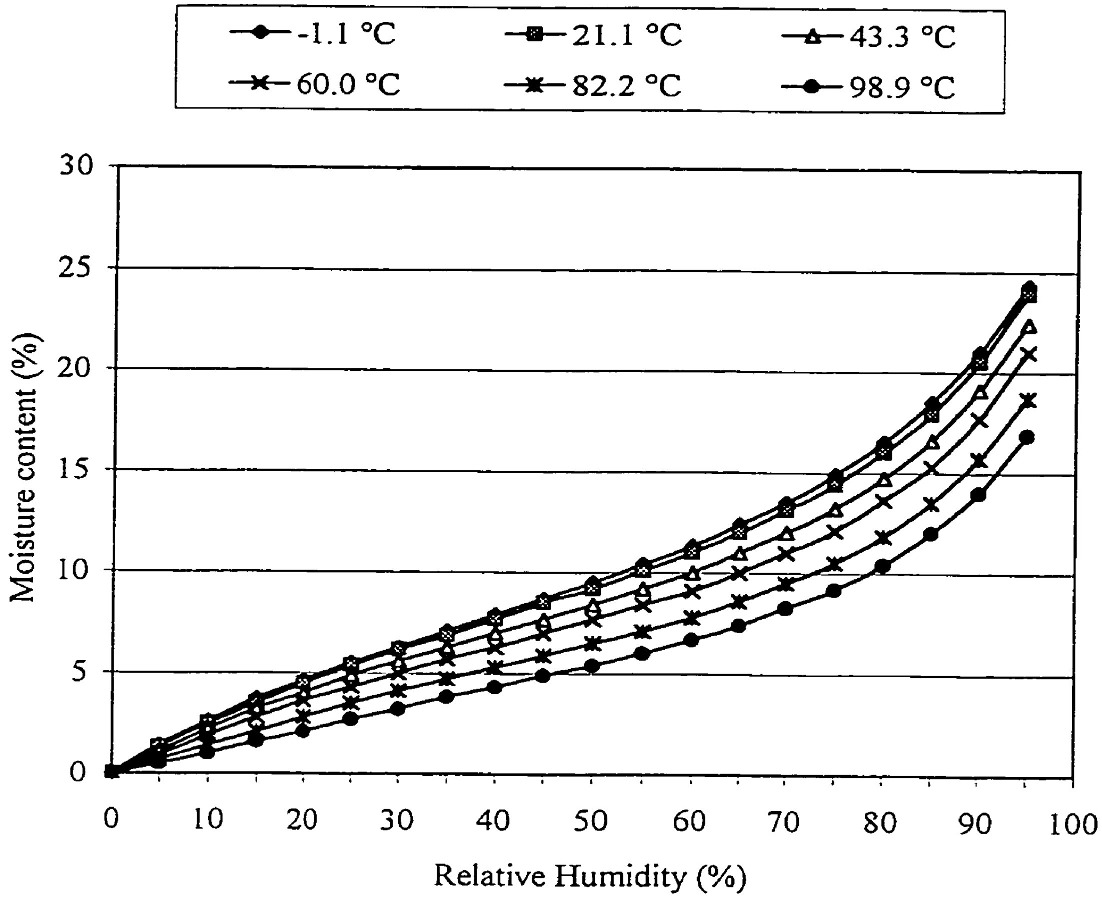

Figure 1. Equilibrium moisture content (EMC) of wood with temperature (°C) and relative humidity (%) (USFPL 1999).

Below the FSP, water moves by diffusion, usually as water vapor through the void structure (vapor diffusion) and as bound water through the cell walls (bound-water diffusion) (Stamm 1960a, 1960b, Choong 1963, Hart 1964, Kollmann and Côté 1968). Fick's first law of diffusion describes the diffusion phenomenon as:

$$F = -D\frac{dC}{dx} \tag{2}$$

where F is the rate of diffusion; D is a diffusion coefficient; and dC/dx is the concentration gradient, which is also known as the diffusion gradient (Kollmann and Côté 1968, Skaar 1972). The vapor diffusion occurs due to the vapor pressure gradient; and bound-water diffusion occurs due to the moisture gradient across the cells. The two types of diffusion occur simultaneously during drying in wood. In the first type of diffusion, moisture first passes through the cell walls by bound-water diffusion, where it evaporates into the cell lumen. The next water to move by diffusion passes across the lumen by vapor diffusion, where it is absorbed by the next cell wall (Stamm 1964, Kollmann and Côté 1968). The rate of diffusion is related to the temperature, the steepness of the moisture gradient across the cells, and the characteristics of species that determine the ease with which diffusion can occur (Haygreen and Bowyer 1996). It should be noted that although Fick's first law has been used to describe diffusion in wood, it has been suggested that water diffusion in wood is more complicated due to time dependent deformation of the cellulose-lignin matrix (Kollmann and Côté 1968) and the restriction of Fick's law to isothermal conditions (Bramhall 1979, 1995).

Chapter 3. STUDY AREA

Two study areas were selected for sampling. The Study Area 1 was located in the Whitecourt Forest District (54°07'N, 116°53'W) (Figure 2) in Alberta, Canada. In this study area, the frequency and location of bole splits were recorded in trees that had been fire-killed during the spring and summer of 1998. The fire, which served as this study area, was numbered N03-018-1998 by the Alberta Land and Forest Service, and was commonly known as "Virginia Hills Fire". This fire was started on May 4 1998 by lightning. It burned 370,000 ha of the forested land during May and June 1998 (FERIC 1998).

The area burned in the Study Area 1 occurred in the Upper Foothills and Lower Foothills natural sub region (Beckingham et al. 1996). The plant communities and forest stands in this area varied greatly across the range of conditions found within this "sub-region". The forest cover in the Lower Foothills sub-region is dominated by aspen (*Populus tremuloides*[1]), balsam poplar (*P. balsamifera*), and lodgepole pine (*Pinus contorta*). A list of the understory shrubs commonly found in this sub-region would include low-bush cranberry (*Viburnum edule*), prickly rose (*Rosa acicularis*), green alder (*Alnus crispa*) and Canada buffalo-berry (*Shepherdia canadensis*). The common forbs and grasses are wild sarsaparilla (*Aralia nudicaulis*), dewberry (*Rubus pubescens*), marsh reed grass (*Calamagrostis canadensis*) and hairy wild rye (*Elymus innovatus*) (Beckingham et al. 1996b). The elevation of this sub-region is varies from about 500 m to 1150 m (Beckingham et al. 1996). The elevation of the Upper Foothills sub-region can range from 900 m to 1500 m depending on geographic location (Beckingham et al. 1996).

The common tree species in this Upper Foothills sub-region are white spruce (*Picea glauca*), lodgepole pine, and black spruce (*Picea mariana*). On dry uplands white spruce and pine may be the dominant tree species, while in some stands they occur as co-dominates. In the wet areas, black spruce is the dominant overstory tree cover. A list

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[1] The scientific names of plants appeared in this chapter follow Beckingam and Archibald (1996) and Beckingham et al. (1996)

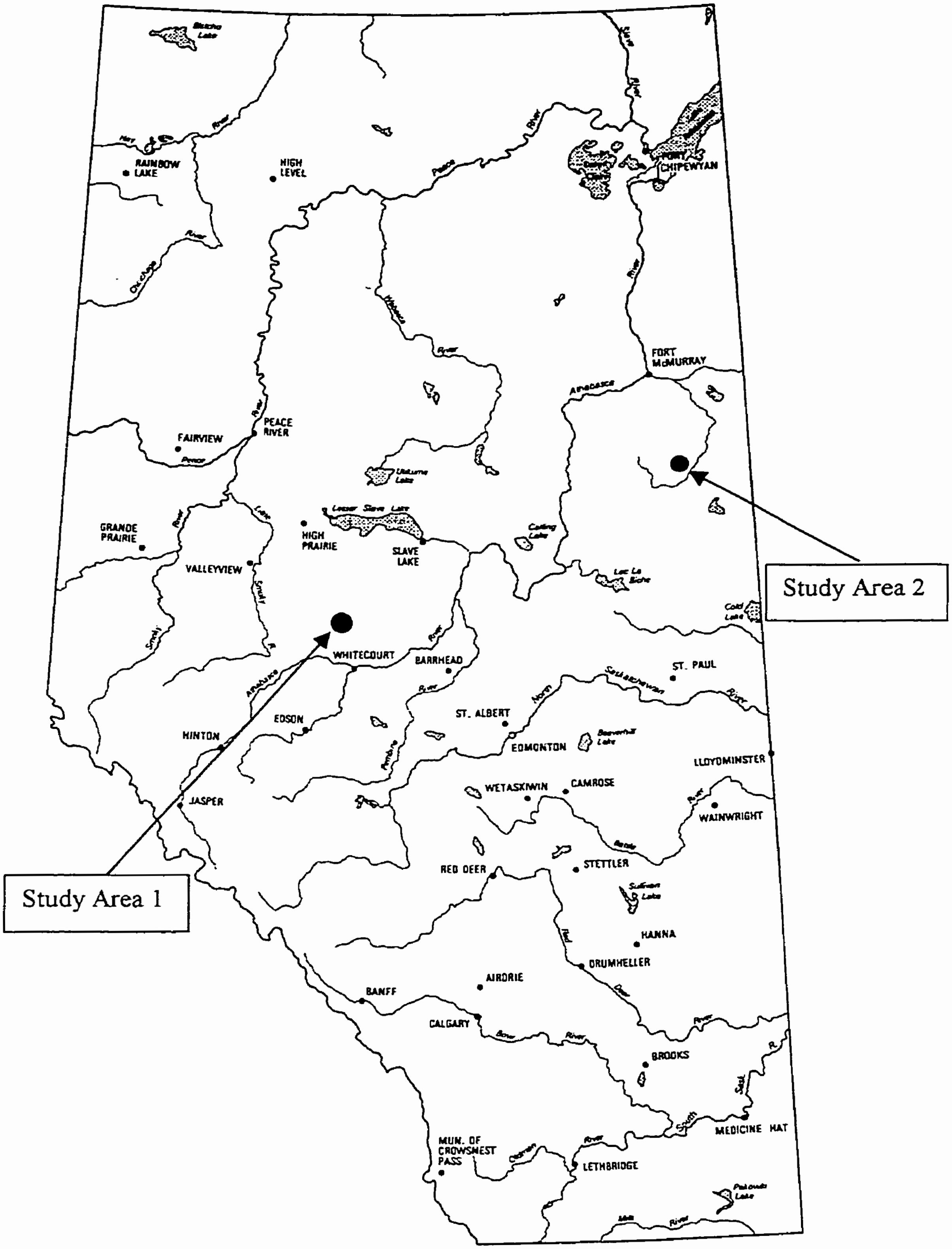


Figure 2. Map of the province of Alberta, Canada showing the locations of Study Area 1 (54°07'N, 116°53'W) and Study Area 2 (55°85'N, 110°95'W).

of common understory shrubs would include Labrador tea (*Ledum groenlandicum*), tall bilberry (*Vaccinium membranaceum*), bog cranberry (*Vaccinium vitis-idaea*) and green alder. The weather conditions vary greatly by location, sub-region and among years; the averages of the natural sub-regions are provided by Beckingham et al. (1996) (Table 1).

In the Study Area 2, the stem moisture content in fire-killed trees was measured and the formation of splits was observed at the time of 1.5-month, 2.5-months, and 3.5-months after burning. This study area was located in a burned forest stand in the Lac La Biche Forest District (55°85'N, 110°95'W) in Alberta, Canada (Figure 2). The Alberta Land and Forest Service numbered this fire E02-043-1999. This fire was started by lightning on May 25, 1999 and burned 900 ha of the productive land. The area is classified as Central Mixedwood in natural sub region (Beckingham and Archebald 1996). The Central Mixedwood is dominated by aspen, balsam fir, white birch (*Betula papyrifera*), white spruce and balsam fir (*Abies balsamea*). Dry and sandy sites tend to be dominated by jack pine (*Pinus banksiana*); and the forested wetland areas are dominated by black spruce and tamarack (*Larix laricina*). The common understory shrubs are beaked hazelnut (*Corylus cornuta*), prickly rose, low-bush cranberry, Saskatoon berry (*Amelanchier alnifolia*), Canada buffaloberry, twin-flower (*Linnaea borealis*) and green alder. The common understory forbs are bunchberry (*Cornus canadensis*), wild sarsaparilla and dewberry. The weather conditions vary greatly by location, but the average values for temperature, relative humidity (R.H.), wind and rain for the Boreal Mixedwood (an ecological area) are provided by Beckingham and Archebald (1996) (Table 1).

The sampling locations were randomly in each of the two study areas. However, the exact location of sampling was influenced by the availability of fire-killed stands and their location relative to the road. The 1999 field season was particularly wet. Rain in and around the burned sites was very frequent during the summer and produced very slippery conditions on extraction and haul roads, which are commonly constructed on the clay soils found in the area. Hence in the absence of funding or access to an all-terrain vehicle, this study selected stands that were close to all weather roads within the Green Zone. In the Study Area 1 many of the fire-killed trees had been salvaged over the winter

Table 1. Summary of climate data in (a) Lower Foothills and Upper Foothills of natural subregion (Beckingham and Archebald 1996) and (b) Boreal Mixedwood of ecological area (Beckingham et al. 1996).

(a)

Natural subregion	Lower Foothills	Upper Foothills
Summer (May-August)		
Mean typical temperatures (°C)	12.8	11.5
Minimum typical temperatures (°C)	6.9	5.9
Maximum typical temperatures (°C)	18.3	16.7
Total precipitation	295	340
Growing degree days	1008	752
Number of days < 0°C	8	13
Winter (November-February)		
Mean typical temperatures (°C)	-7.8	-6.0
Minimum typical temperatures (°C)	-14.3	-12.5
Maximum typical temperatures (°C)	-2.1	0.5
Total precipitation	60	60
Annual		
Total precipitation (mm)	464	538
Mean temperature (°C)	3.0	3.0

(b)

Ecological area	Boreal Mixedwood
Summer (May-August)	
Mean typical temperatures (°C)	13.7
Minimum typical temperatures (°C)	7.2
Maximum typical temperatures (°C)	20.2
Total precipitation	238
Growing degree days	1147
Number of days < 0°C	9
Winter (November-February)	
Mean typical temperatures (°C)	-11.9
Minimum typical temperatures (°C)	-17.2
Maximum typical temperatures (°C)	-6.5
Total precipitation	63
Annual	
Total precipitation (mm)	389
Mean temperature (°C)	1.5

Note: Typical temperatures were estimated by summing 25th and 75th percentile values; annual totals and means were estimated by summing median values (Strong 1992) .

(October through March) of 1998 and 1999. Therefore, many of the affected stands were not available for study. However, 14 stands were sampled at various locations along the Virginia Hills hauling road and the haul road maintained by Blue Ridge Lumber Ltd. of Blue Ridge, Alberta. There was no problem for access to the Study Area 2.

Fire-killed trees were sampled in severely burned stands in the Study Area 1. All trees regardless of size were killed as a direct result of burning. Evidence of the severity of the fire was obvious because all trees within the burned area were missing their foliage and small diameter branches. In most cases death was due to the consumption of the tree crown by fire. In addition much of the organic soil layer was consumed. The bark on all trees was badly charred over the whole surface area.

Chapter 4. METHODS

Occurrence of splits and insects

Fire-killed trees in the 14 stands in the Study Area 1 were sampled from half-circle plots, which measured 0.05 ha in size. A maximum of three plots for each of the different topographic characteristics (north-facing slope, flat, south-facing slope) was sampled at every sample location. In each plot, the following parameters were recorded:

1. Stand characteristics of the sample plot (aspect of slope, angle of slope, stem density),
2. Tree characteristics within the sample plot (species, height, diameter at breast height [DBH], which is at 1.3m above mean ground level), and
3. Burn type experienced within the sample plot based on a classification scheme by Richmond and Lejeune (1945) (Appendix 1).

Each tree was visually inspected to determine if it had splits/checks and insect holes on the tree bole. For each tree exhibiting a split, the position (relative height), orientation, and type of split (s) were recorded. Splits along the bole were stratified into one or more of the three sections of trees ("*bottom*" as bottom third of tree height, "*middle*" as middle third of tree height, "*top*" as top third of tree height). The orientation of each split was stratified relative to the eight directions (N, NE, E, SE, S, SW, W, NW). Splits were classified by type: "*straight*", "*spiral*", "*multiple*". The frequency of splits was calculated as percent of trees with splits in sampled trees in each plot, species, and DBH size class. The DBH size classes used were: Class 1 (10cm-14cm); Class 2 (15cm-19cm); Class 3 (20cm-24cm); Class 4 (25cm-29cm); and Class 5 (30cm-35cm). These sizes classes were used for the statistical analysis. Sampling for this phase of the study was done during three time periods: May 11-15, June 15-19, and June 29-July 1, 1999.

In the Study Area 2, three half-circle plots, 0.05 ha in size, were located yet widely spaced, within one burned stand. The observation and classification of splits followed procedure used in the Study Area 1. Sampling was preformed 1.5 months (July 9-11), 2.5 months (August 10-13), and 3.5 months (September 9-13, 1999) after the fire.

Measurement of moisture content

In the Study Area 2, fire-killed trees were sampled from within a single 1-ha plot in the burned stand while live trees were sampled as control trees from an adjacent unburned area. Moisture content was determined in "outer" wood (5cm in depth) for the all sampled trees. For the trees with DBH over 33cm, moisture content in the "inner" wood (5-10cm in depth) was also determined. One moisture content measurement was obtained from four cores taken at one point of a tree stem. The four cores (5.1 mm diameter, 5 cm long) were taken by increment borer at breast height (at 1.3 m above mean ground level) at every cardinal direction (north, east, south, west) in the outerwood and innerwood (Figure 3). The cores were stored in sealed plastic bags, and frozen within hours of extraction. Thermo-gravimetric techniques were used to determine moisture contents of the cores. Drying occurred in a forced-air oven for 24 hours at a temperature of 105°C.

Moisture content (MC) were calculated as percent moisture content from green weight (GW) and ovendry weight (ODW) as follows:

$$MC(\%) = \frac{(GW - ODW)}{ODW} \times 100 \qquad (1)$$

The cores were sampled at 1.5 months (45-47 days), 2.5 months (77-81 days), and 3.5 months (107-110 days) after the fire or during the periods of July 9-11, August 10-13, and September 9-13, 1999, respectively. The sampled trees were stratified into three DBH size classes (Class 1 [15cm-22cm]; Class 2 [23cm-33cm]; and Class 3 [>33cm]) for the purpose of statistical analysis. Averages of moisture content values in the 4 cardinal directions of a tree were calculated; and they are referred as moisture content in a tree.

Figure 3. Sampling of wood cores by increment borer.

Statistical analysis

A chi-square test was conducted to determine the associations between "species of tree" and "type of splits", and between "type of splits" and "position of splits". The "orientation of splits" was also analyzed with the chi-square test to determine if the frequency of splits was significantly different among orientations. The chi-square tests were conducted with PROC FREQ procedure of the SAS software (The SAS institute 1990).

The effects of various factors (aspect of slope, tree species, tree size) on split frequency were tested with the analysis of variance (ANOVA) using a split-plot design as shown by Model 1, below. The ANOVAs were conduced with PROC MIXED procedure of the SAS software (The SAS institute 1990).

Model 1: $Y_{ijkl} = \mu + \beta_i + C_l + (\beta C)_{il} + A_j + B_k + (AB)_{jk} + (AC)_{jl} + (BC)_{kl} + (ABC)_{ikl} + \varepsilon_{ijkl}$

where: Y_{ijkl} is the frequency of splits at i^{th} level of β (block), j^{th} level of A (species of tree), k^{th} level of B (size of tree) and l^{th} level of C (aspect of slope);

μ is an overall mean;

β_i is the random effect of block (stand);

A_j is the fixed effect of species of tree ($j=2$);

B_k is the fixed effect of size of tree ($k=3$ or 4);

C_l is the fixed effect of aspect of slope ($l=3$);

$(\beta C)_{il}$ is the random interaction effect;

$(AB)_{ik}$, $(AC)_{il}$, $(BC)_{kl}$, $(ABC)_{ikl}$ are the fixed interaction effects;

ε_{ijkl} are the error terms;

i is any given block;

j is any given species of tree, lodgepole pine or black spruce;

k is any given size of tree, DBH size class of 1,2,3, or 4;

l is any given aspect of slope, north, flat, or south.

The repeated-measures of moisture content were analyzed using multivariate analysis of variance (MANOVA). The significant effects of the between-subject factors (time after fire, size of tree) and the within-subject factor (orientation of tree) on moisture content of outerwood were tested with Model 3; and the significant effects of the between-subject factor (time after fire) and the within-subject factors (orientation of tree, depth of wood) on moisture content of trees in DBH size class 3 (DBH: >33cm) were tested with Model 4. The MANOVAs were conducted with PROC GLM procedure of the SAS software (The SAS institute 1990). If any effects of the factors were significant, individual ANOVAs (F-tests) were conducted on each of the contrasts among and between the levels of the factors.

Model 2: $Y_{ijkl} = \mu + \beta_i + T_j + S_k + (TS)_{jk} + \varepsilon_{ijkl}$

where: Y_{ijkl} is the vector of moisture content for the four orientations of tree ($l=1$ to 4) at i^{th} level of β (block), j^{th} level of T (time after fire), and k^{th} level of S (size of tree);

μ is the vector for overall means;

β_i is the vector for random effect of block (tree);

T_j is the vector for fixed effect of time after fire ($j=3$);

S_k is the vector for fixed effect of size of tree ($k=3$);

$(TS)_{jk}$ is the vector for fixed interaction effect;

ε_{ijkl} is the error term;

i is any given tree;

j is any given time after fire, 1.5 months, 2.5 months, or 3.5 months;

k is any given size of tree, DBH size class of 1,2, or 3;

l is any given orientation of tree, north, east, south or west.

Model 3: $Y_{ijkl} = \mu + \beta_i + T_j + \varepsilon_{ijkl}$

where: Y_{ijkl} is the matrix of moisture content for the four orientations of tree (O) ($k=1$ to 4), the two depths of wood (D) ($l=1$ to 2), and the interaction of O and D at i^{th} level of β (block), j^{th} level of T (time after fire);

μ is the matrix for overall means;

β_i is the matrix for random effect of block (tree);

T_j is the matrix of fixed effect of time after fire ($j=3$);

ε_{ijkl} is the error term;

j is any given time after fire, 1.5 months, 2.5 months, or 3.5 months;

k is any given orientation, north, east, south, or west;

l is any given depth of wood, outerwood or innerwood.

For all the statistical analyses conducted in this study, the probability (pr=0.05) was used to determine statistical significance.

Chapter 5. RESULTS

5.1. Observation of fire-killed tree

5.1.1 Characteristics of sampled plots and trees

In the Study Area 1, fire-killed trees were sampled in the 23 plots, which were established in 14 different stands. Eight of the plots were on north-facing slopes, nine were on flat terrain, and six were located on south-facing slopes. The stem density within the plots ranged from 200 to 2600 trees/ha. There were on average 1300 trees/ha (standard deviation [SD]=500 trees/ha). The characteristics of sampled plots were summarised in Table A-1 (Appendix 2).

A total of 1485 trees were sampled within the 23 plots. The main tree species in the plots were lodgepole pine (*Pinus contorta* Dougl. ex Loud.) and black spruce (*Picea mariana* [Mill.] B.S.P.), which accounted for 60% (n=894) and 38% (n=538) of the trees encountered, respectively. White spruce (*Picea glauca* [Moench] Voss) (n=47) and balsam fir (*Abies balsamea* [L.] Mill.) (n=6) were also found in the plots. The DBH for lodgepole pine trees ranged from 10cm to 49cm and averaged 18 cm (SD=6cm). The DBH for black spruce trees ranged from 10cm to 28cm and averaged 14cm (SD=3cm). The average DBH in sampled trees was influenced by the removal of trees after salvage logging in the study area, which started about one year before the samplings.

Most of the sampled trees had severe fire damages with charred bark over all portions of stem. The damage to most trees was classified as "*Burn type 1*" or "*Burn type 2*" according to the burn type classification by Richmond and Lejeune (1945) (Appendix 1). The fire damage to some trees in plots 4-1 and 7-2, were less severe with partly unburned portion; and their fire damages were classified "*Burn type 3*" or "*Burn type 4*". The characteristics of sampled trees were summarised in Table A-2 (Appendix 2).

5.1.2 Split formation

Frequency of splits

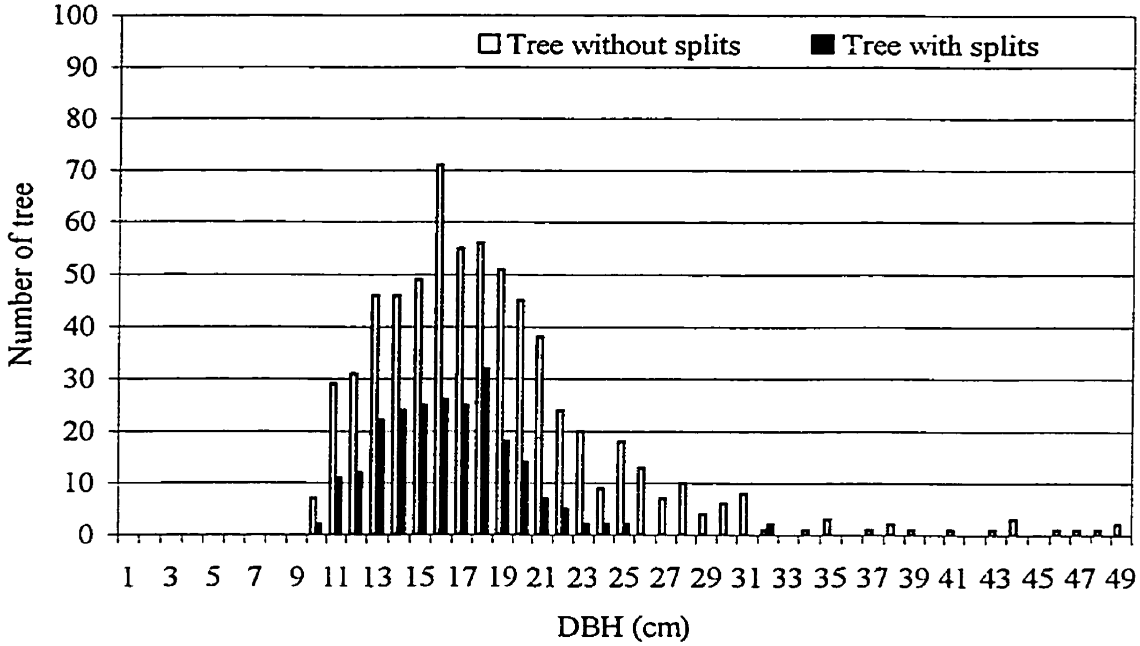
Bole splits were found on 614 trees among 1485 trees encountered in the sample plots within one year after burning. The frequency of splits ranged from 2% to 73% among the sample plots and averaged 40% (SD=21%) a plot. The frequency of splits in the sample plots was summarised in Table A-3 (Appendix 2). In lodgepole pine trees, splits were found on 26% of the trees encountered (230/894); and in black spruce trees, splits were found on 66% of the trees encountered (353/538). The distribution of split and non-split trees by DBH for the two most common species is shown in Figure 4.

Type and position of splits

There were three types of splits observed in the fire-killed trees. Those were "straight splits", "spiral splits", and "multiple splits". The "straight splits" occurred as one straight crack that extended vertically up the tree bole (Figure 5). The "spiral splits" occurred as one or some number of spiral crack (s) along the spiral grain of trees (Figure 6). The "multiple splits" occurred as multiple straight lines of splits in different orientations (Figure 7). Among the three types of splits, straight splits were the main split type in lodgepole pine, black spruce and white spruce. The frequencies of straight splits in the affected trees were: 74% for lodgepole pine, 53% for black spruce, and 64% for white spruce. Spiral splits were also commonly found in the three species; and the frequencies of these splits in affected trees were: 25% for lodgepole pine, 45% for black spruce, and 32% for white spruce. There was a significant association between type of splits (straight, spiral) and species (lodgepole pine, black spruce) (Chi-Square pr=0.001). Among the spiral splits, about 70% of them were right-hand spiral splits, which developed along the spiral grain of right-hand helix. Multiple splits were most typical in balsam fir trees. In fact, all balsam fir trees sampled had multiple splits. The frequencies of three types of splits were summarized by tree species and DBH size class and are presented in Table A-4 (Appendix 2).

Relative to the position of splits along a tree bole, all splits were found at three positions, which were the "bottom" section (bottom third of tree height), between the bottom and the "middle" section (middle third of tree height), and between the bottom and "top" section (top third of tree height) (Table 2). There was a significant association between type of splits (straight, spiral) and the three positions of splits (Chi-square pr=0.001). Straight splits were found in all three positions of the tree sampled; but they were most frequently found in the bottom 1/3 of the bole (the bottom section). Spiral splits were also found within every section of tree; however, they frequently reached

(a)



(b)

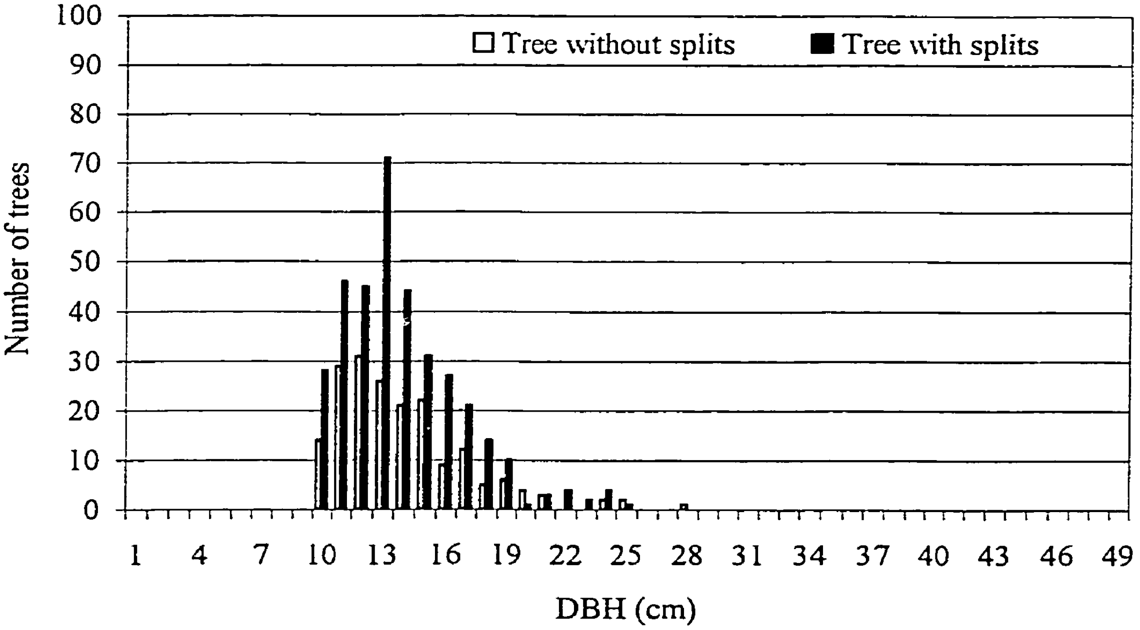


Figure 4. Number of trees without and with splits by diameter at breast height (DBH) in lodgepole pine (a) and black spruce (b) trees sampled one-year after burning in Study Area 1.

Figure 5. An example of a straight split in a lodgepole pine tree.

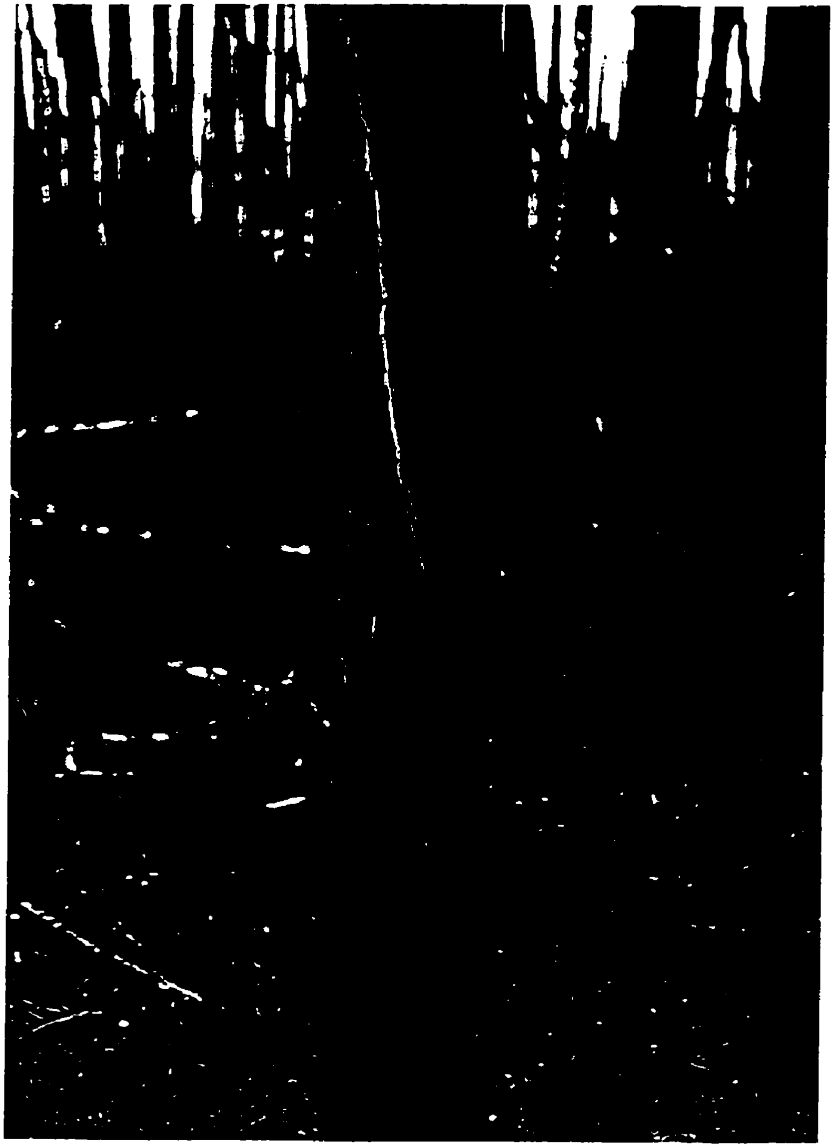


Figure 6. An example of a spiral split in a black spruce tree.

Figure 7. An example of multiple splits in a balsam fir tree.

Table 2. Frequency of splits stratified by position and type in fire-killed trees sampled one-year after burning in Study Area 1.

Position of splits	*Type of splits*							
	Straight		*Spiral*		*Multiple*		*Total*	
	# of tree	%	# of tree	%	# of tree	%	# of tree	%
Bottom	212	57%	75	33%	1	6%	288	47%
Bottom-middle	126	34%	121	54%	4	25%	251	41%
Bottom-top	36	10%	28	13%	11	69%	75	12%
Total	374	100%	224	100%	16	100%	614	100%

higher positions in the tree. Multiple splits were often found from the bottom to top section of the tree.

Orientation of splits

Straight splits were found in all orientations of tree bole. There was no association between size of tree (DBH size class) and orientation of splits (Chi-Square pr=0.343) (Table 3). The frequency of straight splits in the all sampled trees was significantly different among orientations (Chi-Square pr=0.002). Straight splits were found more frequently on west side than on east side of tree bole (Figure 8). Spiral splits were also found in all orientations of tree, but there was a limitation to analyze the orientation of spiral splits because of the rotation of splits. Multiple splits occur randomly in every orientation in a split tree.

5.1.3 Insect damage

In the Study Area 1, there were 66 trees with insect holes among the 1485 sampled trees in the 23 plots (Table A-3; Appendix 2). Therefore about 4% of sampled trees had sustained insect damage within one-year after the fire. Among the 23 sample plots, the highest frequency of insect damage was found in the plot 7-2, where trees had less severe fire damages (*Burn type 3* or *4*). Among the 66 damaged trees, 48 trees, 15 trees, and 3 trees were found on north-facing, flat, and south-facing slopes, respectively. This suggests insect damage was found on 10%, 2%, and 1% of the sampled trees on north-facing, flat, and south-facing slopes, respectively. Most of the damaged trees were lodgepole pine (57 trees); and most of the damaged trees (56 trees) had a DBH in excess of 20 cm (Table A-4; Appendix 2).

In the Study Area 2, there was no sign of insect damages in 80 fire-killed white spruce trees at the first sampling period (July 9-11, 1999). However, by the second sampling period, almost 2.5 months later (August 10-13, 1999), almost all trees showed evidence of insect damage, such as insect holes or wood chips and wood frass at the stem or base of trees (Figure 9). During this second sampling period, the adults of the white-spotted sawyer beetle (*Monochamus scutellatus* [Say]) were observed in the burned stand. Sounds of feeding and chirping sounds produced by the larvae were heard.

Table 3. Frequency of straight splits in fire-killed trees sampled one-year after burning in Study Area 1 as stratified by orientation and diameter at breast height (DBH).

Orientation	DBH size class (DBH)											
	Class 1 (10-14cm)		*Class 2 (15-19cm)*		*Class 3 (20-24cm)*		*Class 4 (25-29cm)*		*Class 5 (>30cm)*		*Total*	
	# of tree	%	# of tree	%	# of tree	%	# of tree	%	# of tree	%	# of tree	%
N	30	10%	17	8%	5	14%	0	0%	2	0%	54	14%
NE	22	8%	15	7%	3	8%	0	50%	0	50%	40	11%
E	10	3%	13	6%	1	3%	0	0%	0	0%	24	6%
SE	19	7%	16	7%	3	8%	0	0%	1	0%	39	10%
S	14	5%	22	10%	9	25%	0	0%	0	0%	45	12%
SW	25	9%	33	15%	4	11%	1	50%	0	50%	63	17%
W	21	7%	28	13%	5	14%	1	0%	0	0%	55	15%
NW	28	10%	22	10%	4	11%	0	0%	0	0%	54	14%
Total	169	100%	166	100%	34	100%	2	100%	3	100%	374	100%

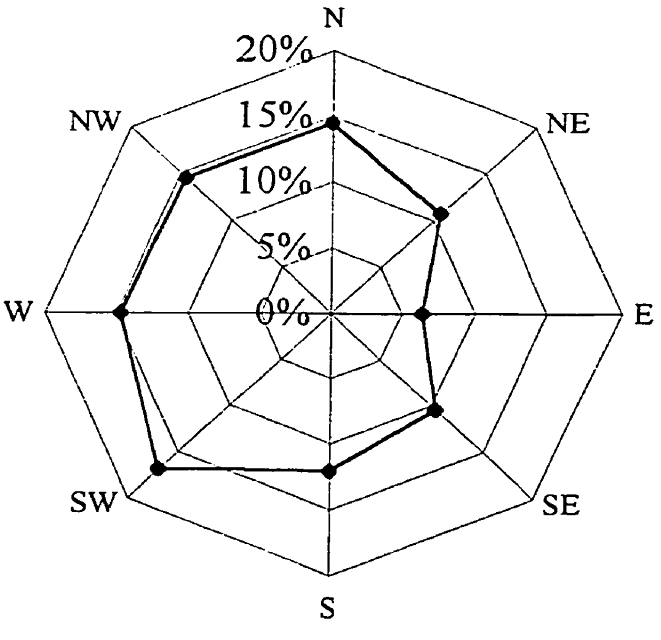


Figure 8. Percent of straight splits by orientation found in fire-killed trees, which were sampled one-year after burning in Study Area 1.

Figure 9. Wood chips and frass from insect activity can been seen at the base of the largest fire-killed white spruce tree in the photograph.

The sound was also heard during the third sampling period (September 9-13, 1999). However, these sounds were much louder during the second sampling than in the first and the third sampling visit. This suggests insect activity was greatest during the second sampling visit.

5.2 Factors influencing on frequency of splits in trees

Among the four independent variables tested (aspect of slope, species of tree, size of tree), the variable "species of tree" most significantly affected the frequency of splits encountered in this study (pr=0.0051) (Table 4). The frequency of splits was different between lodgepole pine and black spruce trees, and black spruce trees split more frequently than lodgepole pine (Figure 10). The frequency of splits decreased with the diameter size (DBH) in lodgepole pine (Table 4, Figure 10). However, the same trend was not found in black spruce. This later result may be due to the shortage of sampled trees in the DBH size class 4 (DBH: 25-29cm) and 5 (DBH: 30-35cm).

Table 4. ANOVA results: (a) testing the effects of the factors (aspect of slope, tree specie, tree size) and their interactions in lodgepole pine and black spruce trees, and (b) testing the effects of aspect of slope, tree size and the interaction of these two factors and a relationship (linear, quadratic) between tree size and frequency of splits in lodgepole pine trees (SAS software, PROC MIXED procedure).

(a)

Source	*NDF*	*DDF*	*Type III F*	*PR>F*
Aspect	2	5	0.17	0.8457
Species	1	60	8.45	**0.0051**
Size	2	60	0.09	0.9120
Aspect * Size	2	60	0.90	0.4133
Aspect * Species	4	60	0.36	0.8395
Species * Size	2	60	0.81	0.4512
Aspect * Size * Species	4	60	0.84	0.5046

(b)

Source	*NDF*	*DDF*	*Type III F*	*PR>F*
Aspect	2	4	0.63	0.5789
Size	3	35	2.76	0.0570
Aspect * Size	6	35	1.09	0.3890
Linear trend	1	35	3.63	0.0650
Quadratic trend	1	35	5.33	**0.0269**

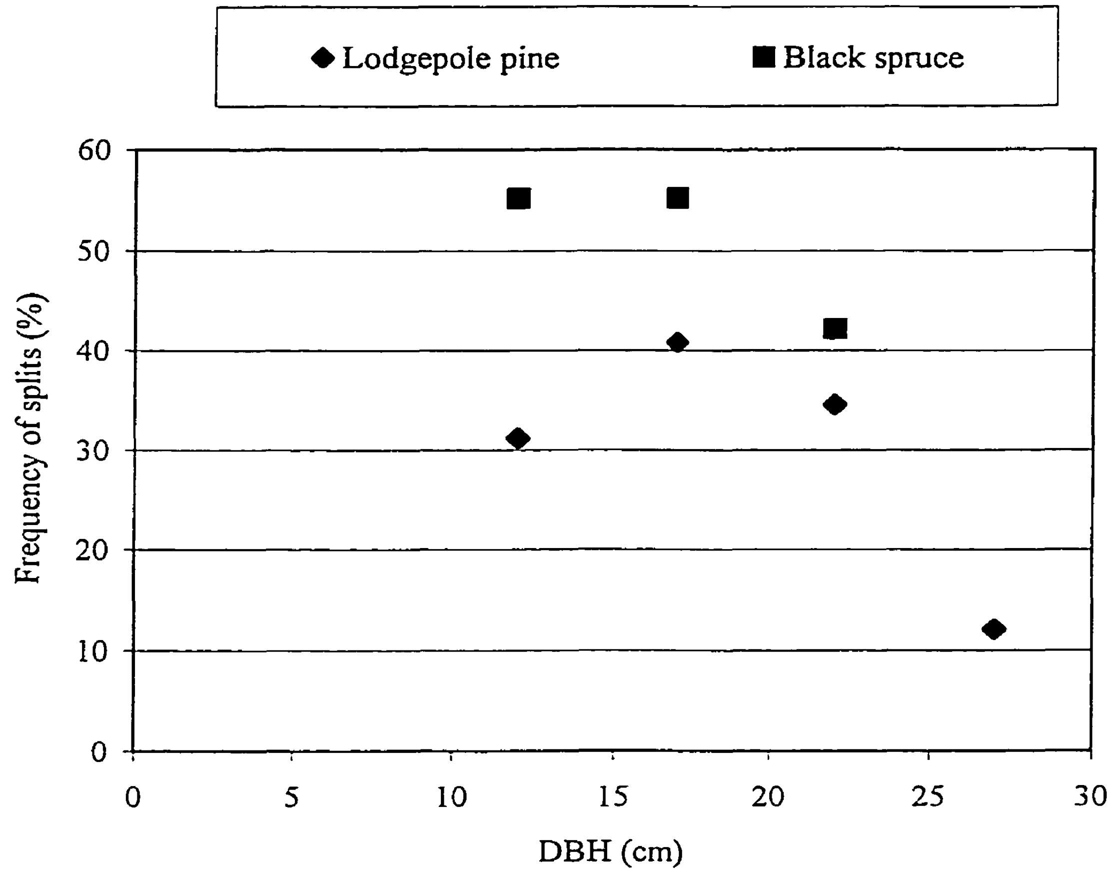


Figure 10. Relationship between frequency of splits and diameter at breast height (DBH) in fire-killed lodgepole pine and black spruce trees sampled one-year after burning in Study Area 1. The values of frequency of splits are the least square means; and the values of DBH are the midpoints of DBH in each DBH size class (Class 1 [DBH: 10-14cm]; Class 2 [DBH: 15-19cm); Class 3 [DBH: 20-24cm]; Class 4 [DBH: 25-29cm]; Class 5 [DBH: 30-35cm]).

5.3. Moisture content in trees

5.3.1 Sampled trees, weather, and moisture content

The stem moisture content was measured in 34 unburned (live) white spruce trees and 89 fire-killed white spruce trees in a 1-ha plot located in Study Area 2. The DBH of sampled trees ranged from 15cm to 58cm in live trees and 15cm to 55cm in fire-killed trees. The characteristics and the numbers of the sampled trees were summarised in Table 5. The numbers of annual rings in cores ranged from 50 to 75 in trees of DBH size class 1 (DBH: 15-22cm), 65-75 in trees of DBH size class 2 (DBH: 23-33cm), and 75 to 95 in trees of DBH size class 3 (DBH: >33cm) (Table 6). The daily weather information (maximum and minimum temperatures, relative humidity at noon, and precipitation) during the sampling period was obtained from the Cowpar Lake fire lookout tower as provided by personnel with the Alberta Land and Forest Service in Edmonton (Figure 11). During 110 days from the date of fire (May 25, 1999) to the date of the last sampling (September 13, 1999), the averages of maximum and minimum temperatures were 20°C (SD=5°C) and 8°C (SD=4°C), respectively. The average relative humidity at noon was 56% (SD=19%); and the total precipitation of the period was 205mm. The bole moisture content in a tree was summarised in Table A-5; Appendix 3. The bole moisture content by each orientation (north, south, east, west) was summarised in Table A-6; Appendix 3.

5.3.2 Moisture content with time after fire

Moisture content of outerwood (5cm in depth) did not change significantly in live trees with time after fire (pr=0.8546) (Table A-7: Appendix 3), yet fire-killed trees did lose moisture (pr=0.0022) (Table A-7). The moisture content of fire-killed trees generally decreases with time after fire (Figure 12). The moisture content in the fire-killed trees was significantly different between 1.5 months and 2.5 months after fire (pr=0.0109), and between 1.5 months and 3.5 months after fire (pr=0.0005) (Table A-8).

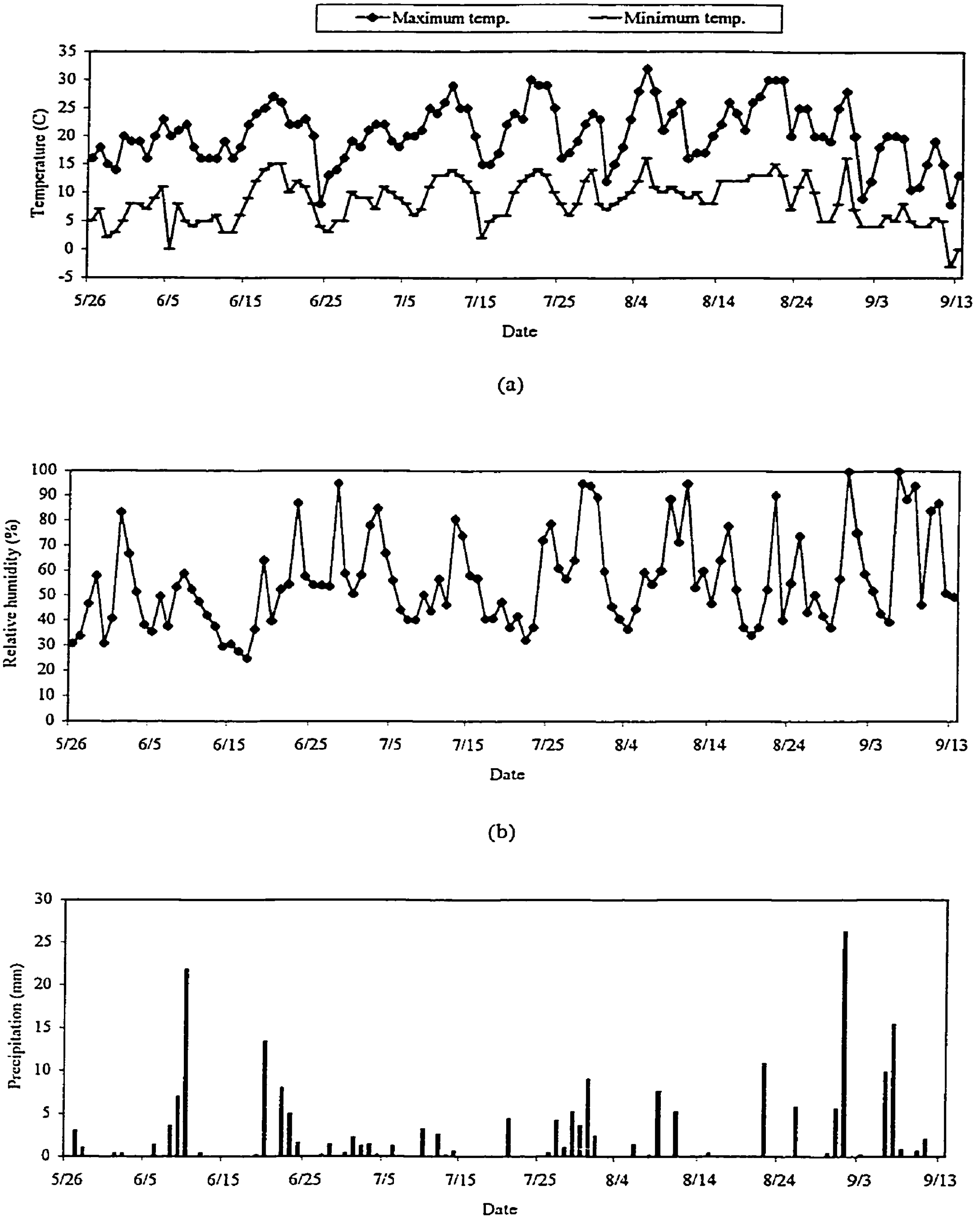
Moisture content of innerwood did not change with time after fire both in live and in fire-killed trees of DBH size class 3 (DBH: >33cm) (Table A-9).

Table 5. Characteristics of the live and fire-killed white spruce trees sampled for moisture content measurements in Study Area 2.

	Time after fire	*DBH size class (DBH)*	*# of sampled trees*	*Tree characteristics*			
				Height (m)		*DBH (cm)*	
				Mean	*S.D.*	*Mean*	*S.D.*
Live trees	1.5 months	Class 1 (15-22cm)	1	16	-	18	-
		Class 2 (23-33cm)	2	19	0.7	30	3.5
		Class 3 (>33cm)	1	21	-	45	-
	2.5 months	Class 1 (15-22cm)	6	17	2.4	18	2.4
		Class 2 (23-33cm)	4	20	1.9	26	1.3
		Class 3 (>33cm)	5	22	1.9	40	5.6
	3.5 months	Class 1 (15-22cm)	5	18	1.1	18	3.0
		Class 2 (23-33cm)	5	20	1.1	26	2.6
		Class 3 (>33cm)	5	22	1.3	49	9.2
Fire-killed trees	1.5 month	Class 1 (15-22cm)	8	17	1.1	19	2.4
		Class 2 (23-33cm)	7	20	1.0	29	3.3
		Class 3 (>33cm)	5	22	1.3	38	2.5
	2.5 months	Class 1 (15-22cm)	13	17	0.9	19	2.0
		Class 2 (23-33cm)	12	19	1.5	26	2.7
		Class 3 (>33cm)	7	22	0.9	43	4.0
	3.5 months	Class 1 (15-22cm)	12	17	1.1	17	1.7
		Class 2 (23-33cm)	12	20	1.0	30	3.0
		Class 3 (>33cm)	12	22	1.0	43	6.7

Table 6. The height, diameter at breast height (DBH) and age of 12 fire-killed white spruce trees sampled in Study Area 2 as stratified by DBH size classes used in this study.

DBH size class (DBH)	*Tree characteristics*		*# of year rings*
	Height (m)	*DBH (cm)*	
Class 1 (15-22cm)	16	15	50-55
	21	17	65-70
	17	19	70-75
Class 2 (23-33cm)	18	23	70-75
	20	27	65-70
	21	30	70-75
Class 3 (>33cm)	21	35	85-90
	22	37	90-95
	22	38	75-80
	22	42	90-95
	23	46	85-90
	23	54	85-90



(a)

(b)

(c)

Figure 11. The daily noon temperature (a) , relative humidity (b) and precipitation (c) readings obtained at the Cowpar Lake fire lookout tower for 110 days from the date of fire (May 25, 1999) to the date of the last sampling (September 13, 1999) (Source: Alberta Land and Forest Service).

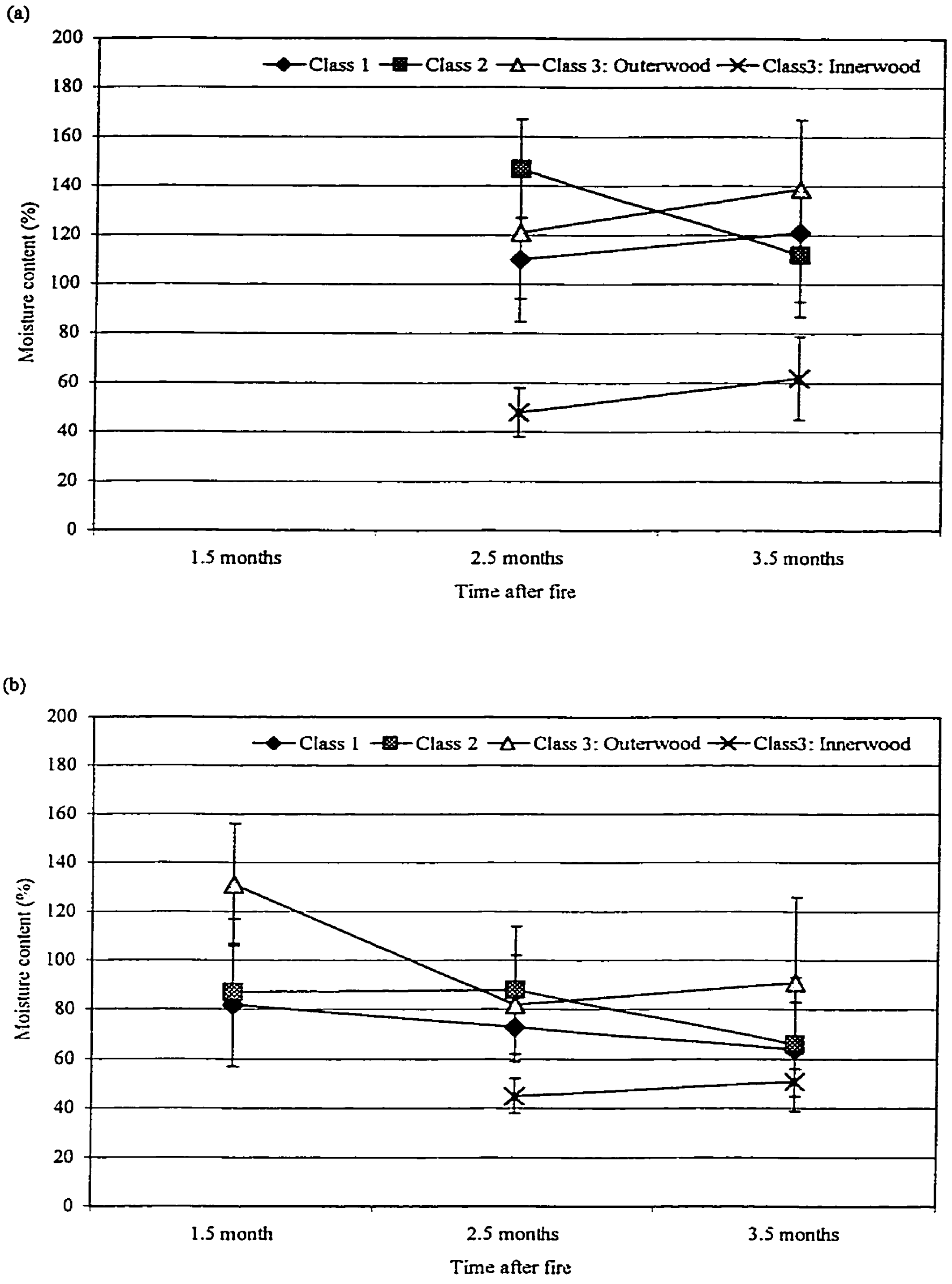


Figure 12. Moisture content relative to time after fire (1.5 months [45-47 days], 2.5 months [77-81 days], 3.5 months [107-110 days]) in (a) live and (b) fire-killed white spruce trees as stratified by the three diameter at breast height (DBH) size classes (Class 1 [DBH: 15-22cm]; Class 2 [DBH: 23-33cm]; Class 3 [DBH: >33cm]) sampled in Study Area 2. The bars indicate the standard deviations.

5.3.3 Moisture content in relation to size of tree

Moisture content of outerwood in live tree was not significantly different among three DBH size classes (Class 1: [DBH: 15-22cm]; Class 2: [DBH: 23-33cm]; Class 3 [DBH: >33cm]) (pr=0.3966) (Table A-7). However, the moisture content of outerwood in fire-killed trees was significantly different among the DBH size classes (pr=0.0007) (Table A-7). The greatest difference in moisture content was between DBH size class 3 and other classes in fire-killed trees; their differences were significant at the time of 1.5 months after fire (Table A-9).

5.3.4. Moisture content in relation to orientation of tree

Moisture content in outerwood was not significantly different among the four orientations (north, south, east, west) in live trees (pr=0.6649) (Table A-7); but it was significantly different in fire-killed trees (pr=0.0305) (Table A-7). The moisture content in east was significantly different from the moisture content in west and south in fire-killed trees (Figure 13, Table A-8). The moisture content in innerwood was not significantly different among orientations both in live and fire-killed trees of DBH size class 3 (DBH: >33cm) (Table A-9).

5.3.5. Moisture content in relation to depth of wood

Moisture content in outerwood and innerwood was significantly different both in live (pr=0.0001) and fire-killed trees (pr=0.0001) of DBH size class 3 (DBH: >33cm) (Table A-9). The moisture content in outerwood (5cm in depth) was always higher than it in innerwood (10cm in depth) both in live and fire-killed trees during the sampling periods (Figure 12).

5.3.6 Moisture content and split formation

There were no trees with splits at the first and second samplings in 80 fire-killed white spruce trees in the Study Area 2. Splits were first found in 8 trees at the third sampling (September 9-13, 1999), which was 3.5 months after fire. The characteristics of the sampled trees and frequency of splits are shown in Table 7.

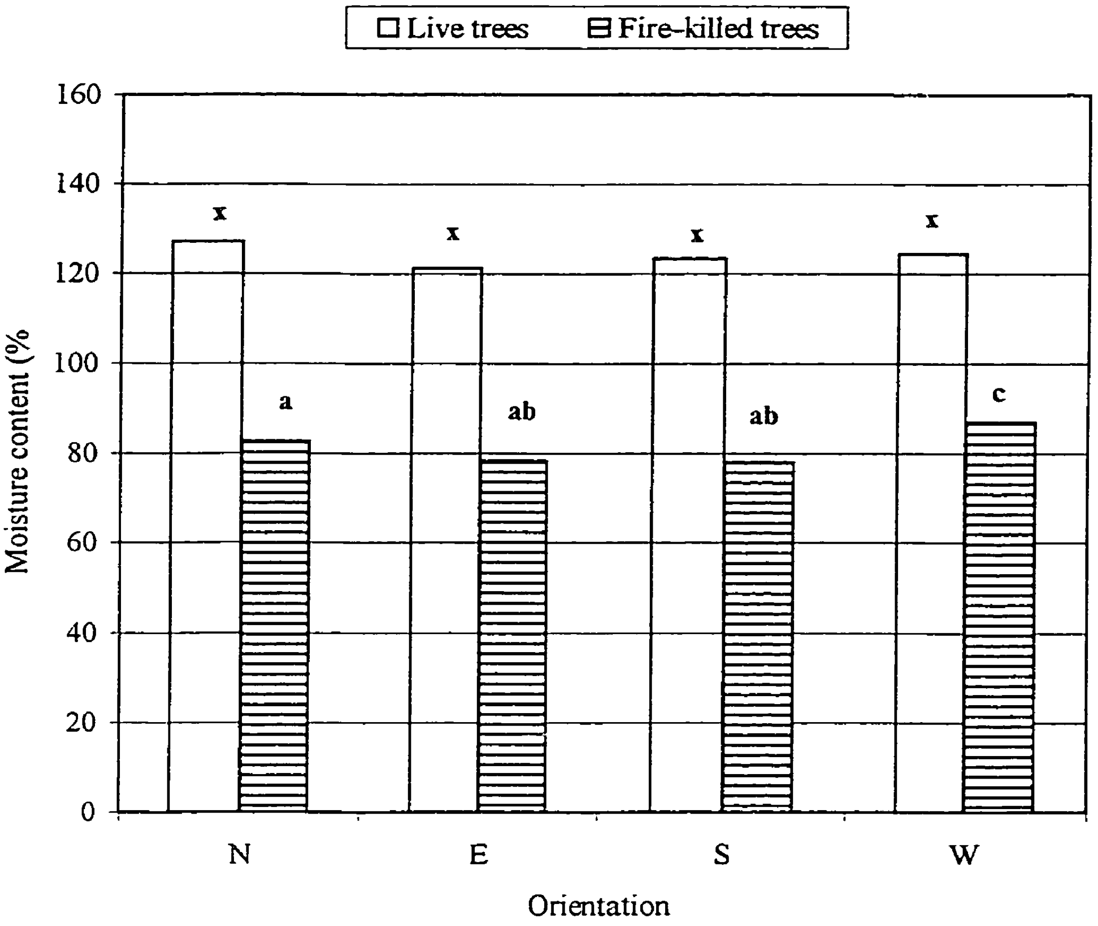


Figure 13. Moisture content with relative to orientation. The values of moisture content were averaged in trees of three diameter at breast height (DBH) size classes (Class 1 [DBH: 15-22cm]; Class 2 [DBH: 23-33cm]; Class 3 [DBH: 33cm<] sampled at the three time periods [1.5 months (45-47days), 2.5 months (77-81 days), and 3.5 months (107-1 10 days) after fire] in Study Area 2. The averages with the same letter are not significantly different.

Table 7. Tree characteristics and split frequencies in the fire-killed trees sampled 3.5 months (107-110 days) after burning in Study Area 2.

DBH size class (DBH)	*Tree characteristics*				*# of sampled trees*	*# of split trees*	*Percent of split trees*
	Height (m)		*DBH (cm)*				
	Average	*S.D.*	*Average*	*S.D.*			
Class 1 (10-14cm)	12	2.4	11	1.4	48	6	13%
Class 2 (15-19cm)	16	1.6	17	1.6	16	1	6%
Class 3 (20-24cm)	18	1.8	21	0.8	4	1	25%
Class 4 (25-29cm)	22	-	26	-	1	0	0%
Class 5 (>30cm)	22	1.6	46	7	11	0	0%
Total	15	3.9	17	10.2	80	8	10%

Chapter 6. DISCUSSION

6.1 Split formation

Type of splits

In this study, three types of splits were found in fire-killed trees at the time of one year after fire. "Straight splits" and "spiral splits" were most commonly found in lodgepole pine, black spruce, and white spruce trees; while balsam fir trees were always affected by "multiple splits".

Splits are ruptures in bole wood that occur along the grain, which is the longitudinal alignment of wood cells (Panshin and de Zeeuw 1980). The "straight splits" occurred in trees where straight grain is most common and "spiral splits" occurred in trees where the grain is spiralled. The later is the result of fiber growth in a left- or right-hand helix around the stem. The direction of spirality is defined as left-hand spiral grain when the deviation is to the left of upper extremity of the longitudinal axis of a tree as viewed by an observer on the ground, and right-hand spiral grain when the deviation is to the right (Harris 1989).

In this study, black spruce had the highest frequency of spiral splits (45%) among the species sampled; and right-hand spiral splits were observed more frequently than left-hand spiral grain in all the split trees. Spiral grain is considered as a normal growth pattern because of the widespread presence of spiral grain in conifers and hardwoods (Panshin and de Zeeuw 1980). It is known that the pattern of spiral grain in softwoods changes from left-hand spiral grain in the first 10 years of growth to straight grain and finally to right-hand spiral, which increases in magnitude with age (Harris 1989). The higher frequency of right-hand spiral splits in this study agreed with the pattern of spiral grain development as described by Harris (1989). It is believed that the basic patterns in spiral grain arrangements are, to all large extent, genetically controlled. However, environment factors can also affect the development of spiral grain (Noskowiak 1963, Panshin and de Zeeuw 1980, Harris 1989). Therefore, the frequency of spiral splits found in this study was determined by the frequency of spiral grain in fire-killed trees, which is influenced by the age of the trees, their genetic characteristics, and local environmental factors.

The "straight splits" and "spiral splits" are ruptures of a single line but the "multiple splits" are ruptures of several lines of tracheids. Splits in tree bole occur when drying stress in tangential direction become larger than the fracture strength (tensile strength perpendicular to grain) of wood. The tangential stress builds up in a tree bole during drying due to the differential (anisotropic) shrinkage of wood. In trees with “straight splits” and “spiral splits”, a single line of rupture releases the drying stress in tree bole thus compensating the dimensional change. However, in trees with "multiple splits", it would appear the drying stress is too large to be compensated by a single line, and further dimensional stress cause other ruptures. The ratio of tangential to radial shrinkage (T/R) is a good indicator of the dimensional stability of any given wood; and this ratio ranges from 1.40 to more than 2.0 for most trees native to North America (Panshin and de Zeeuw 1980). The ratios (T/R) are 1.6 (6.7%/4.3%) for lodgepole pine and 1.7 (6.8%/4.1%) for black spruce (USFPL 1999). Balsam fir is known to have a very high T/R ratio (6.9%/2.9% = 2.4) (USFPL 1999), which contributes to its very low dimensional stability. This accounts for the occurrence of large drying stresses near the circumference of the bole (Hsu and Tang 1974); and the multiple splits commonly found in dead balsam fir.

Position of splits

Splits observed in this study were located at all height positions along the boles of fire-killed trees, but the majority of them were found in the lower 1/3 and 2/3 of the tree height. There appears to be a relationship between the types of splits and the positions of splits. The "straight splits" were found more frequently in the lower position (1/3 of the tree height). The occurrence of "spiral splits" appeared to be more common in the higher position (middle 1/3, upper 1/3) of trees. “Multiple splits” were commonly found throughout the whole bole of the tree (from bottom to top portion of tree).

Lowell et al. (1992) stated in the review of the previous studies that weather checking in fire-killed trees occurred most frequently in the top log of larger trees where there was less volume to be lost. In contrast, splits in fire-killed trees were found more frequently in the lower portion of tree boles in this study. The high frequency of splits in lower position may be explained by the number of smaller size (diameter) trees encountered in this study compared to the larger size trees studied in the past. For example, Kimmy and Furniss (1943) studied fire-killed Douglas-fir trees where the DBH's ranged from 30 to 264cm (12 to 104inches). The average DBH of tree encountered in this study was 18cm for lodgepole pine and 14cm for black spruce. As shown in this study, large fire-killed trees maintain higher moisture content than small trees. Within a fire-killed tree, drying is rapid in the upper bole portion of the tree, but slower and less extensive in the lower boles (Wright and Grose 1970). Therefore it is likely that splits in large trees first appear in the top of log where the moisture content is first to fall below the FSP. Whereas in small trees, splits can occur in every position of tree due to the rapid bole drying but they occur most often in the lower position. Moisture gradient occurring in the top log of small trees may not be severe enough to cause large drying stress and splits. It is shown that specific gravity declines with tree height (Choong and Fogg 1989); thus the top position of tree is expected to have less shrinkage and drying stress.

Orientation of splits

Among the trees sampled in the Study Area 1 at the time of one year after fire, splits were found in all 8 orientations (N, NE, E, SE, S, SW, W, NW), but they occurred less frequently in eastern orientations than any other. Geiger (1965) showed the temperature maximum follows the sun from southeast via south to southwest and the parts that receive direct solar radiation later in the day can experience even higher temperature since they have already been warmed to some extent. Therefore, it was expected that west and south sides of a tree bole would have a higher drying rate than east and north sides. In this study, moisture content was significantly different among 4 orientations (N, E, S, W) in fire-killed trees sampled at 1.5, 2.5 and 3.5 months after fire in the Study Area 2. The moisture content was significantly higher in west side of tree boles than in eastern and southern sides of the trees. However, there were no significant differences in moisture content between in north side and south side of a tree bole. From the results of this later study, it is likely that the difference of sun radiation received might cause the variation of moisture content thus the different split frequency relative to orientations. However, other factors such as wind direction might have influenced the variation of moisture content. In addition, winter freezing may be responsible for the split pattern observed the following spring and summer after fires near Whitecourt.

6.2 Factors influencing on frequency of splits in trees

Aspect of slope

In this study, aspect of slope was not a factor influencing on the frequency of splits at the time of one year after fire. Aspect of slope might have been factor influencing the split frequency because fire-killed trees receive different solar radiation depending on the aspect of slope. Byram (1943) showed that aspect of slope influenced the moisture content of surface fuels in forests due to the different amounts of solar radiation received. There are some possible reasons why aspect of slope did not influence the frequency of splits in this study. Firstly, the slopes encountered in the Study Area 1 were gentle. The magnitude of difference in sun radiation received might not be large enough to influence split frequency in fire-killed trees on the slope of different aspects. Secondly, moisture content of fire-killed trees is much less susceptible to change than that of small forest fuels such as leaves and twigs (Brackebusch 1972). Therefore, the difference of sun radiation received might not cause large difference in drying rate of fire-killed trees on slopes of different aspects. In this study, sampling was done at the time of one year after fire. It is possible that there is difference in time of split occurrence as splits occur earlier in trees on south facing slope than north facing slope but with time this difference is masked. The failure of this study to detect a difference due to slope position may simply be due to sampling limitations.

Species of tree

There were significant differences in the frequencies of splits between lodgepole pine and black spruce at the time of one year after fire in the Study Area 1. Also, the frequency of splits in black spruce was significantly greater than that for lodgepole pine. The degree of fire-damages in tree is often explained by bark thickness of species; and trees with thinner bark are more prone to moisture loss than those with thicker bark (Lowell and Cahill 1996). However, both lodgepole pine and spruce (*Picea* spp) are known as thin bark species (Starker 1934); thus the bark thickness seems to be not the primary factor causing the different frequency of splits between the two species. The different shrinkage properties of the two species may be a possible factor influencing split frequencies between them. Hsu and Tang (1974) calculated the drying stresses occurring in a cylindrical log of the eight common commercial woods from their elastic compliance and free linear shrinkage values. They showed lodgepole pine had the smallest tangential drying stress among eight species including Engelmann spruce (*P. engelmannii* Parry), which was considered to be similar to black spruce.

The differences in shrinkage among and within species are caused by several factors such as: specific gravity, extractive content, different amount of wood such as sapwood and heartwood, earlywood and latewood, and juvenile and mature wood (Boyd 1987). Within same species, the shrinkage properties can vary because of environmental, geographical, and genetic influences, all of which may cause variations in the physical, chemical and hydrologic structure of the wood. For example, it is well known that competition within the stand or the fertility of the soil with in a stand can cause variations in the wood of the same species of tree growing in the same stand (Panshin and de Zeeuw 1980). Wiedenbeck et al. (1990) reported a general decrease in equilibrium moisture content (EMC) in lodgepole pine with increasing latitude. They concluded that this change in EMC was highly related to the observed decrease in hygroscopicity, which was caused by a decrease in hemicellulose content and an increase in extractive content with increasing latitude. Genetic influences on wood formation and growth rate have been well documented (Panshin and Zeeuw 1980, Zobel and van Buijtenen 1989). Therefore, split frequency may be influenced by shrinkage properties of tree, which can vary with genetic characteristics of tree and environmental and geographical conditions of forest stands.

Size of tree

Splits were more common in smaller lodgepole pine trees than in large ones but the same trend was not apparent in black spruce. This later outcome was probably due to the lack of larger DBH size classes in black spruce available for sampling. According to Hsu and Tang (1974), tangential stress, which induce splits or checks, is a function of moisture loss and the elastic and shrinkage properties of wood, and is independent of the radius of the log. Therefore, the decrease of split frequency with the size of tree can be explained by different moisture loss occurring in the trees of different sizes. In general, small diameter trees sampled in the Study Area 2 had lower moisture contents than large diameter trees until 3.5 months after fire. Wright and Grose (1970) found the drying rate in fire-killed trees was largely independent of tree size, and large logs contained a much greater portion of moist wood than smaller tree. For large trees, it takes longer for the wood in the bole to reach its moisture content below the FSP because large trees have larger amount of water and lower ratio of surface area to volume. Hence, the rapid drying and the resultant development of drying stresses in small trees will causes splits more quickly in small trees.

The effect of interaction between size of tree and species of tree on the frequency of splits was nearly statistically significant in lodgepole pine. Split frequency decreased with size of tree showing linear-quadratic trend in lodgepole pine. Although the results of this study cannot be used to determine the cause of splits in various tree species of various sizes, the linear-quadratic trend in lodgepole pine indicated that moisture gradient occurring in trees of the smallest DBH size classes might not be severe enough to cause large drying stress and splits.

Other factors

There are other important factors influencing the frequency of splits in tree boles. These would include: time of burning, moisture content at time of death, fire severity or intensity, and type of forest. Time of burning may impact on how long fire-killed trees are exposed to dry conditions. In Alberta, there is a high probability that trees killed by fire in the spring or summer, under normal conditions, will be exposed to a longer period of drying than trees burned in late summer or fall. In this study, the fires that occurred in the month of May killed all trees sampled. Hence these samples experienced the maximum amount of drying possible for this geographic area. Somewhat related to time of burning, is the fact that the moisture content in a tree at the time of death can influence splits formation. Moisture content of tree varies with season (Clark and Gibbs 1957, Chrosciewicz 1986); when trees are killed with low moisture content, their moisture content will reach the FSP faster than trees with high moisture content at the time of death. It is well know that trees in Alberta commonly experience a moisture deficit during the spring months (Chrosciewicz 1986). Due to the long drying period and the low moisture content in trees in spring, the most severe split damages in fire-killed trees are expected after spring fire.

Fire intensity or severity may directly or indirectly influence the rate of drying in fire-killed trees. The heat of the flames may remove the moisture in the wood, when the fire is intense (Lowell and Cahill 1996). Skolko (1947) found a direct relation between fire severity and the rate of bark shedding. In this study, bark shedding was only found in some large trees with DBH over 30cm sampled one-year after burning. I found no evidence of bark shedding in trees sampled for moisture content measurement within 3.5 months after fire of 1999, north of Lac La Biche. It is likely that trees with bark shed may lose its moisture faster than trees with bark intact because of direct exposure of wood to sunlight and wind.

Fire severity and type of forest also has influences on microclimate and regeneration of plants in the burned stands after fire. Microclimate created after fire may influence the temperature, and the humidity regime in burned areas (Martin 1955, Ahlgren and Ahlgren 1960, Fowler and Helvey 1981, Johnson 1992, Schimmel and Granstrom 1996, Belillas and Feller 1998). Plant regeneration can change the microclimate covering the blacked ground (Martin 1955, Johnson 1992). Comparing the post-burn vegetation response in Study Area 1 to that for Study Area 2, it was noted that the understory vegetation was more vigorous in the Study Area 2. Aspen saplings, which quickly regenerated after fire in the Study Area 2, likely created less severe drying conditions because of their impact on changing the temperature and humidity regime in the burned area.

6.3 Insect damage

In Study Area 1, 4% of sampled trees (66/1485) had insect-damages at the time of one year after burning, and in the Study Area 2, all 80 sampled fire-killed trees had insect-damages at the time of 3.5 months after fire. Previous studies have shown that insect-damage in fire-killed trees is influenced by the timing and type of burn. The type and size of the insect populations in the vicinity are also important.

The damages by wood borers are usually intensive in trees killed by spring fires and they are heaviest when fire occurs before mid-June (Parmelee 1941, Ross 1960). The damages will be less in trees killed by autumn fires; and the trees will likely remain uninfested by wood borers throughout the winter (Gardiner 1957). In this study, the both fires occurred in the month of May when the damages by wood borers were expected to be intensive. However, few trees showed signs of insect-damage in the Study Area 1. Yet, all trees sampled in the Study Area 2 had been attacked by the white-spotted sawyer beetles (*Monochamus scutellatus* [Say]). From these results, time of fire is considered to be not the cause of different insect-damages in the two study areas.

White-spotted sawyer beetles are often attracted to the burned areas (Richmond and Lejeune 1945; Gardiner 1957); and they are the most damaging species in lodgepole pine and white spruce in Alberta because the larvae cause the defect known in the lumber trade as "worm holes" (Cerezke 1975). According to Cerezke (1975), the adults of white-spotted sawyer beetle are seen in the field from May to early September but are most common in June and early July. Eggs are laid between late June and early September; and the young larva hatch after 9-14 days, bore through the bark in 2-3 days, and feed for 2-3 weeks in the bark and outer sapwood. Worm-hole damage begins in early August when the larvae are 2.0-2.5cm long and begin boring into the wood. In this study, the adults were frequently observed in the Study Area 2 during the first sampling (July 9-11,1999). Sounds produced by feeding of the larvae were heard during the second sampling (August 10-13, 1999) and third sampling (September 9-13, 1999). These sounds were much louder during the second sampling period. It is likely that the larvae fed intensively on the bark and outer sapwood during the second sampling. As well as the sounds produced by feeding, distinctive chirping sounds were heard. Victorsson and Wikars (1996) reported the similar chirping sounds (sounding like a finger-nail being scratched repeatedly over a comb) produced by pine-sawyer beetle (*Monochamus sutor* L.) in fire-killed Norway spruce (*Picea abies* [L.] Karst.) and Scots pine (*Pinus sylvestris* L.). They suggested the sound productions had an adaptive value for a larva to secure resources by keeping away other potentially competitive larvae in spite of the risk of attracting parasites and predators such as woodpeckers.

Burn type is another factor known to be responsible for some insect damages. Richmond and Lejeune (1945) found that there was relationship between degree of burn (Appendix 1) and damages caused by white-spotted sawyer in fire-killed white spruce trees. They reported severely burn trees "Burn type 1" were permanently immune from damages caused by white-spotted sawyer. The trees classed as "Burn type 2" were attacked first, while trees with scorched or blackened bark "Burn type 3" showed the greatest degree of borer damage. Trees subjected only to reflected heat (radiation as part of flaming combustion) and not burned "Burn type 4" or trees, which experienced root burning only "Burn type 5" were the last to become infested. These later trees showed the shallowest average penetration depth in the bole at any given date during larval activities. As drying progresses in fire-killed trees, Burn types 2 and 3 become unattractive for use by these insects and Burn types 4 and 5 become more attractive (Richmond and Lejeune 1945).

In this study, most of the fire-killed trees were severely burned. The possible reason for the absence of the intense insect damages in the Study Area 1 was the rapid dehydration that occurred in severely burned trees before the insects' populations had developed. The wood feeding insects such as bark beetles and wood borers require the favourable conditions (temperatures, moisture content) for their development and survival (Gaumer and Gara 1967). Rose (1957) observed that the greatest mortality of white-spotted sawyer occurred between oviposition and larval establishment on the wood surface. The main causes of the mortality were cannibalism and desiccation of the eggs in logs most exposed to the sun.

6.4 Moisture content in fire-killed trees

Moisture content change with time after fire

In this study, moisture content of outerwood in fire-killed white spruce trees decreased with time after fire; and large trees had higher moisture contents on average than smaller trees. The moisture content in fire-killed trees decreases after burning unless the trees are exposed to rain or ambient relative humidity stays high for long periods of time. The drying rate lessens once moisture content reaches the FSP. Wright and Grose (1970) reported that the rate of drying lessened considerately in the second year after fire.

The precipitation during the sampling period seems to have little effect on the moisture content. That is probably because moisture added by the rain is confined to the bark or surface of wood and there is hardly time for deep penetration (Brackebusch 1972). The results of the study generally agree with other studies (Wright and Grose 1970, Onodera et al. 1971, Hood and Ramsden 1997), but the rate of drying of fire-killed trees seems to be different depending on the regions. For example, Onodera et al. (1971) reported that there was a difference in the moisture content between fire-killed trees and green trees at the time of one year after fire but not three months after fire. Again these results are highly influenced by the ambient conditions after the fire.

Moisture content in dead trees were studied in trees defoliated and killed by the spruce budworm (*Choristoneura fumiferana* Clem.) (Barnes and Sinclair 1983, Ip et al. 1996). The studies also showed lower moisture content in smaller size of trees as found in this study; but drying seems to be more rapid in fire-killed trees than insect-killed trees. The rapid drying in fire-killed tree may be due to the initial moisture loss by heat, change of bark character and black surface of tree stem, which absorbs greater portion of solar radiation. The conditions after fire also encourage the fast drying due to increasing temperature and increasing wind velocity after removal of branches of trees in burned stands.

Moisture content variation

Some variations were found in moisture content of outerwood and innerwood of this study. The one possible source of the variations is moisture content variations occurred among trees or within a tree. In living trees of coniferous species, sapwood moisture content in radial direction is highly variable (Rothwell 1974); and it generally decreases with depth to near fiber saturation point in the heartwood (Stewart 1967). Some species (eg. *Abies, Cryptomeria, Larix, Pinus,* and *Tsuga*) often have wetwood, which are portions of the heartwood where the moisture content of the fibre is higher than that of surrounding wood (Ward and Pong 1980). In those species, water distribution in heartwood can be highly variable (Nakada et al. 1999). In this study, the sapwood and heartwood areas were not identified because there were no colour distinctions between sapwood and heartwood. However, based on the moisture content values of the innerwood and outerwood in live trees and their differences, it is likely that cores of outerwood (5cm in depth from bark) were taken from sapwood; and cores of innerwood (5-10cm in depth from bark) contained some portion of heartwood in the sampled trees in the DBH size class 3 (DBH: >33cm). It is known that the relative amount of heartwood within a tree bole generally increases with the age (Hazenberg and Yang 1991). The ages of sampled trees in the DBH size class 3 (DBH: >33cm) were estimated 75 to 95 years old from the numbers of year rings. In this case, the variations of moisture content in outerwood were likely caused by the moisture content variation in sapwood among trees or within a tree; and the variations of innerwood were likely caused by different amounts of heartwood occurred in sampled trees.

Sampling error may be another source of the variations in moisture content measurement of this study. Historically, the moisture content of dead or damaged trees was often measured using wood blocks or disks taken from cut trees (Reid 1961, Barns and Sinclair 1983, Ip et al. 1996, Hood and Ramsden 1997). However, when the wood sample specimens are small as in the case of increment cores, the sampling error can be large due to the small sample size relative to water loss (Rothwell 1974). Determining the moisture content of wood using increment borer, which is fast and relatively easy, a large numbers of trees can be sampled in short time period. However at present, the sampling error associated with this technique are unknown because few previous studies have used this approach. Also in the tree species sampled, it was difficult to know where to expect changes in moisture levels. Hence the results reported here more likely reflect the average of the portion of the core sampled and may not reflect moisture differences that would cause splits.

Moisture content and split formation

In this study, splits were first found at the time of 3.5 months after fire in 8 fire-killed white spruce trees, the DBH of which ranged from 10-21cm. The average moisture content of fire-killed trees of DBH class 1 (DBH: 15-22cm) was 64% at the time of 3.5 months after fire. Wright and Grose (1970) are the only researchers who have reported the moisture content at which splits occurred in fire-killed trees. They stated fire-killed trees had splits when moisture content of the outerwood dropped below about 65-70%.

The detail descriptions of moisture measurement were not available in their publication (Wright and Grose 1970).

It is known that shrinkage of wood does not occur unless the moisture content is lower than the fiber saturation point (FSP), which for most species is around 30% ODW (Kollmann and Côté 1968, USFPL 1999). The results in this study indicated that there was moisture gradient in sampled wood (5cm-wood cores); and it is likely that moisture content is below FSP in shallow wood and it is above FSP deep wood in 5cm-wood cores. It is important to remember that moisture content tells when shrinkage of wood occur in fire-killed trees, but it does not tell how tangential drying stresses develop in tree bole. Splits occur when the tangential drying stress becomes larger than fracture strengths (tensile strength perpendicular to grain) of wood. Theoretically, the prediction of moisture content at which splits occur in a cylindrical log is possible only when moisture is homogeneously distributed in tree bole (Hsu and Tang 1974). Because of heterogeneous distribution of moisture and stress during drying in fire-killed trees, there is a limitation to predict the moisture content at which splits occur in a single tree. However, moisture content can tell when splits likely occur in trees at a stand level if the relationships between moisture content and split formation in certain type of forest stand are widely observed.

Chapter 7. CONCLUSIONS

This study documented the occurrence of splits and insect activity that occurred in fire-killed trees in the two burned forested areas in Alberta. The results obtained in this study contained one of the few documentation ever attempted on the split damages and moisture content change in standing fire-killed trees in Alberta. The results are summarized relative to the three objectives of this study.

The first objective (O_1) was to determine if aspect of slope, tree species, tree size influenced frequency of splits in fire-killed trees. A total of 1485 fire-killed trees were observed in 23 sample plots established in 14 different stands. Of the 1485 trees sampled, 614 trees had split within one field season after burning. In these split trees, three types of splits were observed. From the data collected, it was concluded:

- The "straight splits" were often found in the lower bole of lodgepole pine, black spruce and white spruce fire-killed trees. This type of splits occurred in every orientation of tree bole but less frequently in east side of tree bole.

- The "spiral splits" were another type of split found in the three species of tree, which frequently reached higher position of tree bole following the spiral grain.

- The "multiple splits" were typical in balsam fir trees occurring from bottom to top portion of tree bole in every orientation.

- Lodgepole pine splits less frequently than black spruce.

- The frequency of splits decreased with increasing of DBH for lodgepole pine.

The second objective (O_2) of this study was to document the change in stem moisture content in fire-killed trees. Moisture content in fire-killed white spruce trees was measured during 3.5 months after fire. From the data collected, it was concluded:

- Moisture content decreased significantly with time after fire; and it was significantly different among trees of different sizes.

- Moisture content was significantly different among the 4 cardinal orientations (north, east, south, west).

- The average moisture content of DBH size class 1 (DBH: 15cm-22cm) was 64% when splits were first found in 8 trees with DBH ranged from 10cm to 22cm at the time of 3.5 months after fire.

The third objective (O_3) of this study was to record the frequency of insects in fire-killed trees. From the data collected, it was concluded:

- Insects occurred in 66 fire-killed trees among the1485 trees observed in the Study Area 1 at the time of about one year after fire.

- In Study Area 2, all trees (n=80) in the sample plot exhibited signs of insect attacks at the time of 3.5 months after fire. In this Study Area, the all affected trees had been attacked by the white-spotted sawyer beetle (*Monochamus scutellatus* [Say]), which is known as one of the most common species attracted to burned area and most damaging species in lodgepole pine and white spruce in Alberta.

Chapter 8. MANAGEMENT CONSIDERATIONS

Splits are the main cause of value loss in lumber recovered from fire-killed trees (Szabo and Kasper 1971, Willits and Sampson 1988, FERIC 1998). Splits can occur in standing fire-killed trees relatively quickly as observed at the time of 3.5 months after fire in this study. More importantly the results of this work suggest smaller trees split much faster than larger trees of the same species. Also, black spruce has more severe split damages than lodgepole pine. The simplest solution to reducing merchantable losses in fire-killed trees is to harvest and process the affected timber immediately. Even short delays can be expensive when high ambient temperature and low relative humidity are common. However, in the Boreal Forest of Alberta, wet soils often prevent or greatly inhibit the harvesting of trees. And for the same reasons extraction is often impossible.

Small trees may be salvaged for post, pilings or just wood fibre if processing facilities are available. In pulpwood from fire-killed trees, very low moisture content causes problems in pulping process. The moisture content in fire-killed trees may be as low as 20 % to 40 % ODW. This may require adding moisture back into wood by steam (FERIC 1998) or by long-term soaking before processing can occur. Since rapid dehydration in fire-killed trees can result in a value loss in lumber and pulpwood commodities, the best way to maintain the value of this wood is to prevent the rapid moisture loss. Felling and piling of fire-killed trees immediately after fire may be one way to slow their drying rates. Felling and piling will reduce the stem to exposure of sun and wind. Of course the rate of water loss will be highly influenced by the amount and condition of the bark remaining on the tree. Trees without bark or trees with blacked (charred) bark will likely dry faster than trees in similar condition with bark intact. Storing fire-killed logs in water, snow cashes, or under water spraying are other known ways to reduce moisture loss (Gray and Pfitzner 1985, FERIC 1998). The feasibility of using water soaked logs or felled trees needs to be studied. Such simple attempts at reducing splitting may result in fungal, insect or other problems (Peralta et al. 1993).

Although, fire-killed trees are mainly utilised for lumber and paper production now because of their high recovery values, board production from fire-killed trees will be feasible in the future. Current technology and markets of wood products have shifted from using larger diameter softwood timber species to using smaller diameter timber and hardwood species with development of the engineered wood products such as oriented strand board (OSB) (Skog et al. 1995). With new technologies, smaller or a lower grade of fire-killed trees can be source of fibers for the engineered wood products. In this case, low moisture content can be advantage because it will lower the cost of transporting the logs.

From an economic viewpoint, it is important to salvage the greatest amount of highly valued logs in the least time to gain maximum profit (Gray and Pfitzner 1985, Willits and Sampson 1988). However, salvage logging should be carefully conducted with full consideration for the environmental impacts on the site. Salvage logging can cause beneficial or harmful effects on the environment depending on time and methods of harvesting and stand characteristics.

Time of harvesting may be critical for regeneration of burned stands. Summer logging can be done to minimise value loss of fire-killed trees burned in spring and summer, however, it can cause negative impacts on soils and vegetation in wet areas or those with shallow soil profiles (Klock 1975). Winter logging may result in less impact in those areas. Salvage logging should be carefully done steep watersheds and with riparian environments. Salvage logging can improve watershed conditions by increasing ground cover (Poff 1989); however, it can cause negative effects such as water pollution from soil erosion, particularly if access roads are constructed for temporary use only (Barker 1989). These types of roads usually are not resistant to normal water inputs.

Clearcutting is the common harvesting method for harvesting of fire-killed trees. However, often some fire-killed trees should be left for wildlife habitat needs. For example, woodpeckers are often attracted burned forests where dead trees become infested with woodboring insects (Blackford 1955, Emlen 1970). Saab and Dudley (1998) suggest retaining clumps of trees after fire may benefit the cavity-nesting birds native to the area. However, there is a shortage of information on how salvage logging will impact the regeneration of the next stand, the historic watershed values, and the wildlife native to the area.

In sustainable forest management, it is important to achieve an optimum mix of commodities and services from the forest (e.g. timber, range, water, wildlife, and recreation) (Armstrong 1999). In Alberta, it is important to incorporate fire risk into the sustainable forest management (Armstrong 1999). Successful salvage logging is one of the key components to incorporate forest fire into the forest management. Salvage operations can be highly variable due to different forest management and different rates of deterioration among forest regions (Basham 1986). For successful salvage operations, economic and environmental assessments are important. Guideline or regulations help foresters to plan quick and successful salvage operations.

Chapter 9 FUTURE STUDIES

The results of this study provided important information on occurrence of splits and insects in fire-killed trees. However, more work is required. This is because of the large number of environmental factors that are controlling these effects in fire-killed trees. Much of this work remains because our work only spanned the environmental conditions present during our sampling periods. These likely do not cover all of the possible conditions/parameters that could be experienced by a fire-killed tree. It should also be mentioned that in my opinion all future research on this topic will have to be done under field conditions because foresters know very little about how harvesting and handling will affect the drying of stems, which is responsible for these two important causes of wood or bole deterioration. To this end, I recommend the following future studies:

1. Physical and biological deterioration should be studied in the typical merchantable trees (lodgepole pine, white spruce, black spruce, aspen) and typical stands (Mixedwood, pure stand) in Alberta by looking at:

    a. The deterioration process in standing fire-killed trees by species with regard to the various possible level of fire severity, and

    b. The deterioration process in felled fire-killed trees by species depending on tree condition (condition of bark in particular), log length (cut to length, tree length), and piling methods (size, height, orientation).

2. Moisture content in the boles of standing, downed, piled and scattered (left where they fall) trees should be measured from varieties of burned stands in Alberta. Specifically, we need information on:

    a. The moisture content change in fire-killed trees over time as related to such weather variables as temperature, relative humidity, precipitation and the three code and three indices of the Canadian Forest Fire Weather Index System, and

b. The moisture content in fire-killed stems from the perspective of the various end uses (lumber, pulp, board) in mind. It is well known that different end uses have different moisture requirements, which is known to affect processing, splitting and insect, blue-stain, and decay.

3. Effects of salvage logging on burned area should assess the effects of harvesting on:

a. Regeneration of the stand depending on the type of forests, harvesting methods, and regeneration methods;

b. Watershed quality, and

c. Wildlife populations.

4. Economic studies should be conducted to identify the costs and benefits associated with salvage operations with the goal of analysing:

a. Costs of new activities for salvage operations such as construction of access road, introduction of machines for processing, and replanting of burned areas,

b. Value loss of end products depending on the types of deterioration, and

c. Value recovery from fire-killed trees based on areas of salvageable stands and volumes of wood obtained from the stands.

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Appendix 1. Classification of burn types

The “Burn types” classification scheme developed Richmond and Lejeune (1945) was used to stratify fire-killed trees encountered in this study into broad disturbance classes. The 5 “Burn types” are described below.

Burn type 1:

This is the most severe of all the burn types. The characteristics of this burn type are: the bark is burned thin with no scales or flakes remaining. The bark is brittle, fails to bend without breaking. Entire patches of bark are often missing due to either having been burned away or subsequently peeled off. The cambium is usually cooked and the wood is dry and brown. This degree of disturbance is most commonly found along the lower portion of the tree, where it has been subjected to the greatest heat. In high intensity crown fires, it may occur over a greater portion of the tree.

Burn type 2:

This is a less severe disturbance than “Burn type 1”. Trees with this burn type exhibit badly charred bark, which may have small areas burned through to the wood. The bark may be thin as a result of burning but it is still pliable immediately after the fire and can be peeled in a shingle sheet. The cambium may be cooked in patches giving a matted appearance, where the color of the wood may fluctuate from tan to brown. Also, the wood tissue may be dry to be sticky. On thick-barked trees all bark scales burned off while 50% are consumed on thin-barked trees.

Burn type 3:

Tree in this category exhibit blackened bark because the bole was touched by the flames but the bark is of normal thickness with scales still present; inner bark moist, pliable. The bark will peels readily in one unbroken sheet because the bark was not burned through. Hence the cambium is moist and sticky, creamy-tan in color and without darkened areas caused by excessive heat.

Burn type 4:

Trees in this category have bark that was not scorched nor darkened by flames but has been subjected to much heat from nearby fires. Heating is due to intense radiation. The external appearance of the bole appears normal and the cambium is still generally white. However, there may be traces of discoloration developing in the cambium. This zone of tissue is still moist but shows signs of drying and, when peeled, is decidedly sticky. Generally these characteristics are found on trees outside of the burned area but adjacent to and facing it.

Burn type 5:

This last type is called the "ground-fire" type because trees within this class are injured by ground fires that affect only the roots. The above ground portion of the tree is entirely uninjured. Although the tree may be dead or dying, it appears normal and healthy. Even the cambium on these trees appears normal and the bark on these trees peels similar to that on a standing healthy trees.

Appendix 2. Data summary of sample plots, trees, and occurrence of splits and insects.

Table A-1. Summary of characteristics of the sampled plots in Study Area 1.

Stand-Plot No.	Aspect	Slope angle (degree)	# of sampled trees	Stem density (trees/ha)	Species composition							
					Lodgepole pine		Black spruce		Balsam fir		White spruce	
					# of tree	Percent	# of tree	Percent	# of tree	Percent	# of tree	Percent
1-1	flat	0	55	1100	16	29%	35	64%	4	7%	0	0%
2-1	N	11	32	600	13	41%	19	59%	0	0%	0	0%
2-2	flat	0	36	700	14	39%	22	61%	0	0%	0	0%
3-1	S	8	60	1200	32	53%	28	47%	0	0%	0	0%
3-2	flat	0	82	2600	34	41%	48	59%	0	0%	0	0%
4-1	S	21	40	800	20	50%	0	0%	0	0%	20	50%
5-1	SW	9	72	1400	55	76%	11	15%	2	3%	4	6%
6-1	flat	0	74	1500	74	100%	0	0%	0	0%	0	0%
6-2	SE	6	67	1300	67	100%	0	0%	0	0%	0	0%
7-1	NW	10	70	1400	48	69%	22	31%	0	0%	0	0%
7-2	NE	5	59	1200	57	97%	2	3%	0	0%	0	0%
8-1	NE	8	61	1200	50	82%	11	18%	0	0%	0	0%
8-2	flat	0	76	1500	65	86%	11	14%	0	0%	0	0%
8-3	N	7	60	1200	58	97%	2	3%	0	0%	0	0%
9-1	flat	0	90	1800	50	56%	40	44%	0	0%	0	0%
10-1	SW	13	15	200	15	100%	0	0%	0	0%	0	0%
11-1	flat	0	92	1800	61	66%	31	34%	0	0%	0	0%
11-2	SE	5	70	1400	17	24%	53	76%	0	0%	0	0%
11-3	NW	5	93	1900	44	47%	49	53%	0	0%	0	0%
12-1	N	7	81	1600	30	37%	51	63%	0	0%	0	0%
13-1	SW	5	101	2000	49	49%	52	51%	0	0%	0	0%
14-1	flat	0	72	1400	25	35%	47	65%	0	0%	0	0%
14-2	NW	9	27	500	0	0%	4	15%	0	0%	23	85%
Total			**1485**	**1300**	**894**	**60%**	**558**	**38%**	**6**	**0%**	**47**	**3%**

Table A-2. Summary of tree characteristics in the sample plots in Study Area 1.

Stand-Plot No.	Lodgepole pine					Black spruce					Others (*Balsam fir, ** White spruce)				
	# of Trees	Height (m)		DBH (cm)		# of Trees	Height (m)		DBH (cm)		# of Trees	Height (m)		DBH (cm)	
		Average (Range)	S.D.	Average (Range)	S.D.		Average (Range)	S.D.	Average (Range)	S.D.		Average (Range)	S.D.	Average (Range)	S.D.
1-1	16	16 (12-20)	2.4	25 (16-37)	6.9	35	13 (10-20)	3	17 (11-28)	4.2	*4	17 (15-18)	1.4	22 (16-26)	4.9
2-1	13	21 (18-22)	1.3	28 (19-34)	4	19	11 (8-15)	2	13 (10-20)	2.7	0				
2-2	14	21 (18-22)	1.3	25 (15-35)	5.7	22	13 (8-22)	3.8	15 (10-25)	4.1	0				
3-1	32	18 (15-24)	2.2	19 (11-35)	5.2	28	16 (8-21)	3.1	16 (10-24)	4.2	0				
3-2	34	20 (16-22)	1.7	16 (11-24)	3.3	48	18 (8-22)	2.4	14 (10-24)	2.9	0				
4-1	20	19 (15-20)	2.1	20 (11-31)	6	0					**20	17(10-23)	2.6	18 (11-25)	3.6
5-1	55	17 (15-20)	2.0	16 (10-23)	3.2	11	15 (10-18)	2.0	13 (10-18)	2.7	*2 **4	13 (10-16) 20 (16-22)	3.0 2.3	12 (11-13) 22 (15-25)	1.0 3.8
6-1	74	16 (12-18)	1.0	16 (11-23)	2.8	0					0				
6-2	67	16 (12-18)	1.2	14 (10-21)	2.7	0					0				
7-1	48	16 (12-16)	1.2	16 (11-22)	3	22	13 (10-16)	1.6	13 (10-18)	1.8	0				
7-2	57	19 (14-22)	2.2	19 (11-30)	4.7	2	16 (15-17)	1.4	17 (16-18)	1.4	0				
8-1	50	21 (18-24)	1.8	21 (14-31)	4.7	11	16 (14-21)	2.1	15 (11-21)	3.3	0				
8-2	65	19 (14-22)	1.8	16 (10-28)	3.6	11	15 (12-18)	1.5	14 (10-19)	2.9	0				
8-3	58	19 (15-22)	2.1	19 (11-31)	4.1	2	14 (14)	0	13 (12-14)	1.4	0				
9-1	50	16 (14-17)	1.0	17 (12-23)	2.9	40	15 (12-17)	1.2	14 (10-24)	2.5	0				
10-1	15	23 (21-24)	1.4	45 (25-59)	6	0					0				
11-1	61	16 (14-18)	1.2	16 (10-25)	4.2	31	14 (12-16)	1.2	14 (9-19)	2.4	0				
11-2	17	16 (13-19)	1.5	17 (13-25)	3.1	53	14 (10-17)	1.8	14 (10-22)	2.8	0				
11-3	44	17 (15-18)	1.1	17 (10-26)	3	49	15 (13-17)	0.9	14 (10-20)	2.3	0				
12-1	30	18 (16-19)	0.9	18 (12-27)	3.5	51	15 (13-17)	1	12 (10-17)	1.7	0				
13-1	49	18 (15-19)	1.0	19 (12-26)	3.6	52	15 (11-18)	1.4	15 (10-24)	2.9	0				
14-1	25	17 (14-21)	1.6	18 (13-28)	2.9	47	14 (10-17)	1.3	12 (10-16)	1.5	0				
14-2	0					4	17 (15-22)	3.5	16 (12-18)	2.6	**23	19 (14-23)	3	21 (10-39)	8.9
Total	894	18 (12-24)		20 (10-59)		538	15 (8-22)		14 (10-28)		*6 **47	15 (10-18) 19 (10-23)		17 (11-26) 20 (10-39)	

Table A-3. Summary of frequencies of splits and insect damages in fire-killed trees sampled one year after fire in Study Area 1.

Stand-Plot No.	Aspect	Slope angle (degree)	# of sampled trees	# of insect-damaged trees	% of insect-damaged trees	# of split trees	% of splits	Lodgepole pine			Black spruce			Balsam fir			White spruce		
								# of trees	# of split trees	% of splits	# of trees	# of split trees	% of splits	# of trees	# of split trees	% of splits	# of trees	# of split trees	% of splits
1-1	flat	0	55	3	5%	37	67%	16	9	56%	35	24	69%	4	4	100%	0	0	-
2-1	N	11	32	0	0%	13	41%	13	2	15%	19	11	58%	0	0	-	0	0	-
2-2	flat	0	36	1	3%	13	36%	14	2	14%	22	11	50%	0	0	-	0	0	-
3-1	flat	0	60	1	2%	44	73%	32	19	59%	28	25	89%	0	0	-	0	0	-
3-2	flat	0	82	2	2%	60	73%	34	18	53%	48	42	88%	0	0	-	0	0	-
4-1	S	21	40	0	0%	14	35%	20	2	10%	0	0	-	0	0	-	20	12	60%
5-1	SW	9	72	0	0%	20	28%	55	17	31%	11	1	9%	2	2	100%	4	0	0%
6-1	flat	0	74	0	0%	25	34%	74	25	34%	0	0	-	0	0	-	0	0	-
6-2	SE	6	67	0	0%	17	25%	67	17	25%	0	0	-	0	0	-	0	0	-
7-1	NW	10	70	0	0%	40	57%	48	28	58%	22	12	55%	0	0	-	0	0	-
7-2	NE	5	59	23	39%	1	2%	57	0	0%	2	1	50%	0	0	-	0	0	-
8-1	NE	8	61	11	18%	12	20%	50	3	6%	11	9	82%	0	0	-	0	0	-
8-2	flat	0	76	2	3%	22	29%	65	18	28%	11	4	36%	0	0	-	0	0	-
8-3	N	7	60	4	7%	10	17%	58	10	17%	2	0	0%	0	0	-	0	0	-
9-1	flat	0	90	0	0%	26	29%	50	7	14%	40	19	48%	0	0	-	0	0	-
10-1	SW	13	15	0	0%	1	7%	15	1	7%	0	0	-	0	0	-	0	0	-
11-1	flat	0	92	1	1%	23	25%	61	10	16%	31	13	42%	0	0	-	0	0	-
11-2	SE	5	70	0	0%	43	61%	17	2	12%	53	41	77%	0	0	-	0	0	-
11-3	NW	5	93	2	2%	51	55%	44	14	32%	49	37	76%	0	0	-	0	0	-
12-1	N	7	81	4	5%	59	73%	30	16	53%	51	43	84%	0	0	-	0	0	-
13-1	SW	5	101	3	3%	41	41%	49	8	16%	52	33	63%	0	0	-	0	0	-
14-1	flat	0	72	5	7%	27	38%	25	2	8%	47	25	53%	0	0	-	0	0	-
14-2	NW	9	27	4	15%	15	56%	0	0	-	4	2	50%	0	0	-	23	13	57%
		Total	**1485**	66	4%	614	41%	**894**	**230**	**26%**	**538**	**353**	**66%**	**6**	**6**	**100%**	**47**	**25**	**53%**

Table A-4. Summary of occurrence of splits and insects by DBH size class in fire-killed trees sampled one year after fire in Study Area 1.

Species	DBH size class (DBH)	# of sampled trees	# of tree with insect damages	% of tree with insect damages	# of tree with splits	% of tree with splits	*Type of split*							
							Straight		***Spiral***				***Multiple***	
							# of tree	**%**	**# of tree**	**L**	**R**	**%**	**# of tree**	**%**
Lodgepole pine	Class 1 (10-14cm)	230	0	0%	70	30%	54	23%	16	3	8	7%	0	0%
	Class 2 (15-19cm)	408	8	2%	127	31%	93	23%	32	5	12	8%	2	0%
	Class 3 (20-24cm)	166	23	14%	29	17%	21	13%	8	-	3	5%	0	0%
	Class 4 (25-29cm)	54	22	41%	2	4%	1	2%	1	-	-	2%	0	0%
	Class 5 (30-59cm)	36	4	11%	2	6%	2	6%	0	0	0	0%	0	0%
	Total	**894**	**57**	**6%**	**230**	**26%**	**171**	**19%**	**57**	**8**	**23**	**6%**	**2**	**0%**
Black spruce	Class 1 (10-14cm)	354	1	0%	235	66%	114	32%	120	30	67	34%	1	0%
	Class 2 (15-19cm)	154	1	1%	103	67%	62	40%	37	4	15	24%	4	3%
	Class 3 (20-24cm)	25	2	8%	14	56%	10	40%	2	-	-	8%	2	8%
	Class 4 (25-29cm)	5	1	20%	1	20%	1	20%	0	-	-	0%	0	0%
	Class 5 (30-39cm)	0	0	-	0	-	0	-	0	0	0	-	0	-
	Total	**538**	**5**	**1%**	**353**	**66%**	**187**	**35%**	**159**	**34**	**82**	**30%**	**7**	**1%**
Balsam fir	Class 1 (10-14cm)	2	0	0%	2	100%	0	0%	0	0	0	0%	2	100%
	Class 2 (15-19cm)	1	0	0%	1	100%	0	0%	0	0	0	0%	1	100%
	Class 3 (20-24cm)	1	0	0%	1	100%	0	0%	0	0	0	0%	1	100%
	Class 4 (25-29cm)	2	0	0%	2	100%	0	0%	0	0	0	0%	2	100%
	Class 5 (30-59cm)	0	0	-	0	0%	0	-	0	0	0	-	0	-
	Total	**6**	**0**	**0%**	**6**	**100%**	**0**	**0%**	**0**	**0**	**0**	**0%**	**6**	**100%**
White spruce	Class 1 (10-14cm)	10	0	0%	3	30%	1	10%	2	0	2	20%	0	0%
	Class 2 (15-19cm)	22	0	0%	16	73%	11	50%	4	-	-	18%	1	5%
	Class 3 (20-24cm)	8	1	13%	3	38%	3	38%	0	0	0	0%	0	0%
	Class 4 (25-29cm)	2	0	0%	1	50%	0	0%	1	0	0	50%	0	0%
	Class 5 (30-59cm)	5	3	60%	2	40%	1	20%	1	1	0	20%	0	0%
	Total	**47**	**4**	**9%**	**25**	**53%**	**16**	**34%**	**8**	**1**	**2**	**17%**	**1**	**2%**
Total	Class 1 (10-14cm)	596	1	0%	310	52%	169	28%	138	33	77	23%	3	1%
	Class 2 (15-19cm)	585	9	2%	247	42%	166	28%	73	9	27	12%	7	1%
	Class 3 (20-24cm)	200	26	13%	47	24%	34	17%	10	-	3	5%	3	2%
	Class 4 (25-29cm)	63	23	37%	6	10%	2	3%	2	-	-	3%	3	5%
	Class 5 (30-59cm)	41	7	17%	4	10%	3	7%	1	1	0	2%	0	0%
	Total	**1485**	**66**	**4%**	**614**	**41%**	**374**	**25%**	**224**	**43**	**107**	**15%**	**16**	**1%**

Appendix 3. Summary of Moisture Content (MC) data.

Table A-5. Moisture content (MC) by DBH size class with time after fire in live and fire-killed white spruce trees sampled in Study Area 2.

	Time after fire	*1.5 month (45-47 days)*				*2.5 months (77-81 days)*				*3.5 months (107-110 days)*			
	DBH size class	MC mean (%)	MC range (%)	S.D.	# of samples	MC mean (%)	MC range (%)	S.D.	# of samples	MC mean (%)	MC range (%)	S.D.	# of samples
Live trees	.Class 1 (DBH: 15-22cm)	104	104	-	1	110	81-151	25	6	121	91-168	28	5
	Class 2 (DBH: 23-33cm)	98	89-107	13	2	147	120-168	20	4	112	90-151	25	5
	Class 3 (DBH: >33cm) :Outerwood	93	93	-	1	121	93-141	27	5	139	115-186	28	5
	Class 3 (DBH: >33cm) :Innerwood	-	-	-	0	48	41-60	10	4	62	41-80	17	5
Fire-killed trees	Class 1 (DBH: 15-22cm)	82	62-139	25	8	73	46-104	14	13	64	41-98	19	12
	Class 2 (DBH: 23-33cm)	87	38-126	30	7	88	44-130	26	12	66	37-136	27	12
	Class 3 (DBH: >33cm) :Outerwood	131	107-167	25	5	82	52-107	20	7	91	38-158	35	12
	Class 3 (DBH: >33cm) :Innerwood	-	-	-	0	45	32-67	12	7	51	35-93	20	12

Table A-6. Moisture content (MC) in four orientations by DBH size class with time after fire in live and fire-killed white spruce trees sampled in Study Area 2.

	Time after fire		*1.5 month (45-47 days)*				*2.5 months (77-81 days)*				*3.5 months (107-110 days)*			
	DBH size class		MC mean (%)	MC range (%)	S.D.	# of samples	MC mean (%)	MC range (%)	S.D.	# of samples	MC mean (%)	MC range (%)	S.D.	# of samples
Control trees	Class 1 (DBH: 15-22cm)	North	99	99	-	1	116	87-170	31	6	120	86-174	33	5
		East	-	-	-	0	106	80-152	25	6	129	93-178	32	5
		South	109	109	-	1	108	73-150	27	6	125	97-171	28	5
		West	-	-	-	0	110	85-142	23	6	115	90-151	22	5
	Class 2 (DBH: 23-33cm)	North	96	90-102	8	2	146	106-170	28	4	106	79-148	29	5
		East	-	-	-	0	156	138-174	15	4	107	71-165	35	5
		South	100	88-111	16	2	144	134-159	14	4	120	89-166	32	5
		West	-	-	-	0	141	107-167	25	4	114	90-153	28	5
	Class 3 (DBH: >33cm) :outerwood	North	133	133	-	1	127	99-158	31	5	153	122-195	28	5
		East	-	-	-	0	103	71-154	33	5	135	115-173	22	5
		South	54	54	-	1	123	89-161	29	5	127	105-185	34	5
		West	-	-	-	0	132	87-169	36	5	141	104-191	33	5
	Class 3 (DBH: >33cm) : innerwood	North	-	-	-	0	46	38-51	6	4	63	44-84	17	5
		East	-	-	-	0	45	41-51	6	4	63	52-82	15	5
		South	-	-	-	0	51	39-76	17	4	60	33-86	24	5
		West	-	-	-	0	52	45-61	8	4	60	36-73	16	5
Fire-killed trees	Class 1 (DBH: 15-22cm)	North	83	51-136	30	8	71	25-103	25	13	63	33-101	25	12
		East	75	39-151	35	8	73	27-107	17	13	69	44-111	20	11
		South	78	41-130	27	8	73	50-110	18	13	55	33-82	14	12
		West	93	62-140	30	8	73	44-101	13	13	71	40-127	32	12
	Class 2 (DBH: 23-33cm)	North	86	30-110	30	7	97	55-148	31	12	68	41-140	31	12
		East	84	46-130	36	7	87	37-146	37	12	57	30-78	13	12
		South	83	28-123	30	7	80	34-134	30	12	65	32-171	39	12
		West	93	50-150	32	7	88	38-141	26	12	73	32-156	34	12
	Class 3 (DBH: >33cm) :outerwood	North	131	107-147	44	5	73	36-115	34	7	94	41-173	42	12
		East	114	67-163	31	5	88	52-113	22	7	85	30-167	42	12
		South	136	89-170	16	5	86	52-125	28	7	84	52-125	39	12
		West	143	105-189	34	5	80	35-116	32	7	101	37-191	44	12
	Class 3 (DBH: >33cm) :innerwood	North	-	-	-	0	45	31-64	13	7	50	35-86	14	12
		East	-	-	-	0	51	36-78	15	7	52	35-90	18	12
		South	-	-	-	0	42	32-66	12	7	57	34-121	32	12
		West	-	-	-	0	42	30-59	10	7	48	34-75	13	12

Appendix 4. Summary of results of statistical analysis of moisture content (MC).

Table A-7. MANOVA results for the effects of the between-subject factors [time after fire (Time), size of tree (size)] and the within-subject factor [orientation of tree (Orientation)] on moisture content (MC) of outerwood in (a) live and (b) fire-killed trees (SAS software, PROC GLM procedure).

(a)

Source	*DF*	*SS*	*MS*	*F value*	*P>F*
Time	1	92.1	92.1	0.03	0.8546
Size	2	5159.9	2580.0	0.96	0.3966
Time x Size	2	15445.2	7722.6	2.88	0.0758
Error	24	64414.0	2683.9		

Source	*F value*	*NDF*	*DDF*	*P>F*
Orientation	0.53	3	22	0.6649
Orientation x Time	0.21	3	22	0.8913
Orientation x Size	1.82	6	46	0.1157
Orientation x Time x Size	1.96	6	46	0.0917

(b)

Source	*DF*	*SS*	*MS*	*F value*	*P>F*
Time	2	33394.3	16697.2	6.65	**0.0022**
Size	2	40389.9	20195.0	8.05	**0.0007**
Time x Size	4	21166.8	5291.7	2.11	0.0877
Error	78	195797.3	2510.2		

Source	*F value*	*NDF*	*DDF*	*P>F*
Orientation	3.13	3	76	**0.0305**
Orientation x Time	1.36	6	154	0.2336
Orientation x Size	0.47	6	154	0.8329
Orientation x Time x Size	0.84	12	234	0.6055

Note:
DF: Degree of freedom
DDF: Denominator degree of freedom
MS: Mean square
NDF: Numerator degree of freedom
SS: Sum of squares

Table A-8. ANOVA results on each of the contrasts of (a) between-subject factors [time after fire (Time), size of tree (size)] and (b) the within-subject [orientation of tree (Orientation)] for comparison of means of moisture content (MC) (SAS software, PROC GLM procedure).

(a)

Contrast variable*:	**Pr>F** **(α=0.05/3=0.0166)**
Time 1 vs. 2	**0.0109**
Time 1 vs. 3	**0.0005**
Time 2 vs. 3	0.2934

*
Time 1 = 1.5 months after fire
Time 2 = 2.5 months after fire
Time 3 = 3.5 months after fire

Contrast variable:**	**Pr>F** **(α=0.05/3=0.0166)**
Size 1 vs. 2	0.3042
Size 1 vs. 3	**0.0002**
Size 2 vs. 3	**0.0042**

**
Size 1 = DBH size class 1
Size 2 = DBH size class 2
Size 3 = DBH size class 3

Contrast variable:	**Pr>F** **(α=0.05/9=0.0055)**
Size 1 vs. 2 in Time 1	0.7156
Size 1 vs. 2 in Time 2	0.1338
Size 1 vs. 2 in Time 3	0.9867
Size 1 vs. 3 in Time 1	**0.0010**
Size 1 vs. 3 in Time 2	0.4345
Size 1 vs. 3 in Time 3	0.0182
Size 2 vs. 3 in Time 1	**0.0034**
Size 2 vs. 3 in Time 2	0.6177
Size 2 vs. 3 in Time 3	0.0166

(b)

ontrast variable***	**Pr>F** **(α=0.05/6=0.00833)**
N vs. E	0.2057
N vs. S	0.2958
N vs. W	0.1212
E vs. S	0.7597
E vs. W	**0.0078**
S vs. W	**0.0078**

***
N = North
E = East
S = South
W = West

Table A-9. MANOVA results for the effects of the between-subjects factor [time after fire (Time)] and the within-subject factors [orientation of tree (Orientation) and depth of wood (Depth)] on moisture content (MC) of (a) live and (b) fire-killed trees in DBH size class 3 (DBH: >33cm) (SAS

(a)

Source	*DF*	*SS*	*MS*	*F value*	*P>F*
Time	1	6043.4	6043.4	2.48	0.1593
Error	7	17060.6	2437.2		

Source	*F value*	*NDF*	*DDF*	*P>F*
Depth	94.51	1	7	**0.0001**
Depth x Time	0.45	1	7	0.5227
Orientation	2.69	3	5	0.1570
Orientation x Time	1.20	3	5	0.3999
Depth x Orientation	4.03	3	5	0.0838
Depth x Orientation x Time	1.37	3	5	0.3538

(b)

Source	*DF*	*SS*	*MS*	*F value*	*P>F*
Time	1	2081.3	2081.3	0.66	0.4262
Error	17	53234.3	3131.4		

Source	*F value*	*NDF*	*DDF*	*P>F*
Depth	36.14	1	17	**0.0001**
Depth x Time	0.05	1	17	0.8299
Orientation	0.18	3	15	0.9065
Orientation x Time	0.81	3	15	0.5057
Depth x Orientation	0.60	3	15	0.6255
Depth x Orientation x Time	1.69	3	15	0.2112

Note:
DF: Degree of freedom
DDF: Denominator degree of freedom
MS: Mean square
NDF: Numerator degree of freedom
SS: Sum of squares