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Gradients in microclimate and spruce growth adjacent to young aspen stands

by

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Abstract

This study examined how aspen patches influence microclimatic conditions in adjacent openings and how these are reflected in the growth of white spruce. Gradients in light levels and air temperature increased continuously across the aspen edge to a maximum within the opening, while soil moisture increased right at the edge and then decreased. Light levels were reduced over a greater distance when moving north from aspen stand edges compared to openings located south of the young aspen. These young aspen stands provided frost protection within one tree length from the edge. The growth of white spruce was related to either light levels or distance from the edge and initial seedling crown surface area, and it increases as both of these independent variables increase. Stem volume growth was best predicted by initial tree size and the light levels available for use at the midcrown of seedlings, followed by distance from the edge and initial seedling size.

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Chapter 1. General introduction

The boreal mixedwood forest, dominated by aspen (*Populus tremuloides* Michx) and white spruce (*Picea glauca* [Moench] Voss), accounts for the majority of Canada's well-drained upland forest association, although variable proportions of balsam poplar (*Populus balsamifera* L.), white birch (*Betula papyrifera* Marsh.), black spruce (*Picea mariana* (Mill.) B.S.P.) and balsam fir (*Abies balsamea*(L.) Mill.) are encountered (Rowe 1972; Thorpe 1992; Beckingham and Archibald 1996). In the boreal plains ecozones mixedwood forests are found on moraine or lacustrine luvisols, in cold and moist climates, where human activities like forestry, agriculture, tourism, and oil and gas development are found (CCEA 2004). These forests occupy about 15 million ha, representing almost 1/3 of the productive forest sites in the Prairie Provinces (Brace Forest Services 1992; Navratil *et al.* 1994). The main components of mixedwood stands in western Canada are white spruce and aspen (Lieffers *et al.* 1996), while in eastern Canada white spruce is frequently substituted by balsam fir (Kneeshaw and Bergeron 1998).

A critical period in mixedwood stand development appears to occur between 5 and 15 yrs after logging or fire, when the proportion of conifers declines due to crown closure of competing hardwoods (MacIsaac and Navratil 1996; Lieffers et al. 2002). However, by opening the canopy understory spruce could face problems from other competitors such as *Calamagrostis canadensis (Michx.) Beauv.* (particularly on moister sites), which can take over the site for a long time if not surpassed by aspen (Lieffers *et al.* 2003). Therefore, foresters must identify and balance the factors limiting tree growth and stand development when managing boreal mixedwood forests. The key factor for successful management of conifers within mixedwood stands is to find a balance between the unfavorable effects of deciduous competition with its benefical effects on nutrient availability, microclimate, insect and disease damage, and biodiversity (Comeau *et al.* 1999a). Moreover, sustainable management of mixedwood forests requires a clear understanding of succession and the critical phases at which foresters might manipulate stands to effectively achieve stated objectives (Lieffers *et al.* 2003). There is substantial interest in maintaining mixedwood stands in the landscape, because they are a natural feature, are important habitat for many species, and there may be tangible benefits (including economic) to growing mixedwood stands rather than monocultures.

1.1 Nature and major characteristics of boreal mixedwood forests

The nature and structure of boreal mixedwood forests results from the combined effects of several factors, including disturbances (mainly wildfire), ecological variability of the landbase on which the disturbances take place, and differences in autoecology of the component species (Chen and Popadiuk 2002). Because species composition can vary extensively, Ontario uses soil types to delineate potential boreal mixedwood sites (MacDonald 1996). A boreal mixedwood site is defined as an area that shows climatic, topographic and edaphic conditions capable of sustaining mixedwood stands (MacDonald 1996). When classifying boreal mixedwood stands in Ontario there are no restrictions on the proportions of hardwoods or softwoods (MacDonald 1996). In other areas a mixedwood stand is often defined as a stand that has recognizable components of at least two species, and is typically defined based on each component species contributing at least 20% to the total stand volume or canopy composition. This definition may need some expansion to accommodate young stands, where there may be substantial numbers of small white spruce or balsam fir growing in the understory, but where basal area, volume or cover are not currently sufficient to meet these criteria. Western boreal mixedwood forests are comprised of three major types of stands: aspen dominated, spruce dominated, or mixtures of the two (Lieffers and Beck 1994).

Mixedwood forests emerge as a consequence of natural succession. Following the harvesting of mixedwood stands, trembling aspen regenerates vigorously and dominates the early stages of subsequent development (Thorpe 1992). Complementary to aspen, white spruce grows slowly during the early stages of development and usually does not become dominant in the canopy until much later (Lieffers and Beck 1994). Several studies indicate a potential reduction in conifer growth (primarily due to reduced light) and whipping damage from hardwood species (Lees 1966; Thorpe 1992; MacIsaac and Navratil, 1996).

Stand dynamics in boreal mixedwoods depend on interactions between and among species, interactions between species and site, and the nature of disturbance and its impact on stand development (Andison and Kimmins 1999). Changes in mixedwood stands over time frequently include changes in species composition (Chen and Popadiouk 2002) with stand development being strongly influenced by the type, intensity, and timing of disturbances, stand and site conditions, biotic factors (i.e. insects), and adjacent stands on the site, as well as by the consequences of those disturbances for seedbeds, seed production, competition, survival, growth, and tree mortality (Andison and Kimmins 1999; Chen and Popadiouk 2002).

Some of the main characteristics of boreal forest as summarized by Burton *et al.* (2003) are the following:

- Cold continental climate with severe winters, a short growing season, and cold soils;
- Forests dominated by relatively few species of softwoods (i.e. spruce, pine, and fir) and hardwoods (i.e. aspen, birch, and alder);
- Slow tree growth that results in strong wood with a large range of commercial utilization, as well as slow decomposition rates resulting in strong nitrogen limitations to plant productivity;
- Distinct cycles of natural disturbance and succession dominated by wildfire and insect outbreaks.

A critical characteristic of boreal mixedwood forests is that they do not follow exactly (if at all) classical patterns of succession because of the rapid regeneration of the early seral (first generation) tree species (aspen), the frequent lack of replacement species (due to lack of a white spruce seed source or suitable seedbed conditions) or premature arrival of fire disturbances (Rowe 1961; Peterson and Peterson 1992). Boreal mixedwood forests are dominated by young stands as a result of high fire frequency or other disturbances (Peterson and Peterson 1992). Managers in the boreal mixedwood forest face challenges that emerge in young ecosystems (usually in the first years after disturbances) such as high interspecific competition from *Calamagrostis*, fireweed (*Epilobium angustifolium L.),* willow *(Salix* spp.*),* green alder *(Alnus crispa* (Ait.) Pursh) or other early seral species (Peterson and Peterson 1992).

.In the first half of the 20th century, western Canadian mixedwood stands were harvested to remove large white spruce for lumber (Lieffers and Beck 1994; Andison and

Kimmins 1999). The same approach was adopted in Quebec where the management of mixedwood stands involved extracting the valuable softwood or hardwood species (Prevost 1996). By the 1970's, harvesting had resulted in a reduction in white spruce present in the boreal forest compared to what may have been present prior to 1880. This phase was followed by a period when the more desirable spruce was promoted in opposition to aspen (hardwoods being considered as non-merchantable) by trying to convert mixedwood stands to softwood stands (MacDonald 1996; Cumming and Armstrong 2001). However, as technological developments increased the utilization of aspen and poplar (MacDonald 1996; Cumming and Armstrong 2001), the conversion to softwood stands came into question (Andison and Kimmins 1999). In addition, conversion was often unsuccessful and expensive due to competition with trembling aspen and grasses (Lieffers and Beck 1994). Increasing anxiety among environmentalists due to widespread conversion of mixedwood stands to pure softwoods was another key reason for reassessment of the stand conversion strategy (Andison and Kimmins 1999).

1.2 Advantages of growing mixtures rather that spruce monocultures

There has been an increasing interest in promoting mixedwood stands, probably because the formation of mixed stands is almost impossible to prevent, they are a major natural component of the boreal landscape, and because of widespread pressure from the public for sustainable management of boreal forest for many non-timber resource values including emulating natural disturbance patterns. Some of the beneficial effects of mixedwood stands over pure stands include: higher biodiversity; increased resistance to diseases, insects and frost damage; improved litter decomposition and nutrient cycling;

maintainance of soil and site productivity; amelioration of environmental extremes; increased wind stability; and control of other competitors (Kelty 1992; Comeau 1996; MacDonald 1996; Man and Lieffers 1999a; Comeau *et al.* 1999b).

Compared to pure stands, stratified stands made up of species with different light requirements (i.e. shade intolerant species in the upper canopy and shade tolerant species underneath) make better use of site resources, including available light (Kelty 1992; Mielikainen 1996). This can result in higher stand productivity as found in a vertically stratified aspen-conifer mixture (Edgar and Burk 2001; MacPherson *et al.* 2001). However, the presence of a reduction in competition for nutrient and water uptake is not clear, especially during the establishment phase (Kelty 1992).

Some modeling studies indicate that growing mixtures may provide greater yield than pure stands as suggested by studies in hardwood-hemlock mixtures (Kelty 1992), Douglas-fir and red alder stands (Comeau 1996), in birch and conifer stands (Mielikainen 1996), or in mixedwood stands of white spruce and aspen (Wang *et al.* 1995, MacDonald 1996). In addition, the results of Edgar and Burk (2001) showed that the most productive stands in northeastern Minnesota were vertically stratified mixtures of aspen, conifers, and paper birch. However, the optimal proportion of hardwoods in a mixedwood stand varies with species (25-50% for birch, 20-40% for red alder) (Comeau 1996; Mielikainen 1996). Man and Lieffers (1999a) suggested that a mixedwood stand of aspen and white spruce has greater overall volume production than either pure aspen or pure spruce. Greater productivity of mixedwood stands could be the result of adding the growth of white spruce owing to prolonged photosynthetic periods in spring and fall (Constabel and Lieffers 1996) to the potential yield of purely deciduous aspen stands (Man and Lieffers

1999a). However, because of lack of long term paired growth (mixed/pure) studies there is no strong evidence that the volume production of mixedwood is greater at all ages or that the production of mixedwood at rotation would have been greater than a pure stand.

Long term site productivity can be maintained by keeping both spruce and aspen on the same site (Bergeron and Harvey 1997) because an admixture of hardwood litter can enhance the decomposition rate of coniferous litter (Smith 1962). In that respect, Man and Lieffers (1999a) suggested that the presence of aspen, which has high nutrient concentration in its foliage and faster decomposition rates (Peterson and Peterson 1996), may be important for understory white spruce on nutrient deprived sites. Due to its rapid growth rate, aspen can limit nutrient loss after disturbance, and maintain rapid nutrient turnover (Pare and Van Cleve 1993). The presence of broadleaves (i.e. deciduous broadleaf trees) in a mixedwood forest results in increased decomposition rates (Prescott *et al.* 2000). Greater decomposition and greater nutrient concentration in aspen leaves can accelerate rates of nutrient cycling (Pare and Van Cleve 1993). Furthermore, increases in soil acidification have been reported by Brand *et al.* (1986) 46 yrs after white spruce monoculture plantations were established.

Man and Lieffers (1999b) report that a protective aspen overstory can increase soil temperature and humidity, decrease risk of frost and its severity, and maintain an optimum light environment for growth of white spruce seedlings. The establishment of white spruce on wet sites can be improved by an aspen cover that reduces soil moisture through transpiration and canopy interception of precipitation (Man and Lieffers 1999a). Given that understory vegetation declines as tree cover increases, aspen can be used to reduce competition from *Calamagrostis* and shrubs in young white spruce plantations (Lieffers and Stadt 1994).

Stratified aspen-white spruce stands also have the potential to reduce damage caused by wind gusts (Navratil 1996; Man and Lieffers 1999a). Differences in depths to which the roots of softwoods and hardwoods penetrate can contribute to greater stability, and subsequently protection of mixedwood stands against blowdown (Kelty 1992), and probably lead to better use of soil resources in terms of water and nutrient uptake.

Mixed aspen-conifer forests are very dynamic ecosystems and as a result, could provide insurance that one of the species will survive against potential management errors, and react with increased compensatory growth (Debyle 1991; Kelty 1992). Furthermore, because broadleaves and conifers are used as raw material for different products, and consequently different markets, there is increased stability for the forest industry as a whole (MacDonald 1996). Mixedwoods also have the beneficial effect of increasing the esthetic value of landscapes during the year by the diversity they provide. Furthermore, the greater diversity of species that characterizes the understory of mixedwood stands can create better habitat for wildlife and protect the quality of watersheds (Comeau 1996; MacDonald 1996). Presence of aspen results in early creation of vertical structure, and greater variety of biomass for browsing and foraging (Peterson and Peterson 1996). Because biodiversity is greater in mixedwood than softwood forests, mixedwoods may impede invasion of pioneer species (Bergeron and Harvey 1997).

Economic advantages of growing mixedwoods, as identified by Lieffers and Beck (1994), include: reduced regeneration cost, accelerated regeneration of the site, and a greater diversity of products. In mixedwood stands of Alberta, the release of spruce before it becomes codominant with aspen resulted in increased merchantable spruce as well as reduced whipping damage to conifers (Lees 1966). Comeau *et al.* (1999b) suggested that on sites with *Armillaria* the risk of financial losses could be minimized with little investment and intervention by allowing a natural mixedwood stand to develop. Mielikainen (1996) reported that the best quality veneer logs were found in mixedwood stands in Finland. Technical advancements make mixedwoods more appealing to the forest industry now that the capability exists to process mixedwood timber into a broader range of products. At the same time, the availability of pure conifer stands is decreasing, while mixedwoods stands have emerged as an important, low cost source of fiber close to the mill (MacDonald 1995).

Current treatments using mechanical site preparation, planting, and herbicide applications can effectively create nearly pure spruce stands. However, establishing spruce plantations on mixedwood sites in Alberta is an expensive option (with establishment costs sometimes exceeding $1000 per ha), and up to two-thirds of spruce plantations have reverted to mixedwood or broadleaf stands (Brace and Bella 1988). The economics of stand tending has also shifted in favor of mixedwoods (Macdonald 1995). Furthermore, the justification of using herbicides to boost conifer crops has been increasingly difficult to defend as the commercial value of aspen has increased (Beck 1998). All of the above are important factors to consider in setting the direction for management of mixedwood forests.

1.3 Management options for regeneration and growth of young mixedwood stands

Trembling aspen generally increases in abundance following clearcutting because of its aggressive root suckering after disturbance. Reaching maturity at 60 yr, it is considered a potential competitor to spruce for many years. Although it is moderately shade tolerant, white spruce may not establish or survive under closed canopies, particularly when light levels are below 8% (Lieffers and Stadt 1994). While growing mixedwood stands may be desirable, creating valuable and healthy mixedwood stands may require significant silvicultural investment, as well as an obligation to perform the necessary silvicultural operations. These operations include early and mid-rotation thinning, modified harvesting to protect advance regeneration (MacDonald 1996), and mechanical site preparation techniques adapted to the site conditions to improve conifer establishment (Lieffers and Beck 1994). To maintain mixed stands, pre-commercial thinning is often applied during the first 15 yrs after disturbance (Prevost 1996).

Until the 1980's, harvesting was usually followed by little management in terms of regenerating the harvested area in boreal mixedwood forests. This was the direct result of the low commercial timber volume per hectare, regeneration problems, small log sizes and poor economics perceived with harvesting boreal mixedwood forests (Andison and Kimmins 1999). In the 1980's concern developed as a result of reports of declining conifer volume and an associated increase in the abundance of deciduous stands across the landscape. This led to widespread attempts to convert both young and mature deciduous dominated stands to coniferous stands. In the 1990's, changes in forest economics worldwide and the development of oriented strandboard and pulp industries utilizing aspen and poplar led to increased interest in the utilization and management of mixedwood forests. Factors like increased demand for timber products, new developments in wood processing, a more ecological-based management philosophy, as well as a better understanding of forest ecosystems and loss of timber supplies at global level (Lieffers and Beck 1994; Andison and Kimmins 1999), made the management of boreal mixedwood forest more attractive.

In a young spruce-aspen mixedwood stand there are both aspen and white spruce that require relatively high light levels to grow. On the other hand increasing light can induce damage such as frost, or competition from *Calamagrostis*. To address these problems there are a number of possible ways to manage young mixedwood stands (Comeau and Mihajlovich 2001), which include:

1) Manipulating aspen densities to provide conditions that favor the desired number of spruce. This involves increasing light levels by reducing aspen density. The final result will be a vertically stratified mixture of aspen and white spruce, with spruce occupying a codominant position in the canopy;

2) Treating areas around individual conifers and removing competition within a desired radius. Mechanical or chemical removal of aspen within a 1-2m radius seems to significantly improve white spruce survival and growth. This will generate a vertically stratified mixture of aspen and white spruce, with spruce occupying diverse positions in the canopy;

3) Treating patches or clusters of conifers, while leaving a portion of the stand untreated. This option involves removing aspen from the mixedwood patches and/or fill planting those patches with white spruce. This will result in a horizontally stratified mixture of aspen and white spruce, where spruce can take advantage of the potential nursing

influences of aspen, while getting adequate light levels for sustained growth depending on patch sizes. However, because of the typical slow initial growth of white spruce, it might be necessary to control competition for an extended period of time (Sutton 1986).

Managing mixtures as patches or clusters is very attractive, because it could allow the use of less expensive tending practices such as aerial herbicide application. However, before this last option receives wider implementation there is a need for better information on the potential effects of patch or cluster size and other characteristics on the growth of white spruce.

Many critical factors influence the establishment and early growth of planted white spruce on upland sites in the boreal forest. They include: 1) frost damage relating to Chinook events and summer frost; 2) competition from aspen, balsam poplar and white birch for light and water; 3) competition from *Calamagrostis canadensis* and other vegetation; and 4) cold soil temperatures, which are made worse by grass and other vegetation cover. The implications of the patch or cluster approach to these controlling factors is discussed in the following sections.

1.4 Air temperature, light levels, and soil moisture mirrored in growth of white spruce

1.4.1 Air temperature

Freezing temperatures can occur at any time of the year in the boreal forest. The effects of freezing temperatures are of particular importance for young conifer seedlings as both their survival and growth may be affected. During the growing season frost can occur due to radiative and advection processes (Orcutt and Nielsen 1996).

Radiative frost can occur on calm and clear nights when ground or plant surfaces cool below 0°C by radiating heat back to the atmosphere, (Spittlehouse and Stathers 1990; Orcutt and Nilsen 1996; Grossnickle 2000). Chances of radiative frost are greatest at the beginning and end of the growing season when nights are longer (May and September) (Grossnickle 2000). Advective frost occurs when cold air moves over an area causing low air temperatures that result in rapid freezing of plant parts (Spittlehouse and Stathers 1990; Orcutt and Nilsen 1996; Grossnickle 2000). In the field the distinction between radiative and advective frost is somewhat subjective because both often occur simultaneously. A key difference is that localized advective frosts can be worse in low lying areas due to the pooling of dense cold air, whereas radiative frosts occur at any landscape position.

The rate at which the soil surface cools is determined by the difference between the rate of heat loss from the ground to the sky and the rate at which heat stored in the soil is transferred to the soil surface (Grossnickle 2000). Geiger (1980) showed that during clear nights the rate of thermal radiation loss from the ground to the sky is 5-10 times greater than under cloudy conditions. This might result in a 4-5°C decrease in minimum air temperature at seedling height and the same decrease in minimum soil temperature (Stathers 1989).

The physical properties of air also influence the occurrence of radiative and advective frost (Stathers 1989). As air radiates heat, its temperature will drop rapidly, causing an increase in air density. This will cause cool air to settle near the ground surface, creating an air temperature inversion that increases the risk of frost events. Another important determinant of frost occurrence is air humidity. The risk of frost is greater at sites where the air is initially drier and colder at sunset (Stathers 1989). Windy conditions can reduce the incidence of frost by mixing the radiatively cooled air near the ground with warmer overlying air. Therefore, exposed windy sites are less affected by frost events than sheltered sites where the wind speed is decreased at night (Stathers 1989, Grossnickle 2000). A combination of clear sky, low wind speed and dry air can result in greater incidence of frost events. Clear night skies produce a net loss of longwave radiation while a low wind speed minimizes the mixing of cold surface air with the warmer air well above the surface (Spittlehouse and Stathers 1990). Under clear night sky conditions, the temperature near the soil surface decreases rapidly, and frost occurs near the soil surface (5-15cm) even though the air temperature above the ground (at 1.3m) is well above the freezing point (Grossnickle 2000).

Serious frost damage or even seedling mortality can occur if the air temperature drops below -2 to -5°C during the active growing season when the seedling is not hardened. However, the extent of damage depends on the duration and intensity of low temperatures as well as the type of tissue affected (e.g. growing shoots, needles, unhardened buds) (Spittlehouse and Stathers 1990). Duration of frost predicts frost damage better than minimum temperature. In this regard, Spittlehouse and Stathers (1990) found that the length of period with temperatures below 0°C and -3°C was important for the development of frost damage.

Lundmark and Hallgren (1987) tested whether shading could diminish the impact of low temperature injuries by improving the microclimate for planted Norway spruce and Scots pine. Given that all seedlings experienced the same temperature conditions at night, the difference in development of visible damage to seedlings was most likely due to the difference in irradiance following severe night frost. In the field, clear and cold nights during the growing season are usually followed by clear days with high irradiance. Under such conditions the amount of radiant energy absorbed by plants can become a critical factor, and exposure of plants to direct radiation may enhance the effects of low temperatures. Under these conditions shelter can provide additional protection for seedlings from frost events (Lundmark and Hallgren 1987). Orlander (1993) showed that temperatures as low as -2°C, when combined with high light on the day after frost, can induce injury to needles of unshaded Norway spruce seedlings. Langvall's and Orlander's (2001) study showed that the net radiation received during the night of a frost event, combined with the net and global radiation received the day after the frost event, strongly influenced the amount of visible frost damage and frost-induced photoinhibition. Their results suggested that short exposure to full sunlight did not have an effect as significant as that of the global radiant energy received during the day after the frost event. Gillies and Binder (1996) also found that both dehardened and newly flushed needles were affected by freezing temperature, with freezing effects enhanced by light. Sub-freezing temperatures did not have any effect on hardened needles.

According to Bigrass and Herbert (1996), the influence of exposure duration to freezing temperature depends on the stage of dehardening. They studied the impact of freezing temperatures between 0 and -10°C on buds, needles and roots of black spruce. The effects of spring frost can be summarized as follows: 1) spring frost damaged newly flushed buds and shoots, as well as needles and roots; 2) frost tolerance of all parts of black spruce seedlings decreased as buds started to open and shoots started to grow; 3) a reduction in root mass and needles was noted that affected the subsequent growth of seedlings; 4) damage to the root system and needles before bud swelling decreased stem diameter growth; 5) at the stage of bud swelling and needle emergence, damage to root and needles reduced both new-shoot and diameter growth; and, 6) if elongated shoots survived exposure to low temperatures, damage to needles and root system did not affect shoot growth but diameter growth was reduced (Bigrass and Herbert 1996).

As a result of summer frost, there is a reduction of net photosynthesis rates in conifers consisting of a depression phase and a recovery phase (Dang et al 1992). The length of the depression phase varies with species but not the degree of freezing. During the recovery phase the net photosynthesis rate increased gradually. In Scots pine seedlings exposed to -5°C, net photosynthesis and transpiration decreased immediately after the freezing event (Ryyppo *et al.* 1997). Delucia *et al.* (1991) also found that exposure of unhardened conifers to freezing temperatures may cause a decrease in photosynthesis and transpiration. Following freezing injuries, net photosynthesis of Scots pine recovered after 21 days (Ryyppo *et al.* 1997). During the growing season, temperatures from -3.5 to -5°C appear to cause irreparable damage to Scots pine seedlings (Ryyppo *et al.* 1997).

Soil type and vegetation cover affect the occurrence of frost. Organic soils have a lower capacity to store and transmit heat than mineral soils (Grossnickle 2000). Thick organic surface horizons slow the transfer of heat between overlying air and the underlying mineral soil. Vegetation, particularly forests can have a great influence on the minimum temperature at the forest floor and consequently, on the occurrence of frost. Vegetation cover reduces the amount of radiative heat loss from the ground, thereby reducing the rate of ground surface cooling at night (Grossnickle 2000). Groot and

Carlson (1996) found that in a mixedwood stand of aspen and white spruce, the aspen strongly influenced minimum air temperature near the ground. This resulted in air temperatures as much as 6°C warmer within the aspen than in a clear cut on clear nights, while during cloudy nights there was little difference (Groot and Carlson 1996). Low growing vegetation, such as thick beds of *Calamagrostis* can also inhibit upward heat flow from the soil as well as reducing convective mixing of the air resulting in trapping of cold air, and a higher risk of frost (Stathers 1989; Lieffers *et al.* 1993). Moreover, the accumulation of grass litter on the soil surface insulates the ground, resulting in slower soil warming, lower soil temperatures and less re-radiation from the soil to the overlying vegetation and air (Hogg and Lieffers 1991; Kabzems and Lousier 1992).

Site preparation treatments also influence frost hazard. The risk of frost occurrence is increased by mulching, and decreased by herbicide, broadcast burning, trenching, ripping and mounding treatments or shelterwood (Spittlehouse and Stathers 1990). Planting in microsites that reduce the seedling sky view factor or in microsites that store and radiate energy back toward the seedling at night (e.g. near large stumps or fallen logs) can also reduce frost hazard (Spittlehouse and Stathers 1990; DeLong *et al.* 1997).

Control of competing herbaceous and shrubby vegetation in conifer plantations, even when successful, can have an adverse effect on young conifers because removal of overtopping vegetation exposes them to potential frost damage (Sutton 1984). In contrast, removal of surface organic horizons and placement of seedlings on elevated microsites can reduce the risk of summer frost injury. Finding a balance between the advantages and disadvantages of silvicultural treatments is important.

The risk of frost damage to seedlings can be alleviated by both residual aspen and young aspen that are taller than the planted white spruce (Groot and Carlson 1996; DeLong 2000, Pritchard 2003). The risk of damage in Norway spruce seedlings was found to be diminished by greater minimum temperatures and greater shading offered by the residual canopy (Langvall and Orlander 2001). Shelter trees can reduce the incidence and degree of frost damage, thereby improving seedling survival (Orlander 1993). Shading by shelter trees might also reduce the risk of frost damage by reducing the exposure of seedlings to high intensity light during the days after a cold night (Lundmark and Hallgren 1987). Orlander and Karlson (2000) found that frost damage appeared with greater frequency in clear-cuts than in shelterwood cuts. The incidence of frost was also high in shelterwoods with low densities.

Small openings or strips can provide the combined benefits of increased light levels for spruce, and adjacent shelter. Creation of openings of an optimum size (circles of 18m diameter or 9m width strips), where light is sufficient to promote white spruce growth (while reducing that of trembling aspen), frost hazard is reduced, and low soil temperatures enhance white spruce development rather than aspen suckering, was suggested by Carlson and Groot (1997) as being one potential way to establish spruce in mixedwood stands. However, the optimal size of openings is likely to be influenced by several factors, particularly the height of the surrounding stand.

Determining optimal opening sizes requires knowledge of the influence of the surrounding stand on the opening as well as the influence of opening size and location. At the edge of an opening, air temperature is intermediate between that in the forest and that in the clearcut during night and early morning, but not midday (Saunders *et al.* 1999).

Compared to inside an intact forest, the adjacent openings allow more solar radiation to reach the ground during the day, while losing higher amounts of radiation to the atmosphere at night (Geiger 1980). Air temperature and radiation both increase as opening size increases (Groot *et al.* 1997).

The forest edge can provide some protection against frost. To avoid severe night frost during natural establishment of lodgepole pine seedlings, Cochran (1969) suggested the width of strip clearcuts should not be wider than twice the height of the adjacent stand. The risk of frost damage to white spruce seedlings increases as the opening size increases, with frost incidence minimized in openings with a view factor of less than 0.3 (or 2 tree lengths in diameter) (Groot *et al.* 1997; Carlson and Groot 1997). Matlack (1993) found that north-facing edges showed the lowest temperatures, while the reverse was true for south-facing edges. Different microclimates specific to the two sides of the edges are expected to generate gradients of temperature that run perpendicular to the edge (Murcia 1995).

In mature forests of the northeastern U.S., temperature gradients extend into adjacent fields for 15 to 20 m (Cadenassoo *et al.* 1997). Similarly, Saunders *et al.* (1999) showed that variation in temperature was dependent on the distance from the forest edge. The size of patches is also an important factor that affects the temperature dynamics across edges. Kapos (1989) found that 1 ha forest patches had less effect on temperature dynamics across edges than did 100 ha patches.

1.4.2 Light levels

Light is essential for photosynthesis, survival and growth of understory plants (Canham *et al.* 1990; Pacala *et al.*1994; Chen and Klinka 1997; Lieffers *et al.* 1999; Greene *et al.* 2002; MacDonald and Thompson 2003). Light levels can also be the easiest factor to control in management of mixedwood forests. Vigorous regeneration of aspen following natural or artificial disturbance of a mixedwood stand reduces light available to the slower growing conifers. On productive mixedwood sites, understory light reduction by overstory hardwoods is considered to be the chief factor limiting the growth of understory conifers (Comeau *et al.* 1998). Similarly, findings by Pacala *et al.* (1994), Lieffers *et al.* (1999) and Coates and Burton (1999) emphasize light as the main factor affecting the development of understory trees in boreal forest. West *et al.* (1989) presented results indicating that light was the dominant competitive factor in a *Pinus radiata* plantation, rather than below-ground competition for soil resources.

Growth of planted white spruce seedlings was found to react to increases in soil temperature, light, moisture and nutrients when competition was decreased (Brand and Janas 1988). However, soil surface temperature was found to be strongly associated with light penetration through the canopy of mixed aspen/conifer, and aspen stands (Amacher *et al.* 2001). Similarly, patterns of soil and air temperature within strips sheltered by a 40 yr old aspen stand were related to light levels, and increased as opening size increased (Groot *et al.* 1997). Findings in the boreal mixedwood forest of Quebec showed that the understory species present in a stand were well-adapted to soil characteristics and their growth depended mainly on light and water availability rather than nutrients (Legare *et al.* 2002). Similarly, giant sequoia and Douglas-fir grown in small openings were sensitive to light levels and water availability, while for ponderosa pine growth; only light was the determining factor (York *et al.* 2003). For white pine and Douglas-fir growing at light levels under 55% and 43% of full sunlight, respectively, light is the main factor determining growth, with soil moisture and nutrient regime having a secondary influence (Logan 1959; Drever and Lertzman 2001). However, clear separation between the contributions of light, water and nutrient levels is difficult to depict, as all three are influenced by leaf area index of the competitors as well as ambient environmental conditions (Cannell and Grace 1993).

White spruce shoots reach maximum photosynthesis when available light is between 40 and 60% of the above canopy levels (Man and Lieffers 1997a). However, diameter and volume growth for conifers grown in the understory is generally found to reach a maximum at full sunlight (Eis 1970; Klinka *et al.* 1992; Comeau *et al.*1993; Lieffers and Stadt 1994). Even the lowest level of vegetation cover, and the correspondingly reduced light levels, significantly impede conifer seedling diameter and volume growth (Jobidon 2000). There are also thresholds of transmitted light below which the survival of conifer seedlings is not possible. Lieffers and Stadt (1994) found that for white spruce the minimum light level for survival is 8% of full sunlight. Eis (1970) found that spruce die when exposed to light levels under 15% for 10 to 15 years.

For adequate growth, minimum light levels of 30% to 45% (for subalpine fir and white spruce) or 40% (for Douglas fir) of full sunlight have been suggested (Logan 1969; Klinka *et al.* 1992; Drever and Lertzman 2001). While the height growth of white spruce, balsam fir, and white pine seedlings was similar at full sunlight as that at 45 to 55% light, seedlings grown at light levels above 60% of full sunlight showed greater height increment over those grown at 20 % of full sunlight (Gustafson 1943; Logan 1959; Eis 1967; Logan 1969; Kabzems and Lousier 1992; Lieffers and Stadt 1994) Maximum height growth of understory conifers frequently levels off around 40% of full sunlight (Wright *et al.* 1998; Coates and Burton 1999). However, height and diameter growth of white spruce after 5 to 7 growing seasons were greater in a clear-cut than under any vegetation cover (Jobidon 2000; DeLong 2000) even though the opposite was observed for the first 3 growing seasons (DeLong 2000).

The distribution of light also has an important influence on seedling growth. For example given the same total light levels, larger seedlings were obtained under uniform diffuse light environments than under heterogeneous, diffuse light environments supplemented by direct high light (sunflecks) for relatively short periods of time (Wayne and Bazzaz 1993; Sims and Pearcy 1993). It is also likely that the development of other vegetation in the absence of aspen may reduce overall growth rates, leading to the results obtained in some studies.

Light levels are expected to vary within the crown as well. Findings by Comeau (2002) and Comeau and Heineman (2003) showed how light levels increase with height in aspen and white birch canopies. The basal area of overstory species is widely considered a surrogate measure of the understory microclimate that affects seedbed conditions, light, composition, and other biotic and abiotic factors directly shaping the establishment of advanced regeneration (Greene *et al.* 1999). Messier (1996) and Lieffers and Stadt (1994) suggested that mature broadleaf dominated stands transmit a greater proportion of light compared to conifer dominated ones. Presumably, because of those higher light levels, growth of the understory white spruce is superior under broadleaf dominated canopies compared to that under a conifer overstory (Lieffers and Stadt 1994). In the understory of deciduous stands, light levels over the growing season were inversely proportional to the basal area of pure young birch or red alder (Comeau 1996; Comeau *et al.* 1999a; Comeau and Heineman 2003), as well as to that of trembling aspen (Comeau 2002). As a result, the growth of understory conifers declines as either density or size of the deciduous trees in the overstory increases (Comeau 2002).

Another immediate effect of those differences in canopy structure is on the abundance of shrub and herb layers. Cover and leaf area index of understory shrubs, herbs and grasses varies in response to understory light levels and other factors (Cannell and Grace 1993; Lieffers and Stadt 1994; Constabel and Lieffers 1996), decreasing under a dense conifer overstory (Rowe 1956) and reaching higher values under older aspen stands (Constabel and Lieffers 1996).

Knowledge of the light requirements of both crop and non-crop species, as well as the effects of canopy opening on understory light, is useful for developing strategies to provide sufficient light for the crop species to develop, while keeping light levels below those needed for development of non-crop species (Messier 1996). In this respect, an effective deciduous nurse crop should transmit enough light to allow for acceptable growth of conifer regeneration, while limiting growth of other competitors (e.g. *Calamagrostis canadensis, Epilobium angustifolium*) (Lieffers and Stadt 1994). This can be done by keeping understory light levels below 40% of the above-canopy light (Lieffers and Stadt 1994; Constable and Lieffers 1996; Lieffers *et al.* 1999).

Seasonal variation in light levels under aspen stands is also important for the survival and growth of understory conifers. Light levels under mixedwood stands reach a maximum early in the spring before hardwood leaf development, as well as late in the fall after hardwood leaves fall off (Messier 1996; Constabel and Lieffers 1996). Therefore, more light is available during those leaf-off periods than in mid-summer (Messier 1996; Constabel and Lieffers 1996; Prevost and Pothier 2003). During those high light periods, understory conifers in mixedwood stands in Alberta were able to photosynthesize for a month in spring and a month in fall regardless of low soil temperatures (spring) and frequent night frost events (fall) (Man and Lieffers 1997b).

Due to the presence of canopy gaps there are differences in light levels within and around the canopy caused by sun angle, size of the gap, height of the trees at the edge of the gap, and sky conditions (Messier 1996). The sky view factor, which at night determines radiation loss to the sky, and the frequency of the growing season frost events decrease with increasing tree height and decreasing opening size (Groot and Carlson 1996; Groot *et al.* 1997). Light levels at the center of an opening (either strip or gap) increases with increasing opening size and decreases with the height of the trees at the edge of the gap (Lieffers *et al.* 1999). By modifying the width and orientation of the strips, and accounting for the adjacent canopy height, composition and density, the desired light levels reaching the forest floor could be accomplished (Berry 1964). By laying out north-south strips on level terrain, the variability in daily light across the strip will be at minimum as the sun moves from east to west (Berry 1964). On the other hand, at high latitudes, narrow strips oriented east-west will show high light levels under the crowns of the adjacent residual trees to the north of the opening (Lieffers *et al.* 1999). Variation within openings, with greater light levels usually recorded on the south-facing edges (i.e. north side of openings) than on the north-facing edges (i.e. south side of openings) may be reflected in lower white spruce growth at the north-facing edges (Groot et al. 1997).

Light levels have been recognized as the main factor modeling edge microclimate, as shown in several studies in different forest ecosystems (Geiger 1980, Kapos 1989, Matlack 1993). Light underneath forest gaps varies with gap size, height of boundary trees, and height and density of the vegetation in the patch (Belsky and Canham 1994). Light levels in openings increase with distance from the edge of conifer stands, reaching a maximum around one tree length from the edge (Emmingham and Waring 1973; Huggard and Vyse 2002). However, at high latitudes maximum light levels due to direct sunlight are unlikely to reach the forest floor within the gap/strip boundaries when gaps are small, but several meters north of the gap boundaries (Canham *et al.* 1990).

Edge orientation influences the amount of light reaching the ground, and therefore the microclimatic conditions near the ground. Edge effects on microclimate were maximal for south and southwest facing edges (Chen *et al.* 1995) mainly due to a combination of light levels and wind (Burton 2002). Higher light levels for the south-facing edges than for the north-facing ones (Matlack 1993) resulted in stronger correlation between conifer growth and light levels for conifers grown on south-facing edges compared to those grown on north-facing ones (York *et al.* 2003). However, maximum light levels, as well as maximum conifer heights were found at the center of the opening (York *et al.* 2003).

1.4.3 Soil moisture

Soil moisture is an important factor affecting vegetation growth (Rowe 1956). Root growth of white spruce seedlings is highly sensitive to soil moisture (Day and MacGillivray 1975), and soil moisture influences seedling establishment. However, for eastern hemlock and white pine, Pacala *et al.* (1994) found no relationship between water availability and sapling growth, compared to a strong relationship between light and sapling growth. They suggest that either sapling growth was not limited by water, or that growth differences were due to variation in light rather than water. Similarly, Logan (1969) showed that moisture regime had no direct effect on seedling height growth, but had an indirect effect through variation in vegetation density. Control of competing vegetation generally results in increased light levels, higher soil moisture, and higher soil and air temperature (Groot *et al.* 1997; Reynolds *et al.* 2000).

Soil moisture inside aspen stands was consistently lower than in clear-cuts due to evapotranspiration, interception by the tree canopy, and water use by the trees (Chen *et al.* 1993; Groot *et al.* 1997). Differences in root densities inside the forest and in clearcuts could also contribute to differences in soil moisture. The prevalence of white spruce roots in the forest floor above aspen roots may constitute a competitive advantage for spruce (Kabzems and Lousier 1992), as well as an explanation for the differences in water use in aspen stands compared to clear-cuts planted with white spruce. Mladenoff (1987) suggested that greater moisture levels in young gaps could be the result of fewer active roots present. Overall fine-root production is usually less at the center of an opening compared with the edges and within the forest (Bauhus and Bartsch 1996; Campbell *et al.* 1998; Hagerman 2001; Welke *et al.* 2003; Taskinen *et al.* 2003; Muller and Wagner 2003).

Variation in vegetation cover can influence soil moisture (Rowe 1956). Aspen forests allow more ground water to recharge than conifers by intercepting less, but at the same time exhaust soil moisture faster and to greater depth than conifers due to higher evapotranspiration (Peterson and Peterson 1996). Near the edge of a gap a decrease of available soil moisture and an increase in evapotranspiration (Giambelluca *et al.* 2003) can occur as a result of combined understory and overstory precipitation interception, coupled with higher solar radiation and wind activity (Ranney *et al.* 1981; Mladenoff 1987; Canham *et al.* 1990). Soil moisture levels were also influenced by cooler temperatures and reduced evapotranspiration in the shade of an adjacent aspen stand (Belsky and Canham 1994). North and northwest-facing edges showed higher soil moisture than either the forest interior or south-facing edges (Matlack 1993; Chen *et al.* 1993).

In an opening there is a balance of light levels with edge orientation. What one edge gains in light levels, the other edge loses by being shaded (Geiger 1980). Higher soil moisture next to the forest edge may balance shade effects (Hansen *et al.* 1993). A gradient of moisture that runs perpendicular to the edge is expected due to differences in microclimate across the two sides of the edge (Murcia 1995). Matlack (1993) showed that litter moisture was dependent on light, which in turn was a function of distance from the forest edge. For a north-facing Engelmann spruce stand, the highest levels of soil moisture were found within half a tree length of the forest edge on both sides of the border (Huggard and Vyse 2002). However, differences in soil moisture between patches and gaps are less obvious than those for air temperature and light because soil moisture depends on precipitation interception, soil penetration, and evapotranspiration (Belsky and Canham 1994).

1.4.4 Edge effects on growth of small conifers

Knowledge of how vegetation varies with distance from the forest edge is needed to understand the dynamics of forest edges (Gehlhausen *et al.* 2000). The influence of tree crowns expands further than their vertically projected margins (Runkle 1984; Canham *et al.* 1990). This results in the edge reducing the adjacent herbaceous vegetation growth in the opening by shading it, through smothering by litter fall, and by root competition for growing space (Williams-Linera 1990, Matlack 1994, Oliver and Larson 1996).

Douglas-fir leader growth across the edge increased rapidly, reaching a maximum between 4-21m from edge of a 20-25m tall forest (Emmingham and Waring 1973). Also, Hansen *et al.* (1993) showed that significant differences in natural regeneration, seedling establishment and growth of Douglas fir seedlings were related to distance from forest edge into the opening. Similarly, Burton (2002) found that conifer natural regeneration decreased with distance from the forest edge, and was especially great on north-facing edges. However, in terms of seedling growth, Burton's (2002) findings showed no difference in growth due to seedling position within the clear-cut. Coates (2000) also found little to no difference between seedlings grown at south and north-facing edges. This is in contradiction to Hansen's (1993) findings that showed reduced growth of Douglas-fir seedlings 20m north of a mature stand. Conifer seedling height was more strongly correlated with light levels for south-facing than north-facing edges (York *et al.* 2003). Growth of white spruce planted at the north-facing edge of the strip was lower than that at the center of the strip, presumably because of the combined effects of reduced light availability and reduced soil moisture (Groot *et al.* 1997). Also, maximum conifer heights were found at the center of the opening (York *et al.* 2003). Conversely, growth of seedlings in the shade of a forest edge was the same as that of those grown in the open (Burton 2002). Growth of Douglas fir increased as light levels and distance from the forest edge increased (Hansen *et al.* 1993). Coates (2000) documented that conifer seedling growth 5 years after planting was related to opening size. Growth rapidly increased from small gaps to 1000-2000m^2 gaps, but from this threshold to 5000m^2, growth remained fairly constant (Coates 2000). York *et al.* (2003) found higher light levels and higher conifer seedling height on south-facing than north-facing edges for openings smaller than 1 ha. However, they did not find a growth threshold which could be linked to opening size.

1.5 Project objectives

Knowledge of edge effects may be very important in the design of forest plantations (Hansen et al. 1993). Harvest unit size, and edge orientation may influence regeneration of white spruce, as well as microclimate in the white spruce plantations adjacent to young aspen stands.

Given that white spruce is moderately shade tolerant it may be easier to grow this species in mixture with aspen using small patches or narrow corridors (MacDonald and Thompson 2003). Alternating corridors of aspen and spruce would support a dual rotation system in which aspen is harvested every entry and spruce is harvested every second entry (e.g.100 yr rotation) (MacDonald and Thompson 2003). Alternatively, on suitable sites it may allow harvesting of both spruce and aspen at about age 80.

Treating patches or clusters of conifers, while leaving a portion of the stand untreated is a potentially useful option for tending mixedwood stands in order to enhance the growth of white spruce. This option has also been termed cluster planting (Sutton 1974). An important question related to the use of this option is the extent and degree to which the adjacent aspen stand influences growing conditions (light levels, air temperature, and soil moisture) and associated growth of conifer in patches or clusters. Information on the extent of these influences can be used in determining the optimal strip or gap width.

The first component of this thesis examines how light, air temperature, and soil moisture change across the boundary between young aspen patches and small clearings. The stands studied consisted of young aspen stands (13-15 yrs old), situated next to 30 X 30m openings planted with white spruce. This first component is presented in chapter 2. The second component is presented in chapter 3 and focuses on how these changes in microclimatic conditions at the edges of young aspen stands are reflected in white spruce seedling growth within the adjacent openings. Chapter 4 provides a synthesis and discusses the application of results presented in chapters 2 and 3.

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Chapter 2. Influence of young aspen on air temperature, soil moisture, and light levels in the adjacent spruce area

2.1 Introduction

As described in chapter 1, establishment and tending of white spruce in patches, or cluster planting (Sutton 1974), is a potentially cost-effective option for growing white spruce in mixture with trembling aspen in boreal forests. However, there is concern that the faster growing aspen surrounding spruce patches may cast sufficient shade to reduce spruce growth. In addition, there is interest in the degree to which such an arrangement can provide for beneficial nurse crop effects from the aspen.

To comprehend the kinetics of forest edges, knowledge of how microclimate and vegetation vary with distance from the forest edge is needed (Gehlhausen *et al.* 2000). The shade cast by tree crowns, litterfall, and root competition may influence development of vegetation near the edge of openings (Runkle 1984; Canham *et al.* 1990; Williams-Linera 1990; Matlack1994, Oliver and Larson 1996), and due to differences in shading effects may result in greater suppression of vegetation in the openings along north-facing edges than those along south-facing edges. Several studies in different forest ecosystems (Emmingham and Waring 1973; Geiger 1980, Kapos 1989, Matlack 1993) show dramatic changes in light levels as one moves from inside a stand into adjacent openings. Light in forest openings varies with opening size, height of boundary trees, and height and density of the vegetation in the patch (Belsky and Canham 1994). Light levels in an Engelmann spruce dominated stand increased linearly with distance into an opening, reaching a maximum at one tree length (Huggard and Vyse 2002). In mature forests of the northeastern U.S., light gradients extended into adjacent fields for 15 to 20 m (Cadenassoo *et al.* 1997).

In boreal forests the south edge of an opening receives diffuse light from the northern hemisphere of the sky, as well as some light transmitted through the stand, while the northern edge of the opening (if the opening is of sufficient size) will receive both diffuse and direct radiation (Canham et al. 1990). At high latitudes in openings less than two tree lengths in width, maximum light levels may occur closer to the north side of the opening instead of at the center of the opening (Canham *et al.* 1990). In an opening there is a balance of light levels with edge orientation. What one edge gains in light levels, the other edge loses due to shading (Geiger 1980).

Within openings, Matlack (1993) found that north-facing edges of a mature oak-beech forest in eastern U.S. had lower light levels than south-facing edges. In a mixed conifer forest in California light levels were more strongly correlated with conifer height on the south-facing edges than on the north-facing ones with higher light levels on south-facing edges than on north-facing ones for openings smaller than 1 ha (York *et al.* 2003).

Inside an old-growth Douglas fir forest, the edge effects on light levels extended to 60m for the south-facing edges, but only to 20m for the north-facing ones (Chen *et al.* 1995). Similarly, in stands dominated by white spruce and subalpine fir, the influence of the opening on light levels extended 70m inside the forest for a south-facing edge, but only 50m for the north-facing edge (Burton 2002).

Increases in both light and heat, coupled with proximity to the stand and the presence of abundant tree roots result in higher evapotranspiration, and therefore lower soil moisture near the north edge of an opening/strip (i.e south-facing). In tropical forests lower soil moisture content at the edge of a forest patch than in an adjacent clearcut was thought to be due to higher evapotranspiration (Giambelluca *et al.* 2003). At the same time, because the newly regenerated understory resulted in increased interception and evapotranspiration along the edge, there was an increasing need for soil moisture (Ranney *et al.* 1981). Reduced soil moisture could also result from increases in solar radiation and wind penetration leading to increased drying along forest edges (Ranney *et al.* 1981). Litter moisture in an oak-beech forest in the eastern U.S. was dependent on light and was a function of distance from the forest edge (Matlack 1993).

For a north facing Engelmann spruce stand, the highest levels of soil moisture were found within one-half tree length of the forest edge on both sides of the border (Huggard and Vyse 2002). Higher levels of soil moisture in small forest openings in a hemlock-hardwood forest were due to a lower precipitation intercept by overhead canopies and less soil moisture lost to evapotranspiration (Mladenoff 1987).

Soil moisture levels were influenced by cooler temperatures and reduced evapotranspiration in the shade of an adjacent aspen stand (Belsky and Canham 1994). Differences in soil moisture between forest patches and openings are less obvious than differences in air temperature and light because soil moisture depends on precipitation interception, water infiltration, the ability of the soil to store water, and evapotranspiration (Belsky and Canham 1994). However, different microclimates specific to the two sides of the edges are expected to generate gradients of moisture that run perpendicular to the edge (Murcia 1995). In a mature oak-beech forest in eastern U.S., Matlack (1993) found that north-facing edges had higher soil moisture than south-facing edges. Soil moisture was also three times greater at northwest facing edges than within the interior of a Douglas-fir forest (Chen *et al.* 1993). Higher soil moisture next to the forest edge may compensate for the effects of low light levels on growth of tree seedlings (Hansen *et al.* 1993).

Because of the different microclimates specific to opposing edges, a gradient of temperature that runs perpendicular to the edge is created (Murcia 1995). In this respect, Saunders *et al.* (1999) showed that air temperature was intermediate between forest and clearcut during night and early morning, but not during midday. However, for a mature Douglas fir stand, air temperature at the edge was not intermediate between the clearcut and forest interior (Chen et al 1993). Openings adjacent to the forest received more solar radiation at the ground during the day, while higher amounts of radiation were lost to the atmosphere at night (Geiger 1980). As opening size increases, the air temperature also increases (Groot *et al.* 1997). In mature forests of the northeastern U.S. gradients of air temperature extended into adjacent fields for 15 to 20 m (Cadenassoo *et al.* 1997). Similarly, Saunders *et al.* (1999) showed that variation in temperature was dependent on the distance from the forest edge.

The size of the patches is also an important factor that affects the air temperature dynamics across edges. Kapos (1989) found that 1 ha forest patches had less effect on temperature dynamics across edges than 100 ha patches. Furthermore, Matlack (1993) showed that temperature was dependent on light and distance from the forest edge.

Several studies (Spittlehouse and Stathers 1990; Orcutt and Nilsen 1996; Grossnickle 2000) have shown that low air temperatures can damage plants by rapid freezing. Furthermore, exposure of plants to direct radiation during the day after a frost may magnify the extent of the initial damages (Lundmark and Hallgren 1987; Orlander

1993; Gillies and Binder 1996; Langvall and Orlander 2001). Residual aspen and taller young aspen can alleviate the risk of frost damage to planted white spruce seedlings within the opening (Groot and Carlson 1996; DeLong 2000, Pritchard 2003). Higher minimum temperatures and greater shading offered by a residual canopy reduced the risk of damage to Norway spruce seedlings (Langvall and Orlander 2001). Seedling survival can be increased by using shelter trees that protect against the incidence of frost and reduce the degree of frost damage (Orlander 1993). By shading and reducing the exposure of seedlings to high intensity radiation during the day following a cold night, shelter trees might reduce the risk of frost damage (Lundmark and Hallgren 1987). Frost damage frequency increases as the density of shelterwoods decrease (Orlander and Karlson 2000).

Despite a broad general knowledge of edge influences in older stands our knowledge of the effects of young aspen on light, soil moisture and air temperature in adjacent openings in boreal forest communities is currently limited. A knowledge of the distance over which young aspen influences microclimatic conditions is of potential value in the development of management practices designed to provide optimal conditions for the growth of white spruce. This chapter presents results from a study designed to examine gradients of light, air temperature and soil moisture adjacent to the edges of young aspen stands in Alberta.

Hypotheses tested in this chapter are:

1) Light levels (in terms of transmittance) are related to distance and direction from the adjacent aspen stand edge;

2) Soil moisture is related to distance from the adjacent aspen stand edge and aspen leaf area index (LAI) of and/or understory vegetation LAI;

3) Air temperature is related to distance and direction from the adjacent aspen stand edge;

4) Frequency of summer frost events is related to distance and direction from the adjacent aspen stand edge.

2.2 Materials and methods

2.2.1 Study area and experimental design

The study used selected Long-Term Study (LTS) field installations established by the Western Boreal Growth and Yield (WESBOGY) Association. The WESBOGY Long-Term Study was established to evaluate the effects of spruce and aspen densities on the development of mixedwood stands (Titus and Wang 2000). These installations consist of white spruce planted at three densities (0, 500, 1000sph) and aspen thinned at approximately age five to 0, 200, 500, 1500, and 4000sph, plus an untreated control (Titus and Wang 2000). My study was carried out during 2002 and 2003 at 3 WESBOGY installations located near Grande Prairie and Peace River (Figure 2-1) using only the 0 aspen plots. The first location, called Grande Prairie, is located south of Grande Prairie, Alberta (54° 55′ N, 118° 55′ W); the second location, called Hines Creek, is located west of Peace River, Alberta (56° 20′ N, 118° 30′ W); and the third location, called Manning, is located north of Peace River, Alberta (56° 41′ N, 117° 72′ W). These 3 locations consist of white spruce raw planted in 30x30 m plots at two densities (500 and 1000sph spruce) next to natural or spaced (1500, 4000sph aspen) aspen or without aspen (0 aspen sph). All ingress vegetation within the 30x30m plots was periodically removed, starting five years after spruce establishment. The white spruce seedlings at the two densities (500, 1000sph) were assumed to respond in a similar manner to the biotic and abiotic conditions and thereby considered as replications independent of plot density. Ideally, all the adjacent aspen patches would have been made of natural aspen. However, differences in adjacent aspen densities (natural, 1500, and 4000sph) were accounted for by describing the light environment within 1 tree length inside the adjacent aspen patches from the borderline (stem line) and thereby their influence was included in data analysis. In 2003 aspen and white spruce saplings were 11 to 13 yr old at each of the 3 WESBOGY locations.

A detailed description of the 13 plots used in this study is presented in Table 2-1. The final number of 13 plots was reached by dropping one of the replications at Hines Creek (0sph aspen and 1000sph spruce) because of scarce adjacent aspen (density under 500sph). The Grande Prairie installation hosted an additional set of plots compared to Hines Creek or Manning (Table 2-1). Study sites were all located in the Central Mixedwoods Ecological Subregion and occurs on mesic low-bush cranberry (BM-d) ecosites (Beckingham and Archibald 1996). Precipitation normals and 2003 monthly averages (rainfall from June to September) for the Hines Creek installation are detailed in Table 2-2. Soils at all installations were orthic gray luvisol, on morainal parental materials, generally with less than 10% coarse fragments, and clay to clay-loam texture. Slopes at all installations were less than 5%.

I examined gradients in air temperature, soil moisture, and light moving away from the intact young aspen canopy into the spruce plot without aspen.

2.2.2 Data collection

To characterize the microclimate in the plots in terms of light levels, soil moisture, and air temperature, two out of the 13 above-mentioned plots were selected (GP 4003-8 and HC 1-07). The number of plots examined was limited to two due to availability of dataloggers and sensors. These plots were selected because they provided reasonably intact adjacent stands of young aspen, and were felt to be representative of mesic sites.

Diffuse non-interceptance (DIFN) is a value provided by LICOR LAI-2000 sensors (LI-COR Inc., Lincoln, NEB) that represents the proportion of light reaching the top of a canopy that penetrates to the understory (LI-COR, Inc. 1992). Previous studies indicate that DIFN measurements provided by LAI-2000 are unbiased estimates of average growing season transmittance (Comeau *et al.* 1998, Gendron *et al.* 1998, Lieffers *et al.*1999, Comeau 2000). LAI-2000 measurements were taken at the top of the white spruce seedlings and at mid-crown height with the sensor pointed away from the tree to estimate growing season light (diffuse non-interceptance). For this purpose, 2 transects were established in each plot: one going north to south, and the other going east to west through the center of each zero density aspen plot. Transects were oriented to run perpendicular to plot boundaries. Since plots were not consistently oriented going north to south, transect orientation was another factor used in determining the position of the spruce seedlings (where light levels were measured) in relation to the aspen edge. As a result of this, transects orientation ranges from 355^0 to 27^0 (Table 2-1). At all spruce locations along each transect (2.5 m on both sides of the transects) LAI-2000 measurements were taken (Figure 2-2). The position of each seedling relative to the center of the plot was mapped and distance from center of the plot to the edge of adjacent aspen (stem line) was measured.

An 180^0 view restrictor was used to block direct radiation from the sun at the time of each measurement. Measurements were taken west-facing early in the morning (8-10a.m.) and east-facing late in the afternoon (5-7p.m.). The sensors were leveled for each reading using bubble levels attached to the optical sensor support. Measurements were taken using just one LAI-2000 unit (one sensor mode) (LI-COR, Inc. 1992) between July 10 and 31, 2002. Therefore, the open sky readings were taken before and after taking the understory readings for each direction and each plot. In 2003 (July 7 to July 27) two LAI-2000 units were used simultaneously (remote mode) (LI-COR, Inc. 1992): one in the open on a tripod automatically logging readings every 30 seconds, and the other at each white spruce seedling within the plots. To calibrate the two units, each morning and afternoon, open sky readings were also taken using the 'understory unit'.

Diffuse non-interceptance (DIFN) was determined for each spruce tree using C2000 software (Licor Inc., Lincoln, NEB), with the average of the east and west-facing values used for analysis. The lens of LAI-2000 measures openness within five concentric rings. A previous study (Comeau *et al.* 1998) indicated that the outer ring (i.e. ring 5 equivalent to a sky view of 62.3^0-74.1^0 from vertical) may give poor estimates of growing season transmittance. Therefore, ring 5 was masked and transmittance values were determined using only rings 1-4 (equivalent to a sky view of 58.1^0 from vertical).

Between July 7 and July 27, 2003, light levels were also measured under the adjacent aspen stand using LAI-2000 plant canopy analyzers. DIFN light levels were measured at points located on a 3m x 3m grid starting at the edge of the aspen stand (Table 2-1, Figure 2-2). The grid was established as a continuation of the north-south and east-west transects along which the spruce was measured. The measurements were taken above the herbaceous and shrubby vegetation at 1.0m height.

To calibrate estimates of growing season transmittance obtained using LAI-2000 sensors, I used calibrated photodiode sensors (Comeau *et al.* 1998). These were installed at two (out of 13) selected sites, and were located at -25, -15, 0, 15, and 25m north from the center of the plot (Figure 2-3). In addition, another photodiode was mounted above the canopy, on a tower, to obtain matching open sky readings. All photodiodes were connected to AM 16/32-XT multiplexers [Campbell Scientific (Canada) Corp., Edmonton], which were connected to a CR-10X [Campbell Scientific (Canada) Corp., Edmonton] datalogger. Measurements of photosynthetic photon flux density (PPFD) in the photosynthetically active range (400-700nm) were taken at 1.0m height every 10 minutes, and hourly averages recorded. Light data were collected throughout 2002 and 2003 (June 19 to October 5, 2002, and May 9 to October 4, 2003). These data were used to calibrate the LAI-2000 measurements. For this particular purpose LAI-2000 measurements were taken at each of the photodiode sensor locations on July 10, 2003.

Soil moisture was measured in 2003 (June 19 to October 7, 2003) at one study site (Hines Creek) using CS616 water content reflectometers [Campbell Scientific (Canada) Corp., Edmonton]. The number of plots and directions examined was limited to one due to availability of dataloggers and sensors. The soil moisture sensors were located at -3, -1, 1, 2, 3, 5, and 7 m north from the south edge (ie. north-facing edge of the adjacent aspen stand) of the plot (stem line). Sensors were inserted vertically to give an indication of the water content in the upper 30 cm of soil (CS616 water content reflectometer instruction manual). They were connected to a CR-10X [Campbell Scientific (Canada)

Corp.] datalogger. Soil volumetric water content (m^3/ m^3) was measured hourly and recorded.

To account for possible variation in the leaf area index (LAI) of understory vegetation, LAI-2000 measurements were taken on July 10, 2003 at ground level and above the herbaceous and shruby vegetation (roughly 1.0 m above ground), with both occurring directly above each soil moisture sensor. Understory (grass, forb and shrub), aspen, and total vegetation LAI were calculated using C2000 software (LI-COR Inc., Lincoln, NEB). Total LAI was estimated using the ground level LAI-2000 measurements, aspen LAI was estimated using the measurements taken above understory layers, and understory LAI was calculated as the difference between the two. For these LAI measurements rings 4 and 5 were masked and LAI were determined for rings 1-3 only (equivalent to a sky view of 43.4^0 from vertical). This was done in order to best characterize values at the sample point by minimizing the potential negative influence of the adjacent stand on the LAI measurements (especially those at ground level). The understory vegetation along the studied transect was dominated by *Calamagrostis canadensis,* with some fireweed (*Epilobium angustifolium*), and prickly rose (*Rosa acicularis* Lindl.)

To measure air temperature, custom built unshielded fine-wire chromel-constantan thermocouples were installed in the spring of 2002 at 1.0 m height at nine locations (-25, -17.5, -15, -7.5, 0, 15, 17.5, and 25m north of the plot center) along the north-south transect at each of the 2 sites (Grande Prairie and Hines Creek) (Figure 2-4). Analysis of data collected during 2002 indicated that hourly average air temperature during frost events decreased with increasing distance from the adjacent aspen edge, with a dramatic change occurring within 1 tree length of the stand edge. Due to a lack of sensors closer to the edge, the location and nature of this change could not be evaluated. Therefore, four additional air temperature sensors were added in 2003 (-12.5, -10, 10, and 12.5 m north of the center of the plot). Temperature sensors were connected to two AM 16/32-XT multiplexers [Campbell Scientific (Canada) Corp., Edmonton] which were connected to a CR-10X [Campbell Scientific (Canada) Corp., Edmonton] datalogger. Measurements (degrees Celsius) were taken every 10 minutes, and hourly averages were recorded. Air temperature was collected continuously during 2002 and 2003 (June 19 to October 5, 2002, respectively May 9 to October 4, 2003).

Information on the adjacent aspen stand conditions was obtained by establishing one $50m^2$ circular plot for each cardinal direction at 3.99m from the stand edge in the adjacent aspen stands (Figure 2-2). Each tree within the plot that was taller than breast height (1.3m) was measured for diameter at breast height and its species noted and basal area for the plot calculated. The tallest aspen in each plot was also measured (Table 2-1).

All wires used to connect the air temperature, soil moisture, and light sensors to multiplexers and dataloggers were enclosed in plastic split-loom and buried 5-10cm in the ground to protect them from damage by rodents, bears, and other factors. Multiplexers and dataloggers were protected by plastic, water resistant cases and wooden or metal boxes. Silica gel packages were used to minimize the moisture level inside plastic cases and were replaced every 2-3 weeks during the growing season. Wooden/metal boxes were secured in place using buried sticks and electrical wire.

Data recorded by the dataloggers were downloaded every 2-3 weeks during the growing season using a portable laptop computer and PC208W software [Campbell Scientific (Canada) Corp., Edmonton].

2.2.3 Data preparation

The following dependent/independent variables were calculated in preparation for analysis:

- Growing degree hours (GDH) calculated as: GDH=$\sum_{May}^{Sept}(Havg-5^0)$, where *Havg*- hourly average air temperature, 5^0 C -represents the base air temperature at which the GDH was calculated. When $(Havg-5^0)$ <0, it was forced to 0. Calculations were based on the period between May 9 and September 30, 2003.
- To standardize GDH for the two sites (Grande Prairie and Hines Creek) delta growing degree hours (ΔGDH) were calculated as: ΔGDH= GDH*i*-GDH*o*, where GDH*i* -growing degree hours calculated for each air temperature sensor, GDH*o*- the minimum value calculated along each transect.
- Number of hours with temperature under 0^0C was calculated as sum of hours with temperatures under the 0^0C threshold from June 1 to August 31, 2003.
- Number of hours with soil moisture under 25% volumetric water content was calculated as the sum of hours with soil moisture under the 25% threshold from June 19 to September 30, 2003.
- Growing season transmittance for the period May 9 to October 4, 2003 for each sensor was calculated by dividing total below canopy values (recorded by

each photodiode sensor) by above canopy values (PPFD values recorded by the unobstructed photodiode on the tower).

2.2.4 Data analysis

Multiple linear and nonlinear regression analysis was used to evaluate the relationships between dependent and independent variables. A summary of the dependent and independent variables used in data analysis is presented in Table 2-3.

In an earlier study of the same species (Comeau and Bedford, *unpublished*) the Gompertz equation was found to best predict light levels (in terms of transmittance) as a function of distance from the adjacent stand. Based on the distribution of my data points and previous studies, I used the Gompertz function to develop transmittance functions for each of the four cardinal directions as a function of the proportional distance from the adjacent aspen stand. Proportional distance is defined as distance from the aspen stand edge divided by the difference between adjacent stand height (i.e. height of the tallest aspen) and height of the air temperature sensor. Negative proportional distances are within the aspen stand, while positive proportional distances are within the adjacent spruce area. The equation takes the form:

$$Y = ae^{-e^{-\left(\frac{X-c}{b}\right)}}, \qquad (1)$$

where Y=transmittance, X=proportional distance, *a*=asymptote or the potential maximum of the transmittance, and *b* and *c*= parameters governing how transmittance approaches its potential maximum.

Based on data distribution, the Gompertz function was also used in a slightly different form to describe the relationship between air temperature and distance from the adjacent stand. The equation takes the form:

$$Y = Y_0 + ae^{-e^{-\left(\frac{X-c}{b}\right)}} , \qquad (2)$$

where Y= air temperature (in terms of number of days with temperatures below 0^0C, or delta growing degree hours), X=proportional distance, Y_0=the minimum air temperature, *a*=asymptote or the potential maximum of air temperature, and *b* and *c*= parameters governing how air temperature approaches its potential maximum.

Several other sigmoidal models were initially tested, including Weibull, Hill, and Chapman. However, based on these analyses and resulting R^2_{adj}, RMSE, parameter significance, and residual distribution, the Gompertz equation was considered to provide a better fit to these data.

To evaluate the soil moisture relationship to the distance from the adjacent stand, a polynomial model was used based on the distribution of the data, R^2_{adj}, RMSE values, and plot of residuals. A multiple linear regression equation was used to examine effects of aspen LAI and understory LAI on soil moisture.

Initial analysis used the indicator (dummy) variable approach (Draper and Smith 1981; Ott 1997) to compare coefficients for regressions fitted to data from the different sites or to data from the different cardinal directions. This technique was used to determine whether the sites or the cardinal directions could be pooled and analyzed as a single relationship.

All analyses were done using version 8.2 of SAS Statistical Software (SAS Institute, Cary, NC). The dependent versus independent variable were graphed using SigmaPlot, version 8.0 (SPSS Inc.).

2.3 Results

2.3.1 Light gradients

2.3.1.1 LAI-2000 vs. photodiode measurements

Transmittance measurements obtained using photodiodes and those obtained using LAI-2000 plant canopy analyzers were compared using linear regression techniques to determine the relationship between the two measurement techniques. The two methods were highly correlated ($R^2=0.966$). T-tests indicate that the relationship has a slope that is not significantly different than 1 ($p>0.05$) and an intercept term that is not significantly different from 0 ($p>0.05$) (Figure 2-5). These results indicate that the LAI-2000 estimates of transmittance provide consistent estimates of actual growing season transmittance as measured by the photodiodes. To test if the data from the two sites (Grande Prairie and Hines Creek) could be pooled together into a single relationship, the indicator variable principle was used (Draper and Smith 1981; Ott 1997). Results indicated that the data from the two sites could be analyzed as a single population ($p>0.05$).

2.3.1.2 Light levels

Relationships between growing season transmittance (DIFN) and proportional distance and edge orientation were examined. Given the distribution of points, and based on previous work (Groot *et al.* 1997; Groot 1999; Comeau and Bedford, *unpublished*), nonlinear regression procedures were used. A Gompertz equation was superior at explaining the relationship between transmittance and proportional distance. Statistical information on these models is provided in Table 2-4. For each direction (i.e. N, S, E, and W-facing) the indicator variable test showed no difference among data from the three different locations ($p>0.05$). Therefore, data were pooled together and analyzed as a single relationship for each direction. However, when the indicator variable principle was used to test if the data from all four cardinal directions could be analyzed together, it showed there were differences among directions ($p<0.05$). Therefore the results are presented separately for each cardinal direction.

For north-facing edges the relationship between transmittance (DIFN) and distance from the edge of the adjacent aspen stand is presented in Figure 2-6. Light levels increase starting from inside the aspen stand, approaching maximum values 2 tree lengths from the edge and then flattening out (Figure 2-6). The threshold of 60% of full sunlight required for white spruce shoots to reach maximum photosynthesis (Man and Lieffers 1997) was reached at 0.3 tree lengths from the edge. For the south-facing aspen edges, light levels again increased moving from the aspen stand into the opening, reaching a maximum at 1.5 tree lengths from the edge, while 60% of full sunlight was reached only 0.1 tree lengths from the edge (Figure 2-7). For both the east and west-facing aspen edges, light levels increased from within the aspen stand into the opening, reaching a maximum 2.5 tree lengths from the edge, while 60% of full sunlight was reached 0.3 tree lengths from the edge (Figure 2-8, and Figure 2-9).

2.3.2 Soil moisture

2.3.2.1 Growing season variation

Soil moisture variation during 2003 is presented in Figure 2-10. Regardless of soil moisture sensor position, maximum volumetric water content (VWC) was reached at the end of June, while the minimum was reached toward the end of July, and again in late September (Figure 2-10). The lowest soil moisture values during the measurement period were recorded 3 m inside the edge of the aspen stand, while maximum levels were found 1 m into the opening. The trends for 1, 2, and 3 m into the opening are essentially the same. However, a pronounced decrease in VWC is apparent at 5m and 7 m from the aspen edge (Figure 2-10).

The relationship between soil moisture on July 31, 2003 (the midsummer day with the lowest VWC) and distance from the edge is shown in Figure 2-11. Soil moisture increased starting in the aspen stand at 0.4 tree lengths from the edge to a maximum at approximately 0.4 tree lengths into the opening, then decreased again.

The number of hours with VWC below 25% in 2003 was used as an indicator of the duration of soil moisture stress for white spruce. A threshold of 25% was chosen because in 2003 soil moisture rarely reached values below the 15% value suggested as the threshold at which white spruce growth is seriously impeded (Grossnickle 2000). However, growth reductions are also expected to occur when values are below 25% (Grossnickle 2000). The number of hours with volumetric water content under 25% decreased starting 0.4 tree lengths into the aspen stand to a minimum between 0.1 and 0.4 tree lengths into the opening. The number of hours with VWC under 25% then increased again with greater distance from the aspen edge (Figure 2-12).

2.3.2.2 Soil moisture, leaf area index, and distance from edge

Total leaf area index (LAI-T) and aspen leaf area index (LAI-As) decreased as one moved from the aspen stand into the opening, while the understory vegetation leaf area index (LAI-H) showed a steady increase as the distance from edge increased (Figure 2-13).

The relationship between volumetric water content and leaf area index was investigated for one of the days the lowest VWC (July 31, 2003). VWC on this date decreased as either aspen or understory vegetation leaf area index increased (Figure 2-14). During the entire period of the study the number of hours with volumetric water content under 25% increased as either aspen or understory vegetation leaf area index increased (Figure 2-15). Although comparison of the slopes of these relationships for the aspen and understory vegetation is not powerfull enough due to the limited sampling of the aspen gradient, the difference in values suggests that understory vegetation may be a much stronger user of soil moisture than aspen (Figure 2-14 and Figure 2-15).

2.3.3 Air temperature

Air temperature was characterized in terms of growing degree hours, number of days with temperature under 0^0C during the growing season, and air temperature during nights of frost events.

2.3.3.1 Growing degree hours (GDH)

The relationship between growing degree hours (hours with mean air temperature over 5^0C) and proportional distance from the adjacent aspen stand is shown in Figure 2-16. Testing using the indicator variable principle indicated no difference between data from north-facing and south-facing edges ($p > 0.05$). Therefore, data were analyzed after being pooled together in a single relationship (Figure 2-16). Given the distribution of points, a nonlinear Gompertz equation was selected to fit the relationship between the growing degree hours and proportional distance. The amount of accumulated heat increases starting 0.5 tree lengths inside the aspen stand, increasing steadily as one moves from the edge of the aspen stand into the adjacent clearing, reaching a maximum at 1.3-1.5 tree lengths (Figure 2-16).

2.3.3.2 Number of hours with freezing temperatures

2.3.3.2.1 *Growing season of 2002*

The lack of air temperature sensors within 1 tree length from the stand edge in 2002 makes it impossible to characterize the shape of the gradient or the distance over which the adjacent aspen provide protection against frost. Therefore, additional sensors were installed next to the stand edges for the growing season of 2003. These results are presented next.

2.3.3.2.2 *Growing season of 2003*

The relationship between number of hours with a temperature under 0^0C from June 1 to August 31 of 2003, and proportional distance is presented in Figure 2-17. The relationship is presented for one site (Grande Prairie) where both south and north-facing adjacent aspen edges consisted of natural aspen. There was no difference between data from north and south-facing edges ($p > 0.05$). Therefore data were analyzed after being pooled together in a single relationship (Figure 2-17). Given the distribution of points, a nonlinear Gompertz equation was selected to describe the relationship between the number of hours below 0°C and proportional distance. There were 10-15 fewer frost hours inside the aspen stands than in adjacent openings. Moreover, the frequency of summer frost starts to increase 0.2 tree lengths inside the adjacent aspen, and increases rapidly as one moves from the edge of the aspen stand into the adjacent clearing, reaching a maximum 1.0 tree lengths into the clearing (Figure 2-17).

2.3.3.3 Night of frost event

2.3.3.3.1 *Growing season of 2002*

During 2002 there were only 2 nights with a temperature under 0°C at all points along the transects. Data for a frost event on the night of September 7, 2002 are presented in Figure 2-18. Air temperature during the night of the frost event (1a.m. to 7a.m.) is graphed against proportional distance. Results indicate the same trend over time for all sensors regardless of their position within the aspen understory or the opening (i.e. temperatures decrease from 1 to 7a.m., and then start to increase). There is also a large amplitude in temperature during the night of the frost event that is approximately the same for all sensors regardless of their position (Figure 2-18). At each hour, air temperature decreased at all positions from inside the aspen stand into the opening (Figure 2-18).

2.3.3.3.2 *Growing season of 2003*

To illustrate the dynamics of temperature changes, hourly data (i.e hourly average temperatures) for the temperature transect are presented in Figure 2-19 for the morning of

August 24, 2003. The same temporal trends can be observed for all sensors regardless of their position within the aspen or opening (i.e. temperatures decrease from 2 to 7 am, then start to increase). Additionally, the amplitude in temperature changes during the night of the frost event is approximately the same for all sensors regardless of their position. For each hour air temperatures decrease moving from inside the aspen stand into the opening, reaching a minimum between 1-1.5 tree lengths from the edge. This trend is similar to that found on September 7, 2002.

2.4 Discussion

2.4.1 Light levels

Light is crucial for photosynthesis and is one of the most important factors influencing the growth of understory plants (Canham *et al.* 1990; Pacala *et al.*1994; Chen and Klinka 1997; Lieffers *et al.* 1999; Greene *et al.* 2002; MacDonald and Thompson 2003). Competition for light within young hardwood-conifer stands is also recognized as being of decisive significance for growth and survival of conifer seedlings (Coates and Burton 1999). Light levels required for white spruce shoots to reach maximum photosynthesis are between 40 and 60% of the ambient light levels (Man and Lieffers 1997). However, Lieffers and Stadt (1994) found that for white spruce the minimum light necessary for seedling survival is 8% of full sunlight.

The diffuse light measured using LAI-2000 plant canopy analyzers was found to be a good estimator of growing season transmittance measured using photodiode sensors. This is consistent with previous findings in a variety of mixedwood stands (Comeau *et al.* 1998, Gendron *et al.* 1998, Lieffers *et al.*1999, Comeau 2000).

Light transmittance was strongly related to the distance from the adjacent young aspen stand for each of the four cardinal directions. Light increased rapidly across the aspen edge into the opening reaching a maximum between 1.5 and 2.5 tree lengths. This is consistent with the findings of Emmingham and Waring (1973) who acknowledged that light levels across a Douglas-fir edge into the adjacent opening increased rapidly, reaching maximum levels at 1 tree length. Similarly, light levels in an Engelmann spruce dominated stand were shown to increase smoothly into the opening, reaching a maximum at one tree length (Huggard and Vyse 2002).

My results also show that the influence of north-facing aspen edges extends over a greater distance into adjacent openings compared to the south-facing edges. Transmittance reached 60% of full sunlight within shorter distance from the edge for the aspen stand facing south than for the aspen stand facing north. The influence of north-facing edges on maximum light levels within the opening also extended over a greater distance than that of south-facing edges. This is consistent with previous studies that have shown the shade cast by stand edges is influenced by stand height and orientation of the edge, with more shading near north-facing edges and less shading near south-facing edges (Berry 1964, Groot and Carslon 1996). However, the potential negative impact of shade cast by the faster growing aspen into adjacent patches of spruce does not extend very far from the aspen edge (i.e. under 0.3 tree lengths from the edge).

2.4.2 Soil moisture

Soil moisture increased from the interior of aspen into an adjacent opening. For these young aspen stands, maximum soil moisture levels were reached within 0.4 tree lengths from the edge of the aspen. Because of the lack of replication, these results should be treated more as a trend than as a definitive relationship. However, they are consistent with findings for white spruce planted next to a 40 yr old aspen stand (Groot *et al.* 1997) and for a 60 yr old mixedwood forest in New York, U.S.A. (Cadenassoo *et al.* 1997).

Low soil moisture recorded inside the aspen stand can be explained by greater evapotranspiration and rainfall interception resulting in drier soil inside the forest than within the opening (Chen *et al.* 1993; Groot *et al.* 1997). The area right at the edge, but inside the forest, receives more light from the side, which in combination with increased wind penetration, may result in increased evapotranspiration and consequently decreased available soil moisture (Ranney *et al.* 1981; Canham et al 1990; Giambelluca *et al.* 2003). The influence of tree crowns extends further than their vertically projected margins, resulting in reduced cover and LAI of understory vegetation adjacent to the edge due to shade, litterfall, and belowground competition (Runkle 1984; Canham *et al.* 1990; Williams-Linera 1990; Matlack 1994; Oliver and Larson 1996). Maximal soil moisture was recorded right at the edge of the adjacent aspen stand within the opening. While the small number of replications limits the interpretation of these results, a number of potential explanations can be advanced. One possibility is that the north-facing edge cast shade for longer periods of time, resulting in increased snow accumulation and extended persistence of the snowpack during the spring close to the stand. A second possibility is that soil moisture is also under the influence of litter depth. More aspen litter at the edge compared with shallower litter further from the edge could result in reduced evapotranspiration, and consequently greater soil moisture values near the edge. Water use by vegetation is a third potential explanation for the recorded variation in soil moisture. As leaf area index increases with changes in vegetation type and abundance, there is an increase in water use (Johns and Lazenby 1973). In this regard, soil moisture decreases as either understory LAI or aspen LAI increases. Results from this study also suggest that understory layers may contribute more to the soil moisture stress than aspen. In addition, differences in root densities inside the forest and in clearcuts could contribute to differences in soil moisture. Fine-root production in a variety of openings was lowest at the opening center (Bauhus and Bartsch 1996; Campbell *et al.* 1998). In a beech forest opening in Germany, fine-root production shifted from trees to herbs as one moved away from the edge to the center of the opening (Bauhus and Bartsch 1996). Another factor influencing soil moisture content is the amount of incident solar energy and air temperature, which affect both transpiration and evaporation rates. It appears likely that all of these factors may work together to influence soil moisture levels during the growing season.

Differences in soil moisture are often reflected in vegetation changes. Soil moisture is an important factor affecting vegetation growth (Rowe 1956). Root growth of white spruce seedlings is highly sensitive to soil moisture (Day and MacGillivray 1975), which influences white spruce seedling establishment. Therefore, soil moisture levels under a given threshold (25% in this case) may have a negative influence on white spruce seedlings. The duration of the soil water stress period appears to be reduced in openings up to approximately 0.4 tree lengths from a north-facing edge. At distances greater than this it appears as though the increase in leaf area index of the understory vegetation, together with other factors, results in increased moisture stress. These results suggest that control of understory vegetation may be necessary to reduce competition for water in openings larger than 0.8 tree lengths in width. Additional studies should be conducted to isolate the influence of understory vegetation and other factors such as microclimate on soil moisture levels and associated stress to seedlings.

2.4.3 Air temperature

Extremely low air temperatures may result in rapid freezing of plant parts (Spittlehouse and Stathers 1990; Orcutt and Nilsen 1996; Grossnickle 2000). In addition exposure of plants to direct radiation during the day after a frost event may enhance the effect of low temperature (Lundmark and Hallgren 1987; Orlander 1993; Gillies and Binder 1996; Langvall and Orlander 2001). Under these conditions the shelter offered by the adjacent aspen stand may reduce impacts of frost events. The amount of accumulated heat increases steadily as one moves from the edge of an aspen stand into the adjacent opening. Results suggest that the influence of aspen edge, in terms of growing season air temperature, extends 1.5-2 tree lengths from the aspen stand edge into adjacent openings.

These results are consistent with those from previous work demonstrating differences in air temperature between aspen stands and adjacent openings (Groot *et al.* 1997). Moreover, influences of the adjacent stand on the openings in terms of air temperature were previously verified in a variety of stands for distances ranging from 0.7 to 210m (Williams-Linera 1990; Chen *et al.* 1996; Cadenassoo *et al.* 1997; Saunders *et al.* 1999) as a function of time of the day, orientation, and stand height. However, I found that orientation (south-facing versus north-facing) did not have significant effects on the amount of accumulated heat during the growing season within these young aspen stands.

The frequency of summer frost increased rapidly as one moves from the edge of an aspen stand into the adjacent opening. No significant effect of edge orientation (south-facing versus north-facing) on the frequency of frost events was documented. Results from this study suggest that frost protection occurs within one tree length from the edge of 5 to 7 m tall aspen. However, these effects may change with stand age, with frequency of growing season frost events declining as tree height increases (Groot and Carlson 1996; Groot *et al.* 1997; Pritchard 2003). Other studies have indicated that frequency of frost decreases as the density and height of the surrounding stand increase (Orlander and Karlson 2000; Pritchard 2003).

During the night of a frost event, aspen can provide increased frost protection within 1 tree length of the aspen edge. However, observed increases in minimum temperature at the center of the opening (2.5 tree lengths from the edge) when compared to values at 1 tree length might be due to higher rates of air movement and mixing at this distance. This could have resulted in higher air temperature by mixing the radiatively cooled air near the ground with warmer overlying air (Stathers 1989, Grossnickle 2000) and requires further investigation. Moreover, the temperature inside the aspen stands decreases at almost the same rate as within the opening. Therefore, when an extreme frost event of extended duration occurs, the aspen stand (at least at this age) may provide only limited reduction in frost damage to spruce. However, the relatively small number of air temperature sensors and the lack of replication suggest a need for caution in interpretation of these results.

2.5 Conclusions

The young 5 to 7 m tall aspen stands studied influenced microclimatic conditions in adjacent openings. Gradients in light levels and air temperature increased continuously across the aspen edge to a maximum within the opening, while soil moisture revealed a different pattern, increasing right at the edge and then decreasing.

These young aspen stands provide some reduction in the duration of frost within one tree length from the aspen stand edge. This, in combination with shade, has the potential to reduce the incidence of frost injury to growing white spruce shoots. However, protection against either frost or intense radiation following frost exposure does not depend on edge orientation. Further studies that look at the effect of duration of cold temperature on the degree of frost injury are suggested.

Soil moisture also showed high levels within 1 tree length from the aspen edge, with a maximum at 0.4 tree lengths from the edge. Further research is needed to confirm the trends in soil moisture, and to examine the effect of edge orientation on the variation in soil moisture. These studies should also include examination of root abundance distribution in the opening. Soil moisture was also found to be dependent on the leaf area index of aspen and understory vegetation layers.

Light levels were different for the different cardinal directions with the greatest influence from the north-facing aspen stands and the smallest by the south-facing ones. Because of the short distance from the edge to which shade by adjacent aspen is cast, there is little reason for concerns regarding potential negative influences of adjacent aspen stands on spruce patches. Increases in soil moisture levels and increased frost protection may compensate for the lower light levels within 0.3 tree lengths from the edge.

The observed trends and gradients in microclimate indicate that growing aspen and white spruce in separate small patches may be a reasonable forest management option (Sutton 1974). From the perspective of modifying the microclimate, growing separate patches of aspen and spruce that are two tree lengths wide seems to be a viable option for young mixedwood stands. However, it is likely that the width of the patches will be determined primarily as a function of the height of stand. Therefore, these results should not be extrapolated to older stands or to very different sites without careful consideration. Further research involving additional replication, older stands and more ecosites is required to determine the broader application of these results.

Table 2-1 Location and stand characteristics of the 13 plots located near Grande Prairie (GP), Hines Creek (HC), and Manning (M), Alberta. na = no adjacent aspen stand.

General location	Plot #	Latitude (N)	Longitude (W)	Elevation(m)	Azimuth (0^0)	Spruce density(sph)	Adjacent aspen maximum height (m)				Adjacent aspen basal area(m^2/ha)				DIFN inside adjacent aspen at 1.0m height			
							N	S	E	W	N	S	E	W	N	S	E	W
GP	4003-4	54° 54'	118° 54'	762	6	1000	6	7	6	6.9	17	17	11	13	0.12-0.37	0.17-0.61	0.35-0.53	0.12-0.23
GP	4003-8	54° 54'	118° 54'	762	355	500	7	6	6	6.8	18	16	14	12	0.21-0.31	0.22-0.66	0.21-0.45	0.21-0.29
GP	4016-4	54° 54'	118° 54'	762	6	1000	5	5	5	3.8	8	7	6	3	0.1-0.3	0.18-0.57	0.1-0.21	0.33-0.46
GP	4016-8	54° 54'	118° 54'	762	6	500	6	na	6	6.4	13	na	13	21	0.11-0.18	na	0.16-0.26	0.15-0.48
GP	4024-4	54° 54'	118° 54'	762	8	1000	7	7	6	na	16	9	5	na	0.06-0.51	0.26-0.66	0.3-0.51	na
GP	4024-8	54° 54'	118° 54'	762	12	500	7	7	6	6.1	10	8	7	7	0.13-0.43	0.14-0.64	0.22-0.32	0.27-0.4
HC	1-01	56° 23'	118° 35'	800	25	1000	7	7	6	8.3	5	6	11	16	0.27-0.66	0.51-0.73	0.08-0.34	0.07-0.12
HC	1-07	56° 23'	118° 35'	800	27	500	7	6	8	7.2	6	9	14	14	0.26-0.58	0.15-0.6	0.06-0.14	0.07-0.11
HC	2-07	56° 23'	118° 35'	800	22	500	6	na	7	5.4	15	na	12	10	0.1-0.3	na	0.11-0.17	0.09-0.23
M	1-01	56° 41'	117° 72'	731	15	1000	7	na	6	5.6	13	na	7	5	0.17-0.26	na	0.19-0.69	0.41-0.62
M	1-07	56° 41'	117° 72'	731	18	500	5	na	na	5.7	13	na	na	9	0.08-0.36	na	na	0.1-0.28
M	2-01	56° 41'	117° 72'	731	14	1000	6	6	6	5.7	15	9	13	7	0.1-0.27	0.15-0.61	0.14-0.28	0.23-0.42
M	2-07	56° 41'	117° 72'	731	13	500	7	na	6	na	17	na	8	na	0.05-0.17	na	0.26-0.5	na

Table 2-2 Precipitation data for Hines Creek installation. Data shown for the FAIRVIEW weather station (Latitude 56^0 4' N; Longitude 118^0 22' W)

Precipitation (rainfall)	Monthly averages			
	June	July	August	September
Normals (mm)	76.6	78.8	60.4	35.9
2003 (mm)	42.1	27.5	66.4	17.7

Table 2-3 Summary of the statistical procedures used to examine relationships between dependent and independent variables. Proportional distance is the number of tree lengths from the edge of the aspen stand.

Dependent variable		Independent variable
Light levels	Difuse non-interceptance (DIFN)	Proportional distance
Soil moisture	Volumetric water content (VWC)	Proportional distance
	Volumetric water content (VWC)	Leaf area index aspen and herbaceous vegetation (LAI As & LAI G)
Air temperature	Air temperature during night of frost event	Proportional distance
	Number of days with temperature under 0^{0}C	Proportional distance
	Growing degree hours (ΔGDH)	Proportional distance

Table 2-4 Summary of the coefficients from least square fitting of the Gompertz equation (1) for the relationship between light levels and distance from the stand edge. Y=transmittance, X=Proportional distance, a;b;c=equation coefficients.

Orientation	a	b	c	n	R^2Adj	P-values model
N- Facing	0.9987	0.6488	-0.2334	162	0.88	<0.0001
S- Facing	0.9768	0.5226	-0.2848	245	0.86	<0.0001
E- Facing	0.9792	0.6457	-0.2438	194	0.83	<0.0001
W- Facing	0.9731	0.6789	-0.2537	214	0.84	<0.0001

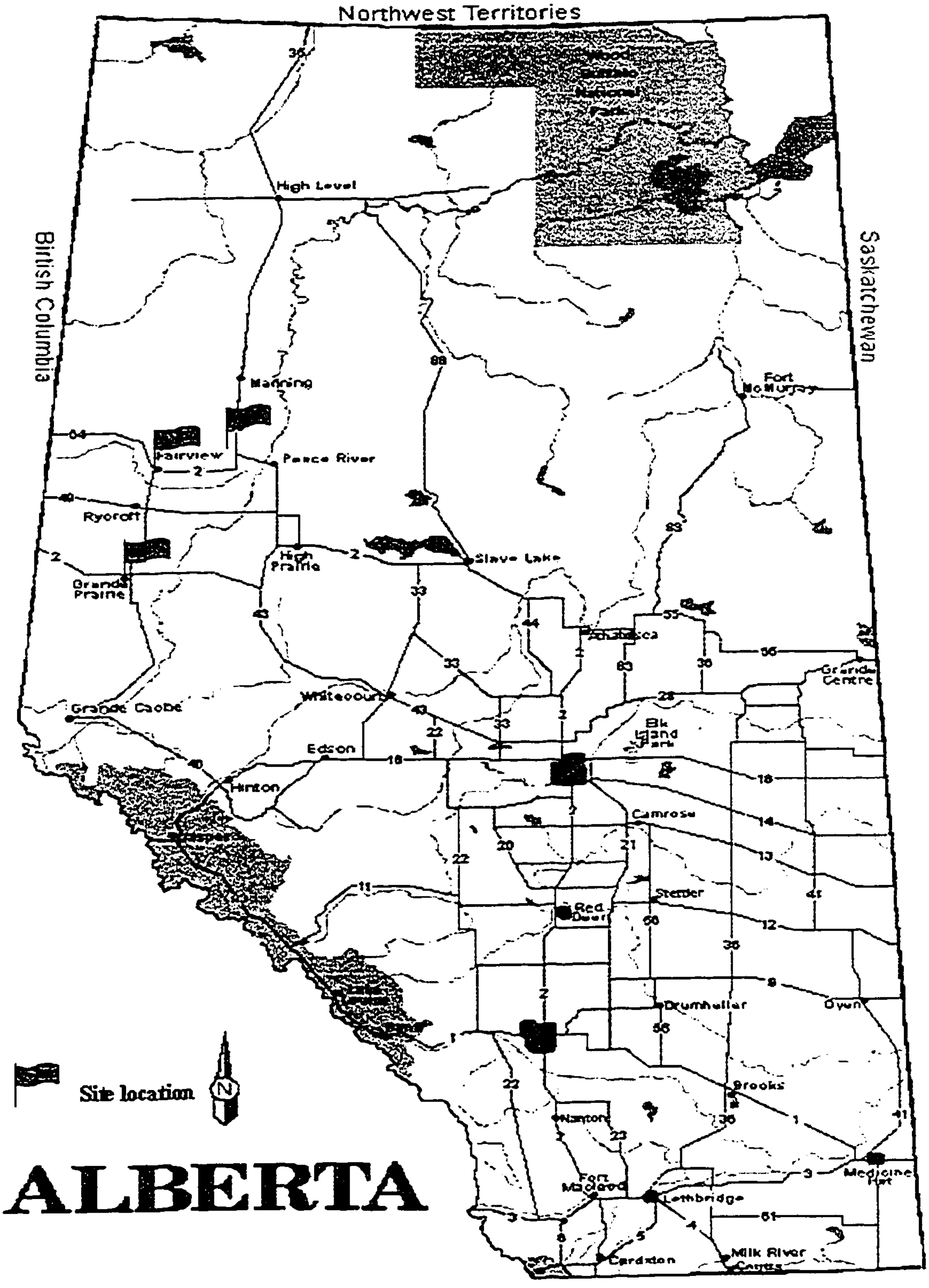

Figure 2-1 General location of the selected study sites near Grande Prairie and Peace River, Alberta.

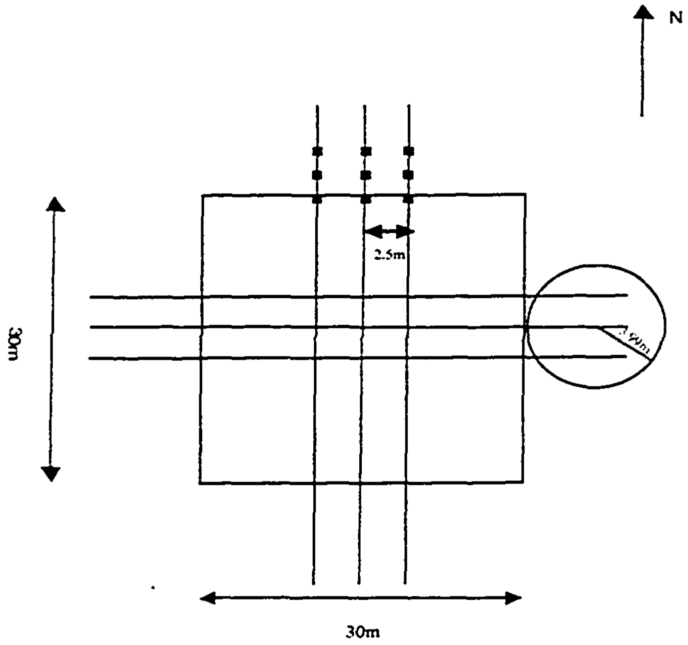

Figure 2-2 Diagram showing transect positions within the plot. The squares on the north side of the plot represent locations where light levels inside adjacent aspen stand were measured. The circle on east side of the plot represents the location where aspen basal area and height were measured.

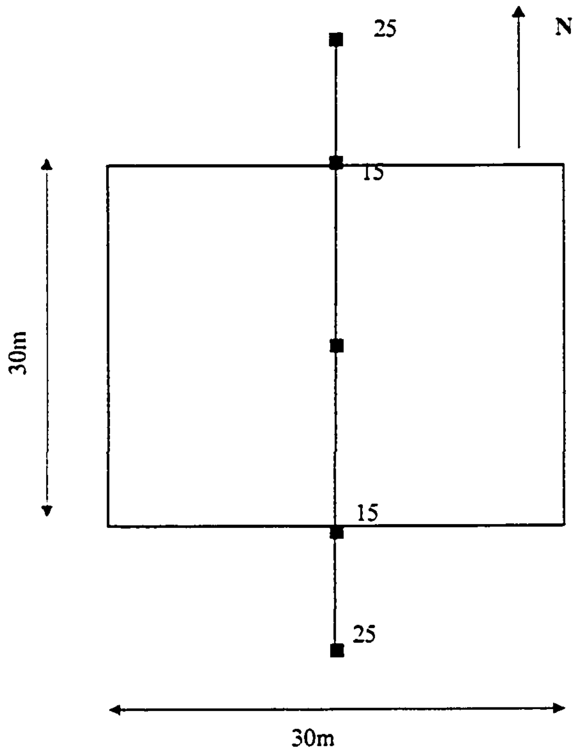

Figure 2-3 Diagram showing photodiode sensor position within the plot.

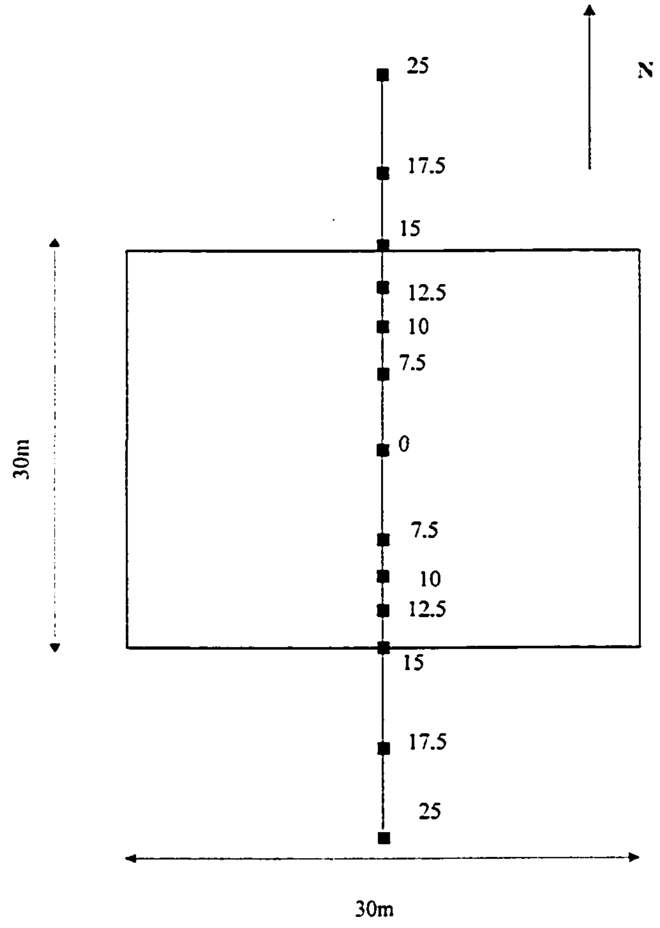

Figure 2-4 Diagram showing air temperature sensor positions within the plot in 2003.

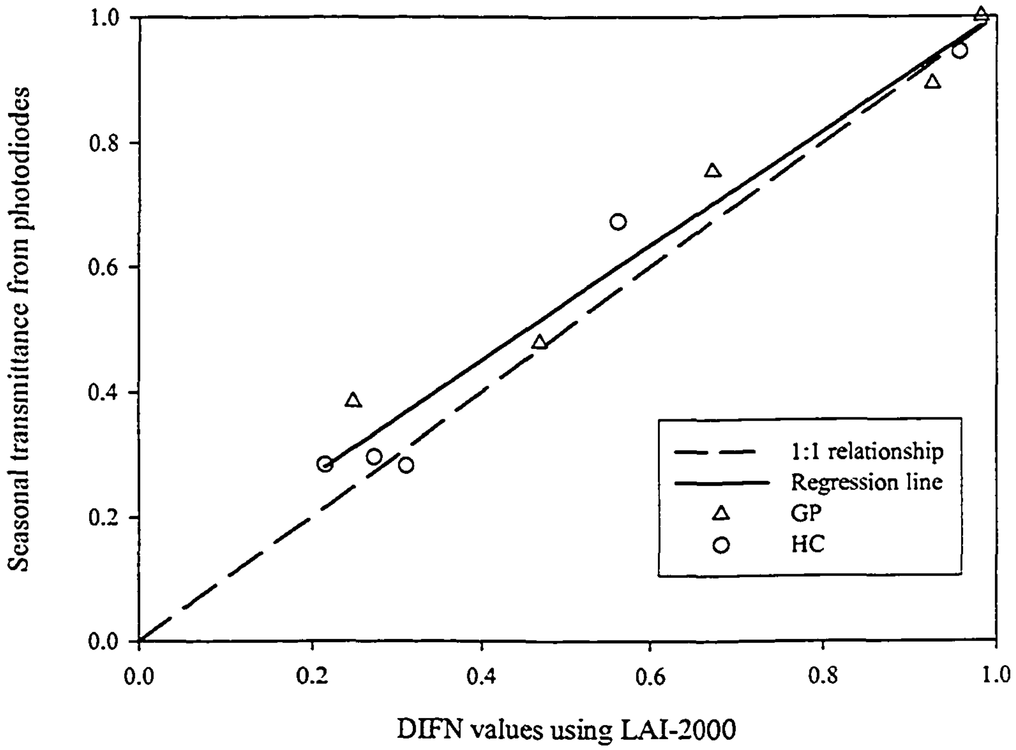

Figure 2-5 Relationship between growing season transmittance (May 9 to October 4, 2003) measured with photodiodes and DIFN values calculated from measurements taken using LAI-2000 sensors. The dashed line shows a 1:1 relationship and the solid line is described by the equation: growing season transmittance = 0.0835+ 0.9184*DIFN, R^2=0.966, n=10. The intercept is not significantly different than 0 ($p>0.05$) and the slope is not significantly different than 1 ($p>0.05$). GP, HC=data from Grande Prairie and Hines Creek, respectively.

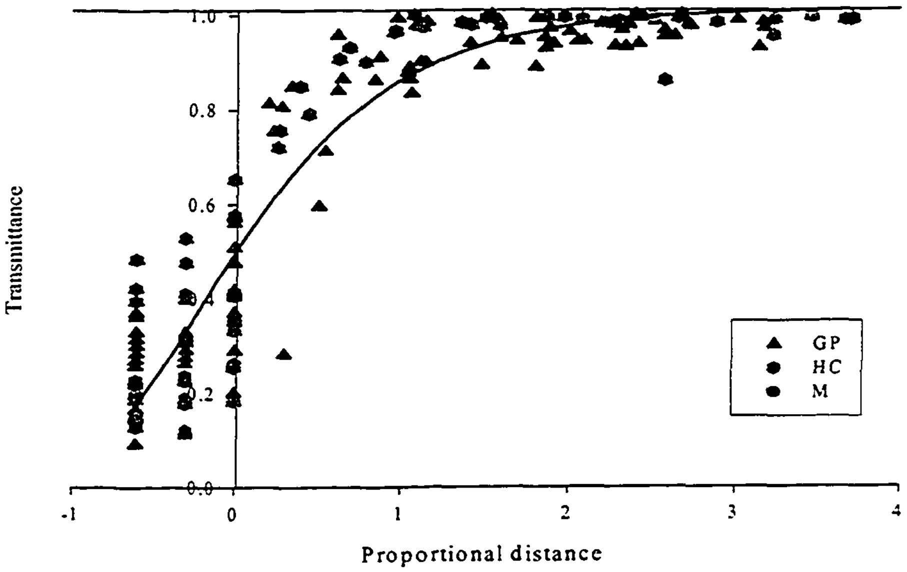

Figure 2-6 Relationship between transmittance and proportional distance for north-facing edges. The line is described by a Gompertz equation: $Y = 0.9987e^{-e^{-\left(\frac{X+0.2334}{0.6488}\right)}}$ with $R^2_{adj}=0.88$, $p<0.0001$, n=162, Y=transmittance, X=Proportional distance, GP=Grande Prairie, HC= Hines Creek, M=Manning. Proportional distance is defined as the number of tree lengths from the edge of the aspen stand, with negative proportional distances indicating points inside of the aspen stand.

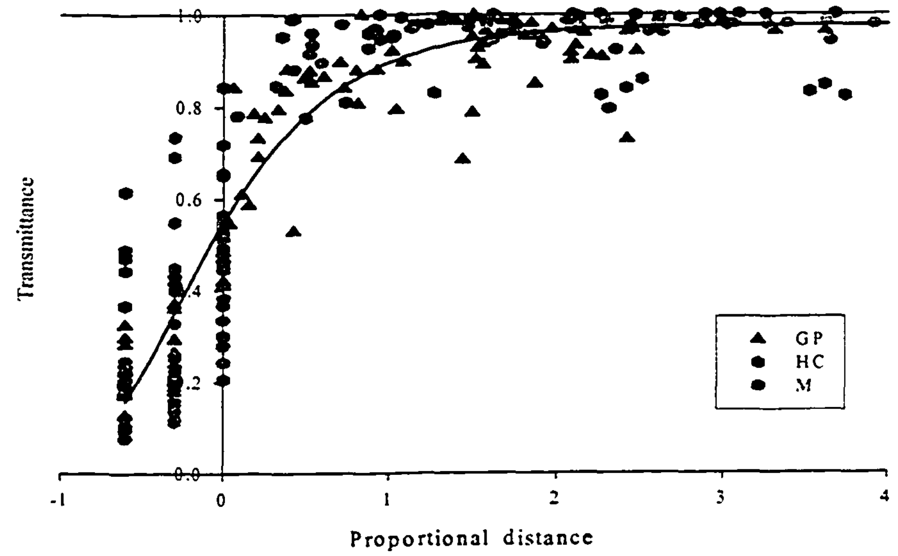

Figure 2-7 Relationship between transmittance and proportional distance for south-facing edges. The line is described by a Gompertz equation: $Y = 0.9768e^{-e^{-\left(\frac{X+0.2848}{0.5226}\right)}}$ with $R^2_{adj}=0.86$, , $p<0.0001$, n=245Y=transmittance, X=Proportional distance, GP=Grande Prairie, HC= Hines Creek, M=Manning. Proportional distance is defined as the number of tree lengths from the edge of the aspen stand, with negative proportional distances indicating points inside of the aspen stand.

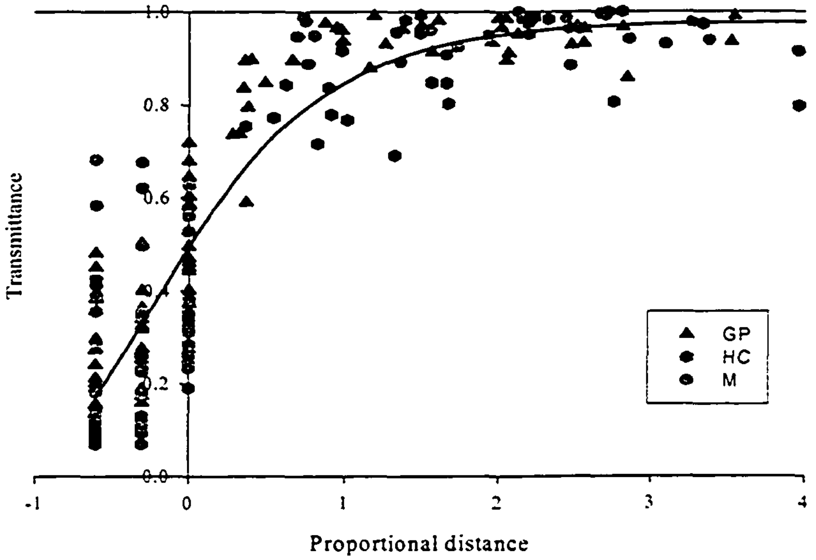

Figure 2-8 Relationship between transmittance and proportional distance for east-facing edges. The line is described by a Gompertz equation: $Y = 0.9792e^{-e^{-\left(\frac{X+0.2438}{0.6457}\right)}}$ with R^2_{adj}=0.83, $p<0.0001$, n=194, Y=transmittance, X=Proportional distance, GP=Grande Prairie, HC= Hines Creek, M=Manning. Proportional distance is defined as the number of tree lengths from the edge of the aspen stand, with negative proportional distances indicating points inside of the aspen stand.

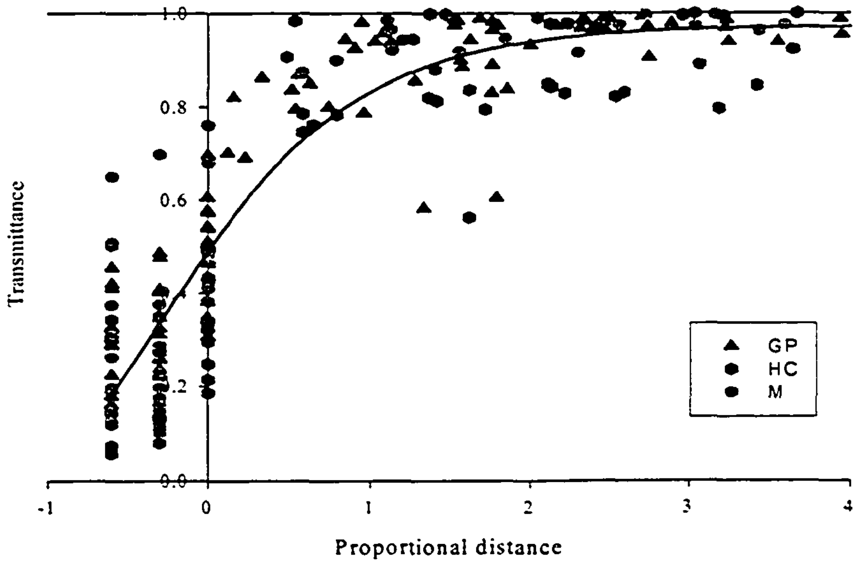

Figure 2-9 Relationship between transmittance and proportional distance for west-facing edges. The line is described by a Gompertz equation: $Y = 0.9731e^{-e^{-\left(\frac{X+0.2537}{0.6789}\right)}}$ with R^2_{adj}=0.84, $p<0.0001$, n=214, Y=transmittance, X=Proportional distance, GP=Grande Prairie, HC= Hines Creek, M=Manning. Proportional distance is defined as the number of tree lengths from the edge of the aspen stand, with negative proportional distances indicating points inside of the aspen stand.

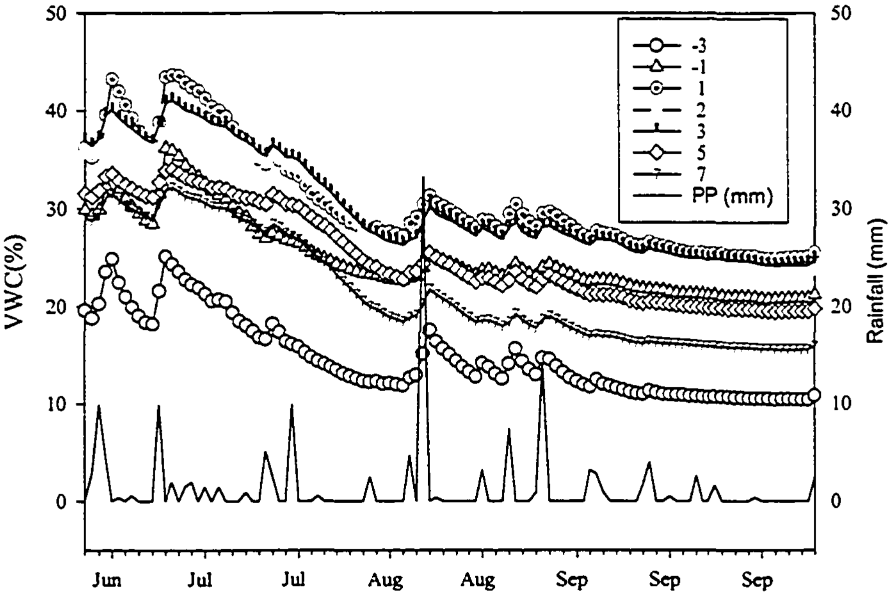

Figure 2-10 Daily average variation in volumetric soil water content (VWC) and precipitation (mm) during 2003 at Hines Creek. The lines on the graph represent position of soil moisture sensors in m from the aspen stand edge. Negative numbers represent locations within the adjacent aspen stand, while positive ones mark locations in the opening. Precipitation variation is illustrated by the continuous line at the bottom of the graph.

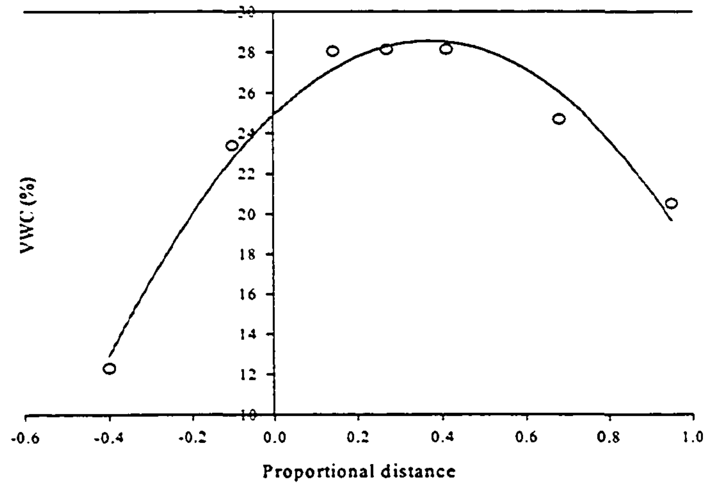

Figure 2-11 Relationship between volumetric water content (VWC) on July 31, 2003 and proportional distance at Hines Creek. The curve is described by a polynomial equation: $Y = 24.9286 + 19.5239X - 26.3443X^2$,with $R^2_{adj}=0.97$, $p=0.0005$, $n=7$, Y=VWC, X=proportional distance. Proportional distance is defined as the number of tree lengths from the N-facing edge of the aspen stand, with negative proportional distances indicating points inside of the aspen stand. The height of the adjacent aspen stand is 7m.

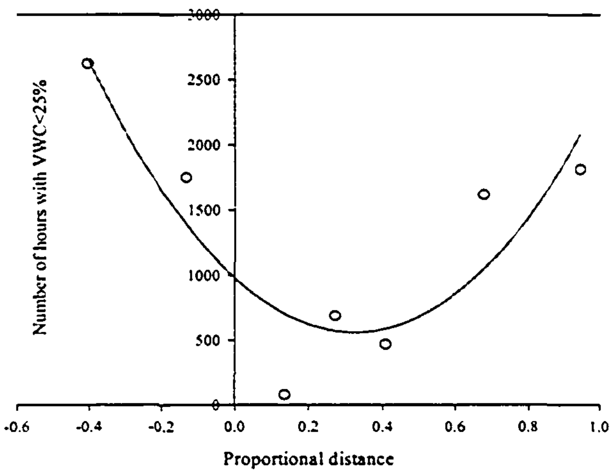

Figure 2-12 Relationship between number of hours with volumetric water content under 25% (VWC<25) and proportional distance (June 19 to September 30, 2003), at Hines Creek. The curve is described by a polynomial equation: $Y = 975.9328 - 2558.0888X + 3939.4221X^2$ **,with** $R^2_{adj}=0.71$**, p=0.0375, n=7, Y=VWC<25%, X=proportional distance. Proportional distance is defined as the number of tree lengths from the N-facing edge of the aspen stand, with negative proportional distances indicating points inside of the aspen stand. The height of the adjacent aspen stand is 7m.**

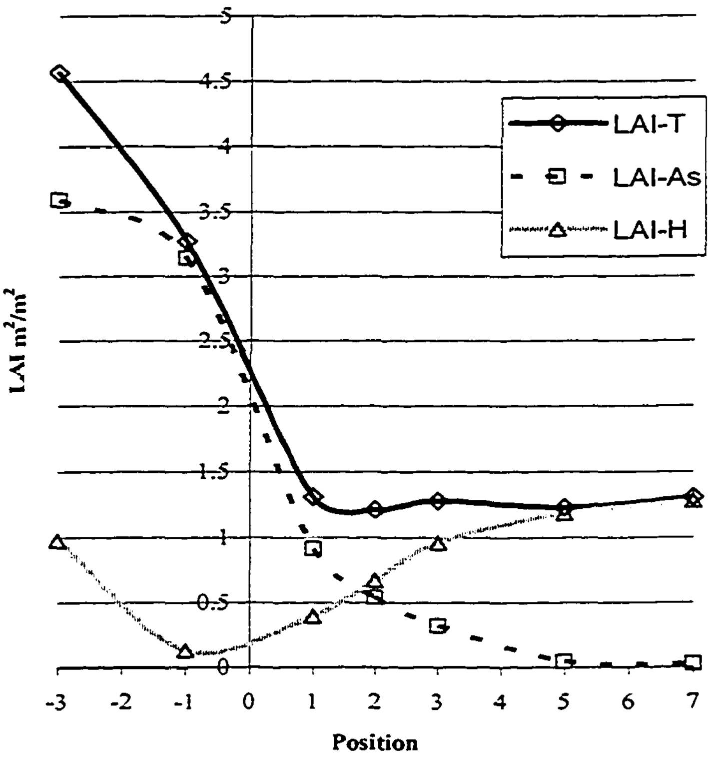

Figure 2-13 Patterns of aspen and understory leaf area index (LAI) measured along a transect across the boundary between the young aspen and the adjacent opening. LAI-T= total LAI, LAI-As= aspen LAI, LAI-H understory LAI. Negative numbers on X axis indicate measurement locations inside the aspen stand.

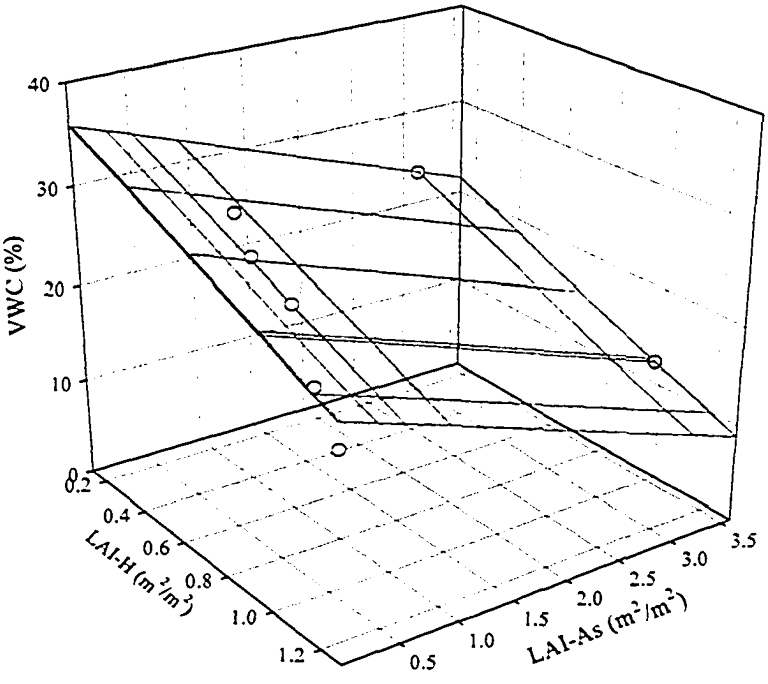

Figure 2-14 Relationship between soil moisture (VWC) on July 31, 2003 and aspen leaf area index (LAI-As) and understory vegetation leaf area index (LAI-H) , at Hines Creek. The plane is described by a multiple linear regression: $VWC = 37.3739 - 3.9807 LAIAs - 11.1175 LAIH$ **,with R^2_{adj}=0.88, p=0.0064, n=7.**

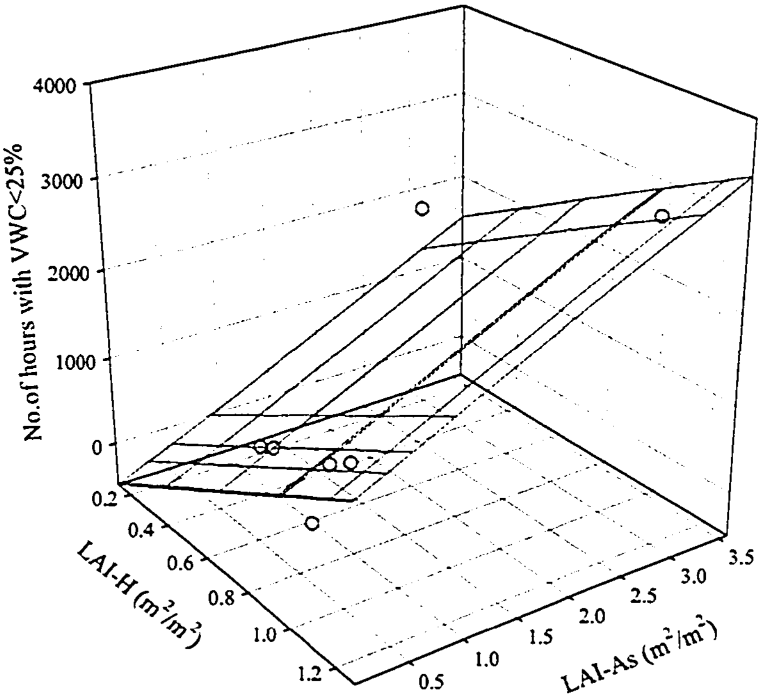

Figure 2-15 Relationship between number of hours with volumetric water content under 25% (VWC<25%) and aspen leaf area index (LAI-As), and understory vegetation leaf area index (LAI-H) for 2003, at Hines Creek. The surface is described by a multiple linear equation of regression: $VWC < 25 = -728.4862 + 563.3849 LAIAs + 1664.0532 LAIH$ **,with** $R^2_{adj}=0.67$**, p=0.049, n=7.**

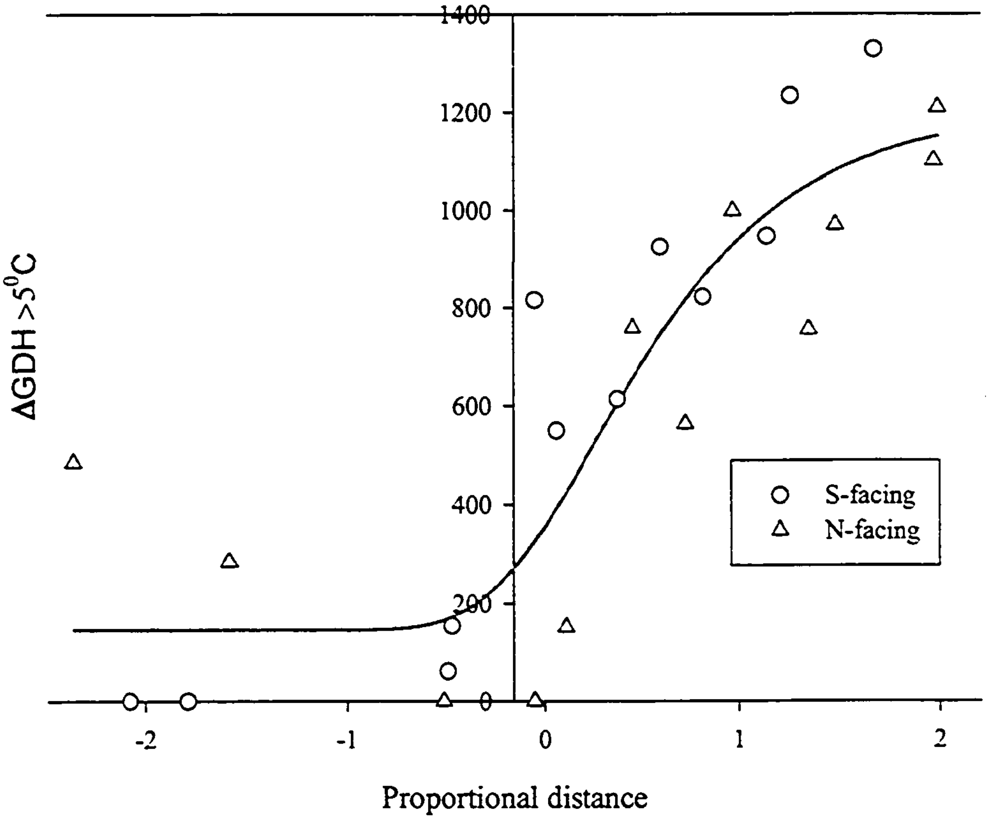

Figure 2-16 Relationship between growing degree hours (ΔGDH) and proportional distance (May 9 to September 30, 2003). The line is described by the Gompertz equation:

$Y = 145.5284 + 1057.8694e^{-e^{\left(\frac{X-0.5754}{-0.2776}\right)}}$ **. Y= ΔGDH, X=Proportional distance, $R^2_{adj}=0.75$, $p<0.0001$, n=24, Proportional distance is defined as the number of tree lengths from the edge of the aspen stand, with negative proportional distances indicating points inside of the aspen stand. Growing degree hours (ΔGDH) was calculated as: ΔGDH= GDH*i*-GDH*o*, where GDH*i* -growing degree hours calculated for each air temperature sensor, GDH*o*- minimum value out of all growing degree hours calculated for each air temperature sensor.**

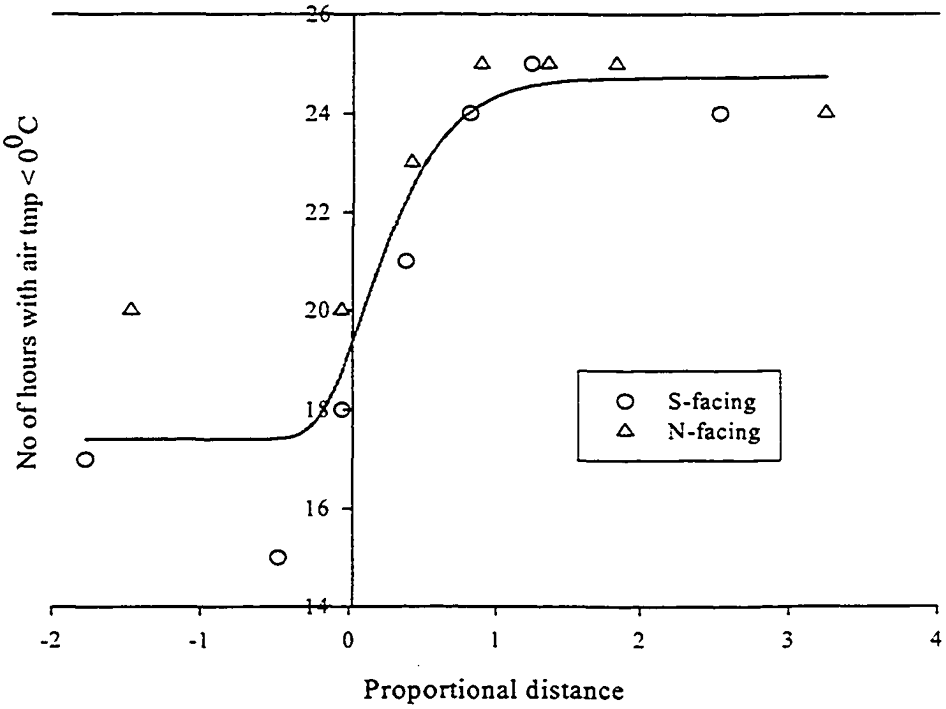

Figure 2-17 Relationship between number of hours with temperatures below zero degrees Celsius and proportional distance (June 1 – August 31, 2003) at Grande Prairie. The line is described by the Gompertz equation: $Y = 17.4089 + 7.3368e^{-e^{\left(\frac{X-0.1083}{-0.3079}\right)}}$. Y=Number of hours with temperatures under zero degrees Celsius, X=Proportional distance, $R^2_{adj}=0.83$, $p<0.0001$, $n=14$. Proportional distance is defined as the number of tree lengths from the edge of the aspen stand, with negative proportional distances indicating points inside of the aspen stand.

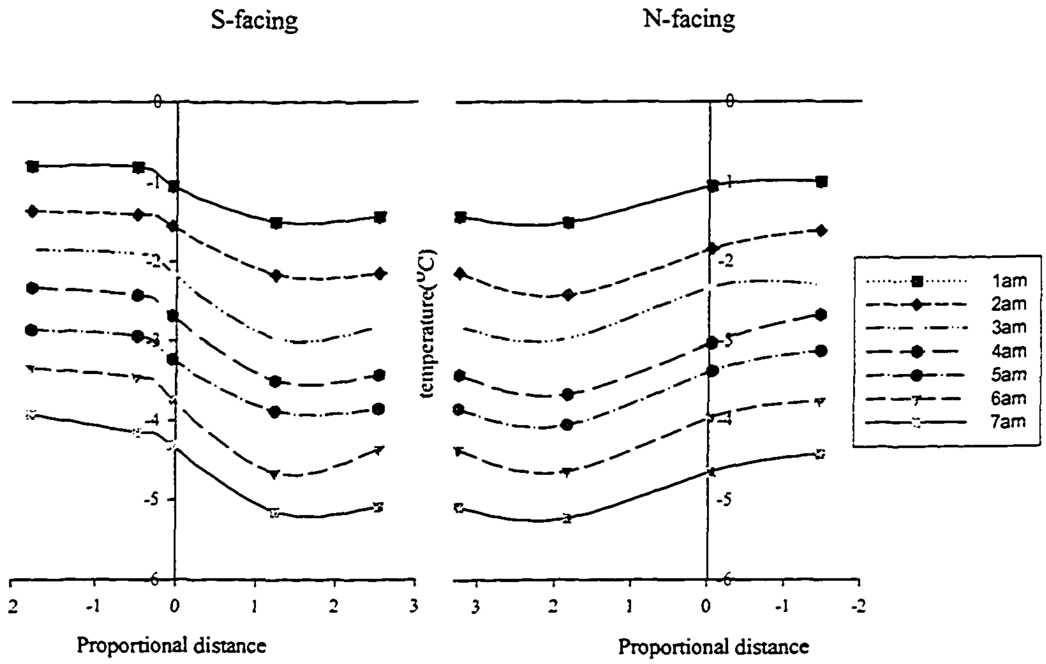

Figure 2-18 Air temperature (hourly average) versus proportional distance for two directions at Grande Prairie, during the night of a frost event (September 7, 2002). Proportional distance is defined as the number of tree lengths from the edge of the aspen stand, with negative proportional distances indicating points inside of the aspen stand.

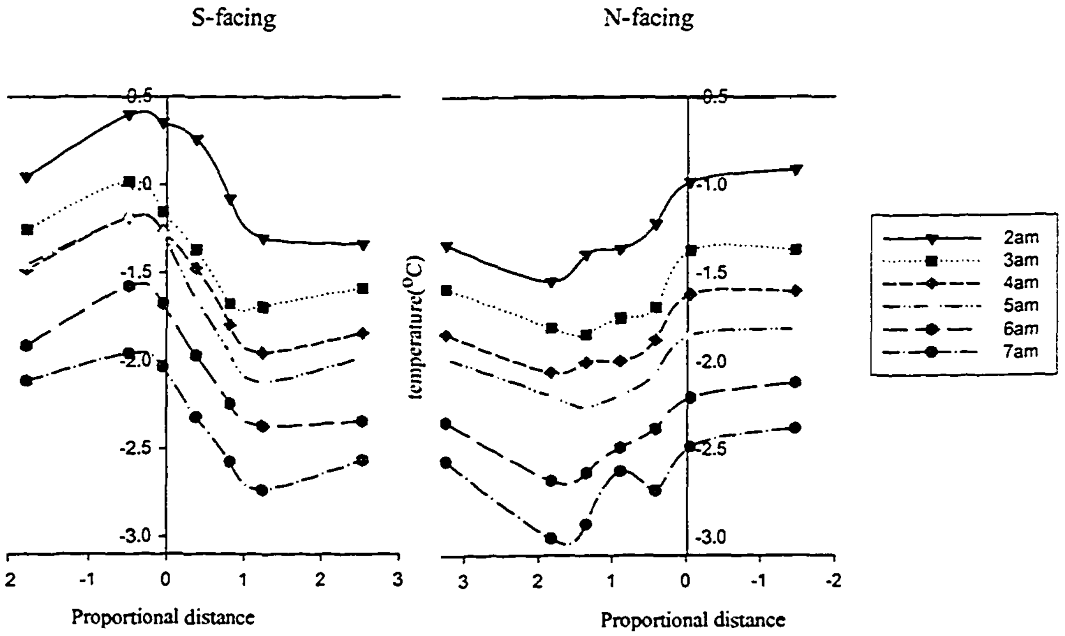

Figure 2-19 Air temperature (hourly average) versus proportional distance for two directions at Grande Prairie, during the night of a frost event (August 24, 2003). Proportional distance is defined as the number of tree lengths from the edge of the aspen stand, with negative proportional distances indicating points inside of the aspen stand.

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Chapter 3. The effect of light levels and distance from young aspen patches on growth of white spruce seedlings

3.1 Introduction

Sutton (1974) proposed the use of a "cluster planting" approach which involves growing aspen and white spruce in small to moderate sized patches. This approach is believed to have potential because of lower cost - because only patches of spruce are tended. Furthermore, if patches are suitably designed foresters might be able to use aerial herbicide applications for tending. In the design of a cluster planting or patch approach to managing a mixedwood stand the extent to which the adjacent aspen stand influences growth of the spruce must be considered.

A small number of studies provide information on tree growth adjacent to stand edges. Hansen *et al.* (1993) showed that significant differences in natural regeneration, seedling establishment and growth of Douglas-fir seedlings were related to distance into the opening from a forest edge. They found reduced growth of Douglas-fir seedlings 20 m north of a 45 m tall mature stand. Similarly, Burton (2002) found that natural regeneration of conifer seedlings decreased with distance from the forest edge, and was higher on the north-facing than south-facing edges. Emmingham and Waring (1975) showed that Douglas-fir leader length reached a maximum between 4 m and 21 m from the edge of a 20 to 25 m tall stand. Groot *et al.* (1997) found that growth of white spruce was reduced within 5 m of the north facing edge of a 19m tall mixedwood stand when compared to the center of the 9m and 18m wide strips. In another study, maximum conifer heights were found at the center of the opening (York *et al.* 2003). However, Burton (2002) showed no difference in growth due to seedling proximity to the stand edge. Similarly, Coates (2000) found little to no difference between seedlings grown at south- and north-facing edges but report that conifer seedling growth 5 years after planting was related to gap size. Growth rapidly increased from small gaps to 1000-2000m^2 gaps, but from this threshold to 5000m^2, growth leveled-off (Coates 2000). York *et al.* (2003) found greater conifer seedling height on south-facing than on north-facing edges for openings smaller than 1 ha.

Information on the influence of adjacent aspen on the amount of light reaching the white spruce and the extent to which changes in soil moisture, soil temperature, and frost incidence occur, has been presented in chapter 2. Results show uniform increases across the young aspen edge within the opening for gradients in light levels and air temperature; whereas fluctuations from a maximum right at edge to lower values within the opening are evident for soil moisture. Also, young aspen provide protection against frost damage within one tree length from the edge. Variation in spruce growth would be expected to occur in response to these changes in microclimate.

Results from several studies indicate that growth of white spruce seedlings in terms of diameter, height and stem volume increases as light levels increase (Eis 1967; Logan 1969; Klinka *et al.* 1992; Lieffers and Stadt 1994; Pacala *et al.*1994; Wright *et al.*1998; Coates and Burton 1999; Groot 1999; Jobidon 2000; Pritchard 2003). A number of studies also indicate that the size of the tree or the tree crown influences growth rates (Hatch et al. 1975; Givnish 1988; Cole and Lorimer 1994; Biging and Dobbertin 1995; Choi et al. 2001, Claveau et al. 2002; Comeau et al. 2003, Webster and Lorimer 2003; Pritchard 2003) since this reflects the leaf area of the tree. In young plantations, spruce growth showed good response in terms of height to diameter ratio (HDR) (Opio et *al.*

2000). Also, height allocation ration (HAR), as a measure of the proportion of stem growth allocated to height growth, could be an even better reflection of spruce growth, especially following spruce release (Comeau et *al.* 2003).

Maximum photosynthesis is reached by white spruce shoots at between 40 and 60% of the above canopy light levels (Man and Lieffers 1997). However, diameter and volume growth of conifers is generally maximal at full sunlight (Logan 1969, Eis 1970; Klinka *et al.* 1992; Comeau *et al.*1993; Wright et all. 1998; Coates and Burton 1999; Comeau et al. 2003). Significant reductions in conifer diameter and volume growth rates occur even when the vegetation increases from minimum to low levels (Jobidon 2000).

White spruce seedlings reached the maximum potential height at light levels between 40 and 100% of full sunlight (Gustafson 1943; Eis 1967; Logan 1969), while minimum was achieved between 20 to 25% of full sunlight (Gustafson 1943; Eis 1967). Growth performance of white spruce seedlings in the understory of a mixedwood stand with light levels of 40% full sunlight was similar to that of those grown in the open (Logan 1969; Kabzems and Lousier 1992; Lieffers and Stadt 1994). In contrast, several other studies suggest that height growth when evaluated over a 5 year period or longer, like diameter growth, reaches its maximum at full light levels (Jobidon 2000; DeLong 2000). Models presented by Wright *et al.* (1998) and Coates and Burton (1999) show that the relationships between height growth and light is curvilinear, with the curves beginning to level off after light levels exceed 60%. Some of the variation in growth responses between studies may involve variation in the importance of adjacent stands as a nurse crop leading to differences in the performance of trees growing in unprotected environments or site conditions.

Despite an interest in the potential use of cluster planting or a patch treatment approach for managing mixedwood stands, there is currently no information on the influence of adjacent regenerating aspen on the growth of white spruce in tended patches. This chapter will present results from a study designed to examine the effects of proximity to adjacent regenerating aspen, edge orientation, light levels and initial seedling size on the growth of white spruce.

Hypotheses being tested are:

1) Growth of white spruce (in terms of diameter, height, and stem volume increment, and height allocation ratio) is related to light levels, initial tree size (in terms of initial crown surface area or initial crown volume), and to the adjacent aspen stand orientation;

2) Growth of white spruce (in terms of diameter, height, and stem volume increment, and height allocation ratio) is related to the distance from the adjacent aspen stand, initial tree size (in terms of initial crown surface area or initial crown volume), and to the adjacent aspen stand orientation.

3.2 Materials and methods

3.2.1 Study area and experimental design

Field installations located near Grande Prairie and Peace River that were established by the Western Boreal Growth and Yield (WESBOGY) Co-operative to evaluate the effects of spruce and aspen density levels on the development of plantations (Titus and Wang 2000) were used in this study. The WESBOGY installations consist of white spruce planted at three densities (0, 500, 1000sph) and aspen spaced at approximately age five to 0, 200, 500, 1500, and 4000sph, plus untreated control (Titus and Wang 2000). Only the 0 aspen plots were used by the present study. The first location is south of Grande Prairie, Alberta (54° 55′ N, 118° 55′ W) and is referred to as Grande Prairie; the second location, called Hines Creek, is located east of Peace River, Alberta (56° 20′ N, 118° 30′ W); and the third location, called Manning, is located north of Peace River, Alberta (56° 41′ N, 117° 72′ W). At all three locations, the aspen and spruce saplings were 11 to 13 years old in 2003. All three locations consist of white spruce raw planted in 30x30 m plots at densities of 500 or 1000sph next to aspen that was either spaced to 1500 or 4000sph or was left natural. All ingress vegetation within the 30x30m plot was periodically removed, starting five years after white spruce establishment. The white spruce seedlings at the two densities (500, 1000sph) were assumed to respond in a similar manner to the biotic and abiotic conditions and thereby considered as replications independent of plot density. I examined white spruce seedling growth within plots with complete aspen removal that had adjoining aspen stands. A detailed description of the 13 plots used in this study is presented in Table 3-1.

3.2.2 Data collection

For this study, 2 transects were established in each plot: one going north to south, and the other going east to west through the center of each zero density aspen plot at each of the 3 locations mentioned above. Density within plots was maintained to zero aspen level by periodical removal of all regenerating vegetation. All spruce seedlings located along each transect (2.5 m on both sides of the transects) were selected for measurement of root collar diameter, height, height to crown base, and crown radius in each of four cardinal directions. The spruce seedlings found within the 5x5m middle square were counted twice, once for each transect, and they were analyzed separately for each transect (Figure 3-1).

A numbered metal tag was attached to each measured spruce seedling, and the location of each seedling relative to the center of the plot mapped. Distance from center of the plot to the edge of adjacent aspen (stem line) was measured. Transects were oriented to run perpendicular to plot boundaries As a result of this, transects orientation ranges from 355^0 to 27^0 (Table 3-1). The proportion of light reaching the top of a canopy that penetrates to the understory is represented by diffuse non-interceptance (DIFN) value (LI-COR, Inc. 1992). The LAI-2000 plant canopy analyzer (LI-COR Inc., Lincoln, NEB) has an optical filter that eliminates radiation above 490 nm, which results in a DIFN value that is a measure of the absorption of diffuse, shortwave radiation. Previous studies have found that DIFN measurements provided by LAI-2000 plant canopy analyzers give unbiased estimates of average growing season transmittance (Comeau *et al.* 1998; Gendron *et al.* 1998). During the mid-summer of 2002 and 2003, LAI-2000 measurements were taken both at the top and mid-crown of the white spruce seedlings with the sensor pointed away from the tree to estimate growing season available light (DIFN). Measurements were taken facing both west and east, early in the morning and late in the afternoon respectively. Measurements were taken using just one LAI-2000 unit (in one sensor mode) in mid-summer of 2002. Therefore, open sky readings were taken before and after taking the understory readings for each direction and each plot. In 2003, two LAI-2000 units were used simultaneously (in remote mode), where the first unit was located in the open on a tripod and collected open sky readings every 30 sec.

The other unit was used to collect data at each white spruce seedling within the plots. To calibrate the two units, open sky readings were also taken by placing the 'understory unit' next to the open sky sensor each morning and afternoon.

Diffuse non-interceptance (DIFN) light was determined using C2000 software (Licor Inc., Lincoln, NEB), with the final transmittance values calculated as an average between east and west facing values. The lens of the LAI-2000 measures openness within five concentric rings, but a previous study (Comeau *et al.* 1998) indicated the outer ring (equivalent to a sky view of 62.3^0-74.1^0 from vertical) may give poor estimates of growing season transmittance. For this study, ring 5 was masked and transmittance values were determined for rings 1-4 only (equivalent to a sky view of 58.1^0 from vertical).

3.2.3 Data preparation

The following variables were calculated:

- Stem volume (SV), assuming the volume of a cylinder, as: $SV = \pi R^2 h$ where R=root collar radius (i.e. ½ of root collar diameter), h=white spruce height,
- Stem volume increment (SVI) is the difference between stem volume at the end of the 2003 growing season (SV_{Oct}) and stem volume at the beginning of the 2003 growing season (SV_{May}).
- Average crown radius as: $R = (r_N + r_S + r_E + r_W)/4$, where r_N, r_S, r_E, r_W represents crown radius measured for each cardinal direction.
- Initial crown surface area (ICSA), assuming the lateral surface of a cone as: $ICSA = \pi R\sqrt{(R^2) + (h_t - h_c)^2}$ where R= average crown radius, h_t=white spruce height, h_c= height to crown.

- Initial crown volume (ICV), assuming the volume of a cone as: $ICV = \pi R^2(h_t - h_c)/3$ where R= average crown radius, h_t=white spruce height, h_c= height to crown.
- Diameter increment as: $DI=D_{Oct}-D_{May}$ where D_{Oct}=root collar diameter at the end of the 2003 growing season, D_{May}=root collar diameter at the beginning of the 2003 growing season.
- Height increment as $HI= H_{Oct}-H_{May}$ where H_{Oct}=height at the end of the 2003 growing season, H_{May}=height at the beginning of the 2003 growing season.
- Height allocation ratio as: HAR=HI/SVI (Comeau *et al.* 2003).
- Light levels at the top of the white spruce seedlings (DIFN-T) as an average between the east and west-facing values using C2000 software (LI-COR Inc., Lincoln, NEB)
- Light levels at the midcrown of the white spruce seedlings (DIFN-M) as an average between the east and west-facing values at the midcrown of the white spruce seedlings obtained using C2000 software (LI-COR Inc., Lincoln, NEB)
- Proportional distance (PD) as distance from the aspen stand edge divided by the difference between adjacent stand height and height of the light measurement.

3.2.4 Data analysis

Multiple nonlinear regression analysis was used to evaluate the relationships between growth of white spruce seedlings (SVI, DI, HI, and HI/SVI) and light levels (DIFN-T, DIFN-M) or distance from the stand edge (PD) and initial size of white spruce seedlings (ICSA, ICV). Various models were tested using SVI, DI, HI, and HI/SVI as dependent variables and combinations of initial crown size (ICSA, ICV) with DIFN-T, DIFN-M or PD as independent variables. Coefficients of determination (R^2), model p-values and root mean square error (RMSE) were calculated. Scatterplot of residuals were examined visually to asses the fit for each equation.

Initial analysis used the indicator (dummy) variable approach (Draper and Smith 1981; Ott 1997) to determine whether the four cardinal directions or sites could be pooled and analyzed as a single relationship.

All analyses were completed using PROC N-LIN procedure of version 8.2 of SAS Statistical Software (SAS Institute, Cary, NC).

3.3 Results

White spruce stands located near Grande Prairie were generally smaller than those located in the other two installations (Hines Creek and Manning). At the Grande Prairie installation, spruce ranged in root collar diameter from 7.3 to 44mm, height from 0.27 to 1.85m, crown radius from 7 to 49cm, midcrown transmittance from 0.284 to 0.991 and top transmittance from 0.494 to 1.000 (Table 3-2).

White spruce at the other two locations (Hines Creek and Manning) ranged in root collar diameter ranged from 23.2 to 74.6mm, height from 0.43 to 3.57m, crown radius ranged from 24 to 95 cm, midcrown transmittance from 0.468 to 0.999 and top transmittance from 0.530 to 1.000 (Table 3-2).

Relationships between height allocation ratio, stem volume growth, diameter or height growth and light transmittance at either the top or midcrown or proportional distance and initial crown surface area or initial crown volume were significant

($p<0.0001$) for all three locations included in this study (Table 3-3). However, R^2_{Adj} values obtained for the regressions of root collar diameter growth or height growth against light transmittance or proportional distance and initial crown surface area were small at all locations (Table 3-3). On the other hand, height allocation ratio (HI/SVI) used as a measure of the proportion of stem growth allocated to height growth (Comeau et al 2003) showed reasonable values for R^2_{Adj} ($R^2_{Adj} > 0.55$, Table 3-3). At all three locations, the highest R^2_{Adj} values were found for the relationship between stem volume increment and light levels at either the top or midcrown, combined with initial crown surface area (Table 3-3). Analysis showed no colinearity between ICSA/ICV and DIFN-M/DIFN-T. When initial crown surface area (ICSA) was used the R^2_{Adj} values were slightly higher (1%) than those found when initial crown volume (ICV) was used (Table 3-3). Because of the very small differences in R^2_{Adj} values for ICSA, or ICV (Table 3-3), graphic representation and equations are shown only for ICSA. While significant, regression using DIFN (models 1 and 4) or PD (models 7 and 10) by themselves, explained only 2% to 3% and 1% to 8% of the variation, respectively (Table 3-4).

For each installation the indicator variable test showed that there was no difference among data from the four different cardinal directions (i.e. N, S, E, and W-facing aspen edges) ($p>0.05$). Therefore, data were pooled and analyzed as a single relationship for each location. When the indicator variable principle was used to test if the data from all installations could be analyzed together, it showed that a difference existed among sites ($p<0.05$). Further testing revealed there was no difference among data from two of the installations (i.e. Hines Creek and Manning) ($p>0.05$), but that these two sites differed significantly from Grande Prairie ($p<0.05$). Therefore data were pooled for Hines Creek and Manning and analyzed together, while data for the Grande Prairie installation were analyzed separately. However, for the height allocation ratio (HI/SVI) as the dependent variable versus DIFN and ICSA as the independent variables, the indicator variable test showed that the data for Hines Creek and Manning could not be pooled together ($p<0.05$), and therefore, were analyzed individually.

3.3.1 White spruce volume increment (SVI) as a function of light levels (DIFN) and initial tree size (ICSA)

Differences in DIFN between the midcrown and top of spruce seedlings were observed (Table 3-2). As a consequence models were established using each measure of DIFN.

3.3.1.1 Midcrown transmittance (DIFN-M)

For the Grande Prairie location, the relationships between stem volume growth and the two independent variables: DIFN-M and ICSA are illustrated in Figure 3-2. Crown surface area alone had a substantial influence on growth rates. White spruce saplings with small crown surface areas (5000 cm^2) displayed a small difference (111 cm^3/yr) between growth rates at high (0.9) and low (0.3) light levels. When crown surface area was larger (12000 cm^2) the difference in growth rates between DIFN-M values of 0.3 and 0.9 was almost three times greater (334 cm^3/yr) and when crown surface area was 19000 cm^2 the difference was approximately 6 times larger (595 cm^3/yr) in favor of the high light levels (Figure 3-2). At low light transmittance levels (0.3), stem volume growth for white spruce with a crown surface area of 5000 cm^2 is predicted to be 40 cm^3/yr, while for bigger trees with ICSA of 19000 cm^2 calculated growth was almost five times greater

(212cm^3/yr). At high light transmittance levels (0.9), an ICSA of 5000 cm^2 would gain 151cm^3/yr, whereas an ICSA of 19000 cm^2 would gain more than five times more (807cm^3/yr) (Figure 3-2).

For the Hines Creek and Manning locations, the relationship between stem volume growth and the two independent variables: DIFN-M and ICSA is illustrated in Figure 3-3. White spruce saplings with low crown surface areas (10000cm^2) displayed a small difference (180cm^3/yr) between growth rates at high (0.9) and moderate (0.5) light levels, although the difference in growth rates between light levels of 0.5 and 0.9 was almost four times bigger (656cm^3/yr) for ICSA levels of 40000cm^2 and more than 6 times bigger (1107cm^3/yr) for ICSA levels of 70000cm^2 (Figure 3-3). At moderate light transmittance levels (0.5) stem volume growth for white spruce with crown surface area of 10000cm^2 is predicted to be 630cm^3/yr. For bigger trees with ICSA of 40000cm^2 calculated growth is almost four times bigger (2300cm^3/yr), whereas for trees with ICSA of 70000cm^2 calculated growth is more than six times bigger (3879cm^3/yr). At high light transmittance levels (0.9), an ICSA of 10000cm^2 would gain 810cm^3/yr. Bigger trees with an ICSA of 40000cm^2 would gain almost four times more (2956cm^3/yr), while trees with an ICSA of 70000cm^2 would gain more than six times extra growth (4986cm^3/yr) (Figure 3-3).

3.3.1.2 Top transmittance (DIFN-T)

For the Grande Prairie and Hines Creek and Manning locations, the relationship between stem volume growth and the two independent variables: DIFN-T and ICSA is illustrated in Figure 3-4 and Figure 3-5. SVI increased as both DIFN-T and ICSA increased (Figure 3-4 and Figure 3-5). However, when DIFN-T was used the R^2_{Adj} values were slightly lower (1% to 6%) than those found when DIFN-M was used (Figure 3-2, Figure 3-4, Figure 3-3, Figure 3-5). Comparison of white spruce stem growth rates estimated by applying these regression models (Figure 3-2 to Figure 3-5) showed that for a specific light level the rate was always substantially higher for Hines Creek and Manning than for Grande Prairie white spruce of the same size. The difference between these two locations also increases as the light levels increase (Table 3-5).

3.3.2 White spruce volume increment (SVI) as a function of the distance from the edge (PD) and initial tree size (ICSA)

For the Grande Prairie location, the relationship between SVI and the two independent variables: PD and ICSA, is illustrated in Figure 3-6 while for the Hines Creek and Manning locations the relationship is illustrated in Figure 3-7 . SVI increases as both PD and ICSA increase. However, because of the small scale differences, Figure 3-6 does not capture their amplitude.

3.3.3 Height allocation ratio (HAR) as a function of light levels (DIFN) and initial tree size (ICSA)

For the Manning location, the relationship between height allocation ratio and the two independent variables: DIFN-M and ICSA is illustrated in Figure 3-8. HAR decreased as either DIFN-M or ICSA increased.

3.3.4 Comparison of the developed models

The growth of white spruce grown next to young adjacent aspen stands at Hines Creek and Manning was found to be reasonably predicted by the following models:

$$SVI = 0.1554 * DIFN^{0.4276} * ICSA^{0.9341} \quad \text{(MODEL 1°)},$$

$$SVI = 0.1935 * PD^{0.1100} * ICSA^{0.9033} \quad \text{(MODEL 2)}.$$

The two models were also compared to see if they could be substituted for each other. However, this comparison is intended to show graphically how the two models behave, without any statistical testing. For the comparison, the relationship between light and proportional distance developed in chapter 2 was used. Here I use the models for one direction (Facing E) at Hines Creek and Manning. The equation to use is:

$$DIFN = 0.98e^{-e^{-\left(\frac{PD+0.24}{0.64}\right)}}.$$

Therefore MODEL 1° becomes:

$$SVI = 0.1554 * \left(0.9792e^{-e^{-\left(\frac{PD+0.2438}{0.6457}\right)}} \right)^{0.4276} * ICSA^{0.9341} \text{(MODEL 1)}.$$

Patterns presented by MODEL 1 and MODEL 2 are shown in Figure 3-9, and indicate both models follow a similar pattern. For smaller trees (ICSA=10000 cm^2) the two models are overlapping for the distances under two tree lengths from the edge. As the initial size increases (ICSA=40000 cm^2 and ICSA=70000 cm^2), the point where the two lines overlap is located at greater distance from the edge. However, the two lines show very close trends regardless of distance from edge.

3.4 Discussion

In terms of edge orientation influences on the growth of young conifers, previous studies provide contradictory results. Hansen *et al.* (1993) documented reduced growth of coniferous seedlings on north-facing edges, while Coates (2000) and Burton (2002) report little or no difference in seedling growth due to edge orientation. In my study, no significant difference in edge orientation occurred in these young stands on the growth of white spruce seedlings.

Having moderate tolerance to shade, white spruce shows flexibility to changes in light availability. Therefore, white spruce may develop strategies to take advantage of increasing light and avoid shade effects. Several studies show that diameter and height growth of white spruce seedlings increase as light levels increase (Eis 1967; Logan 1969; Klinka *et al.* 1992; Lieffers and Stadt 1994; Pacala *et al.*1994; Wright *et al.*1998; Coates and Burton 1999; Groot 1999; Jobidon 2000; Pritchard 2003). However, diameter growth is generally more affected by light availability than height growth (Eis 1967; Logan 1969; Wright *et al.*1998; Coates and Burton 1999; Groot 1999; Jobidon 2000). Results from this study showed poor relationships between diameter or height growth and the measured independent variables. However, the height allocation ratio as a measure of the proportion of stem volume allocated to height growth is best explained by an equation involving the initial seedling size and light levels. My results show that height allocation ratio declines as light levels and initial size increase. This is consistent with findings presented by Comeau *et al.* (2003).

Increasing volume growth has been associated with increases in available light levels in a number of studies (Eis 1967, Logan 1969; Comeau *et al.* 1993; Coates and Burton 1999; Jobidon 2000). The present study showed low proportion of the variation in volume growth could be explained using light (2 to 3%) or distance from the edge (1% to 6%) by themselves (Table 3-4). However, numerous authors found that seedling growth prediction is dependent on both light levels and the initial size of the tree (Hatch et al. 1975; Givnish 1988; Cole and Lorimer 1994; Biging and Dobbertin 1995; Choi et al. 2001, Claveau et al. 2002; Webster and Lorimer 2003; Pritchard 2003). In this respect the present study found that the stem volume growth of white spruce seedlings at Grande Prairie or at Hines Creek-Manning is best described by an equation involving both initial crown surface area and light levels at the tree crown. For trees growing at similar light levels, the potential growth of white spruce seedlings with greater crown surface area is greater than those with lower crown surface area. Growth of the same seedlings is also well predicted by an equation involving both initial crown surface area and the proportional distance from the aspen edge. The two prediction models show that the growth of white spruce increase as both initial seedling size and the light levels or the distance from the edge increase. Those results are similar to earlier studies (Hansen *et al.* 1993; Groot *et al.* 1997). Results comparing the two models suggest that they could be interchangeable; meaning that the distance from the edge could be used as a surrogate measurement for light levels.

My results indicate that the regression equations for growth of white spruce are different for the two locations. These results are consistent with findings of Pritchard (2003). Because of this difference in size of white spruce, equations for the two locations should be compared only for the same initial seedling size. An initial crown surface area of 12000 cm^2 was sampled at both sites and can therefore be used for this comparison. For spruce with a crown surface area of 12000 cm^2 my equations suggest that at low light levels, growth rates for spruce at Hines Creek-Manning are 4 times greater than those at Grande Prairie, while at high light levels the growth rates are only 2 times greater at Hines Creek-Manning than those at Grande Prairie. These differences might be due to microclimatic conditions or other factors (e.g. water, soil, nutrients, etc.) influencing growth. Seedlings growing in the open at the Grande Prairie site had a higher incidence of multiple tops, and dead buds, suggesting that frost and insect injury may be reducing the vigor of spruce at this site. In this regard, Jobidon (2000) suggests that previous competition may affect future growth rates by raising the magnitude of size inequality.

There are a number of possible reasons why mid-crown light levels are more strongly correlated with seedling growth rates than tree top measurements, as demonstrated in this study. Needles at the top of the seedlings may be spending substantial time under saturated light conditions (Cannell and Grace 1993). At the same time needles in the shade near the crown base are probably light limited and rely on brief periods with adequate light to support photosynthetic production (Cannell and Grace 1993). Since most of the leaf area index in young spruce is found near the middle of the crown, and based on low photosynthetic production of the top and base needles it might be suggested that the contribution to the white spruce seedlings growth is bigger for higher light levels that are available for use by midcrown of the seedlings rather than by the top of the seedlings.

3.5 Conclusions

The growth of white spruce is dependent on both light/distance from the edge and initial seedling crown surface area, and it increases as both of these independent variables increase. Stem volume growth is best predicted by initial tree size and the light levels available for use at the midcrown of seedlings, followed by distance from the edge and initial seedling size. More vigorous spruce with bigger crown surface area will show the greatest growth regardless of the light levels or the distance from edge. The best growth will occur when spruce seedlings have a large crown surface area and elevated light availability, which in turn, corresponds to distances further away from the edge.

Results from this study highlight the importance of local development of models relating volume growth of white spruce to light availability and initial crown size. A decisive factor for any model is its ability to estimate tree growth rates across environmental gradients and under variable stand composition (Claveau *et al.* 2002). This study suggests that predicting growth of white spruce seedlings in clusters should be based on either light levels or distance from the edge, and initial crown surface area. I suggest that for operational purposes distance from the edge could be used as a replacement measurement of light levels. However, further studies should be conducted to find additional parameters to account for site to site variation in the relationships observed here.

Results from this study indicate a small level of suppression of white spruce growing adjacent to young aspen stands which amount to less than 14% of trees growing three tree lengths from the aspen.

Table 3-1 Location and stand characteristics for the 13 plots located near Grande Prairie (GP), Hines Creek (HC), and Manning (M), Alberta. na = no adjacent aspen stand.

General location	Plot #	Latitude (N)	Longitude (W)	Elevation(m)	Azimuth (0°)	Spruce density(sph)	Adjacent aspen maximum height (m)				Adjacent aspen basal area(m^2/ha)				DIFN inside adjacent aspen at 1.0m height			
							N	S	E	W	N	S	E	W	N	S	E	W
GP	4003-4	54° 54'	118° 54'	762	6	1000	6	7	6	6.9	17	17	11	13	0.12-0.37	0.17-0.61	0.35-0.53	0.12-0.23
GP	4003-8	54° 54'	118° 54'	762	355	500	7	6	6	6.8	18	16	14	12	0.21-0.31	0.22-0.66	0.21-0.45	0.21-0.29
GP	4016-4	54° 54'	118° 54'	762	6	1000	5	5	5	3.8	8	7	6	3	0.1-0.3	0.18-0.57	0.1-0.21	0.33-0.46
GP	4016-8	54° 54'	118° 54'	762	6	500	6	na	6	6.4	13	na	13	21	0.11-0.18	na	0.16-0.26	0.15-0.48
GP	4024-4	54° 54'	118° 54'	762	8	1000	7	7	6	na	16	9	5	na	0.06-0.51	0.26-0.66	0.3-0.51	na
GP	4024-8	54° 54'	118° 54'	762	12	500	7	7	6	6.1	10	8	7	7	0.13-0.43	0.14-0.64	0.22-0.32	0.27-0.4
HC	1-01	56° 23'	118° 35'	800	25	1000	7	7	6	8.3	5	6	11	16	0.27-0.66	0.51-0.73	0.08-0.34	0.07-0.12
HC	1-07	56° 23'	118° 35'	800	27	500	7	6	8	7.2	6	9	14	14	0.26-0.58	0.15-0.6	0.06-0.14	0.07-0.11
HC	2-07	56° 23'	118° 35'	800	22	500	6	na	7	5.4	15	na	12	10	0.1-0.3	na	0.11-0.17	0.09-0.23
M	1-01	56° 41'	117° 72'	731	15	1000	7	na	6	5.6	13	na	7	5	0.17-0.26	na	0.19-0.69	0.41-0.62
M	1-07	56° 41'	117° 72'	731	18	500	5	na	na	5.7	13	na	na	9	0.08-0.36	na	na	0.1-0.28
M	2-01	56° 41'	117° 72'	731	14	1000	6	6	6	5.7	15	9	13	7	0.1-0.27	0.15-0.61	0.14-0.28	0.23-0.42
M	2-07	56° 41'	117° 72'	731	13	500	7	na	6	na	17	na	8	na	0.05-0.17	na	0.26-0.5	na

Table 3-2 Range of characteristics of white spruce sampled at the 3 installations (Grande Prairie, Hines Creek, Manning). Root collar diameter (RCD), height (H), and average crown radius (AVG CR) measured in May 2003. Light levels at the top (DIFN-T) and midcrown (DIFN-M) of white spruce seedlings measured in July 2003.

Instalation	Plot#	Age	RCD	Height	AVG CR	DIFN-M '03	DIFN-T '03
		years	mm	m	cm	%	%
GP	4003-4	10-13	11.9-40.6	0.47-1.85	7-48	0.332-0.950	0.494-1.000
GP	4003-8	10-13	16.0-44.0	0.63-1.78	17-49	0.284-0.988	0.586-0.994
GP	4016-4	10-13	7.3-29.0	0.27-1.11	8.3-38	0.629-0.992	0.694-0.997
GP	4016-8	10-13	13.9-39.0	0.65-1.56	19-46	0.441-0.983	0.673-0.998
GP	4024-4	10-13	11.7-41.2	0.33-1.31	10-48	0.519-0.989	0.622-0.995
GP	4024-8	10-13	10.4-40.6	0.43-1.47	11-49	0.377-0.991	0.495-1.00
HC	1-01	10-13	35.5-69.8	1.61-3.17	51-182	0.486-0.988	0.632-1.000
HC	1-07	10-13	30.4-73.0	1.35-3.51	43-91	0.468-0.999	0.530-0.999
HC	2-07	10-13	29.1-58.0	1.67-2.91	47-82	0.759-0.999	0.931-1.000
M	1-01	10-13	23.2-55.5	0.84-2.75	24-71	0.679-0.993	0.771-0.997
M	1-07	10-13	33.3-66.9	1.53-3.71	39-97	0.778-0.978	0.855-0.989
M	2-01	10-13	28.6-52.1	1.3-2.93	37-66	0.605-0.999	0.806-0.999
M	2-07	10-13	26.6-74.6	1.63-3.57	39-95	0.720-0.960	0.818-0.977

Table 3-3 R^2_{Adj} and RMSE values for regression models used to explain the variation in white spruce seedling growth. GP=Grande Prairie, HC=Hines Creek, M=Manning, SVI=stem volume increment, DI= diameter increment, HI=height increment, HI/SVI=height allocation ratio, DIFN=% transmittance midcrown,PD=proportional distance, ICSA=initial crown surface area, ICV= initial crown volume.

Installation	Variables		p model	n	R2	RMSE
	dependent	independent				
GP	SVI	DIFN,ICSA	<0.001	202	0.56	24469.8
	SVI	DIFN,ICV	<0.001	202	0.55	24559.5
	SVI	PD,ICSA	<0.001	202	0.49	27979.9
	HI/SVI	DIFN.ICSA	<0.001	202	0.55	0.00472
	DI	DIFN,ICSA	<0.001	202	0.13	0.0265
	HI	DIFN,ICSA	<0.001	202	0.10	89.44
HC	SVI	DIFN,ICSA	<0.001	108	0.54	1044134
	SVI	DIFN,ICV	<0.001	108	0.53	1064155
	SVI	PD,ICSA	<0.001	108	0.58	965841
	HI/SVI	DIFN,ICSA	<0.001	108	0.58	0.000018
	DI	DIFN,ICSA	<0.001	108	0.02	0.1024
	HI	DIFN,ICSA	<0.001	108	0.05	104.7
M	SVI	DIFN,ICSA	<0.001	117	0.72	678982
	SVI	DIFN,ICV	<0.001	117	0.71	697744
	SVI	PD,ICSA	<0.001	117	0.70	710333
	HI/SVI	DIFN,ICSA	<0.001	117	0.61	0.000041
	DI	DIFN,ICSA	<0.001	117	0.19	0.0701
	HI	DIFN,ICSA	<0.001	117	0.16	160.3
HC+M	SVI	DIFN,ICSA	<0.001	225	0.66	858779
	SVI	DIFN,ICV	<0.001	225	0.66	878659
	SVI	PD,ICSA	<0.001	225	0.68	829844
	DI	DIFN,ICSA	<0.001	225	0.07	0.0878
	HI	DIFN,ICSA	<0.001	225	0.12	133.9

Table 3-4 Selected models and parameter estimates for predicting stem volume increment-SVI (cm^3/yr) for white spruce. All models shown are significant ($p<0.0001$). DIFN=% transmittance, PD=proportional distance, ICSA=initial crown surface area GP=Grande Prairie, HC+M=Hines Creek and Manning.

Location	Model no.	Model: SVI=	n	MS res	Radj	a			b			c		
						Estimate	Lower 95%CI	Upper 95% CI	Estimate	Lower 95%CI	Upper 95% CI	Estimate	Lower 95%CI	Upper 95% CI
GP	1	a x DIFN^b	202	53774.3	0.03	314.1	243.8	384.3	0.9618	0.1492	1.7744			
	2	a x ICSA^b	202	27842.6	0.49	0.00347	-0.00372	0.0107	1.2337	1.0149	1.4525			
	3	a x ICSA^b x DIFN^c	202	24469.8	0.56	0.00396	-0.00358	0.0115	1.2538	1.0527	1.455	1.22	0.7348	1.7013
HC+M	4	a x DIFN^b	225	2498533	0.02	3268.6	2967.9	3569.2	0.8438	0.1367	1.5509			
	5	a x ICSA^b	225	878508	0.65	0.1262	-0.0116	0.264	0.9495	0.849	1.0499			
	6	a x ICSA^b x DIFN^c	225	858779	0.66	0.1554	-0.0131	0.324	0.9341	0.8346	1.0335	0.43	0.0736	0.7815
GP	7	a x PD^b	202	55321.3	0.01	246.6	213.2	280	-0.067	-0.213	0.0782			
	8	a x ICSA^b	202	27842.6	0.49	0.00347	-0.00372	0.0107	1.2337	1.0149	1.4525			
	9	a x ICSA^b x PD^c	202	27979.9	0.49	0.00346	-0.00373	0.0106	1.2339	1.0146	1.4532	0.01	-0.078	0.0898
HC+M	10	a x PD^b	225	2343283	0.08	2606.6	2333.3	2879.9	0.2401	0.1299	0.3503			
	11	a x ICSA^b	225	878508	0.65	0.1262	-0.0116	0.264	0.9495	0.849	1.0499			
	12	a x ICSA^b x PD^c	225	829844	0.67	0.1935	-0.0127	0.3998	0.9033	0.8044	1.0023	0.11	0.050	0.1703

Table 3-5 Comparison of stem volume growth rate for white spruce seedlings with an ICSA of 12000 cm^2 at low, moderate, and high light levels. The values are predicted by the equations presented in Figures 3-2 to 3-5. M=midcrown, T=top, DIFN=% transmittance, ICSA=initial crown surface area, GP=Grande Prairie, HC+M=Hines Creek and Manning.

ICSA= 12000cm^2	DIFN	Growth (cm^3/yr)	
		GP	HC+M
M	0.3	119	747
	0.6	277	862
	0.9	435	960
T	0.3	176	787
	0.6	282	870
	0.9	370	937

Table 3-6 Comparison of stem volume growth rate for white spruce seedlings with an ICSA of 12000 cm^2 at distances close and further away from the aspen edge. The values are predicted by the equations presented in Figures 3-6 and 3-7. PD=proportional distance, ICSA=initial crown surface area, GP=Grande Prairie, HC+M=Hines Creek and Manning.

ICSA= 12000cm^2	PD	Growth (cm^3/yr)	
		GP	HC+M
	0.5	372	868
	1.5	374	979
	2	375	1010

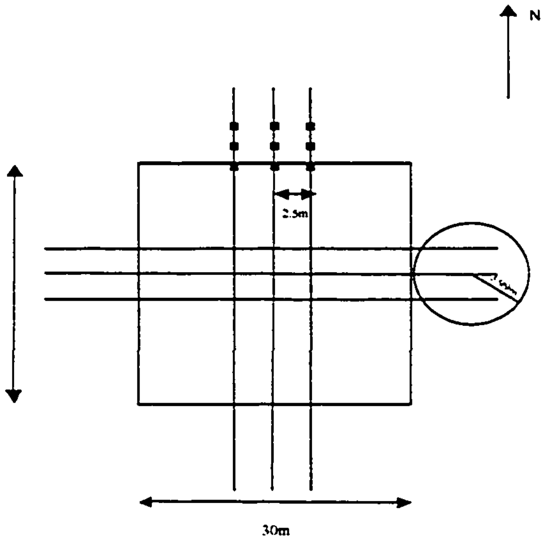


Figure 3-1 Diagram showing transects position within the plot. The squares on the N-side of the plot represent locations where light levels inside adjacent aspen stand were measured. The circle on E-side of the plot represent the location where aspen basal area and height were measured.

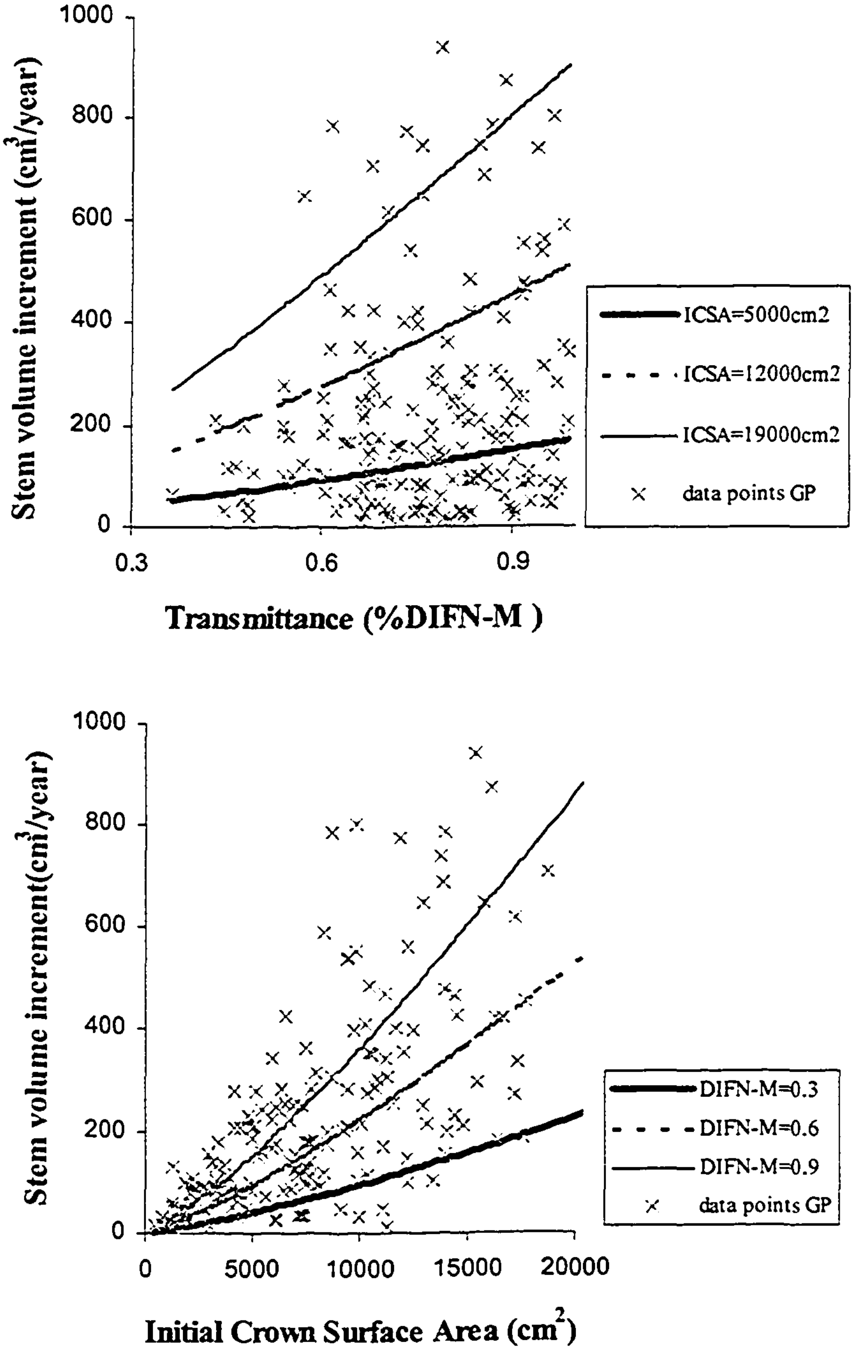


Figure 3-2 Relationship between stem volume increment and the two independent variables: transmittance at midcrown of the white spruce (DIFN-M) and initial crown surface area (ICSA) at Grande Prairie in 2003. The lines are described by the equation:

$SVI = 0.0039 * DIFN^{1.2180} * ICSA^{1.2538}$; $R^2_{Adj}=0.56, p<0.0001$, **RMSE=24469.18, n=202.**

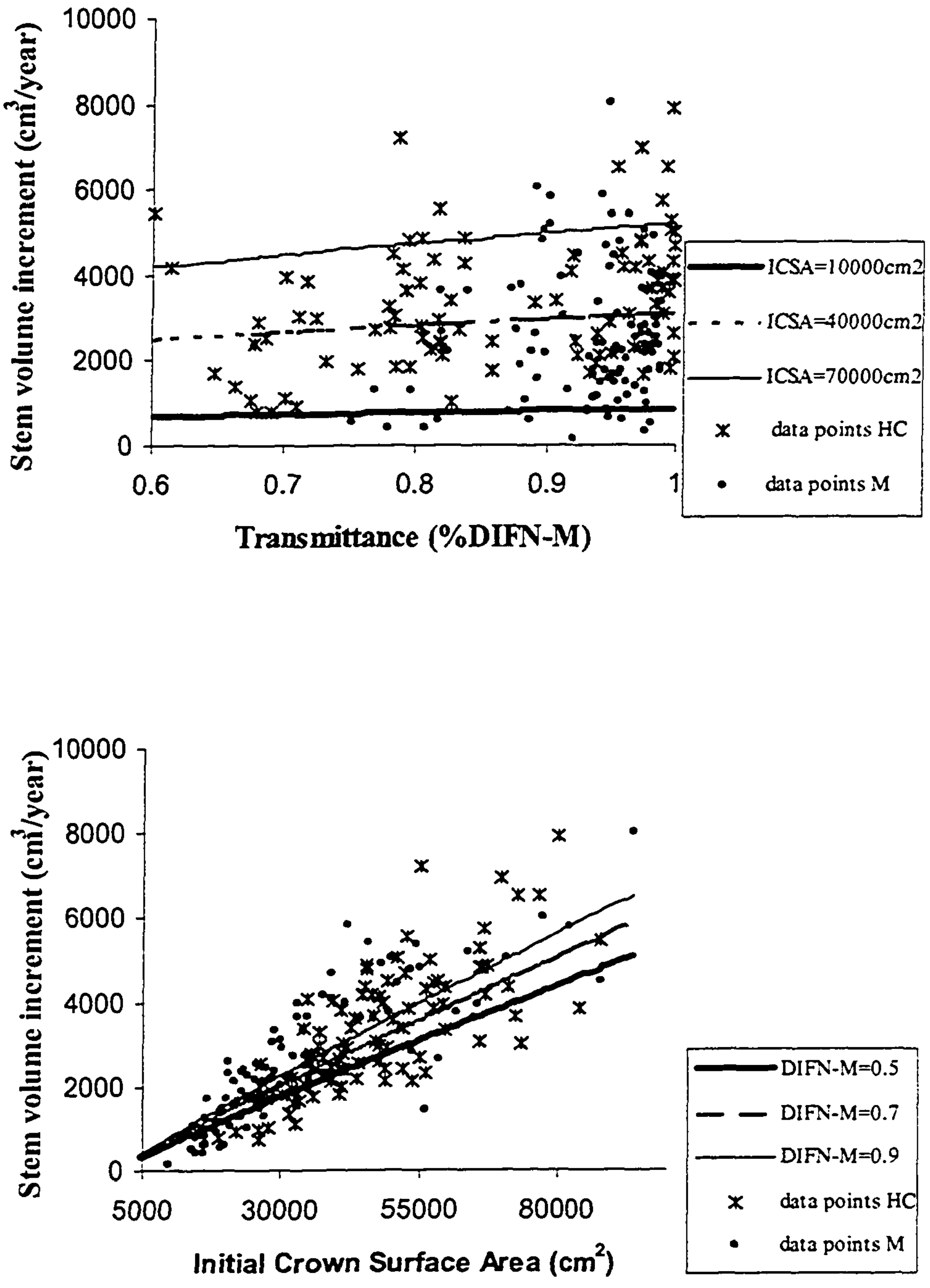
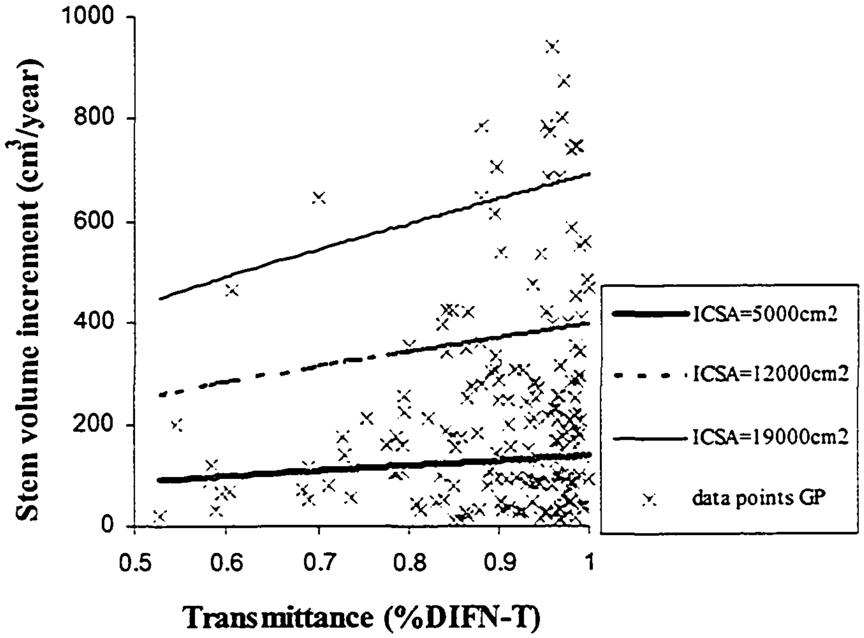


Figure 3-3 Relationship between stem volume increment and the two independent variables: transmittance at midcrown of the white spruce (DIFN-M) and initial crown surface area (ICSA) at Hines Creek and Manning in 2003. The lines are described by the equation:

$SVI = 0.1554 * DIFN^{0.4276} * ICSA^{0.9341}$; R^2_{Adj}=0.66, p<0.0001, RMSE=858 779, n=225.



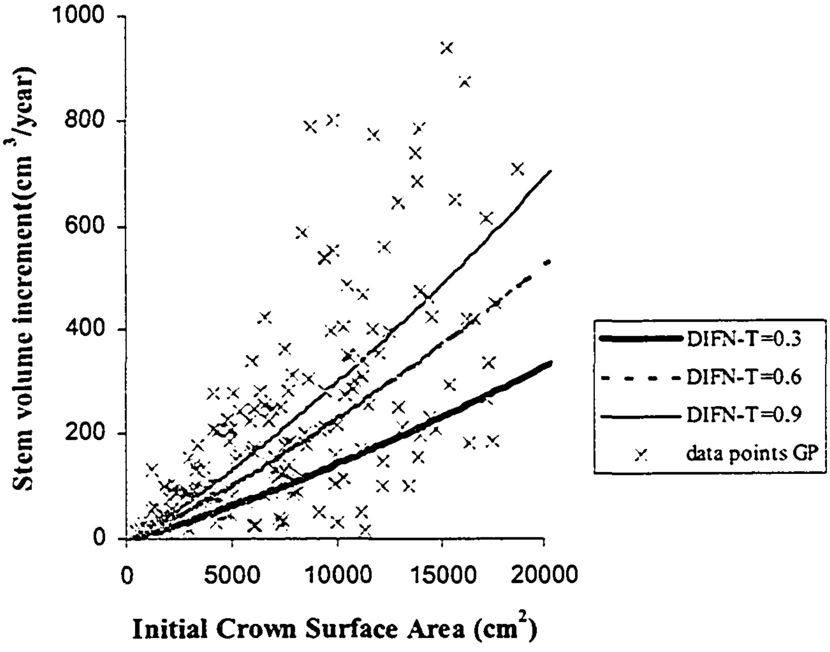


Figure 3-4 Relationship between stem volume increment and the two independent variables: transmittance at the top of the white spruce (DIFN-T) and initial crown surface area (ICSA) at Grande Prairie in 2003. The lines are described by the equation:

$SVI = 0.0047 * DIFN^{0.6770} * ICSA^{1.2062}$; R^2_{Adj}=0.50, p<0.0001, RMSE=27628.7, n=202.

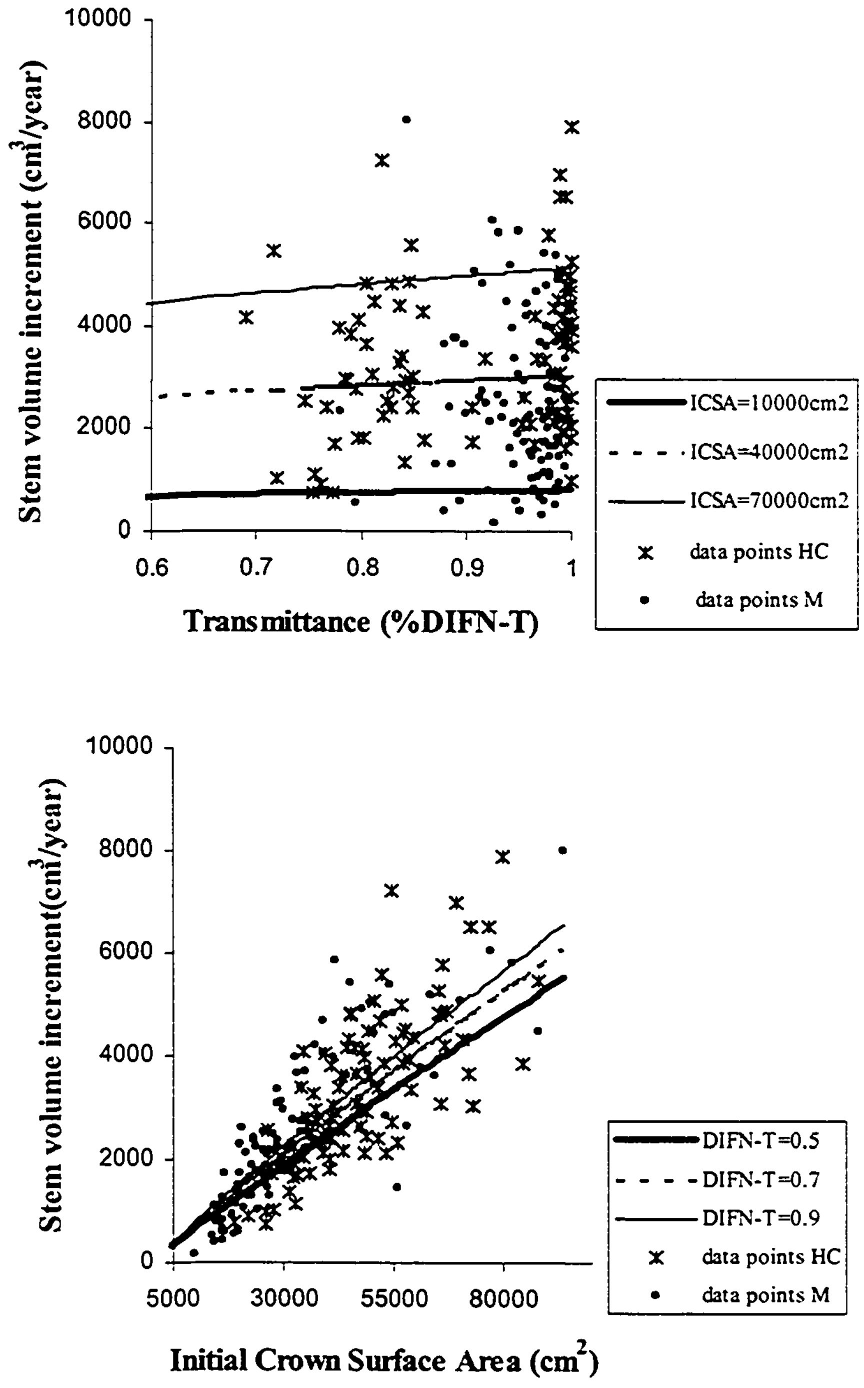


Figure 3-5 Relationship between stem volume increment and the two independent variables: transmittance at the top of the white spruce (DIFN-T) and initial crown surface area (ICSA) at Hines Creek and Manning in 2003. The lines are described by the equation:

$SVI = 0.1320 * DIFN^{0.2958} * ICSA^{0.9474}$; **R^2_{Adj}=0.657, p<0.0001, RMSE=874671, n=225.**

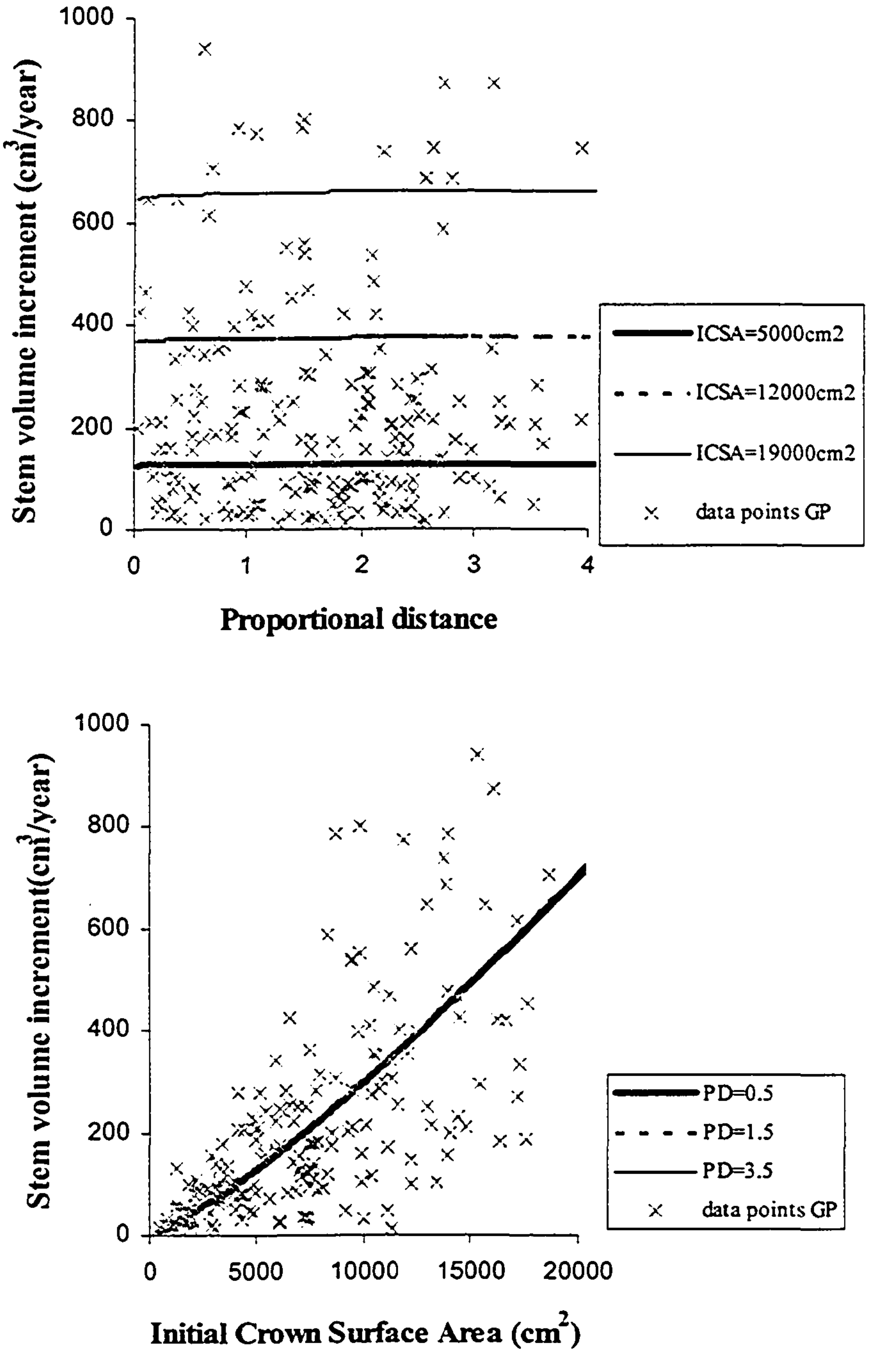


Figure 3-6 Relationship between stem volume increment and the two independent variables: proportional distance (PD) and initial crown surface area (ICSA) at Grande Prairie in 2003. The lines are described by the equation: $SVI = 0.0034 * PD^{0.0057} * ICSA^{1.2339}$; $R^2_{Adj}=0.493$, $p<0.0001$, RMSE=27979.9, n=202.

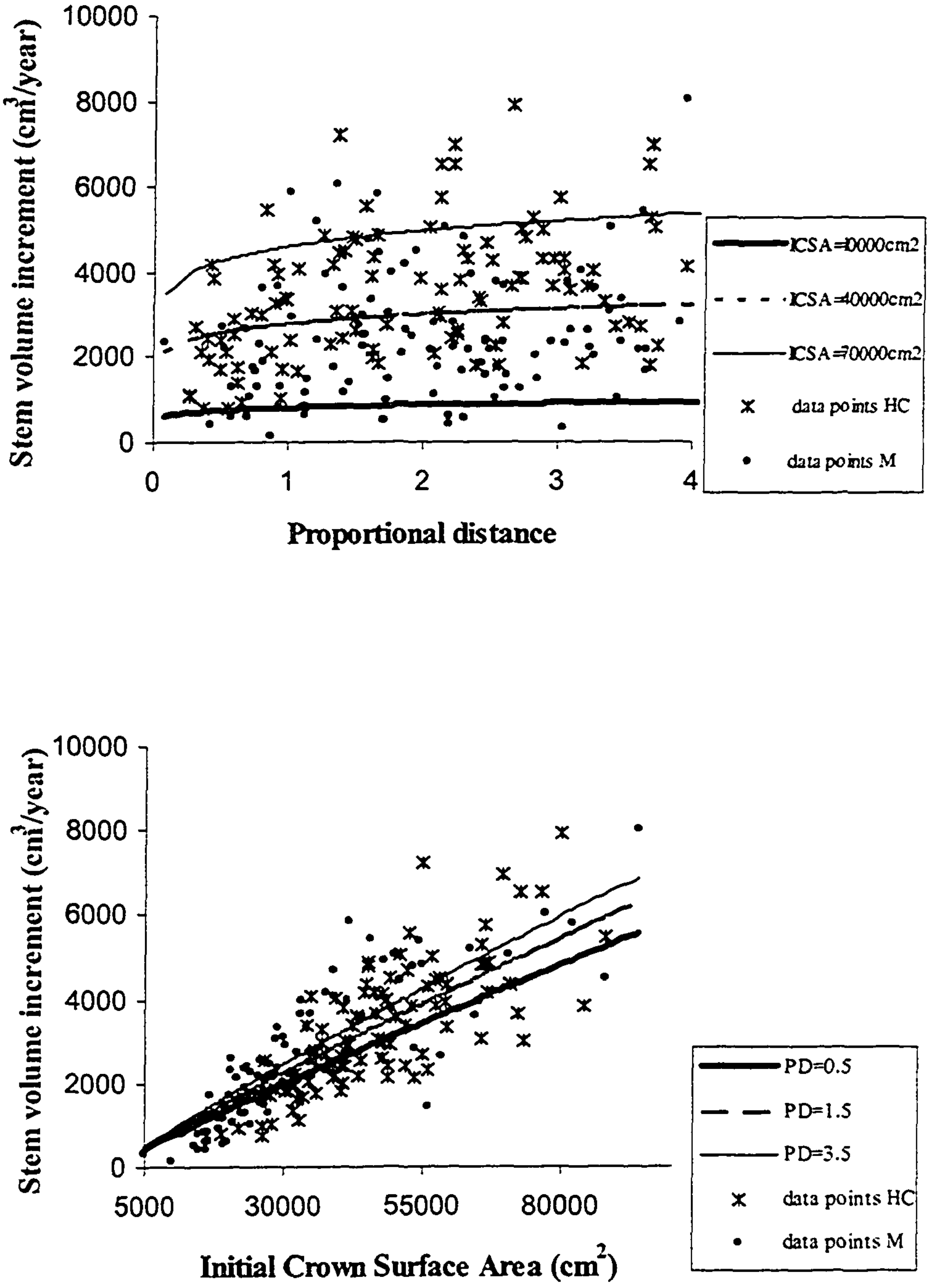


Figure 3-7 Relationship between stem volume increment and the two independent variables: proportional distance (PD) and initial crown surface area (ICSA) at Hines Creek and Manning in 2003. The lines are described by the equation: $SVI = 0.1935 * PD^{0.1100} * ICSA^{0.9033}$; $R^2_{Adj}=0.675$, $p<0.0001$, RMSE=829844, n=225.

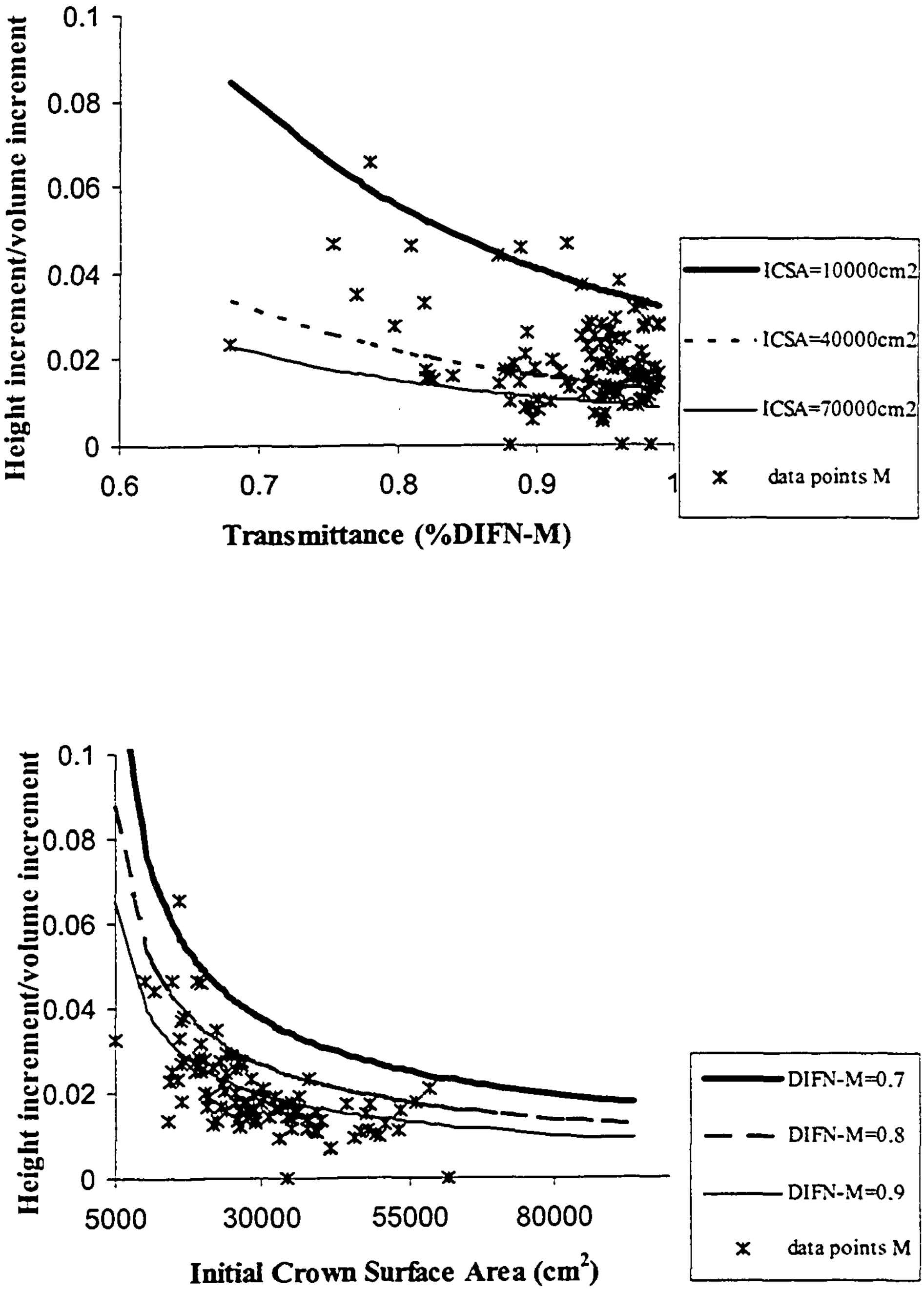


Figure 3-8 Relationship between height allocation ratio and the two independent variables: light levels (DIFN-M) and initial crown surface area (ICSA) at Manning in 2003. The lines are described by the equation: $HAR = 15.0594 * DIFN^{-0.6709} * ICSA^{-2.5773}$; **$R^2_{Adj}$=0.615, p<0.0001, RMSE=0.000041, n=117.**

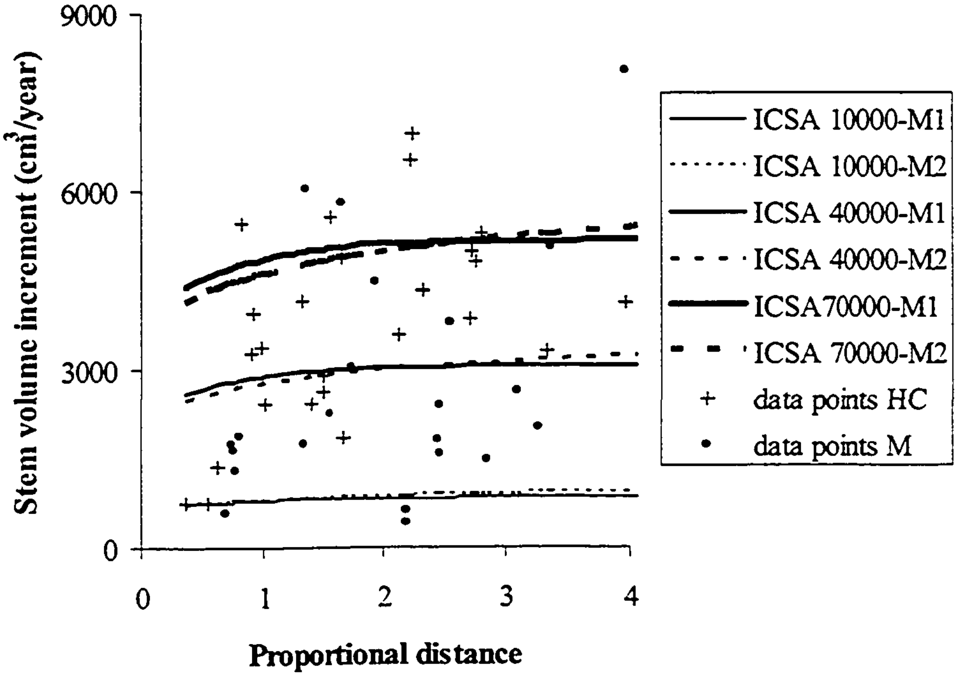


Figure 3-9 Graphic representation of the two models (M1 and M2) used to predict white spruce growth at Hines Creek and Manning. Data points represent the white spruce grown next to the east facing adjacent aspen stands. The continuous lines show the predicted white spruce growth for M1 ($SVI = 0.1554 * \left(0.9792 e^{-e^{-\left(\frac{PD+0.2438}{0.6457}\right)}} \right)^{0.4276} * ICSA^{0.9341}$) while the dashed ones show the predicted growth for M2 ($SVI = 0.1935 * PD^{0.1100} * ICSA^{0.9033}$) at 3 different initial seedling sizes. SVI=stem volume increment, ICSA=initial crown surface area, PD=proportional distance.

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Chapter 4. Implications of tending mixedwood stands using management of patches/clusters

4.1 Introduction

Results presented in Chapters 2 and 3 show:

1) Light levels (transmittance over the growing season) increases as one moves from a young aspen stand into a gap;

2) Air temperature increases across the boundary between young aspen stand and an adjacent gap;

3) Soil moisture increases once outside the aspen stand and then decreases with distance from the aspen stand;

4) The young adjacent aspen stand offers reduction in the duration of frost within one tree length from the boundary;

5) The growth of white spruce is nonlinearly related to light levels (or distance from the aspen stand) and initial tree size (i.e. ICSA or ICV).

Light is an important element of the microclimate in the opening adjacent to an aspen stand. Results presented in Chapter 2 show that light levels are related to the distance from the adjacent aspen stand for each cardinal direction. Light levels increase quickly moving away from the aspen edge, reaching a maximum at 1.5 tree lengths from the edge. Effects of edge orientation on the light gradients across the aspen edge are consistent with results presented for other studies (Berry 1964, Groot and Carslon 1996). Light levels increase more rapidly as one moves away from a south facing edge (60% of full sunlight reached at 0.1 tree lengths) than from a north facing edge (60% of full sunlight reached at 0.23 tree lengths). However, the potential negative impact of shade cast by the faster growing aspen into the adjacent patches of spruce does not extend very far from the edge (i.e. less than 0.3 tree lengths from a 5 to 7 m tall aspen stand) (Table 4-1).

Soil moisture is another important factor that can affect the growth of white spruce, at least during some growing seasons. During a dry summer, soil moisture stress appears to be reduced in the openings only up to 0.4 tree lengths from the aspen edge, while at greater distances the increase in LAI of grasses, forbs and shrubs, in combination with other factors, results in increased moisture. The frequency of growing season frost events also increases steadily as one moves from the edge of an aspen stand into the adjacent opening. However, no significant effect of edge orientation (facing north versus facing south) was documented. My results suggest that for these 5 to 7 m tall aspen stands, frost protection extends only to 1 tree length.

In terms of edge orientation influence on growth of young conifers, my results documented no significant difference. This is consistent with previous studies in central and northern B.C. (Coates 2000, Burton 2002). Variation in growth of white spruce can be explained as a non-linear relationship dependent on both light levels and initial size of the tree. This is consistent with several studies (Hatch et al. 1975; Givnish 1988; Cole and Lorimer 1994; Biging and Dobbertin 1995; Choi et al. 2001, Claveau et al. 2002; Webster and Lorimer 2003; Pritchard 2003). Growth of white spruce seedlings is also well predicted by a model involving both distance from the edge and initial seedling size as independent variables. This second model shows that spruce growth increases as distance from the edge and initial seedling size increase. This is supported by earlier studies by Hansen *et al.* (1993) and Groot *et al.* (1997). An important practical application emerging from comparing these two mentioned models is that they could be exchangeable; meaning that the distance from the edge could be used as a surrogate measurement for the light levels.

A third model investigating the height allocation ratio (HAR) as a measure of the proportion of stem volume allocated to height growth, shows that HAR declines as light levels and initial seedling size increase. This is consistent with the findings of Comeau *et al.* 2003.

An approach similar to the concept of "cluster planting" as described by Sutton (1974) is proposed as an option for managing mixedwood stands. The use of this approach involves growing aspen and white spruce in small to moderate sized patches. Tending costs may be reduced using this approach because only a designated percent of a mixedwood block is tended. Furthermore, foresters can use broadcast treatments (e.g. aerial herbicide) to optimize spruce growth in patches while leaving the remaining portions of the block untended. The portion of the stand left untreated is expected to develop as a deciduous or deciduous dominated stand while the treated area will be dominated by spruce. By keeping the size of spruce patches as small as possible, some of the nurse crop benefits of the adjacent aspen can occur within the treated "clusters". Therefore, in the design of a cluster planting or patch approach to manage a mixedwood stand the extent to which the adjacent aspen stand influences microclimate and growth of the spruce into the opening must be considered. These influences of the adjacent aspen stand change with variation in strip size and orientation. At the same time it is desirable to minimize effects of shading from the faster growing aspen on growth of spruce in the adjacent treated clusters.

Gaps or openings generate a range of light conditions which are influenced by size of the gap, location within the gap, latitude, and height and leaf area of the adjacent stand (Belsky and Canham 1994; Lieffers *et al.* 1999). The light level in the center of a gap increases with the diameter of the gap and decreases with the height of the trees at the edge of the gap (Lieffers *et al.*1999). In boreal forests the north-facing edge of the gap receives diffuse light from the northern hemisphere of the sky, while the south-facing edge of the opening will receive both diffuse and direct radiation (Canham *et al.* 1990). Shade cast by stand edges is influenced by stand height and orientation of the edge with maximum extent of shading being found for north- facing edges and the minimum extent being found on south-facing edges (Berry 1964; Matlack 1993; Comeau 1996; Groot *et al.* 1997). Berry (1964) documented that the light levels at the center of a 61 m long strip oriented north-south through a 15 m tall white spruce forest increased as strip width increased. The desirable size of patches/strips and their orientation should be determined taking into account their effects on microclimate and growth of the white spruce.

4.2 Strip width

Results presented in chapters 2 and 3 are used as a basis for recommendations regarding the desired orientation and width of strips. Figure 4-1 shows the relationship between strip width and the proportion of the strip that is above 60% of full sunlight. In the following calculations it is assumed that good spruce growth would be achieved by achieving levels of 60% of full sunlight over 60% of the width of the strip. For strips oriented north to south, light levels above 60% over 60% of the area of the strip will be reached for widths exceeding 1.2 lengths. When oriented east to west, strips would have to be 0.83 tree lengths wide to provide light levels above 60% over 60% of the area of the strip. These curves and relationships can be applied at any height above the ground as a proportion of stand height above the reference height. Orienting strips east to west provide greater area in excess to the 60% threshold than in the case when strips are oriented north to south (Figure 4-2). However, a greater portion of the north facing side of the east to west strips would be in shade compared to the facing south one (Figure 4-2).

The ideal strip width on leveled sites is expected to change with stand age due to different rates of height growth of aspen and white spruce. To estimate the width of strips which are required at different points in a stands life it is necessary to consider the height growth patterns of aspen and white spruce when growing on the same site. Aspen height growth from establishment was obtained from site index tables developed by Huang *et al.* (1997) for Alberta Land and Forest Service assuming 3 years for aspen to reach breast height. Height growth of planted white spruce was estimated using site index tables developed by Huang (1997) for Alberta Land and Forest Service assuming 8 years for spruce to reach breast height. For this purpose site index of 15m and 20m at 50 yrs is assumed for white spruce and aspen, respectively. Estimated height growth patterns are illustrated in Figure 4-3.

Temporal changes in strip widths required to reach 60% of full sunlight at heights equivalent to 50% and 100% of white spruce height over 60% of the area of the strip were calculated using these height growth estimates (Figure 4-3) and values presented in Figure 4-1 for strips oriented east to west. In this model differences between top height of the aspen and white spruce increase to maximum of 5.9 m at age 36 and then decline.

Strip widths required for 60% of the strip to receive more than 60% of full sunlight at the top of the spruce increase with age and reach a maximum of 4.3 m at age 36 (Figure 4-4). When we are interested in the light levels at the equivalent of 50% of spruce height (i.e. equivalent of white spruce midcrown) the required widths increase continuously with age but approach 10m at age 50 (Figure 4-4). To achieve light levels over 60% of full sunlight, at 50% of spruce height, over 60% of the strip requires strip widths of 7.5 m at age 30. Similarly to achieve light levels over 60% of full sunlight, at 50% of spruce height, over 70% of the strip requires strip widths of 9.8 m at age 30. These examples illustrate how results presented in this study can be used in combination with models of aspen and spruce height growth to determine strip widths required to achieve the desired light levels for white spruce growth. This is based on the assumption that the same relationship found in these 13 yr old stands apply in older stands (up to 40 to 50 yr of age).

4.3 Conclusions

One of the objectives of this study was to examine gradients of light, soil moisture and air temperature in relation to the distance and orientation from the edge of young aspen stands in Alberta. My study has documented relationships between light levels and distance and direction from the adjacent aspen stand edge, soil moisture and distance from the aspen edge, soil moisture and aspen and understory vegetation leaf area index, and air temperature and distance from the adjacent aspen stand. However, no difference in air temperature due to edge orientation was observed in my study.

The other objective of the study was to scrutinize the effects of proximity to the adjacent aspen stands, orientation, light levels and initial seedling size on growth of white spruce. Orientation of the adjacent aspen stand does not appear to significantly affect the growth of white spruce. Results from this study show a strong relationship between stem volume growth and light levels or distance from the edge and initial tree size. Similarly, good prediction of height allocation ratio (HAR) is given by both initial tree size and light levels. However, diameter or height growth alone are weakly correlated with light levels and initial tree size.

In summary, results from this study indicate that the optimal size of spruce patches or clusters is probably between 4 and 10 m at age 30 to 50 (Figure 4-4). While tending in young plantations might be applied to create strips 10 m wide, it may be desirable to keep the width of spruce clusters below 2 aspen tree lengths in order to provide frost protection, particularly during the first 5 years after establishment. Although, there is a low potential negative influence of the aspen stand on spruce patches in terms of casting shade, the lower light levels within 0.3 tree lengths from the edge may be compensated by the increases in soil moisture and protection against frost.

Results from this study indicate that in the study area the potential negative edge effects on tree growth are restricted to a narrow band along the most shaded side of the white spruce strip. At distances closer to the edge (i.e. lower light levels) the models suggest that volume growth will be reduced by only 1% to 14% from values observed at distances further away from the edge (i.e. higher light levels) (Table 4-2). In addition to reductions in stem volume, reduced light levels may result in slower growth of crown volume and ultimately lead to an increasing reduction of the total volume growth. Despite the fact that similar trends in growth response would be anticipated at other similar sites, models presented in this thesis will need validation before being applied to other stands. Another suggestion to be drawn from my results is that control of the understory vegetation may be necessary to reduce competition for water when the openings are larger than 0.8 tree lengths in width. Combining vegetation control with shelter from adjacent aspen stands may provide the optimum environment for growth of white spruce. However, further studies are required to verify this suggestion.

Further research involving additional replication and older stands is required to determine the broader application of the results from this study. Studies to support the suggestion that the light levels measured at the midcrown are a better predictor than that measured at the top of the seedlings are also needed. Influence of the variation in the understory vegetation and other factors (such as edge orientation influence, variation in root abundance and distribution) on soil moisture stress is also of interest. Effect of duration of cold temperature events on the degree of frost injury should be examined in greater detail as well. Investigation of spatial influence of aspen patches on soil nutrients should also be conducted.

Table 4-1 Effect of edge orientation on estimated proportional distances (PD) from the stand edge to reach 60% of full sunlight (based on model shown in Figures 2-3 to 2-6 and Table 2-3). PD= Proportional distance.

Light levels of 60% of full sunlight for	PD
N-facing edge	0.23
S-facing edge	0.1
E-facing edge	0.23
W-facing edge	0.25

Table 4-2 Reduction in volume growth (RVG[1]) of seedlings growing close to the adjacent aspen stand. GP=Grande Prairie, HC+M=Hines Creek and Manning, ICSA=initial crown surface area, PD=proportional distance. The model used to predict the volume growth is the one discussed in Figure 3-5 and 3-6.

Location	ICSA (cm^2)	Volume growth (cm^3yr^{-1}) at:		Reduction in volume groth(%) RVG=100*(1-V0.5/V2.0)
		PD=0.5	PD=2.0	
GP	5000	126.33	127.33	1%
	19000	656	661.23	1%
HC+M	10000	735.81	857.02	14%
	70000	4267.21	4970.2	14%

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[1] The reduction in growth volume was calculated as a proportion of the predicted volume growth of seedlings positioned at 0.5 tree lengths from the edge (V0.5) reported to that of those located at 2 tree lengths from the edge (V2.0)

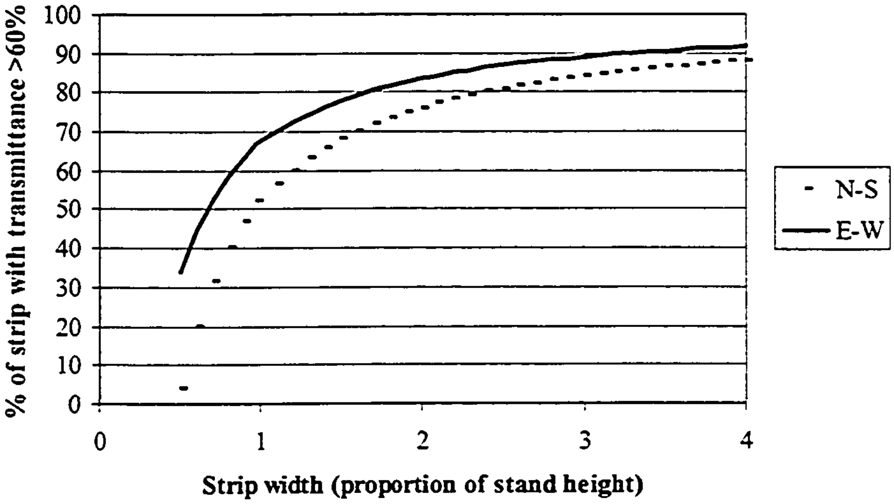

Figure 4-1 Relationship between percent of the strip with light levels above 60% and strip width (expressed as a proportion of height of the adjacent stand above the measurement point).

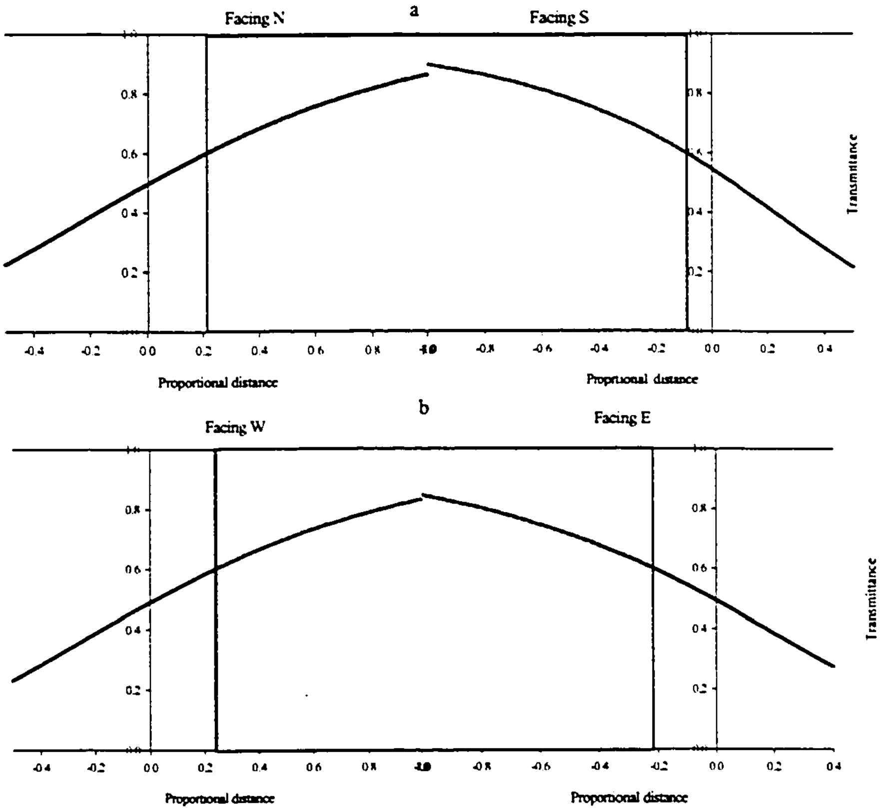

Figure 4-2 Area with light levels exceeding 60% of full sunlight for a 2 tree length wide strip oriented east to west (a), and north to south (b). The regression lines are those presented in Figures 2-3 to 2-6. The highlighted area represents the area with light levels above 60% of full sunlight and was graphed based on data presented in Table 4-1.

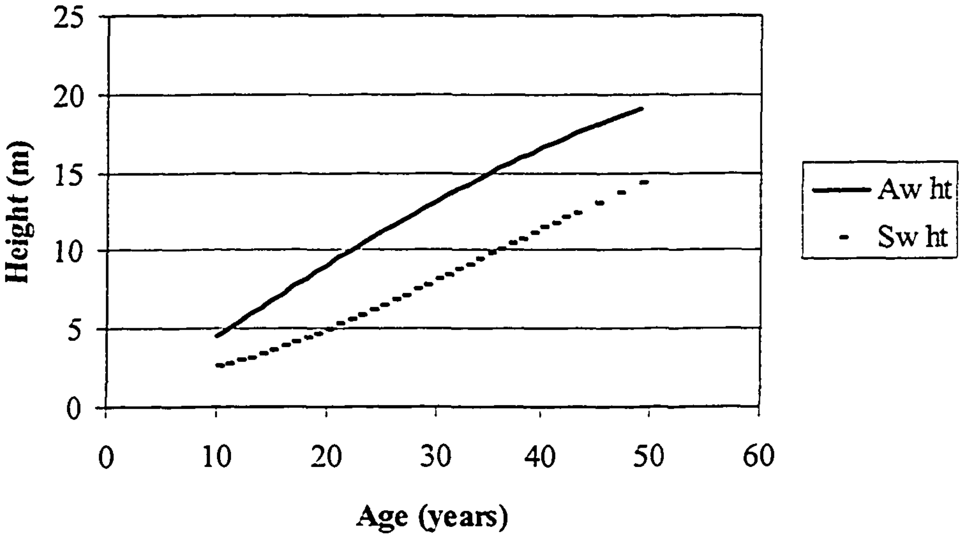

Figure 4-3 Estimated height growth patterns of trembling aspen (Aw) and white spruce (Sw), calculated using site index tables from Alberta Land and Forest Service (Huang *et al.* 1997; Huang 1997). (Aspen SI_{50}=20; spruce SI_{50}=15).

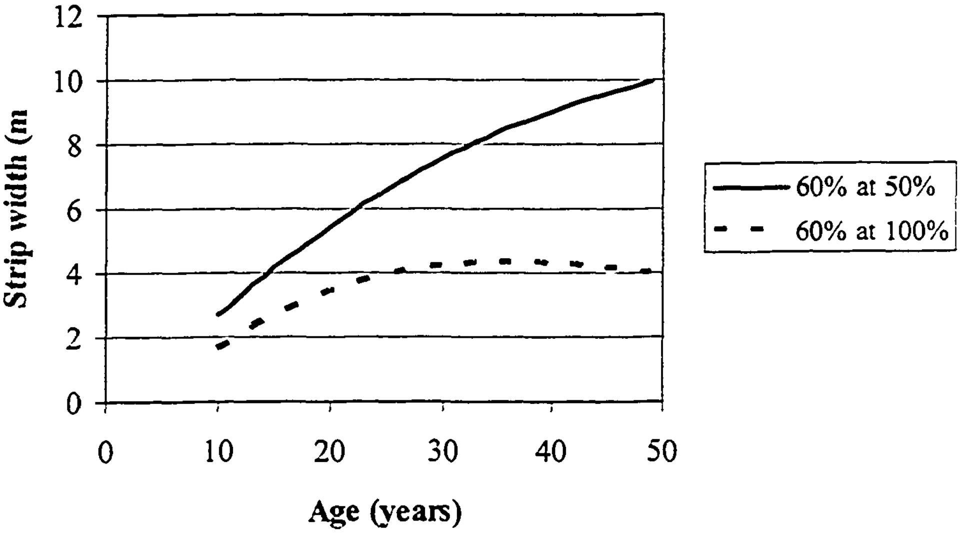

Figure 4-4 Estimated changes in strip width required to reach 60% of full sunlight at 50%, and 100% of spruce height over 60% of the area of the strip (strip oriented east to west). Estimates are based on widths described in Figure 4-1 and models of spruce and aspen height growth shown in Figure 4-2.

4.4 References

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APPENDIX 1

Abies balsamea(L.) Mill. Balsam fir

Alnus crispa (Ait.) Pursh Green alder

Betula papyrifera Marsh. White birch

Calamagrostis canadensis (Michx.) Beauv. Calamagrostis

Epilobium angustifolium L. Fireweed

Picea glauca [Moench] Voss White spruce

Picea mariana (Mill.) B.S.P. Black spruce

Populus balsamifera L Balsam poplar

Rosa acicularis (Lindl.) Brickly rose

Salix spp. Willow