EFFECT OF ASPEN (POPULUS TREMULOIDES (MICHX.)) OVERSTORY REMOVAL ON PRODUCTIVITY OF AN ASPEN AND WHITE SPRUCE (PICEA GLAUCA (MOENCH) VOSS) MIXEDWOOD STAND

by

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B.Sc. Simon Fraser University, 1991

THESIS SUBMITTED IN PARTIAL FULFULLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE
in
NATURAL RESOURCES MANAGEMENT

THE UNIVERSITY OF NORTHERN BRITISH COLUMBIA

July 2002

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Degree: Master of Science

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ABSTRACT

Growth response by white spruce (*Picea glauca* (Moench) Voss) and trembling aspen (*Populus tremuloides* Michx.) to canopy opening was assessed on ten treatments where the forest overstory canopy had been geometrically thinned to meet target cover percents. Thinning was by cutting and girdling at approximate increments of 10% from 0% -100% overstory removals. Objectives were to investigate the response of understory competition, growth of spruce and aspen, and changes in available nitrogen to changes in light environment. The study site is located 100 kilometers northwest of Fort St. John (56°51′30″ N, 121°25′ W) in a 45 year old mixedwood stand in the Boreal White and Black Spruce Biogeoclimatic zone of British Columbia. Growth was measured for two years after treatment. Growth continued for both aspen and spruce in mixed stands and it was heavily dependent on light availability. There was a significant difference in spruce diameter growth among treatments (sites) and between years. Spruce root collar growth was not significant among sites, but was between years. Aspen diameter growth was significantly different among sites and between years. Age and growth prior to release treatment appears to be a controlling factor for the subsequent growth response of spruce.

The potential for using an aspen overstory to control competition from bluejoint grass (*Calamagrostis canadensis* (Michx.)) and fireweed (*Epilobium angustifolium* L) was investigated. Both bluejoint grass and fireweed increased in percent ground cover as light radiation increased. Where aspen has developed an overstory canopy, it may be possible to control competing vegetation to create favorable environmental conditions for spruce re-establishment, growth, and release while encouraging a sustainable mixedwood stand.

The ability of aspen to recycle plant available nitrogen (NH_4^+, NO_3^-) was investigated. Plant available nitrogen was maintained in all sites throughout the growing season. Following thinning nitrogen did not differ among sites, but it was significantly different between years. In 2001, there was a significant difference in nitrogen availability among sites in spring, summer and fall.

Cooperative management of mixed spruce and aspen stands may insure a well balanced and productive stand is achievable in the future. Mixed spruce and aspen stands provide for two pass harvesting systems, which reduce competition from serious competitors and increase soil nutrient cycling. There may be long-term advantages to managing mixed stand to reduce pest management problems and to allow a more diverse forest. Diversification of the forests may aid in the long-term economic return from our forests. However, we need to gain a greater understanding of these stands by conducting long-term studies designed to answer the questions of diversity, pest management and economic returns.

PREFACE

Some decisions had to be made in the presentation of this thesis.

Chapters 2 through 5, representing the experimental results of the investigation, have been prepared as manuscripts for submission to recognized journals. At the time of thesis submission one has been sent, two are in the editorial stage. It was decided to present these chapters in the form in which they would be submitted to the respective journals, except that all references cited appear in a single section at the end of the thesis and acknowledgements are contained in a general statement at the beginning. Page numbers are sequential throughout the thesis to avoid confusion with journal pagination of individual chapters.

Invariably, because of the need for internal consistency of each chapter, some reiteration of points will be evident in the introduction and discussion sections of experimental chapters. The introduction (Chapter 1), which sets the framework for the investigation, and the final conclusions (Chapter 9), which assesses the contribution of the investigation in that context, is designed to tie together the separate parts.

The experimental work was carried out entirely by the candidate (C. Maundrell) under the guidance of the supervisor of the M.Sc. program (C. Hawkins). Manuscripts are written by the candidate with appropriate discussion between the candidate and supervisor. The submissions of papers thus have joint authorship with the candidate as the senior author and the supervisor as the junior author in each case.

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ACKNOWLEDGEMENT

I wish to thank my wife, Glynnis and her daughter Heather for their support and patience and Professor Chris Hawkins for taking me on when I was in limbo, and my graduate studies committee for their patience.

I would also like to thank the Faculty of Forestry at UNBC for supporting me through very difficult financial times. Without support of the Faculty and the Dean this would have been an even greater endeavor.

A number of people helped collect data, they are Kajsa Beck, Dan Turner, Neil Carnell, and Kelly Hambleton. I would also like to thank Jennifer Lange, Anne Cole and Cleo Lajzerowicz for helping in the lab.

Partial funding for the project came from Professor Chris Hawkins (FRBC) Slocan Mixedwood Chair, and Adlard Environmental Ltd.

1. INTRODUCTION

Introduction

Aspen (*Populus tremuloides* Michx.) and white spruce (*Picea glauca* (Moench) Voss) are two of the most widely distributed tree species in North America. Aspen distribution is transcontinental, ranging across the Boreal forests from Newfoundland to Alaska (Farrar 1995; Peterson and Peterson 1995). The south-north range of aspen extends from northern Mexico to the Mackenzie River delta (Peterson and Peterson 1995). White spruce ranges from the northern tree limit in the Northwest Territories and Alaska, southward along the Rocky Mountain to Montana (Brayshaw 1996; Nienstaedt and Zazada 1990; Farrar 1995) and eastward to Newfoundland (Nienstaedt and Zazada 1990; Farrar 1995). Throughout their ranges the two tree species can be found in association with each other as well as other species. Where aspen and spruce ranges overlap it is not uncommon to find the two species in the same stand.

Aspen is the most widely distributed deciduous tree in British Columbia (Pojar and Meidinger 1991). In British Columbia, aspen is a leading species in 16 timber supply areas east of the Coast Mountain Range (Peterson and Peterson 1995). Although white spruce exists throughout the interior of British Columbia, it doesn't begin to dominate the forest cover until it reaches the northern half of the province (Pojar and Meidinger 1991). The Sub-Boreal Pine Spruce, Sub-Boreal Spruce and the Boreal White and Black Spruce are (Pojar and Meidinger 1991) the three biogeoclimatic zones in British Columbia most dominated by white spruce and its naturally occurring hybirds. Aspen is also a dominant species in these biogeoclimatic zones. Throughout these biogeoclimatic zones aspen and spruce can be found in pure stands or in association with each other. The associations encountered in these stands are mixedwoods by all definitions.

Mixedwood Definition

The definition of a mixedwood is still being discussed. Mixedwood stands for some are defined as mixtures of coniferous and deciduous species (Comeau 1996). For others, a mixedwood of two or more species meets the definition. Comeau (1996) defined mixedwood stands as being comprised of mixtures of different species. Corns (1988) defined Boreal mixedwoods as stands of deciduous and coniferous species growing together, but with neither species representing more than 75 % of the stand. Hostin and Titus (1996) defined mixedwood stands where a minimum 80% of the basal area of the stand was in combination of white spruce and aspen, and each species represented a minimum of 20 % of the stand. In the case of Boreal forests of Canada, mixedwood forests can be defined as combinations of aspen, white spruce, lodgepole pine (*Pinus contorta* var. *latifolia* Dougl.), Jack pine (*Pinus banksiana* Dougl.), black spruce (*Picea marianna* (Mill.) B. S. P.), black cottonwood (*Populus balsamifera* L.), paper birch (*Betula papyerifera* Marsh.) and tamarack (*Larix laricina* (Du Roi) K. Koch). In northern British Columbia, white spruce, aspen, cottonwood and birch dominate the deciduous coniferous mixedwoods of the Sub Boreal Pine Spruce, Sub-Boreal Spruce, and the Boreal White and Black Spruce biogeoclimatic zones (Brayshaw 1978, Krajina et al. 1982, Massie et al 1994).

The Boreal mixedwood forests contain some of the most productive forested landbase in Canada, the Pacific coast being the exception (Corns 1988). Many of these Boreal stands comprise a substantial component of regenerating spruce at varying stages of development. Spruce may be in the understory regeneration layer (< 1.3 m tall), or they may be in the sapling (1.3 m – 7.4 cm dbh) or pole layer (7.5 – 12.5 cm dbh) (Anonymous 1995a) or in combinations.

Location of seed source, forest floor environment, and type of stand initiating disturbance will affect the composition of understory regeneration (Kelty 1996). For the most part, mixedwood stands of the Boreal forest are initiated following large-scale disturbance by fire (Anonymous, 1995b). Following such a disturbance, it is not uncommon for forests to be composites of overstory aspen and understory spruce. The abundance of mixedwood where understory spruce is present is unknown. However, a great amount of interest has surfaced regarding the facilitation and protection of this understory for future generations (Brace 1991).

Rationale

Development of oriented strand board (OSB) and improvements in pulp technology has greatly increased the harvest of Boreal mixedwood and deciduous forests (Lieffers and Beck 1994). As a result, there is increasing interest in the mixedwood forests of Northern British Columbia. Aspen is rapidly becoming an important crop tree throughout Northeast British Columbia and Northwest Alberta. Aspen utilization has increased substantially since the construction of Louisiana Pacific pulp and OSB mills in Dawson Creek and Cheywynd, British Columbia, and the Diashowa pulp mill near Peace River Alberta. Most recently, Slocan Forest Products and Louisiana Pacific have announced major investments in the Peace Region of British Columbia. The primary focus is to secure fiber for OSB, pulp, and particleboard plants. The majority of fiber used to fuel these plants will come from new Forest Licensees issued by the Ministry of Forests in 1999. Given the amount of mixedwood forests in Northeast BC, the Fort St. John and Fort Nelson Forest Districts will be the next areas in British Columbia to intensively manage their mixedwood forests.

Total area of the Fort St. John TSA is 4 673 000 hectares (ha). Approximately 1 194 000 ha of this area is suitable for timber harvest. One third, or 424 391 hectares of the suitable timber harvesting area is in one form or another of mixedwood successional stage (D. Cheyne)[1]. The most recent timber supply analysis of the Fort St. John Forest District suggests an annual deciduous harvest of 915 000m3/yr can be maintained for twenty years before being incrementally reduced over thirty years to a sustainable harvest of 658 000m3/yr (Anonymous 1995c). Due to the large amount of deciduous volume, and proportion in mixedwood stands, there is a need to gain a better understanding of mixedwood dynamics. This would allow resource managers to develop management strategies, and maintain mixedwood ecosystems that maximize the long-term productivity of these stands. In the past, the aspen component of the Boreal mixedwood had been treated as a weed (Peterson et al. 1989) and management emphasis has been on the softwood component (Kabzems and Lousier 1992). Currently industry manages for either conifers, or deciduous species, but seldom both, Fort Nelson Timber Supply Area (TSA), possibly, being the exception.

In British Columbia, no standards are set to ensure harvested mixedwood stands are returned to mixedwood forests. Monocultures are the norm rather than the exception (Smith 1986). They were the preferred system of management in the past. This approach has been further entrenched through implementation of stocking standards that ensure monocultures are returned as the preferred forest, either coniferous or deciduous. The growing interest in mixedwood management has forced the government to begin developing Interim Mixedwood Stocking Guidelines (Anonymous 2001a) for British Columbia Boreal Mixedwood Forests.

In addition to increases in productivity attributed to more efficient utilization of the landbase (Peterson et al. 1989), mixedwoods may benefit forest management practices by other means. Managing for mixedwoods may reduce mature wood volume losses attributed to biotic (Volney 1988; Needham et al. 1999) and abiotic (Mann and Lieffers 1996) agents and encourage alternative management methods. Furthermore, mixedwood management can advance site productivity via improved nutrient availability (Mellilo et al. 1982; McClaugherty et al 1985; and Van Cleve et al. 1991). Total wood fiber production can be increased (Kelty 1992) while at the same time, improving market stability through innovation (Russell 1988) and diversity of products produced.

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[1] Pers. comm. June 1997, Fiberco Pulp, Taylor, BC.

The greatest limitation to developing mixedwood management strategies in British Columbia is lack of a knowledge base. Mixedwood systems provide an opportunity to develop new and efficient timber management approaches, while taking advantage of natural succession rather than fighting the dynamics of natural succession. The traditional approach to forest management has been targeted towards harvesting conifers. Most of the industrial infrastructure in British Columbia is designed to process softwood lumber products or by-products (Peterson et al. 1989). Increasing mixedwood ecosystem knowledge may help to overcome ecological and institutional obstacles inherit to existing mixedwood management.

Succession

Fire has been the most influential component of the natural successional dynamics in Boreal forests (Massie et al 1994). However, unlike traditional succession with unidirectional change of species composition over time, the Boreal forest relies on fire to initiate and sustain change (Rowe 1961). Within the first few years following fire, endemic species (aspen, spruce, pine) of the Boreal mixedwood forests become established. Spruce, lodgepole pine, and Douglas fir (*Pseudotsuga menziesii* var. *glauca* (Mirbel) Franco) are the most common conifers associated with aspen in Western Canada (Peterson and Peterson 1995). In many cases, composition and dynamics of the regenerated stand is closely related to the pre-fire stand (Peterson 1988).

In comparison to conifers, aspen is a rapidly growing short-lived tree (Fowells 1965; Perala 1990). It can be free to grow after the first year of a sucker-producing event

(Peterson and Peterson 1995). The development of a mixedwood forest is dependent on a number of variables: 1) site characteristics; 2) availability of a suitable seed source; and 3) the degree of disturbance (Delong 1991; Kabzems and Lousier 1992). In the new stand, spruce establishes at similar stocking densities as the original stand through seeding from adjacent stands or germination of seed in the humus (Peterson 1988).

Aspen propagation in the new stand is strongly dependent on pre-disturbance composition (Peterson 1988). Seed and root suckering dynamics are influenced by past stand dynamics. Aspen, an early successional species, becomes established immediately following disturbance (i.e. logging or fire) because of rapid root suckering (Sakai et al. 1985). The clonal nature of aspen allows this species to take advantage of water and nutrients unavailable to plants with less cooperative root systems (Squiers and Klosterman 1981) by increasing the root surface area available for nutrient uptake. Plants with root systems expressing greater volume of subsurface area, such as aspen clones, have a competitive advantage over individual stems (spruce). The understory vegetation (spruce regeneration) must compete directly with overstory tree root systems. Small individuals with restricted root systems are at a distinct disadvantage (Squires and Klosterman 1981). Therefore, aspen is a stronger competitor for soil nutrients and water availability due to root cooperation and tree physiology that allow it to establish a dominant vertical position in the forest canopy.

In the first 10 years following disturbance, aspen height growth far exceeds that of white spruce (Peterson 1988). Rapid growth and crown definition may have a profound impact on the timing and ability of white spruce to contribute volume increment during stand development (Peterson 1988). High establishment densities of aspen soon thin naturally and with the slowing of growth at maturity (approximately age 80 years) the aspen canopy begins to break-up creating gaps (Kneeshaw and Bergeron 1998) that can be filled by understory spruce or further aspen regeneration. For newly formed gaps to be invaded by aspen, the gap must be large enough to allow sufficient heat and light penetration to the forest floor to promote suckering. In a study in Minnesota, Huffman et al. (1999) reported a decrease in aspen sucking takes place as residual aspen stem density increased. They suggested for every 1% increase in percent residual canopy there can be an expected 210 aspen stems/ha decrease in aspen regeneration. They also reported that in older stands with larger gaps, maintenance of intolerant species occurs. It has been shown that gap formation in young aspen dominated stands results in encroachment by more shade tolerant conifers. Kneeshaw and Bergeron (1998) showed shade tolerant balsam fir was the most prevalent species to occupy newly formed gaps in a study in northwestern Quebec.

As early successional aspen stands develop into mature stands and spruce begin to emerge, a number of profound changes occur. A change from deciduous to needle dominated litter allows development of a complete moss ground cover (Van Cleve et al. 1991). Reduced soil temperature, rates of decomposition, and increased organic matter accumulation are the result of declining litter quality associated with increased needle litter (Van Cleve et al. 1991). Nutrient availability, uptake and return in white spruce litter are 20 to 40% of rates in early successional deciduous stands (Van Cleve et al.

1991). Productivity declines as coniferous litter dominates the forest floor (Van Cleve et al. 1991) and as aspen falls out of the canopy, gap dynamics creates niche opportunities for white spruce. A combination of increasing spruce and less decomposable litter shifts the nutrient dynamics of the forest floor and plant available nutrients.

From a productive perspective, there may well be advantages gained by managing a stand with more than one species. Niche theory states that two species occupying the same site must partition resources if they are to coexist (Kelty 1992). Differential use of resources suggests that species in a mixture utilize resources more efficiently leading to greater productivity (Kelty 1992). Greater productivity of mixed-species stands over monocultures can be realized when there are differences in height, form, photosynthetic efficiency, duration or photosynthetic activity, timing of foliage production, phenology, root structure and rooting depth (Kelty 1992). For aspen-spruce mixtures, a combination of two or more of these factors, such as timing of foliage production and root structure, may be sufficient to secure niche differentiation. The silvics of aspen and spruce are dissimilar enough to allow spruce to fill gaps in the stand as early succession aspen self thins. Aspen does not replace itself under its' own canopy because it is intolerant to lower light levels experienced in these stands. However, spruce has a lower light threshold and can survive in these conditions (Coates et al. 1994).

Other factors contributing to the development of mixedwoods is the differential photosynthesis period of the two species (Constable and Lieffers 1996). Spruce in the understory of an aspen overstory utilize spring and fall leaf-off periods for photosynthesis, while aspen is disadvantaged (Constable and Lieffers 1996). During these times, spruce will be increasing diameter and root biomass. Such species dynamics allows differential stand development creating greater niche exploitation opportunities.

Brown and Parker (1994) reported early aspen successional stages had the lowest level of light transmittance. By age fifty light transmittance has attained its' highest level, followed by a slight decrease and leveling through successive stages of a tulip-poplar (*Liriodendron tulipifera* L.) association. Similarly, in the Boreal forest of Alberta, Constable and Lieffers (1996) reported light transmittance decreased with increasing coniferous component. They also reported that as aspen stands aged there was an increase in available light to the understory. Shade tolerant species typically cast deeper shadows than shade intolerant species because of their deep crowns (Canham and Burbank 1994). This suggests coniferous crowns are responsible for greater attenuation as successional stages develop and include greater numbers of shade tolerant conifers such as spruce.

Light, photosynthesis and growth

As aspen stands mature and thin, with no further recruitment, a greater proportion of solar radiation is transmitted through the canopy and is available for photosynthesis and growth to understory vegetation (Brown and Parker 1994). However, in old mixedwood (deciduous/coniferous) stands, less light is available than in pure aspen stands, due to greater obstruction from conifer crowns (Constable and Lieffers 1996). With respect to age and structure, Ross et al. (1986) reported older white spruce dominated stands filtered less light than younger Jack pine (*Pinus banksiana* Lamb.) stands in the Boreal forests of Alberta. The larger size of the spruce bole (diameter) and latitude may have played a role in this finding. An increase in latitude is directly related to decrease solar angle when the reference point is the equator. At northern latitudes larger boles intercept a greater proportion of radiate light as the angle to the sun increases from the equator.

In deciduous forests with expansion of leaves in spring, attenuation of direct and diffuse radiation increases. In the spring with rising solar elevations and increasing angle, continued leafout is offset and radiation in the forest continues to increase (Hutchison and Matt 1977). By the summer solstice, leaf expansion has reduced the effect of increasing solar angle and radiation begins to decline. Decline continues until autumn leaf drop when there is a short increase of radiation followed by decline until the winter solstice (Hutchison and Matt 1977).

Aspen canopies are relatively diffuse (Squiers and Klosterman 1981) allowing species of moderate shade tolerance sufficient light for germination and growth, although not maximum growth. Canham et al. (1994) reported light transmission through aspen canopies to be greater than through coniferous canopies. Ross et al. (1986) reported no difference in the spectra of light under evergreen needle-leaf and deciduous broadleaf canopies in the Boreal forest of Alberta. However, they did report seasonal variation of light attenuation between forest habitat types. Aspen dominated forests observed a rapid decline in light attenuation in May and June, and then remained stable until August. In the fall light levels increased to values similar to that observed in May. A possible explanation for this observation is the increase in canopy cover that takes place as aspen leaf out occurs in May and June and leaf abscission in August and September.

Coniferous dominated mixedwood stands have declining light levels from the early season high. No increase was observed in September (Ross et al. 1986). Following the summer solstice, reduced solar angle, persistence of coniferous and deciduous leaves combine to reduce the amount of radiant light available until deciduous leaf drop. After deciduous leaf drop, coniferous needles and decreasing solar angle combine to reduce solar radiation to the forest understory (Hutchison and Matt 1977).

In general, species that cast deeper shadows (such as spruce) are more shade tolerant (Canham and Burbank 1994) further suggesting spruce tolerance to understory growing conditions. Although high densities of aspen appear to be detrimental to spruce growth and regeneration, low densities that allow greater light penetration, and inflict less mechanical damage, may not be detrimental. Low density aspen overstories may allow infiltration of sufficient light for maximum spruce growth (Vezina and Pech 1964). Constable and Lieffers (1996) reported photosynthetic active radiation (PAR) average values of 110 $\mu mol \cdot m^{-2} \cdot s^{-1}$ were available to seedlings on a sunny summer day in a young (10-21 year old) aspen stands. This relates to approximately 6% of full sunlight. PAR values on the forest floor of the stand were constantly greater than the compensation point reported by Delong (1991) and higher than that found in old mixedwood stands (Constable and Lieffers 1996).

Availability of light may be one of the most important elements ensuring continued growth of understory vegetation. The amount of solar radiation transmitted through a forest canopy increased with decreasing crown closure (Vezina and Pech 1964). In the aspen-spruce ecosystem, where aspen tends to out-compete spruce during stand initiation and immature stages of development, competition for light is the most likely explanation for spatial patterns of mid-tolerant species saplings (Roberts 1992) such as white spruce. Lees (1966); Steneker (1967); Yang (1989); and Yang and Bella (1994), have all reported improved growth and yield of white spruce with thinning of overstory aspen. Improvement of the light environment is one factor resulting in increased growth. However, in all reported cases thinning was done as a total release by physical removal of aspen. Girdling is another method of thinning aspen. However, there is no information on timing of release or time for death to occur for aspen. Girdling could be used for incremental thinning or to delay and mitigate the impact of overstory removal.

No reports have assessed the release performance of understory spruce to incremental thinning by cutting aspen at root collar or girdling at breast height. Such thinning treatments can improvement the light environment and other factors that may contribute to increased spruce growth, such as a favorable change to nutrient and water availability. However, altering of the light environment can have a negative effect on spruce growth by promoting understory vegetation growth. Understory vegetation can rapidly overtop shorter spruce (<1.3 m) (Lieffers and Stadt 1994), reducing available resources and inflicting mechanical damage.

Intensity, quality and duration (photoperiod) are the three most important characteristics of light (Coates et al. 1994). Photosynthesis increases with light intensity until the saturation point is reached, after which no further photosynthetic gain is realized. For white spruce seedlings the leaf saturation point is reached at 25 to 50 % of full sunlight on a clear day (Coates et al. 1994), but whole tree saturation may be higher. In field studies near Prince George and Williams Lake, white spruce reached maximum photosynthesis at photosynthetic photon flux densities of 400 and 600 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ respectively (Lister and Binder 1985). This corresponds to between 20 and 30 % full sunlight (Lister and Binder 1985), full light being 2000 to 2100 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$

There are no available data as to the exact light saturation point for white spruce in British Columbia (Coates et al. 1994). Saturation point of white spruce may be dependent on stand and tree age, and environmental conditions. Logan (1969) and Eis (1970) studied the affect of light intensity on growth of tree seedlings. Both reported young spruce seedlings can maintain optimal height growth at or near 50% of full sunlight, while for trees older than 10 years, growth is best at or near full sunlight. At light levels

of 13 and 25 %, spruce growth was significantly less than that of full sunlight (Logan 1969). This may be due to self-shading on leaves lower in the tree canopy. A deep canopy requires the tree-top be exposed to near full sunlight to allow maintenance and photosynthesis of leaves at lower canopy positions due to shading of lower canopy leaves.

The light compensation point is the irradiance at which canopy photosynthesis is balanced by energy loss of respiration (Salisbury and Ross 1985). Theoretically, at this point there is neither net gain nor net loss in plant mass. The compensation point of white spruce seedling has been identified by Binder et al. (1987) to be between 2 and 6 % of full sunlight. However, Place (1955) and Eis (1970) reported naturally regenerated spruce seedlings dying within 2-3 years if light levels were below 12 and 15 % of full sunlight respectively.

Deciduous dominated overstories (mostly aspen) were reported by Lieffers and Stadt (1994) to transmit between 14 an 40 % full sunlight depending on stand density. For a young (10 year old) stand on a good site at 14 % overstory cover, the density would be approximately 20 000 stems/ha, while a stand at 30 years may be only 5 000 stems/ha (Constable and Lieffers 1996). The amount of light transmitted through the canopy would increase with increasing age, as reported by Constable and Lieffers (1996).

In addition to improving light environment for white spruce, thinning aspen may increase growth of all understory vegetation. Increasing the growth of understory competitors of white spruce seedlings could complicate the goal of increasing growth of understory conifers. Lieffers and Stadt (1994) showed that growth of bluejoint grass (*Calamagrostis canadensis* Michx.) and fireweed (*Epilobium angustifolium* L.) (both strong competitors of spruce seedlings in the Boreal White and Black Spruce Biogeoclimatic Zone) decreased with decreasing light transmission. At 40% light transmission both species were greatly reduced compared with open-grown. At 10% light transmission both species were virtually eliminated from the site. White spruce increased growth from 5 to 25 cm with an increase of light from 10 to 40% respectively (Lieffers and Stadt 1994). They found that at 40 % sunlight transmittance, height growth was nearly equal to that of full sunlight transmittance. Coates et al. (1994) predicted optimal height growth could be achieved at 50 % full sunlight. Based on these results, light regimes of 40 to 50 % of full sunlight may be a reasonable target for growth of mixedwood understories of immature spruce.

Diameter growth may also be stimulated by improved light conditions. Diameter is more responsive than height to changes in carbon allocation (Gordon and Larson 1968, Rangnekar and Forward 1973) as would be the case with changes in ambient light. Groot (1999) found diameter growth of white spruce increased with vegetation control in clear-cuts and shelterwood situations. He also found diameter and height to be poorest with intact overstories, and that height growth was not always responsive to vegetation control in clear-cuts, but diameter was. The poor growth experienced under intact canopies was presumed to be a function of low light levels.

Direct sunlight can also improve nutrient availability by increasing soil temperatures. Differences in soil temperature, depth, and moisture content strongly influence microbial activity and nutrient dynamics in forest soils (Nadelhoffer et al. 1991). The activity of soil organisms is influenced by changes in temperature. Biochemical processes are positively related to temperature increases up to an optimal temperature for transformation (Pritchett 1979). As sunlight warms the soil, the biochemical activity increases until an optimal temperature is attained, and nutrient cycling is correspondingly affected. Increasing the temperature beyond optimal results in denaturing of proteins and enzymes responsible for biochemical decomposition, reducing decomposition rates.

Mixedwood soils

Mineralization, nitrification and nutrient cycling

Species established in environments where soil nutrients are plentiful allocate more to aboveground components, have greater growth rates, and higher rates of nutrient uptake than species from low nutrient environments (Hobbie 1992).

Greater amounts of annual leaf litter produced by deciduous species may result in higher litter quality due to higher solubility. McClaugherty et al. (1985) tested acid solubility of aspen and hemlock and found aspen litter was richer in acid soluble compounds than hemlock. They showed litters' high in acid soluble compounds decomposed more rapidly than litters low in acid soluble compounds. Pastor et al. (1984) reported deciduous species such as oak, sugar maple, basswood, and ash, dominated sites of greater mineralization rates and higher litter quality. Pastor et al. (1984) and McClaugherty et al. (1985) showed conifer species dominated sites of low mineralization rates and these sites had lower litter quality. McClaugherty et al. (1985) reported nitrification rates in the top 15 cm of mineral soil were nearly double (Table 1) in aspen stands than in white pine. The greater amount and higher quality of deciduous litter results in faster turnover rates as attested by higher decomposition rates of deciduous litter when compared with coniferous (Van Cleve et al. 1985).

Van Cleve et al. (1985) studied nutrient supply and uptake in interior Alaska. They found black spruce and flood plain white spruce forest floors supplied one-fifth the amount of N taken-up by seedlings growing in birch, aspen or poplar forest floors.

Mineralization and nitrification rates are related to C:N ratios and soil characteristics (Pastor et al. 1984). Greater clay content, cation exchange capacity (CEC) and moisture content has been shown to increase nitrogen mineralization potential (Herlihy 1979). Herlihy (1979) studied three loamy soil types in Ireland and reported minerlization to be consistently higher with greater clay and CEC during the growing season between early April and September.

Pastor et al. (1984) reported high C:N and C:P ratio as indicative of species, which produce low quality litter and dominate sites of low nitrogen mineralization. Conversely, species producing high quality litter dominate sites of greater productivity. However, soil constituents, moisture and temperature are also factors affecting mineralization rates. The number of years to replace N, P, and K in the Boreal forest decreases with increasing deciduous component (Table 2) following full-tree harvest (Navratil et al. 1991). This suggests deciduous stands may increase standing nutrient pools and cycling rates sooner after harvest than would conifer stands.

Table 1. Stand nutrient characteristics on Blackhawk Island, south-central Wisconsin (modified from McCaugherty et al. (1985) Table 1).

	STAND TYPE				
	Aspen	Sugar Maple	White oak	White pine	Hemlock
Aboveground					
Production(mg/ha/yr)	7.5	9.5	8.4	6.4	5.3
Litterfall (mg/ha/yr)	3.4	3.8	3.0	3.1	1.3
Forest floor mass(mg/ha/yr)	5.3	5.1	5.5	10	8.4
Forest floor type	mull	mull	mor	mor	mor
Net nitrogen mineralization	(top 15 cm)				
Kg/ha/yr	48	125	84	52	29
% in mineral soil	53	30	11	18	0
Nitrification (top 15 cm)					
Kg/ha/yr	54	126	4	26	6
% in mineral soil	56	31	0	13	0

Table 2. Years to replace N, P, and K following full-tree harvest on mixedwood sites in the Boreal forest (modified from Navratil et al. (1991) Table 2).

Mixedwood stand	N	P	K
25% S – 75 % H*	19	15	17
50 % S – 50 % H	20	16	19
75 % S – 25 % H	21	19	22

*S= softwood, H = hardwood.

Alban (1982) suggested nutrient and organic matter in the forest floor reflected the composition of litter. Pure stands of white spruce may increase soil acidification (Brand et al. 1986) reducing nutrient cycling potential by retaining compounds in organic forms. Pastor et al. (1984) showed a decrease in pH for coniferous stands when compared to deciduous stands. This trend was also reflected in the quality of the litter. Stands with higher deciduous components typically produced higher quality litter and occupied sites of greater mineralization (Pastor et al. 1984).

The quality of organic matter is determined by its' chemical composition. The content of lignin in leaf litter, specific to tree species, will be an important factor influencing the rate of decomposition (Melillo et al. 1982; Meentemeyer 1978). Lignin concentration is an excellent index used to predict decomposition rates and weight loss in forest litter (Meentemeyer 1978). Lignin interferes with the enzymatic degradation of cellulose and carbohydrates (Melillo et al. 1982), the primary components of leaf litter. Melillo et al. (1982) reported that high levels of lignin in leaf litter may slow the decomposition rate. Conifers generally have higher lignin content in leaf litter than deciduous species, leading to slower decomposition rates. McClaugherty et al. (1985) showed that aspen produced more litter ($mg \cdot ha^{-1} \cdot yr^{-1}$) per year than white pine or hemlock and that mineralization and nitrification rates were greater in the aspen stand (Table 1). This may be due to lower lignin content in aspen litter, or possibly the greater litter leaf-fall. In general for a Boreal site, the rate of elemental uptake and recycling of litter declines in the order aspen > birch > white spruce > black spruce (Van Cleve et al. 1991). Prescott et al. (2000) found aspen decomposition to be greater than white spruce in the first year, but after five years decomposition was nearly equal. Forest type showed only marginal differences in decomposition rate. Litters of both spruce and aspen decomposed slightly more rapidly in aspen and mixedwood forests than spruce forests. This study found no difference in decomposition rates of mixtures in buried bags on all forest types.

Alban (1982) reported soils under conifer stands accumulated higher amounts of organic matter, total N, and exchangeable cations than aspen stands. In coniferous forests, nutrients become stored in organic form in the forest floor (Kelty 1992). Van Cleve et al. (1991) and Kelty (1992) suggested the greater accumulation of organic material in coniferous forests was due to cooler soil temperatures and lower litter quality.
Pastor et al. (1984) reported net above ground production, nutrient return to litter, and litter quality were highly related to mineralization. However, nitrogen losses due to denitrification were not measured and this may account for some of the mineralization rate. They reported ecosystems with litter of high C:N or C:P ratios and low mineralization exhibited high soil organic content. The high carbon ratios may be directly related to lignin content, reducing decomposition rates. Ecosystems of low mineralization resulted in lower above ground production (Pastor et al. 1984) and greater organic content.

Density and species composition of a stand will influence the amount of litter produced. Litterfall may be influenced by such factors as dominant tree species, stages of developmental and tree density (Tietema and Beier 1995). Lodhiyal et al. (1994) reported retranslocation, (the rate of nutrient movement out of senescing leaves) in individual trees during senescence of *Populus* species at different densities were similar for nitrogen, phosphorus and potassium. Net primary production was greater in high density stands than low density stands, possibly due to nutrient mass movement induced by higher stand biomass. Also, net nutrient uptake by vegetation in high density stands was greater than low density stands due to higher nutrient concentrations resulting from greater nutrient returns through litterfall. Accordingly, nutrient availability in high density stands was greater due in part to larger amounts of litterfall that would in turn replace nutrient relative to the litterfall. Litter returned to the soil is greater and more efficient nutrient utilization occurs (Lodhiyal et al. 1994) that can be measured by increases in biomass.

Growth and Yield in Mixedwoods

Effect of thinning on understory release

There are five possible reasons to conduct a thinning operation. All five are designed to maximize the economic return of the stand (Smith 1986) by improving its quality. Because economic return is the principal objective of the thinning operation, the yield of the stand becomes secondary. However, thinning must ensure sufficient volume is retained to meet economic sustainability at rotation. According to Smith (1986) advantages that can be attained by thinning are as follows:

1. Salvage of anticipated losses of merchantable volume due to mortality;
2. Increased value of remaining stems by increased and improved diameter growth;
3. Incremental income and control of growing stock;
4. Improvement of tree quality; and
5. Improved stand composition, reduced risk of damage and prepare for establishment of new crops.

There are a number of different thinning strategies. The most common approach to thinning involves removing stems in distinct crown classes. Thinning from below, or low thinning, involves thinning stems out of the stand that are in lower crown classes and generally co-dominants and suppressed stages of development. Thinning from above, or crown thinning removes trees from the upper crown classes. Selective thinning targets specific crown classes. This may include but is not limited to dominant thinning, in which dominant trees are removed in order to stimulate growth of trees in the lower crown classes. Geometric thinning removes stems systematically at a predetermined evenly spaced pattern throughout the stand. Regardless of the way thinning is conducted, the purpose is to create growing space for the benefit of the leave trees (Smith 1986).

Most research conducted to date dealing with release has been directed at either partial (Tucker and Emmingham 1977, Ferguson and Adams 1980, McCaughey and Schmidt 1982, Brandeis et al. 2001) or complete removal of overstory competition (Lees 1966, Steneker 1967, Yang 1991, Yang and Bella 1994). Partial overstory removal, or incremental thinning can target distinct quantities of overstory for removal.

In the Intermountain Western United States height and annual ring growth of understory Engelmann spruce (*Picea engelmannii* Parry) and subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) increased following partial and complete overstory removal on three sites (McCaughey and Schmidt 1982; Helms and Standiford 1985). Helms and Standiford (1985) found the factors responsible for increased growth to be pre-release diameter growth rate, diameter at time of treatment, and pre-release height. They concluded, the response of individual trees to release depends on their physiological ability to function in a changed micro-environment, which may be predetermined before release. Aspen-spruce stands may show similar results from partial cutting or overstory thinning, but this has yet to be determined.

Previous work by Lees, (1966, 1970); Steneker, (1967); Yang (1989, 1991); and Yang and Bella (1994) investigated growth release of understory spruce following total removal of overstory aspen. In general, studies from the Canadian Prairies found that spruce regeneration responded positively to removal of overstory aspen (Table 3).
These data indicate spruce stem growth may increase by 50 % following complete removal of overstory.

Table 3. Mean annual diameter (cm) and height (m) increment for treated and control stems by age classes over a five-year period (modified from Lees (1966) Table 4).

	diameter increment		% increase	height increment		% increase
age class	treated	control		treated	control	
20-30	0.69	0.46*	50	0.29	0.19*	52
30-40	0.66	0.41*	61	0.36	0.25*	44
40-50	0.89	0.56*	59	0.42	0.27*	56
50-60	1.07	0.71*	51	0.43	0.38	13
60-70	0.99	0.64*	55	0.41	0.26*	65

Data converted from standard to metric. * differences significant at $p = 0.05$.

Potential difficulties in promoting mixedwood management are associated with protecting the subordinate components during harvest of the overstory (Navratil et al. 1991). In the aspen-spruce mixedwood forests, aspen forms the upper canopy in young and intermediate age stands, suppressing the understory spruce and subjecting them to mechanical damage by wind and from falling dead aspen stems. (Steneker 1967; Lees 1966; Yang 1989, 1991). The most widely thought scenario when harvesting in mixedwoods is to harvest the aspen around 60 years and the spruce is removed 60 years later (Brace and Bella 1988).

In young mixedwood stands, releasing spruce from overstory aspen may not require the removal of the entire aspen component. Free growing spruce, as defined by Steneker (1967), has growing space above their crowns and is not subject to the mechanical damage of whipping. For spruce established on these microsites, they are capable of attaining height increments comparable to completely released spruce (Steneker 1967).

Spruce are a relatively shade tolerant species (Nienstaedt and Zazada 1990) and therefore survive in light environments below full light. Spruce survival can be maintained in light levels as low as 11 to 13 % of full light (Logan 1969), and full height growth potential can be attained at 50 % full light (Logan 1969). Height and survival has been well correlated to light. Wright et al. (1998) showed diameter growth to also be sensitive to light levels. However, greater attention has been placed on height growth than diameter. When considering growth, some deciduous component may be maintained to establish a mixedwood stand without significantly compromising spruce growth if diameter growth is not adversely affected.

Thinning effect on aspen

Steneker (1964) thinned aspen in Manitoba at different ages (14, 19, and 23 years) to spacing of target stems per hectare of 300, 440 and 680 respectively. He reported aspen diameter increment was greater on all thinning regimes than controls over a ten-year period (Table 4).

Stands thinned to 300sph resulted in the largest increase in diameter increment, 30 % to 56 % greater than controls (Steneker 1964). Although thinning resulted in overall reductions in volume, there was an increase in merchantable volume, resulting in reduction of rotation time if veneer is the end product. Steneker (1964) concluded that the rotation time necessary to produce veneer bolts could be reduced by 10 years with spacing to 300sph. Volumes differed little between all spacing regimes and therefore it could not be concluded that the widest spacing would continue to produce the greatest merchantable volume (Steneker 1964). However, merchantable volume would depend on timing of harvest. Piece size was increased by thinning influencing the timing of harvest if veneer bolts are the product objective.

Table 4. Stand characteristics at different thinning regimes and control stands in Manitoba (modified from Steneker (1964) Table 5).

Age in 1950	Treatment	No. of plots	No. of trees			Total vol.			Merchantable volume (bd ft)		
			*B.T.	A.T.	1960	B.T.	A.T.	1960	B.T.	A.T.	1960
14 years	12 X 12	1	5970	300	260	25.7	2.35	13	0	0	0
	10 X 10	1	6670	440	410	20.2	3.37	18.1	0	0	0
	8 X 8	1	5270	680	630	27.98	8.38	40.33	0	0	0
	control	1	6050		3060	20.16		47.72	0	0	0
19 years	12 X 12	2	2458	300	288	31.12	6.51	21.75	0	0	0
	10 X 10	2	2785	435	428	34.98	10.19	28.66	0	0	0
	8 X 8	2	2138	680	655	31.26	15.35	38.12	0	0	0
	control	2	2475		1085	43.16		52.3	0	0	0
23 years	12 X 12	2	2165	300	208	54.94	16.59	52.02	0	0	4.42
	10 X 10	2	2448	435	422	53.66	20.65	64.68	0	0	4.1
	8 X 8	2	1682	680	628	50.75	31.43	84.08	0	0	3.87
	control	2	2610		1557	75.56		117.3	0	0	0.64

*B.T. = before treatment, A.T. = after treatment.

The purpose of the thinning operation is also paramount in the decision making model. Thinning can increase diameter at breast height by 20 to 40 %, veneer by 140%, and sawtimber yields by 40% (Perala 1977). Penner et al. (2001) examined thinning results by clone. Aspen clones were classified as either good or poor based on site index at base age 50 years. They found good clones to be indistinguishable between thinned and control plots (no thinning) sixteen years after treatment. Perala (1977) suggested aspen on good sites (site index 25 at base age 50) would increase in diameter by up to 40 percent. This study employed geometric thinning at a spacing of three meters. Poor clones didn't differ in terms of height but thinned treatments never regained volumes lost to thinning. Penner et al. (2001) suggested clone identification as paramount to the success of a thinning operation. Good clones can be thinned in order to foresee volumes that would be lost to mortality, but poor clones should not be thinned as the stand would not regain losses (Penner et al. 2001).

Growth and yield of mixedwood stands

Growth and yield information of mixedwood stands is lacking in favor of growth predictions for single species within mixedwood stands, or for site productivity models. Johnstone (1977) developed yield tables for spruce-aspen stands in the mixedwood section of Alberta. Using least square equations he provided yield estimates for spruce, but acknowledged aspen volume and basal area correlated poorly with softwood stand characteristics (Johnstone 1977). Deciduous volume estimates were obtained by subtracting spruce stand volumes from total stand volumes. Given that no deciduous equations were derived, it would be ill advised to suggest accurate estimates of deciduous volume could be obtained by simply subtracting spruce volumes from total stand volumes. A similar process has been used on small landbase tenures in BC. i.e. Woodlots. TIPSY (Table Interpolation Program for Stand Yields) and VDYP (Variable Density Yield Projection) in combination in the Woodlot for Windows version 1.2 is used to set coniferous and deciduous AAC (Anonymous 1998a). Johnstone (1977) used total volume equations with predicted basal area and predicted height as dependent variables. Johnstone (1977) suggested the use of predicted variables might have resulted in a loss of precision.

Hostin and Titus (1996) used age and diameter referenced site indices to construct a multiple linear regression model to predict white spruce site productivity as a function of trembling aspen site index. They used comparative site index to indirectly estimate the site index of one species based on the site index of another. Unfortunately, the model does not predict growth and yield of aspen, but uses aspen site index to predict spruce site productivity. There is no information suggesting the reverse scenario would hold true. That is, using spruce site index to predict aspen site productivity. However, past silviculture practices and assumptions suggesting aspen occupied good sites for spruce growth would suggest this could be the case (Peterson 1988).

Brace and Bella (1988) estimated growth and yield of spruce in Central Manitoba using STEMS (Stand and Tree Evaluation and Modeling System) after the aspen overstory had been removed. With different stocking scenarios following overstory removal and a rotation age between 80 and 100 years, they concluded that 600 spruce trees/ha were sufficient to obtain maximum merchantable volume. Stands with 400 stems/ha yielded 10 % of maximum at the time of harvest. Their planning horizon includes a two pass harvesting system that removes overstory aspen when spruce are approximately 40 year old, and a final harvest 60 years later.

Proper aspen management can achieve a number of objectives. Aspen could act as a competition control mechanism for white spruce, while still adding volume potential to the stand. Grass competition in the Peace River area of BC is at times serious, and can be more difficult to control than aspen if the objective is to re-establish a conifer or mixedwood stand. Maintaining a mixedwood component may also improve long-term site productivity by improving nutrient cycling and availability.

Mixedwood forests may provide some of the most challenging forest management scenarios for foresters (Smith et al. 1997). A broad understanding of the ecological process combined with techniques that allow managers to maximize productivity of mixedwoods is needed. The following objectives have been designed to help increase understanding of mixedwood ecology in order to better manage these ecosystems.

Research questions

In northern British Columbia, aspen has long been considered an inferior species within the mixedwood forests (Massie et al. 1994). Management techniques have placed the deciduous component of our forests at a distinct disadvantage by ignoring the economic and ecological dimension of this resource (Massie et al. 1994). This research has been designed to answer the following questions;

1. Can an aspen overstory be used to protect understory spruce from understory vegetation (herbaceous) competition?
2. What is the response of understory spruce to incremental opening of a 45 year old aspen overstory?
3. What is the response of the overstory aspen to aspen thinning?
4. Can long-term site productivity be sustained or enhanced by maintaining an aspen overstory?

Objectives

The objectives of this research were to:

1) Investigate the response of understory vegetation, bluejoint grass and fireweed, to changing available light through incremental thinning of an aspen overstory;
2) Measure the growth response of residual aspen and spruce to changes in the light environment;
3) Quantify changes in site productivity as it relates to soil nutrient availability of nitrogen to the plant community; and
4) Provide recommendations for mixedwood stocking standards to ensure continued long-term productivity.

2. GROWTH OF ASPEN AND SPRUCE FOLLOWING INCREMNETAL THINNING OF THE ASPEN OVERSTORY

Introduction

North America's Boreal aspen (*Populus tremuloides* (Michx.)) forests often follow a natural successional pattern that stimulates growth of a white spruce (*Picea glauca* (Moench) Voss) understory (Yang and Bella 1994). Aspen is a rapid growing tree (Fowells 1965, Perala 1990, Penner et al. 2001) that far exceeds the height growth of spruce in the early stages of stand development (Delong 1991, Youngblood 1995). This pattern of growth leads to growth impairment of white spruce in Boreal mixedwood stands where aspen and spruce survive in a complex (Kabzems 1952, Yang 1991). Sources of growth impairment can be from severe suppression due to low light levels or by mechanical damage of whipping (Kabzems 1952, Yang 1991). In situations where aspen is inflicting severe damage to the understory spruce, the site may not be achieving it's maximum growing potential (Perala 1977).

A number of studies have investigated the height and/or diameter response of understory spruce to total release from overtopping aspen (Lees 1966, Steneker 1967, Yang 1989, 1991, Yang and Bella 1994). All (Lees 1966, Steneker 1967, Yang 1989, 1991, Yang and Bella 1994) reported increased height and/or diameter growth response by white spruce after treatment when compared to non-treated controls. Results of these trials were reported 10 to 35 years post treatment. No results have been reported for a shorter (two to three year) response period. However, most research was targeted on stand conversion, removing all aspen in favor of the spruce component.

The growth response of aspen to thinning has also been investigated (Steneker 1964, Bella 1975, Huffman et al.1999, Penner et al. 2001). In these studies, aspen was thinned to varying densities and the residual stems were analyzed for height and diameter response. The purpose of the above trials was to investigate whether sawlogs or veneer bolts could be produced at an expedited rate by thinning. In each case, aspen diameter increased significantly with thinning.

Bella and Yang (1991) and Penner et al. (2001) suggested thinning should only be tried on good aspen sites (site index ≥25m@ 50years) if aspen was the targeted tree for response. Poor and medium sites would not regain the volume lost to thinning. Therefore thinning was not recommended for these sites. Results of the treatments were reported five to 16 years post treatment. As with white spruce, no results have been reported for a shorter (two to three year) response period. Aspen has been reported (Steneker 1964, Bella 1975, Bella and Yang 1991, Penner et al. 2001) to increase diameter growth after treatment when compared to non-treated controls.

Other researchers have investigated the growth response of understory trees to partial overstory removal (Tucker and Emmingham 1977, McCaughey and Schmidt 1982, Brandeis et al. 2001) in conifer mixedwoods. Height and diameter growth of grand fir (*Abies grandis* (Dougl. Ex D. Don) Lindl.), western redcedar (*Thuja plicata* Donn.) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) have been shown to be inversely related to decreasing overstory (Brandeis et al. 2001). McCaughey and Schmidt (1982) reported increased height growth of Engelmann spruce (*Picea engelmannii* Parry) and subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) 10-years after partial cutting removal of overstory on four National Forests of the Intermountian West of the United States. Physiologically, a tree can respond to a changed environment in one or two years. Tucker and Emmingham (1977) reported needles of western hemlock (*Tsuga hetrophylla* (Raf.) Sarg.) responded by increasing leaf area and structure two years following release in a shelterwood.

Availability of light may be one of the most important elements ensuring continued growth of understory conifers. The amount of solar radiation transmitted through a forest canopy increased with decreasing crown closure (Vezina and Pech 1964). In the aspen-spruce ecosystem, where aspen tends to out-compete spruce during stand initiation and immature stages of development, competition for light is the most likely explanation for spatial patterns of mid-tolerant species saplings (Roberts 1992), such as white spruce.

Aspen canopies are relatively diffuse (Squiers and Klosterman 1981) allowing species of moderate shade tolerance sufficient light for germination and growth, although not maximum growth. Aspen dominated forests display a rapid increase in light attenuation in May and June, and then remain stable until August. In the fall, light levels again increase to values similar to those observed in May (Constable and Lieffers 1996). This partitioning of the light resource allows spruce in the understory of an aspen overstory to utilize spring and fall leaf-off periods for photosynthesis and growth, while aspen is disadvantaged (Constable and Lieffers 1996). The physiological dynamics of the two species allows differential stand development creating niche exploitation opportunities.

Silviculture treatments, such as thinning, create further opportunities for niche exploitation that would not otherwise exist or would be delayed if left to natural processes.

Understanding the response to treatment after a short two or three-year period may be important in planning other silviculture activities such as prunning or fertilization. The objective of this study was to quantify growth of overstory aspen and understory spruce two to three-years following incremental thinning of the aspen overstory.

Methodology

The study site, located in northeast British Columbia (BC), Canada, in the Boreal White and Black Spruce moist and warm 1 (BWBSmw1) Biogeoclimatic zone described by Delong (1990), is situated 100 kilometers northwest of Fort St. John (56°51′30″ N, 121°25′ W). The stand, of fire origin, is a 45 year-old mixedwood stand dominated by even aged aspen in the overstory and multi-aged white spruce in the understory (Maundrell and Hawkins 2001). Using climate, vegetation and soil attributes the site was classified as a mesic, 01, site series. Prior to treatment there were an average of 3900 aspen stems per hectare (sph) with a site index (base age 50, SI_{50}) of 20m and 1050sph of spruce in the understory. Soils were classified as orthic gray luvisols characterized by silty clay loam of glacial lacustrine origin (Agriculture Canada 1986). Herbaceous vegetation was dominated by bluejoint grass (*Calamagrostis canadensis* (Michx.)), fireweed (*Epilobium angustifolium* L), bunchberry (*Cornus canadensis* L.), creamy peavine (*Lathyrus orchroleucuc* Hook.), prickly rose (*Rosa acicularus* Lindl.), highbush cranberry (*Viburnum edule* [Michx.] Raf.), and lingonberry (*Vaccinium vitis idaea* L.).

Experimental design

Reconnaissance of the site was conducted in the summer of 1998. Under a stereoscope, clones were distinguishable off aerial photographs. Four clones were identified in the research area. The quality of clones is medium to good based on a SI_{50} of 20m. Selection criteria required the treatment sites (plots) be homogenous in understory and overstory with sufficient area available to establish 10, 70m X 70m (0.49 ha) treatment plots. A 30m X 30m measurement plot was located in the geometric center of each treatment. Plots were located to reduce edge effect and to minimize stocking variability among plots (Maundrell and Hawkins 2001). Spruce ranged from 0.3m to 5m in height. Because of the large difference in spruce height, spruce were separated into two cohorts, <2m and >2m.

Basal area was used as the biological element for meeting thinning percentages. We determined basal area by establishing five 3.99 meter inventory plots in each of the treatment sites and summing the basal area (at breast height) for all trees in the plot. Basal areas for trees were calculated using; $\{\pi(D/2)^2=A\}$, where D = diameter and A = basal area. Plots were than randomly selected for percent basal area retention. Using geometeric spacing, each treatment plot was reduced to it's target basal area retention by gridling or physically cutting aspen on a stem per hectare target. Thinning was completed in August 1998 following British Columbia Ministry of Forests Brushing Standards

Agreement (Anonymous 1998b). Treatments ranged from 0% to 100% of the natural stand condition in increments of about 10% for a total of 10 installations (Figure 1) (Maundrell and Hawkins 2001).

In the fall of 2000, approximately 50 spruce stems were destructively sampled in each of the 10 treatment plots. Spruce stems had discs removed at 1.3m (trees greater than 2.0m) or at root collar for trees less than 2.0m height. This provided two cohorts for spruce based on canopy position (<2m, >2m). During the same period live aspen stems were cored at breast height (1.3m) to obtain a core for growth analysis.

Diameter growth was measured for years 1998 through 2000 using WinDENDRO software version 6.5 (Blain Quebec, Canada). A Hewett Packard ScanJet 4C/T scanner was used to measure tree ring width (mm). Prior to scanning all spruce disks required sanding to remove rough edges and highlight growth rings for ease of scanning. All spruce stems were scanned from pith to the beginning of the cambium layer on two adjacent sides of each disk. Growth rings were scanned from the middle of one ring to the middle of the next ring to produce a growth increment for that year. Growth measurements for pre-treatment (1998) and post-treatment (1999 and 2000) were scanned and recorded on each side of the disk for analysis. This produces two growth measurements for each year. The two measurements were averaged to produce a single radial growth measurement for each year.

Growth rings for aspen cores can be difficult to determine. A two times magnifying glass was used to determine ring location. Once the ring was identified it was marked with a fine point pencil. Growth rates were measured from the middle of one mark to the middle of the next mark and outward to the beginning edge of the cambium layer.

Light transmission through the overstory canopy was measured in the summer of 2000 with a portable spectroradiometer (LI-COR LI-1800, LI-COR Inc, Lincoln, NB). This device takes one light reading every second than averages the readings over a programmed time setting. One cumulative measurement (15sec) was taken at breast height (1.3m) and at a distance one meter south of selected trees to minimize the influence of understory vegetation and spruce trees greater than 1.3m (Comeau 2001). Twelve randomly selected white spruce stems in each of the 10 treatment plots were selected for location of measurements. An equal number (12) of readings were taken from an open clearing adjacent to the trial twice each day to standardize measurements. Measurements were taken on clear days between 10:00 and 14:00 Pacific Standard Time on two consecutive days, June 24th and 25th. We endeavored to measure solar radiation as close to the solstice as possible to reduce the amount of light intercepted by tree boles. Thereby, changes in light levels would primarily be a result of leaf out.

The mean transmitted PPFD (photosynthetic photon flux density) was calculated by dividing attenuated light radiation (treatment site) by unattenuated light (open), to produce mean PPFD percent of full light for each thinning treatment. This approach produced a range of light transmission values.

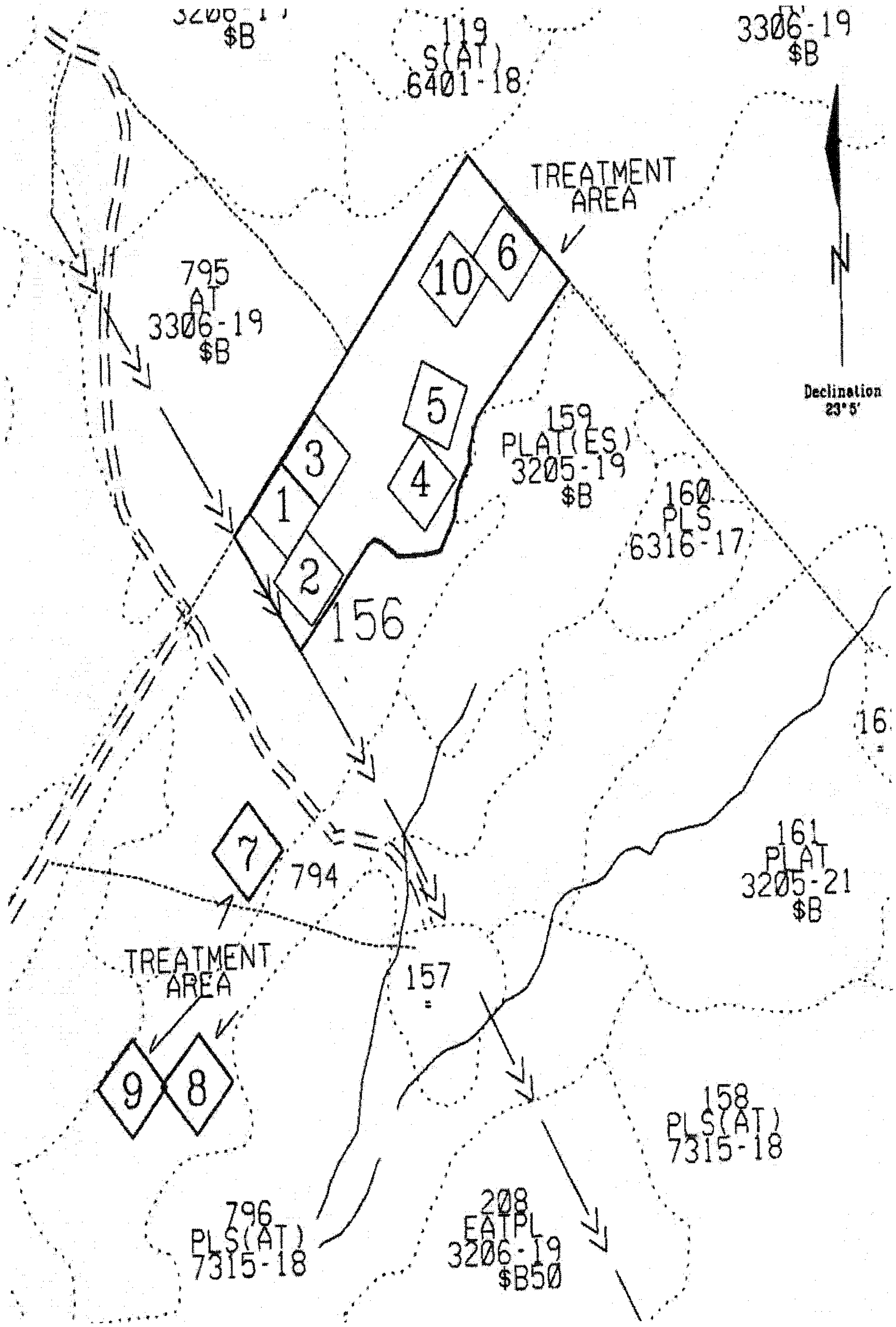

Figure 1. Research plot layout.

Analysis

Growth rates for each year after treatment were compared using repeated measures analysis of variance performed in SYSTAT 10 (2001), $\alpha = 0.05$. Each spruce cohort and aspen were analyzed independently. Pre-treatment growth rates have been identified as a contributing factor in growth response following treatment (McCaughey and Schmidt 1982). Therefore pre-treatment growth rate was used as a covariant in this analysis.

Results

Spruce diameter growth

Growth results varied between spruce breast height diameter and root collar diameter, and between spruce and aspen diameters. Spruce diameter increments show a general trend to increasing growth for all plots between the first (1999) and second (2000) years after girdling except for plots five and 10 (Figure 2). There was a significant difference among treatments $F(9,483) = 2.96$ $p = 0.001$ and between years $F(1,484) = 27.87$ $p = 0.001$: 2000 > 1999. The percent change in diameter growth by treatment from 1998 (pre-treatment rate) to 2000 (two-years post treatment rate), and the corresponding treatment light level in 2000 are shown in Table 5.

No significant differences in pre-release diameters were found for spruce between plots ($F(9,321) = 1.74$, $p = 0.079$) (Table 6). This indicates mean radial growth was approximately the same for all treatments before girdling.

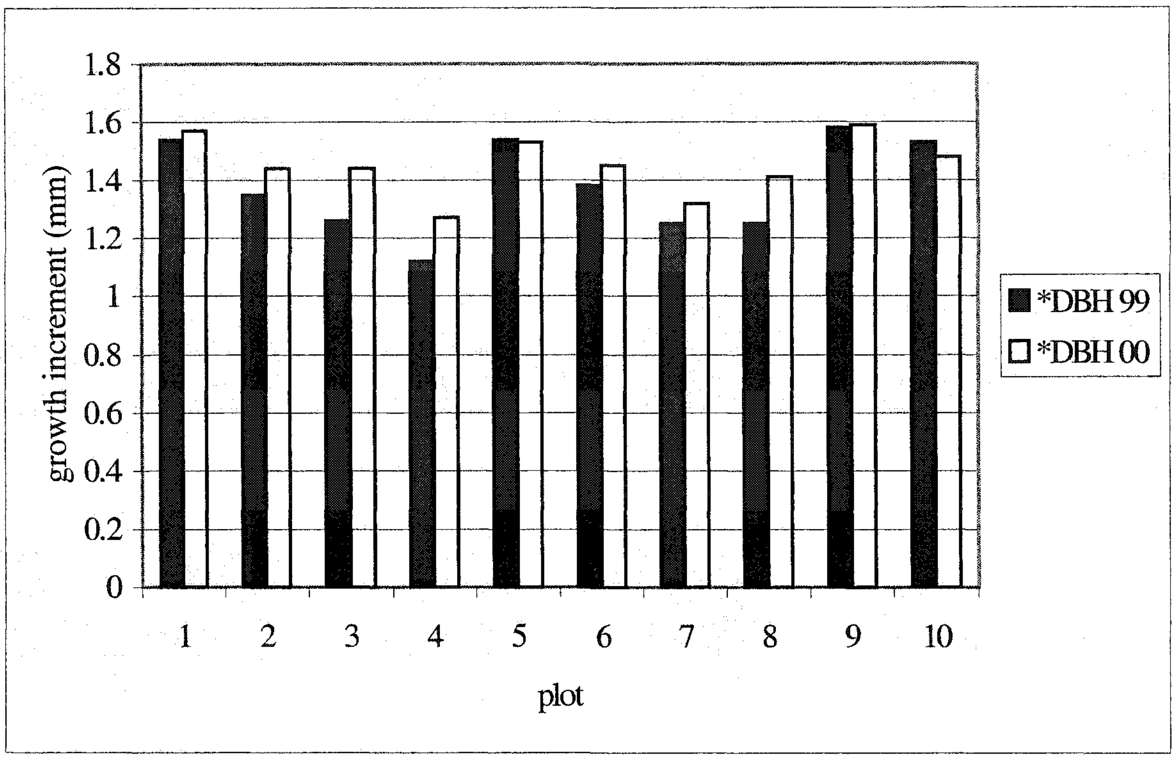

Figure 2. Mean spruce diameter growth increment at breast height (DBH) by plot and year: *DBH99 = DBH in 1999; DBH00 = DBH in 2000.

Table 5. Percent change in growth for spruce diameter at breast height (DBH) and at the root collar (RC), and aspen DBH with respect to incident light (percent of ambient) by plot between 1998 (pre treatment) and 2000 (two-years post treatment).

Plot	DBH	RC	Aspen DBH	Light
1	22	13	3	14.5
2	18	21	15	32.7
3	17	0	15	23.2
4	24	2	n/a	67.2
5	20	3	7	45.2
6	13	6	23	55.8
7	22	33	18	15.7
8	9	8	13	33.7
9	11	4	14	33.1
10	14	-10	19	61.7

Table 6. Mean spruce pre-treatment diameter increment (mm) (growth rate and SEM for each plot). (F(9,321) = 1.74, p = 0.079)

	Plots									
	1	2	3	4	5	6	7	8	9	10
Diameter										
Mean	38.9	53.8	37.3	44.9	50.9	50.1	51.7	43.7	48.7	39.3
SEM	3.2	5.3	4.9	4.6	5.5	5.2	3.6	4.1	4.6	4.3

Spruce root collar growth

Spruce root collar growth increments show no obvious trends (Figure 3) (F(9,475) = 1.48 p = 0.15). There was a significant difference between years F(1,476) = 26.22 p = 0.001. Unfortunately, the reported growth rates are mostly in decline between the years. Percent change in root collar growth between pre (1998) and two-years post (2000) girdling treatment by plot (treatment) are shown in Table 5.

The difference in spruce root collar and diameter growth rates after treatment can be partly explained by the pre-release growth rates. Pre-release diameter growth rates were greater than root collar. A students t-test was performed to test whether the rates differed. Pre-release diameter mean growth rate was 1.237mm, while pre-release root collar growth rate was 0.480 (t(461) = 33.032, p = 0.001).

Aspen diameter growth

Aspen diameter growth increment displays a general trend to increasing growth from 1999 to 2000 except for plot 4 where all aspen were treated (Figure 4). Growth was significantly different among treatments F(8,412) = 2.69 p = 0.006 and between years F(1,413) = 25.78 p = 0.001. Percent change in aspen DBH growth between pre (1998) and two-years post (2000) girdling treatment by plot (treatment) are shown in Table 5. The age for spruce in each cohort to be equal, as was the aspen component of the stand. Percent live crown is also believed to be equal for all cohorts and the aspen component.

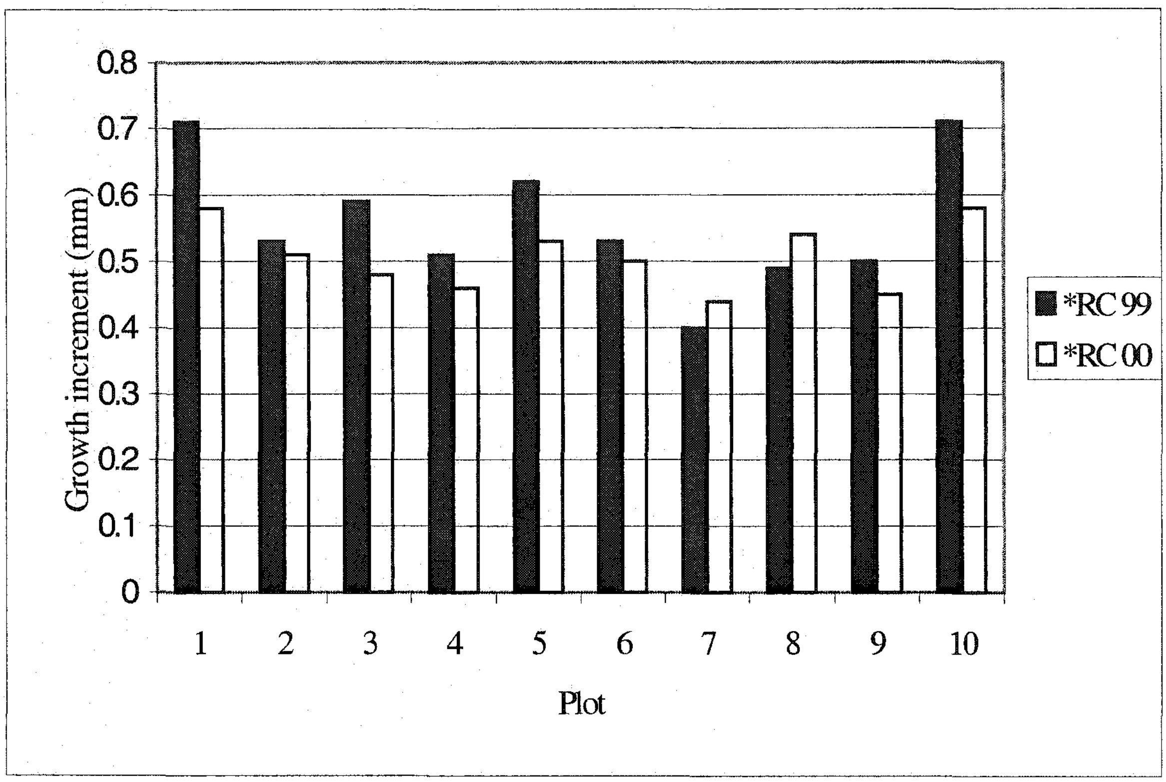

Figure 3. Mean spruce root collar (RC) growth increment by plot and year: *RC99 = RC in 1999; RC00 = RC in 2000.for 1999, 2000 by plot.

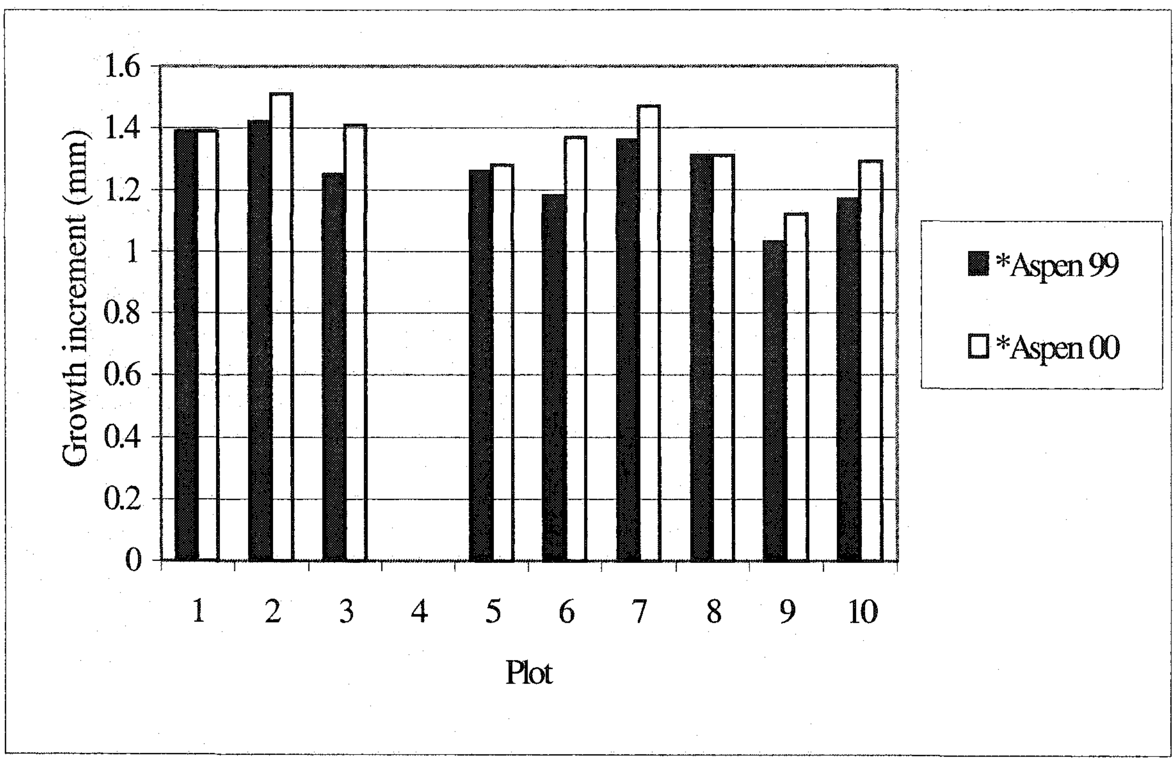

Figure 4. Mean aspen diameter growth increment at breast height (DBH) by plot and year: *Aspen 99 = DBH in 1999; Aspen 00 = DBH in 2000.

Discussion

Diameter was selected as the response variable, rather than height. Diameter is more responsive than height to changes in carbon allocation (Gordon and Larson 1968, Rangnekar and Forward 1973) as would be found, with changes in ambient light, as a result of thinning (Groot 1999).

The ability of understory trees to respond to release is directly dependent on the trees physiological condition and therefore its ability to respond to the changed environment (Helms and Standiford 1985). Morphological attributes that can lend to increased release rates can be pre-release diameter growth rate, total diameter prior to release, age at release, pre-release live crown and pre-release height growth (crown position) (Helms and Standiford 1985). There was no difference in pre-release diameter growth rates for spruce. Therefore, live crown, age or crown position may have influenced the growth rates observed. Larger spruce (>2m) responded greater than smaller spruce (<2m), indicating crown position, presumably related to available light, was influencing growth. As the age for trees in each spruce cohort are equal, and live crown is equal too, any change in growth rate should be a function of the girdling treatments and changed environment.

Thinning rapidly changes the environment the tree occupies. In order for a positive response to take place following treatment, the tree must be capable of utilizing the increased resources. With improved light, moisture, and nutrients at the micro-environment, the tree must be able to adjust its physiological ability to increase photosynthesis to account for increases in respiration (Lieffers et al. 1993, Eastman and Camm 1995, Reynolds et al. 2000). Spruce diameter growth at breast height was found to be significant among treatments and time since treatment. However, the analysis also revealed a significant interaction: most treatments increased in diameter but treatments five and 10 decreased. Given light regimes of 45.2% and 67.2 % respectively of ambient light for the two treatments, and pre-treatment diameter was not the smallest, other factors must be contributing to the observed tree response.

Spruce root collar diameter increment did not respond to treatment. Trees in this cohort are smaller, have less total live crown area, and may be subjected to increased herbaceous vegetation competition. Tree height, being less than two meters, may have subjected these stems to greater competition (Maundrell and Hawkins 2002) and contributed to the above observation. Analysis of vegetation responses to the treatments indicated herbaceous vegetation responded positively in both growth and cover to increasing light (Maundrell and Hawkins 2002). Lieffers and Stadt (1994) found bluejoint and fireweed increased significantly in relation to increases in light environments and could act as a serious competitor to understory spruce after thinning treatments. Such competition could negatively impact spruce advanced regeneration that has yet to reach a height were understory vegetation does not present a competitive impediment.

Thinning treatment had a positive affect on the aspen component of the stand. All treatments, except one, increased diameter growth rates. The response of the aspen component was greater then either of the spruce cohorts. This should be expected as aspen occupies dominance in this canopy and therefore, is physically and physiologically pre-disposed to respond rapidly to this changed environment. There was no interaction between treatment and time suggesting light is driving the aspen diameter growth response. In addition, there would be less competition for water and nutrients after thinning, and therefore access to water and nutrients would be more available to the remaining stems.

The response of aspen to the thinning treatment is consistent with observations of others (Steneker 1964, Bella 1975, Huffman et al. 1999, Penner et al. 2001) and appears to have taken place soon after treatment. Such treatments could be used to shorten aspen rotations (Steneker 1964) while promoting growth of the spruce understory. Spruce on the other hand, have not responded as rapidly. It is not clear how much time will be required to observe a clear response in the spruce component. A minimum of five years may be needed. Further research needs to be conducted in order to quantify the response time for spruce. Without accurate estimates of spruce release from incremental thinning, further silvicultural treatments cannot be planned and the cost-benefit of the treatment cannot be calculated.

Conclusion

This study shows aspen responded rapidly while white spruce growth responses varied depending on the tree's growth rate and canopy position in the stand prior to treatment. Spruce breast height diameter growth rates (trees > 2m) generally increased after girdling the aspen while root collar diameter growth rates (trees < 2m) remained relatively unchanged or declined. The expected growth difference among girdling treatments that would describe a preferred treatment has not yet occurred. On this site, the response of spruce to the changed environment appears to be delayed when compared to the aspen. More time is needed to quantity (biologically and economically) the response of spruce and aspen to aspen overstory removal.

As with all research, there are limitation based on the design and assumptions. The most obvious limitation involves the process of thinning (girdle and physical cutting). The target thinning percent was performed geometrically to alter available light in the understory. The best scenario would have been to physically cut all trees. This would have eliminated the discrepancies encountered between target thinning percent and the current outcome. Although the understory light regimes are close to targets, the amount of leafing by girdled trees meant we didn't have light regimes in clear discrete increments. This may have played an important role on the light and growth relationship findings in this study.

3. USE OF AN ASPEN OVERSTORY TO CONTROL UNDERSTORY HERBACEOUS SPECIES, BLUEJOINT GRASS (*CALAMAGROSTIS CANADENSIS*) AND FIREWEED (*EPILOBIUM ANGUSTIFOLIUM*)[2]

Introduction

Light is the one of the most limiting factors influencing spatial and temporal successional patterns for understory plants (Roberts 1992; Pacala et al. 1994). Many researchers (Atzet and Waring 1970; Hutchison and Matt 1977; Kolb et al. 1989; Canham and Burbank 1994; Brown and Parker 1994; Constabel and Lieffers 1996; Parent and Messier 1996; Man and Lieffers; 1997; Messier et al 1998; Wright et al. 1998), have investigated light transmission through forest canopies. However, few have integrated the light response of the understory layers in their studies (Lieffers and Stadt 1994; Reynolds et al. 1997; Messier et al. 1998).

Boreal mixedwood forest stand structure is commonly a mixture of overstory aspen with understory conifers (Lieffers et al. 1996; Man and Lieffers 1997). Immediately following disturbance, it is not uncommon for aspen to establish as the dominant tree species followed by white spruce. Spruce recruitment can occur immediately after disturbance, or can continue for decades after disturbance (Lieffers et al. 1996). Aspen rapidly overtops white spruce upon initial recruitment. White spruce trees that manage to survive grow at a slow rate for many years in the shaded understory (Messier et al. 1999) before they reach the aspen overstory or the aspen begins to fall out of the overstory creating gaps that white spruce can occupy.

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[2] A paper based on this chapter entitled Use of an Aspen Overstory to Control Understory Herbaceous Species, Bluejoint grass (*Calmagrostis canadensis*) and Fireweed (*Epilobium angustifolium*), was submitted to the Northern J. of Applied Forestry (January, 2002).

During stand initiation the herbaceous understory often re-establishes from seed and rhizomes. Species such as bluejoint grass and fireweed are common understory perennials of mixedwood forests (Corns and Annas 1986). They can negatively impact the survival and growth of conifers (Kabzems and Lousier 1992; Lieffers and Stadt 1994). Opening the canopy increases light availability and warms soils, which benefits crop trees (white spruce) by improving the microsite. However, it can also benefit the competitors. Both bluejoint grass and fireweed respond positively in vigor and height growth to improved light conditions when mixedwood forests are opened (Lieffers and Stadt 1994).

White spruce is a shade tolerant species that can survive in the understory for many years before being released (Man and Lieffers 1997). Young (30 to 60 years old) untreated aspen stands can transmit from 15% - 25% of full light (Lieffers and Stadt 1994). Light levels in younger aspen may be even lower, Lieffers et al. (2002) reported 10% - 15 % levels in 10-30 year old aspen stands. Logan (1969), Eis (1970), Lieffers and Stadt (1994), and Coates et al. (1994) have all reported increased spruce height growth with increasing understory light radiation. Coates et al. (1994) predicted optimal height growth for understory spruce could be attained at 50% of full sunlight, while Logan (1969) and Lieffers and Stadt (1994) reported maximum height growth for white spruce could be attained at lower light levels: 45% and 40% of full sunlight, respectively. Logan's (1969) results were based on nine growing seasons while the others were reported after one year. Lieffers and Stadt (1994) suggested maintaining acceptable leader growth (9 and 25 cm) requires a light environment with 15% - 40% of full light, while bluejoint grass could only be eliminated from the site at light levels below 8% of full sunlight. However, it must be kept in mind that maximum radial growth occurs at or near conditions of full sunlight (Lieffers and Stadt 1994; Wright et al. 1998).

Forest managers typically rely on complete removal of competing vegetation to facilitate conifer growth due to current British Columbia Ministry of Forest's policies. Current regeneration standards require white spruce crop trees be at least 150% taller than competing vegetation within a 1.0 meters (m) radius of the crop tree to be considered free-growing in the Boreal White and Black Spruce moist and warm (BWBSmw1) biogeclimatic zone (Anonymous 2001b). Minimum stocking requirements and uniform crop tree spacing results in little untreated area when doing either manual or chemical brushing treatments.

A number of studies have investigated the effect of competition control on the establishment and survival of white spruce (Sutton 1984; Brand 1991; Wood and von Althen 1993; Groot 1999). On sites where competition is a limiting factor to regeneration, growth, and survival of white spruce, it may be beneficial to accept lower light levels. This can limit understory growth until a minimum height that allows the spruce trees to successfully compete with the understory vegetation. Opening the aspen canopy prior to spruce emergence or canopy gap formation may aid spruce growth. However in doing so, we may also increase understory vegetation competition and thereby impede the opportunity of younger, mostly second cohort, spruce trees from emerging through the canopy and contributing to the future mixedwood stand. The size and configuration of the opening, as it relates to stand structure, may result in ecological changes, such as in light availability and soil warming, that limit the response of understory vegetation to the treatment (Lieffers and Stadt 1994; Groot 1999).

Planting shock (Burdett et al. 1984), susceptibility of the conifers to night frost (Mann and Lieffers 1997) and white pine weevil (*Pissodes strobi* (Peck)) attack (Taylor et al. 1996) all have been positively correlated to reductions in canopy cover. Opening mixedwood canopies may create microclimates that are more extreme than intact canopies, resulting in negative physiological responses of understory spruce and/or increasing the susceptibility of white spruce to biotic pathogens. For example, Needham et al. (1999) showed how the maintenance of a deciduous overstory reduced the incidence of spruce budworm (*Choristoneura fumiferana* Clemens) defoliation on balsam fir.

The objective of this study was to quantify light regimes capable of controlling understory herbaceous and grass competition in a Boreal mixedwood stand.

Methods

See experimental design (Chapter 2) for plot layout, light methodology, and thinning methods.

In late summer of 2000, one individual conducted ocular estimates of percent cover (Delong 1991, Comeau et al. 1993) for bluejoint grass and fireweed. This approach reduces error that can occur by using more than one observer, assuming the basis of the one observer is consistent. We established six 3.99m radius plots ($50m^2$) in each treatment plot. Six plots were randomly selected six plots from the twelve trees randomly selected to collect light data.

The mean percent cover of each species was correlated to percent light transmission and percent cover of fireweed was related to bluejoint percent cover using non linear regression analysis performed in SYSTAT 10 (2001), $\alpha = 0.05$. Linear regression and non-linear regression SYSTAT 10 (2001) were used to establish the relationship between percent PPFD, and basal area, specie's, and light.

Results

Light at 1.3m was significantly greater under the aspen canopy as basal area was reduced (Figure 6, Table 7). With lower basal area, there are fewer stems and more open sky because there is less canopy to intercept light.

A positive and statistically significant relationship was observed between light transmitted through the aspen canopy and the percent cover of bluejoint grass and fireweed (Figures 7 and 8, Table 7). Bluejoint grass and fireweed were never totally eliminated from the stand, although cover declined to less than 5% on the control treatment and light transmission was about 13%.

Table 7. Regression results, for light, bluejoint and fireweed. BA, basal area -m^2, BJ, bluejoint grass % cover, FW, fireweed % cover, and Light, 5 light transmitted to 1.3 m.

Dependent Variable	Equation	n	F	r^2
Light	Light = 61.032 – 1.574*(BA)	10	203.67	0.98
BJ	BJ = -26.915 + 33.554*$\log_{10}$(Light)	60	220.56	0.88
FW	FW = -7.482 + 15.510*$\log_{10}$(Light)	60	249.20	0.90
FW	FW = -9.014 + 19.322* $\log_{10}$(BJ)	60	532.68	0.95

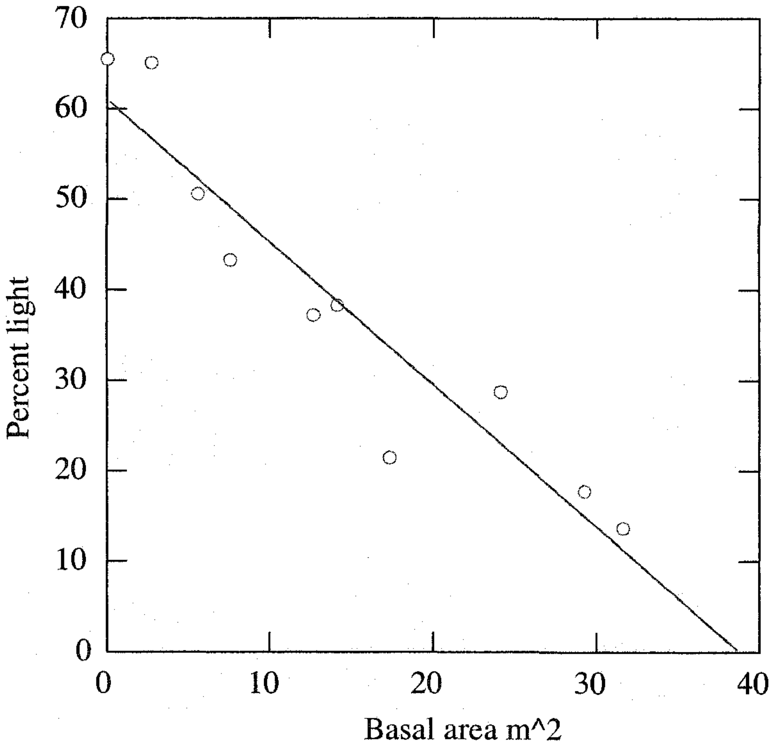

Figure 5. Mean percent light in relation to basal area.

A significant positive relationship also existed between the amount of fireweed and the presence of bluejoint grass (Figure 9, Table 7). Higher bluejoint cover related to higher fireweed cover, up to about 20% cover. Beyond this level, the rate of fireweed cover increased at a slower rate than the cover of grass.

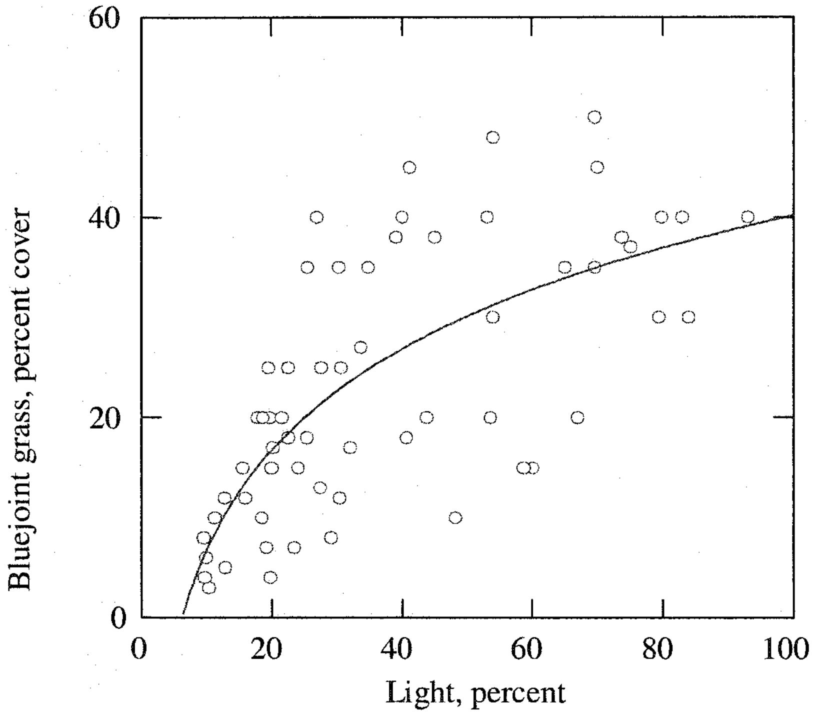

Figure 6. Percent cover of bluejoint grass as a function of light received under an aspen canopy at 1.3m.

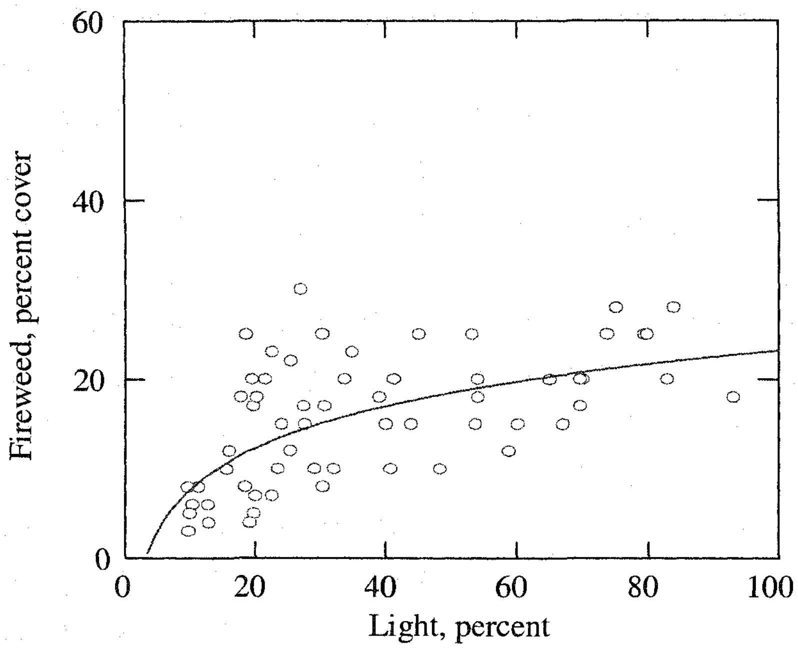

Figure 7. Percent cover of fireweed as a function of light received under an aspen canopy at 1.3m.

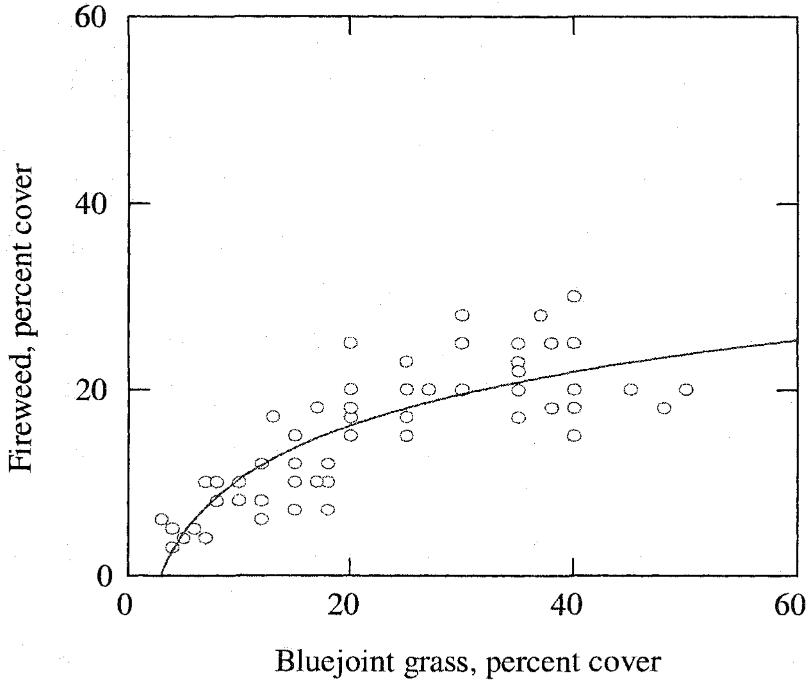

Figure 8. Percent cover fireweed as a function of bluejoint grass percent cover.

Discussion

Reducing aspen density and stocking increased understory light and cover of non-crop vegetation as expected (Lieffers and Stadt 1994). Even in the untreated area with a basal area of 31.7m^2 ha^{-1}, light was slightly higher (13%) than that suggested for the elimination of bluejoint grass (Lieffers and Stadt 1994). Lieffers and Stadt (1994) reported that when bluejoint clones are well distributed, rapid expansion occurs when the site is clear-cut. On their mixedwood sites, the open clear-cut areas were nearly completely covered with the grass. On this site, bluejoint grass appears to have a competitive advantage over fireweed at higher understory light levels as evidenced by increased percent cover under similar light conditions. This suggests these species compete for similar resources.

Vegetation management is paramount to the successful recruitment and growth of white spruce in northeast BC. The traditional management approach has focused on conifer plantations rather than mixedwood stands comprised of aspen and spruce. It was thought that mixedwood stands occupied sites best suited to conifers, and stand conversion practices focusing on conifers were typically prescribed (Peterson et al. 1989). There has been little consideration (research) for the response of understory vegetation with these scenarios (Lieffers and Stadt 1994; Reynolds et al. 1997; Messier et al. 1998). Stand conversion can be detrimental to white spruce if the understory, herb and grass competition increases, affects survival following overstory removal.

Silviculture planning and implementation allows forest managers to use existing stand attributes such as partial overstory cover to mitigate problems that may arise from traditional methods of spruce management involving complete removal of deciduous overstories. In mixedwood stands, managers can manipulate the light environment by incremental thinning to create favorable conditions to improve microsite and habitat to facilitate white spruce regeneration and growth. Techniques that maintain overstories can be applied when managing for spruce regeneration in mixedwood stands by manipulating deciduous canopy structure.

The first entry would be to open the canopy sufficiently (reduce basal area by 15% - 20% to increase light levels by 15% - 20%) to increase spruce growth, while at the same time limiting the response of understory species. Light regimes of 15% - 20% of full light are well within physiological limits of white spruce to meet and exceed the species photosynthetic compensation level of $60\mu mol \cdot m^{-2} \cdot s^{-1}$ reported by Constabel and Lieffers (1996). Such treatment would allow the overstory to suppress the understory layer until the spruce is at least 1m high (minimum height for legislated free-growing standards). Once white spruce has reached an average height of 1m, additional stand entries could be made to further release the spruce.

White spruce has greater radial and height growth responses to increased light at low light levels than at high light levels (Wright et al. 1998). A controlled modest change in light levels in the first entry would take advantage of this attribute. This method of incremental release would take advantage of white spruce ability to acclimate to a changing environment. Furthermore, it would provide a competitive advantage for white spruce over competition from understory vegetation and thereby increase survival during seedling and juvenile stages of development.

The cost of an intensive silviculture approach needs further investigation. It took one person a full day to thin (cut and girdle) 0.5ha of a forty-five year old aspen stand to a target level of 50% basal area removal. For 20% basal area removal, the treatment took four hours. The total cost of thinning a 1ha stand of this age and density is 600-650 $CDN. In comparison, the cost of aerial herbicide is 380-400 $CDN per ha (Thiel 2001 Pers.Comm., Canadian Forest Products, Woodlands, Fort St. John Division). However aerial herbicide is non-discriminatory. It results in total elimination of all competing vegetation, including the aspen overstory. The possibility of a basal bark herbicide needs to be considered. Basal bark application of triclopyr ester (Release™) may be as effective as physical release by cutting and girlding and may be more cost effective. Although the financial cost of an incremental treatment method is at first more expensive, earlier access to valuable timber by increasing spruce growth may out weigh the initial cost. There may also be added benefits to maintaining the aspen for biodiversity, forest health, and future revenue. Residual aspen can mitigate environmental extremes reducing spruce losses from biotic and abiotic sources as described above. Moreover, commercial demand for aspen is increasing in northeast BC.

On the second entry, the light environment could be improved to about 40% - 50% of full sunlight or a basal area about $10m^2 ha^{-1}$ for this stand. Comeau (2001) reported basal areas of $10m^2$ ha^{-1} resulted in light levels of 50% for younger aspen stands. Spruce would then be relatively free of understory competition and capable of attaining near maximum height growth at these improved light levels (Logan 1969; Coates et al. 1994; Lieffers and Stadt 1994). Targeting merchantable aspen stems to meet the desired basal area would generate timber revenue to offset the financial costs of the treatment.

Conclusions

The findings of this study suggest management rather than elimination of competitors may be the most effective and efficient way to control non-crop herb competition and regulate stand growth. Management of the understory light environment can accomplish four objectives: 1) Protect the spruce from excessive understory competition; 2) Maintain an understory light environment that is beneficial to spruce growth; 3) Protect regeneration from environmental extremes that diminish the stand's resilience; and 4) Minimize the risk of insect attack to crop trees. Further, revenue from periodic aspen removal could help defray the costs of intensive management. This study suggests that a long-term approach of incremental release could be used to manage understory competition in mixedwood stands where aspen is overtopping spruce. Future work should evaluate spruce development under these conditions and the economics of such treatments.

As with all research, there are limitation based on the design and assumptions. Although the light regimes correlated well to the herbaceous cover studied, height of competition may be equally important, as the height of competition is important when considering overtopping of crop trees. Furthermore, there may be a direct relationship between height and the mechanical damage to crop trees. It has been widely accepted, although not documented, that the mechanical damage created when grass is pressed by early wet snow is the primary mechanism of damage to planted crop trees.

4. PLANT AVAILABLE NITROGEN IN RESPONSE TO INCREMENTAL THINNING OF AN ASPEN OVERSTORY

Introduction

Light has been identified as a significant limiting resource to the growth and development of Boreal forests (Pacala et al. 1984; Constabel and Lieffers 1996; Palik and Pregitzer 1995; Parent and Messier 1996; Reynolds et al. 1997; Wright et al. 1998; Messier et al. 1998; Reynolds et al. 2000). The importance of light for growth and development is undisputed. However when light is not growth limiting, limitations to growth become dependent on other factors, including nutrient, temperature and water availability. Available nitrogen can be the most limiting nutrient in forest soils (Vitousek et al. 1979; Flanagan and Van Cleve 1983; Weetman et al. 1988; Courtin et al. 1988; Lodhiyal and Singh 1993; Klinka et al. 1994; Lundell 2001), followed by phosphorus (Navratil et al. 1991). Plant available nitrogen comes principally in two forms of inorganic nitrogen (NH_4 and NO_3) (Pastor et al. 1984; Schimel and Firestone 1989). The major source of inorganic nitrogen in forest ecosystems comes from forest plant litter (Flanagan and Van Cleve 1983; Van Cleve et al. 1991; Hobbie 1992).

The quality of organic matter in forest ecosystems is determined by its' chemical composition. Lignin is a rigid structure that contributes to plant strength and form. Lignin is also a major component of the forest litter. The content of lignin in leaf litter is specific to individual tree species and is an important factor influencing the rate of decomposition (Melillo et al. 1982; Meentemeyer 1978). Lignin interferes with the enzymatic degradation of cellulose and carbohydrates (Melillo et al. 1982), the primary components of leaf litter. Melillo et al. (1982) reported that high levels of lignin in leaf litter may slow decomposition. Conifers generally show higher lignin content in leaf litter than deciduous species, leading to slower decomposition rates. McClaugherty et al. (1985) showed that aspen produced more litter (mg·ha^{-1}·yr^{-1}) per year than white pine or hemlock and that mineralization and nitrification rates were greater in aspen stands. This may be due to less lignin content of the aspen litter, or possibly the greater litter leaf-fall. In general, the rate of elemental uptake and recycling of litter declines in the following order: aspen > birch > white spruce > black spruce (Van Cleve et al. 1991). Meentemeyer (1978) suggested lignin concentration to be an excellent index used to predict decomposition rates and weight loss in forest litters. The rate of forest litter decomposition is strongly dependent on the amount of lignin in the litter and this influences litter quality (Meentemeyer 1978; Melillo et al. 1982; Van Cleve 1985). Litter decay is an energy dependent process, and litter with high lignin requires greater energy expenditure than litters low in lignin (Meentemeyer 1978).

In addition to lignin, the rate of litter decomposition is controlled by a number of other factors including moisture, temperature, soil fauna, and quality of the litter (Meentemeyer 1978; Melillo et al. 1982; Viereck et al. 1983; Pastor et al. 1984). Aspen litter has been identified as a high quality litter capable of more rapid decomposition compared to other species (Bartos and DeByle 1981). Deciduous litter tends to be of higher quality than conifer litter because of lower lignin content and consequently more rapid decomposition and high N mineralization (Meentemeyer 1978; Melillo et al 1982; McClaugherty et al. 1985; Bartos and DeByle 1981). However, Prescott et al. (2000) found aspen and spruce decomposition rates to converge 5-years after initial decomposition rates. Litters of both spruce and aspen decomposed slightly more rapidly in aspen and mixedwood forests than spruce forests. Prescott et al. (2000) found no difference in decomposition rates of mixtures in buried bags on all forest types. However, different substrates may have influenced the reported results.

Nadelhoffer et al. (1991) and (Morecroft et al. (1992) found N concentration and mineralization rates in forest soils are highly dependent on soil temperature and moisture. Small increases in soil temperature can result in large increases in net N concentration (Nadelhoffer et al. 1991). This suggests that in cold Boreal systems, these processes may be temperature limited (Lajzerowicz 2000). In Boreal mixedwoods, where highly decomposable litter is plentiful, small increases in soil temperature may increase productivity by increasing nutrients available for growth.

Acid solubility has also been linked to increasing litter decomposition. McClaugherty et al. (1985) showed litters rich in acid soluble compounds, such as aspen, decompose more rapidly than less acid soluble conifers. Deciduous species, such as oak, sugar maple, basswood, and ash, produce higher quality litter and dominate sites of greater mineralization rates and higher productivity. Conifer species dominate sites of low mineralization rates, lower litter quality and lower productivity (Pastor et al. 1984; Van Cleve et al. 1991). The greater amounts, and higher quality of deciduous litter results in faster turnover rates as demonstrated by higher decomposition rates of deciduous litter when compared with coniferous litter (Van Cleve et al. 1985).

In studies in Alaska, Van Cleve et al. (1985) found black spruce and flood plain white spruce forest floors supplied one-fifth of the amount of N taken-up by paper birch seedlings. Spruce forest floors yielded significantly less extractable N than birch forest floors suggesting the birch forest floor could supply more N to growth than the spruce forest floor. Forest floor substrate is also important in the nutrient cycle. As mentioned earlier, moisture and temperature are important factors in litter decomposition. These attributes can be intensified by the forest floor substrate. For example, greater clay content in the substrate increases cation exchange capacity (CEC) and moisture content. This has been shown to increase nitrogen mineralization potential (Herlihy 1979). Herlihy (1979) and Pastor et al. (1984) showed mineralization was consistently higher, with greater clay content and CEC.

Litter quality has also been related to C:N and C:P ratios. High C:N and C:P ratios are indicative of species that produce low quality litter and dominate sites of low nitrogen mineralization (Pastor et al. 1984). Nitrogen, P and K recycling increases in the Boreal forest as the deciduous component of the litter increase (Navratil 1989). This suggests deciduous stands may increase standing nutrient pools and cycling rates sooner after harvest than conifer stands. Species established in environments where soil nutrients are plentiful such as aspen, allocate more to aboveground components, have greater growth rates, and higher rates of nutrient uptake than species from low nutrient environments (Hobbie 1992).

Alban (1982) suggested nutrient and organic matter in forest floors reflected the composition of the litter. Conifer litter may increase soil acidification reducing nutrient cycling potential by retaining compounds in organic forms (Brand et al. 1986). Alban (1982) reported soils under conifer stands accumulated higher amounts of organic matter, total N, and exchangeable cations than aspen stands. In coniferous forests, nutrients become stored in organic form in the forest floor (Kelty 1992). Nitrogen stored in organic forms becomes immobilized and is not readily available to plants for growth (Fogel and Cromack 1977; Flanagan and Van Cleve 1983; Pastor et al. 1984). Van Cleve et al. (1991) and Kelty (1992) suggest the organic material accumulation is due in part to cooler soil temperatures and lower litter quality in coniferous forests.

Pastor et al. (1984) reported net aboveground production, nutrient return to litter, and litter quality were highly related to mineralization. Greater mineralization rates were related to higher production and litter return rates. They also reported higher organic content in ecosystems with litter of high C:N or C:P ratios.

Ecosystems of low mineralization resulted in lower aboveground production (Pastor et al. 1984). The annual litter fall (leaf and twigs) is a major contributor to organic matter and nutrient input by deciduous species (Louiser and Parkinson 1976; Bartos and DeByle 1981). Louiser and Parkinson (1976) found aspen litter weight exceeded balsam litter weight on an annual basis of 6:1. They also found, that other than calcium, nitrogen accounted for the bulk of nutrients returned to the soil on an annual basis. Annual dry weight leaf litter input was 215g dry wt. m^{-2}. This is more than the annual leaf litter input (139.7g dry wt. m^{-2}) reported by Bartos and DeByle (1981).

Density and species composition of a stand will influence the amount of litter produced. Litterfall can be influenced by the dominant tree species, stages of development and tree density (Tietema and Beier 1995). Lodhiyal et al. (1994) reported retranslocation (nutrient movement out of senescing leaves) in individual trees during senescence of *Populus* species at different densities were similar for nitrogen, phosphorus and potassium. Net primary production was greater in high density stands than low density stands, possibly due to mass movement induced by higher densities. Also, net nutrient uptake by vegetation in high density stands was greater than low density stands due to higher nutrient concentrations resulting from greater nutrient returns through litterfall. Accordingly, nutrient availability in high density stands was greater due to larger amounts of litterfall returned to the soil and more efficient nutrient extraction from soil (Lodhiyal et al. 1994). However, there would be greater competition from a high density stand for available nutrients.

The purpose of this study component was to investigate to what degree an aspen overstory can maintain or improve productivity as measured by plant available nitrogen. Annual litter production has been identified as a major source of nutrient recycling from year to year (Vitousek 1982). The ability to recycle nutrients from litter will directly effect the productivity of a site (Wedin and Tilman 1990).

Methods

See experimental design (Chapter 2) for plot layout, light methodology, and thinning methods.

Nitrogen mineralization was assessed from May through September in 1999, 2000 and 2001 using *in situ* incubation of soil cores (Nadelhoffer et al. 1985). Pretreatment samples were also taken in 1998. An assumption is made that mineralization rates are the same as the surrounding soil (Pastor et al. 1984; Nadelhoffer et al. 1985). At twelve locations in each treatment plot, one PVC core (8cm diameter, 35cm depth) was placed in the ground to a depth of 25cm. All humus and organic material were removed from the site prior to inserting the core in the ground. Cores were covered with duct tape and incubated in the ground for 45 days. This was repeated three times over the growing season. Bulk samples retrieved from PVC tubes were sieved (0.5 cm) and thoroughly homogenized by hand. All coarse woody debris, roots, and decaying wood were removed prior to preparation for extraction.

For extractions, 50g weight of soil was treated with 100 ml of 1M KCL to determine extractable NH_4^+-N, and NO_3^--N. Mixtures were shaken for one hour before storing in a refrigerator overnight at 4°C, allowing for settling of solution. The following day samples were decanted and filtered through Whatman No. 40 filter paper. Sample extractions were carried out as soon as possible, or were frozen at -40°C until processing. KCL standards were prepared for analysis of purity. Extractions were frozen at -40°C until sent to either the University of Alberta or the BC Ministry of Forests Analytical

Laboratory. Total available nitrogen was compared over the growing season and between years. Identical analytical processes were used at both the University of Alberta and the Ministry of Forests, however liabilities in data may arise due to separate laboratory logistics (i.e. contamination or equipment calibration). These possible limitations are acknowledged.

Gravimetric soil moisture was determined by drying approximately 100 grams of mineral soil at 40 °C for 72h (Kalna and Maynard 1991). During the first three seasons, samples from each treatment plot were amalgamated into one sample for early, mid and late growing season analysis. In 2001, individual samples were analyzed, providing a large sample size for this year.

The research site and sampling were designed to accommodate a number of analytical processes. Soil nitrogen between seasons and years were compared using repeated measures analysis of variance performed in SYSTAT 10 (2001), $\alpha = 0.05$.

Results

Total soil nitrogen tended to increase from spring through to fall in all treatments for all years (Table 8). Pre-treatment soil nitrogen was lower in all treatments in 1998 than in the spring of 2001, except for treatment plot 1 (untreated). In 2001, available nitrogen over the growing season increased in most treatments, treatments 4, 7, and 8 being the exceptions. Treatment 5 increased from spring to summer, only to return to spring levels in the fall. There was no clear trend in 2000. Available nitrogen increased in four of the ten treatments and decreased in the other six. In the fall of 1999, there was a ten-fold increase in soil nitrogen availability in all treatments from spring and summer.

No significant difference in nitrogen can be established between treatments. Without covariants, there was no significant difference among treatments F(9,20) = 0.223 p = 0.987. However, within subjects ANOVA, produced significant results (F(2,18) = 5.038, p = 0.012, (Table 9) with soil moisture (years 1999 to 2001) as covariants included in the model. In 2001 and 2000 soil moisture was not significant, but it as was in 1999.

Table 8. Total (ppm) available N throughout the growing season by treatment site.

Thin %	Site	Total 01SP	Total 01SU	Total 01FA	Total 00SP	Total 00SU	Total 00FA	Total 99SP	Total 99SU	Total 99FA	Total 98SP
0	1	3.08	2.91	4.07	2.96	4.07	1.78	1.22	2.68	30.33	3.82
15	7	4.93	4.63	3.46	3.46	5.04	6.08	0.99	1.34	22.27	3.2
30	9	4.92	3.94	4.95	24.32	4.79	0.89	0.14	1.21	31.99	3.73
40	8	8.48	8.01	4.1	2.45	6.32	3.15	1.12	2.97	31.94	3.6
50	2	2.63	2.44	5.48	2.92	3.06	0.211	1.22	1.81	33.26	2.43
60	3	2.93	2.31	6.06	2.55	3.99	2.68	1.5	1.44	24.4	2.72
70	5	5.15	8.38	5.12	5.08	3.23	1.66	1.16	1.91	32.75	0.82
80	6	2.81	3.19	5.38	7.77	4.93	0.99	0.73	2.39	33.12	2.06
90	10	4.03	3.85	8.29	2.73	5.32	0.56	0.91	1.08	27.41	0.93
100	4	5.2	2.3	4.19	1.42	2.85	1.73	1.32	1.71	23.86	0.83

SP=spring, SU= summer, FA = fall, 01= 2001, 00 = 2000, 99 = 1999, 98 = 1998.

Table 9. ANOVA table for within subjects, nitrogen, and site, with moisture in years 1999 to 2001 as covariants.

Source	SS	df	MS	F	P
Nutrient	496	2	248	5.038	0.012
Site	572	18	31.8	0.646	0.837
Moisture 2001	39	2	19	0.403	0.671
Moisture 2000	1.11	2	0.559	0.011	0.989
Moisture 1999	386	2	193	3.919	0.029
Error	1675	34	49		

Analysis of variance for nutrients in the spring, summer and fall of 2001 showed a significant difference between sites throughout the year (Spring F(9,103) = 5.825, p = 0.001; summer F(9,110) = 5.753, p = 0.001; fall F(9,110) =5.626, p = 0.001). Plots of the means for spring summer and fall are shown in Figures 9, 10, and 11 respectively. No clear trends in nitrogen availability are identified. With respect to available nitrogen, an equal number of treatments increased and decreased by the fall of 2001.

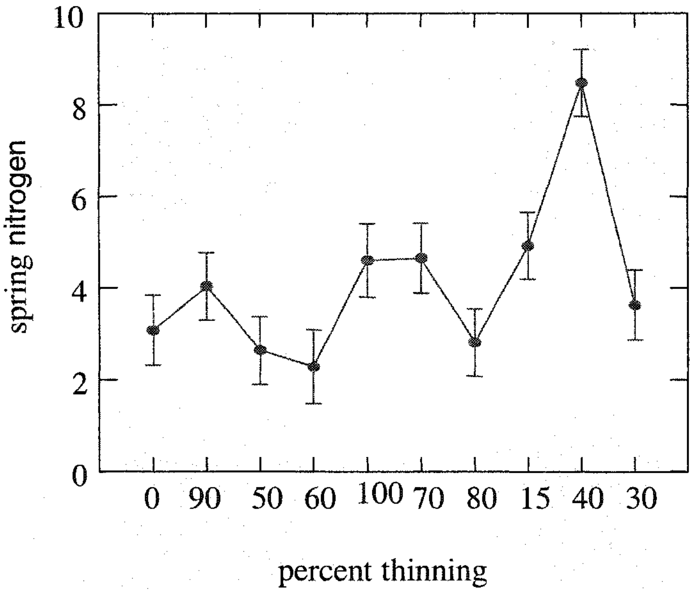

Figure 9. Mean total nitrogen availability by percent thinning for spring 2001.

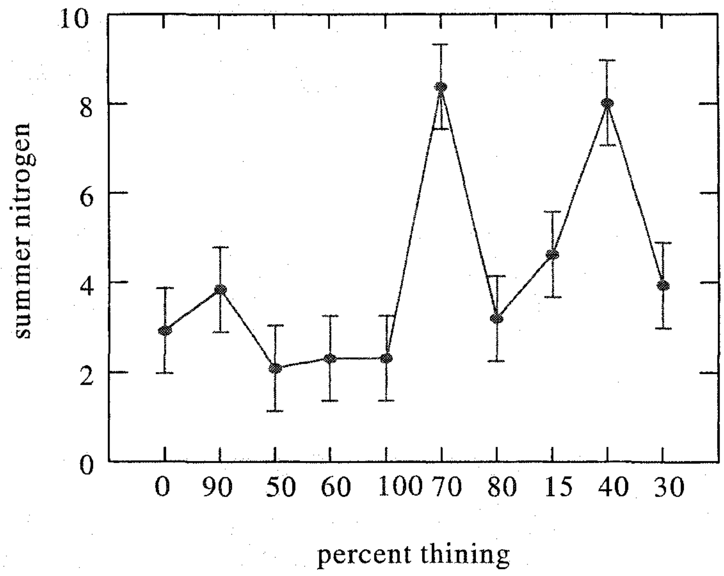

Figure 10. Mean total nitrogen availability by percent thinning for summer 2001.

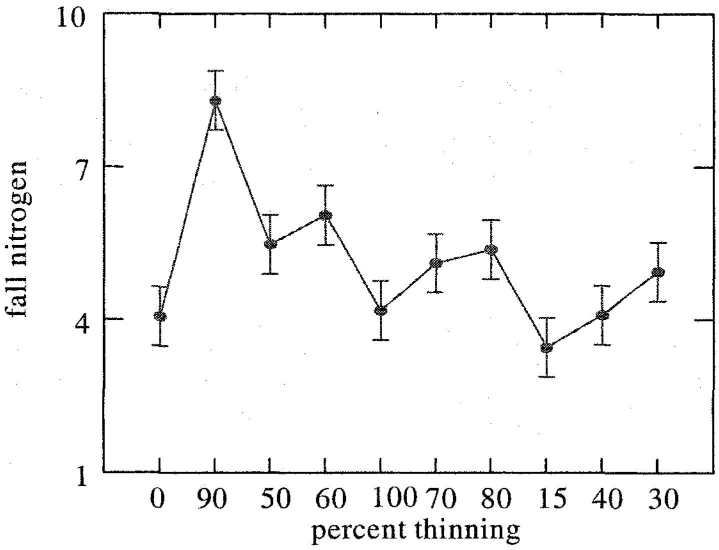

Figure 11. Mean total nitrogen availability by percent thinning for fall 2001.

Environment Canada provided daily precipitation records for April through September in each of 1999, 2000 and 2001, and yearly average (ave) precipitation based on 30 year normal precipitation between 1961 and 1990 (Environment Canada, Canadian Climate Normals 1961-1990, 1993) (Table 10). Monthly precipitation was calculated and the years were tested for differences. Test of precipitation among all years showed a significant difference in the amount of precipitation received in Fort St. John between 1999, 2000 and 2001, F(3,2) = 20.635, p=0.047.

Figure 12 shows the plot of monthly precipitation for the three years. Precipitation in 1999 was less than in 2000 and 2001 for most months shown. The majority of precipitation falls in the form of rain. June was the wettest month in all years.

Table 10. Monthly precipitation at Fort St. John, BC.

Year	April	May	June	July	August	September	Total
1999	8.6	14	77	28.4	23	52	203
2000	13.2	37.4	65.7	74.8	67	55.2	313.3
2001	26.9	56.6	111.1	71	21.8	22.8	310.2
Yearly Ave.	20.8	40.9	67.0	73.7	57.5	43.9	303.8

Total precipitation is significantly different between years, F(3,2) = 20.635, p = 0.047.

June and September precipitation in 1999 was similar to 2000 and 2001. However, total precipitation in the summer of 1999 was a third less than 2000 and 2001. No difference in soil moisture was found between plots in any year (data not shown).

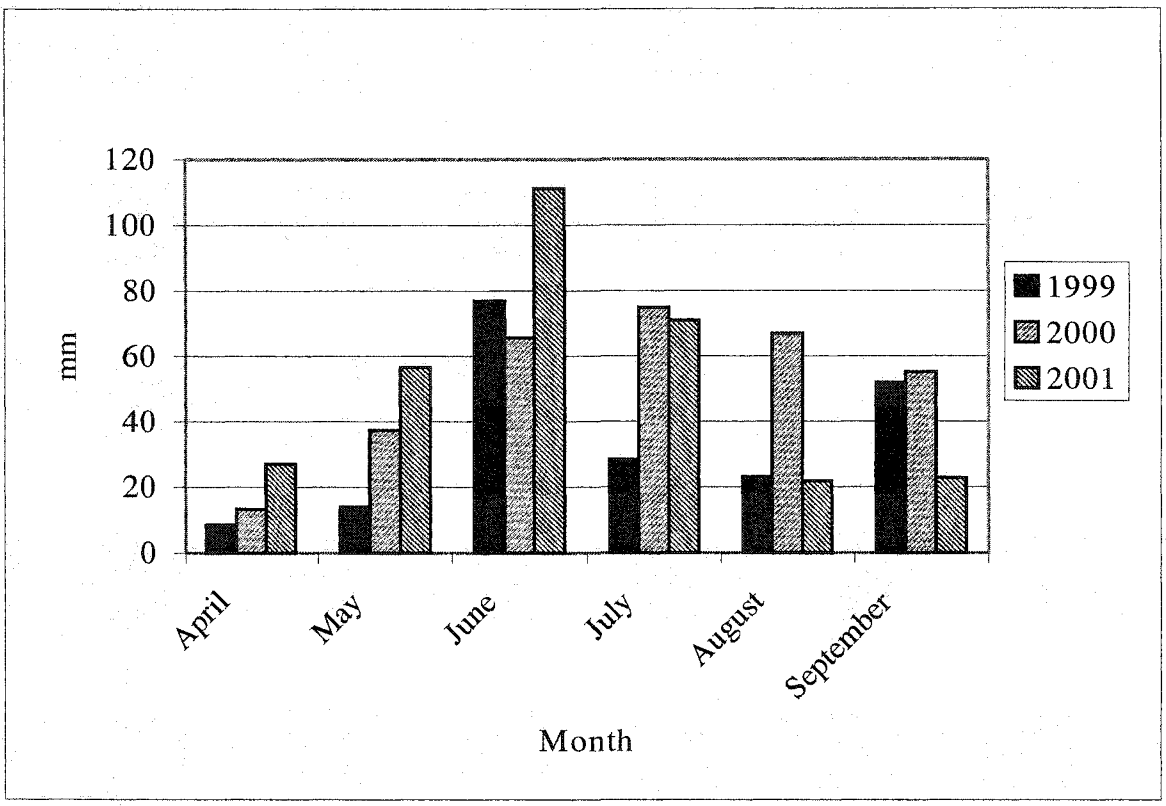

Figure 12. Monthly precipitation at Fort St. John, BC., for April through September, in 1999, 2000, and 2001.

A significant difference in total nitrogen was observed among treatments (F(9,1) = 8.539, p = 0.001) during 2001 (Figures 13, 14 and 15). A post hoc analysis (Tukey HSD) found treatments differed between spring and fall (p=0.027), summer and fall (p=0.024), but not between spring and summer. A greater amount of total nitrogen was available in fall compared to spring or summer. Mean soil nitrogen in spring and summer were both 4.2 ppm and fall was 5.1 ppm. Overall, substantially more nitrogen was available in 1999 than in 2000 (F(28,1)=23379, p = 0.005 (Table 11).

Table 11. ANOVA summary for nutrients in 1999 compared to 2000.

Source	SS	df	MS	F	P
Nutrients 1999	523.7	28	18.7	23379	0.005
Error	0.001	1	0.001		

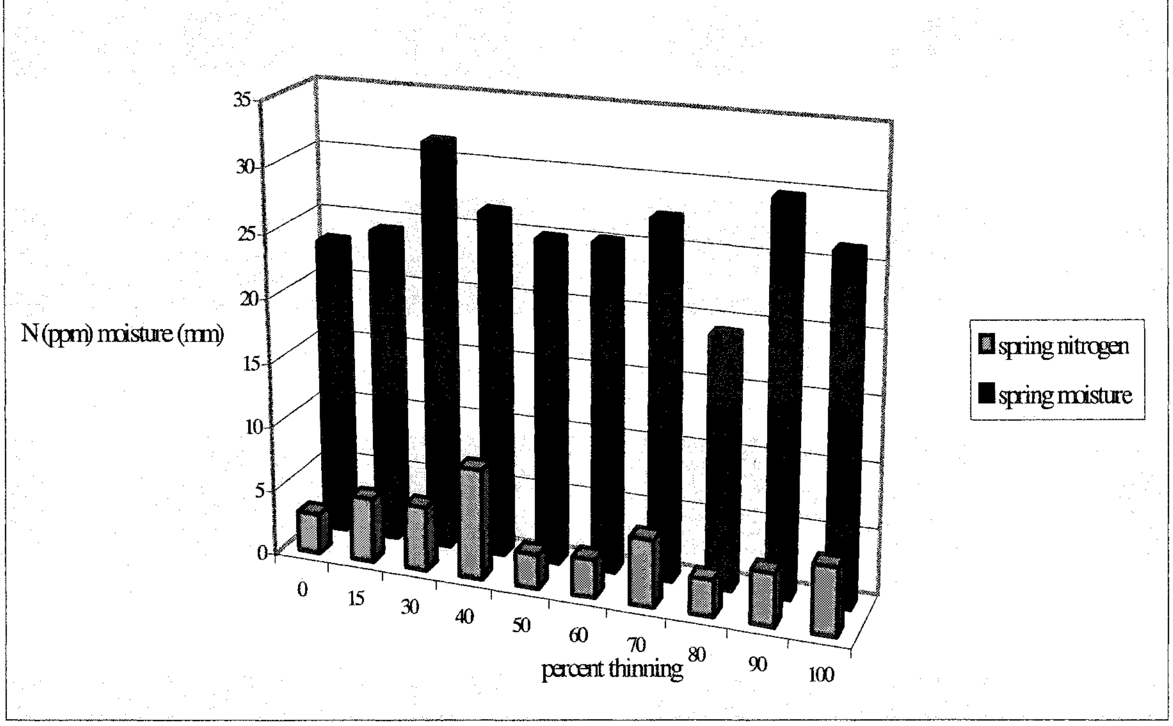

Figure 13. Soil moisture and nitrogen in spring 2001 by thinning treatment.

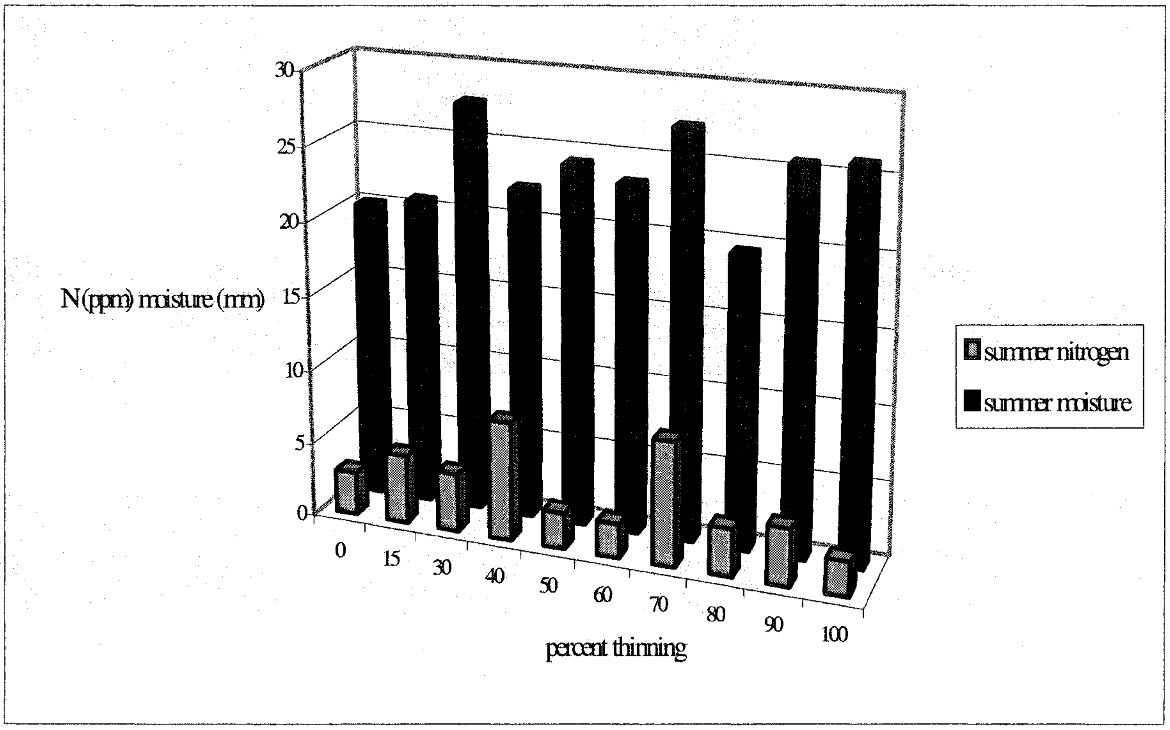

Figure 14. Soil moisture and nitrogen in summer 2001 by thinning treatment.

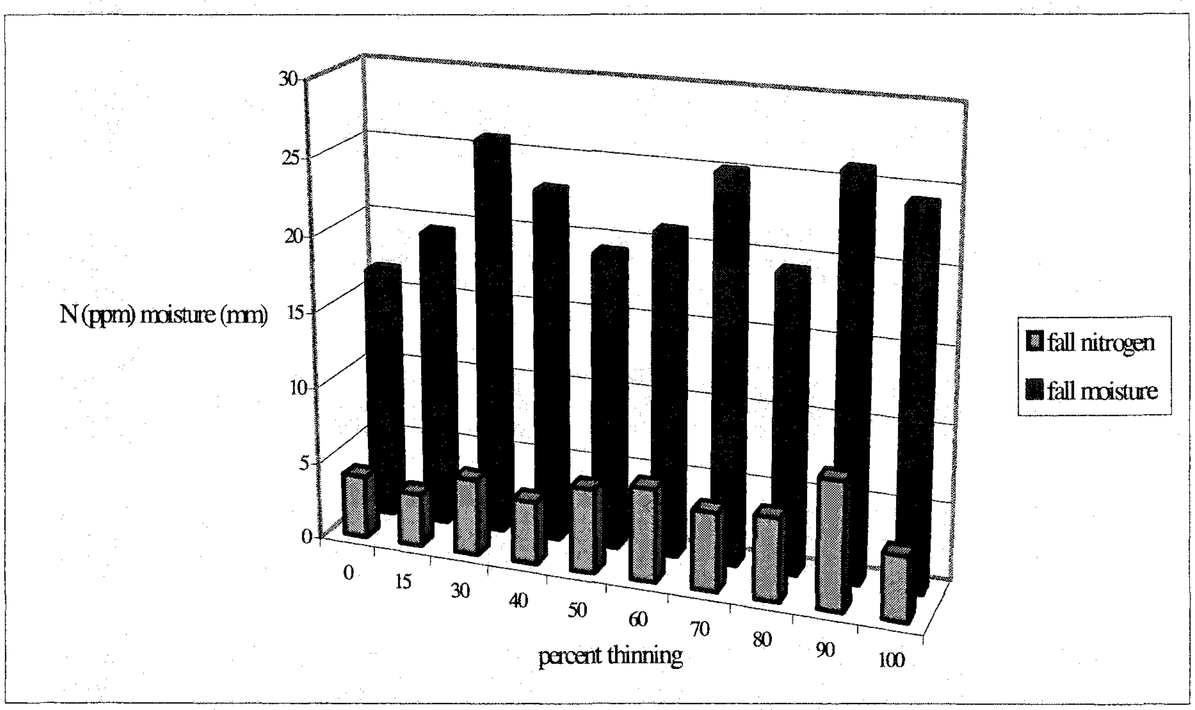

Figure 15. Soil moisture and nitrogen in fall 2001 by thinning treatment

Discussion

Total soil nitrogen availability generally increased throughout the growing season in all years. Soil inorganic nitrogen typically increases in spring, as soil microbial activity increases and microbes take advantage of organic nitrogen that has accumulated from late fall of the following year to spring (Groffman et al. 1993). Litter is the major source of organic nitrogen in forest soils (Bartos and DeByle 1981; Flanagan and Van Cleve 1983; Viereck et al. 1983), and the amount of litter fall has a direct relationship to site productivity (Tietema and Beier 1995) of the stand by providing a potential pool of inorganic nitrogen and other primary elements used in cellular growth and production. The speed at which primary decomposers convert organic nitrogen to inorganic nitrogen, is controlled by factors such as temperature, moisture, substrate, and litter quality

(Meentemeyer 1978; Melillo et al. 1982; Viereck et al. 1983; Pastor et al. 1984). Although not tested, litter fall in each of the treatment sites continued in all years as girdled aspen flushed and senesced each year of the study. This litter fall may have provided a sufficient supply of organic nitrogen in all treatment sites to maintain a relatively constant inorganic nitrogen pool. The amount of inorganic nitrogen is directly related to microbial activity (Muys and Lust 1992) that can either mineralize or immobilize nitrogen (Priha and Smolander 1999). No respiration data was gathered and therefore it is not known if the primary producer population varied among sites. Because this 45-year old stand has remained intact since a stand initiating fire, it can be concluded that soil organisms should be consistent through all treatment plots. Other factors that may affect soil organisms such as soil substrates were homogenous among sites. Soil organisms and substrate were likely not contributing factors in the variation of nitrogen between years or during the growing season.

The half-life of aspen leaf litter has been described by Van Cleve (1971), as 1.8 years and by Bartos and DeByle (1981), as 2.1 years. Aspen litter reduction is rapid in the first year followed by a slowing in decomposition (Bartos and DeByle 1981, Prescott 2000) with 99 percent removal taking approximately 24 years (Lousier and Parkinson 1976). There are many variables involved in the decomposition formula, including temperature, moisture, soil substrate, organisms, and litter type. Nitrogen availability following decomposition, mineralization, and nitrification becomes the most limiting soil element to plant growth (Vitousek et al. 1979; Flanagan and Van Cleve 1983; Weetman et al. 1988; Courtin et al. 1988; Lodhiyal and Singh 1993; Klinka et al. 1994; Lundell 2001).

Soil moisture influences element transfer and leaching in soils. Nitrate itself is highly mobile (Vitousek et al. 1979; Davidson et al. 1992) but mass movement may also occur (Whelan et al. 1995). Precipitation varied markedly between 1999, 2000, and 2001, and between months of each year. Variability in precipitation may have played an important role in the findings. The majority of precipitation fell on a few days in June, July, and August of 2000 and 2001, and although the total monthly precipitation was near normal for the period (Table 10) with the majority falling in a short period of time, the soil would rapidly become saturated. Once field capacity is reached, additional moisture will overtax the soil profile and leave the system, taking nutrients along with it. The largest losses of soil nitrogen come from leaching and this can be exacerbated by heavy rain events (Whelan et al. 1995).

In 1999, precipitation was near normal in June and September. However, for the growing season precipitation was two-thirds of normal. If, as mentioned above, and nutrients are lost via leaching when soils are near field capacity, it is expected that nutrients would be higher in years with less precipitation due to minimal leaching. This may have been the case in 1999. Near normal rainfall in 2000 and 2001 suggest nutrient levels in these years should be similar, as leaching and plant uptake should also be similar in both years. The ten-fold increase in nitrogen reported in the fall of 1999, may be a result of low soil moisture, thus preventing leaching. Additionally, added plant moisture stress in 1999 would have slowed growth and assimulation of nutrients from the soils resulting in a soil nitrogen pool.

The mostly likely source of nitrogen variability is through soil moisture content. The tenfold increase in nitrogen in fall of 1999 is consistent with moisture data. A lack of leaching over the late summer and fall is compatible to what would be expected with other leaching information (Whelan et al. 1995), however one cannot rule out this result being an artifact of different laboratories used in 1999 and 2000/2001.

Conclusions

Aspen litter has been shown to be of higher quality than conifer litter. The ability of aspen to recycle nutrients (nitrogen) may be used as a natural source of nitrogen for forest soils. In this study, plant available nitrogen was maintained in all sites throughout the growing season. The potential for nutrient depletion and immoblization exists if regenerating stands are returned to coniferous monocultures. Mixedwood stands where aspen and conifers (usually white spruce) grow in concert, would stand to benefit over the long-term if available nitrogen can be maintained by allowing aspen to occupy the site. Aspen litter from girdled trees may have distorted the results. Girdled trees will soon die, and this will change the litter and nutrient dynamics of the plots. The changes in nutrient dynamics may be reflected in spruce and aspen growth in future years.

As with all research, there are limitation based on the design and assumptions. The study of nitrogen availability also has its limitations. I looked only at the available nitrogen and not the change in mineralization and nitrification rates over the growing season. Available nitrogen can act as a surrogate to mineralization and nitrification but does not replace the importance of measuring these rates for productivity.

5. SUMMARY

Traditional silviculture techniques in Boreal mixedwood forests of North America have concentrated management efforts on the re-establishment of conifer species. Following harvest of mixedwood stands, it is not uncommon to have a newly planted crop of conifers (usually spruce) quickly overtopped by more rapidly growing aspen. Although changes in BC free growing stocking definitions have began to allow more diverse management strategies, change is slow. Control of competing vegetation remains a priority for licensees and is typically achieved by one of three techniques:

1) Manual brushing and control (physical);
2) Biological control (sheep); and
3) Chemical control (herbicide).

The technique chosen is dependent on the management objectives and the extent of competition.

In western Canada, aspen is most commonly found in association with white spruce, lodgepole pine, or Douglas-fir (Peterson and Peterson 1995). In the Boreal forest, white spruce and aspen are the most common mixedwood types on upland forests (Delong 1991). Understanding the dynamics of Boreal mixedwood succession provides insight into pathways that help establish and transform the forest. This knowledge could be used to develop forest practices that manage mixedwoods to achieve maximum forest productivity.

Growth response of white spruce and aspen

White spruce growth responses varied depending on the growth rate and canopy position in the stand prior to treatment. In the first year following treatment, breast height diameter growth increased for all treatments except one. By the second year, all treatments had increases in radial growth. However, the expected growth difference among sites that would describe a preferred treatment regiment did not occur. The greatest response was at 60 % removal, followed by 80 % and 100 % removal. Root collar radial growth was more variable than diameter. Fifteen percent removal showed the greatest growth response followed by 50 % and no treatment.

Two questions immediately come to mind. First, why was there no clear response to the thinning treatment, and second what mechanisms control the observed response.

To answer the first question, we need to look at the thinning operation. Standards set by the British Columbia Ministry of Forests restricted which trees were physically cut and which were girdled. In 2001, aspen trees that had been girdled in 1998 were still leafing out. This means it will be at least 2002 and possibly 2003 before we achieve target thinning levels.

Diameter growth was bimodal, with the trough in the 32 to 45 light percent range. Other research has found growth response to increase in a linear fashion (Lees 1966; Steneker 1967; Yang 1989, 1991; and Yang and Bella 1994) with the least growth correlated to low light and the greatest growth correlated to high light. This data does not show this response. However, we measured response two years after treatment. Others reported their findings as whole responses 10-35 years after treatment. Ferguson and Adams (1980) suggested grand fir response to overstory removal was correlated to tree characteristics (height, vigor, pre-release growth rate) and site conditions (moisture and temperature) interacting with physiological shock. The shorter response time may not have allowed sufficient time for white spruce to adjust physiologically to the new environment.

Most likely, white spruce at the site is experiencing a similar phenomenon to the planting check described by Mullins (1963). This is related to the physiological responses described by Ferguson and Adams (1980). Burdett et al. (1984) found similar results in ground-line diameter, height, and diameter height ratios in the first two years after out-planting of white spruce in the interior of British Columbia. They did not begin to see increases in any growth attributes until the third growing season.

It may still be too soon after treatment to see a significant difference in growth. White spruce has been described as being relatively plastic (Givinish 1988; Nienstaedt and Zasada 1990) and may begin to respond in the next two to three years.

Aspen responded with increased growth in all treatments. However, the untreated site showed the lowest response at just 3 percent. The greatest response occurred in treatments six (80 % removal) and ten (90 % removal). The response of aspen is expected and is consistent with results of other researchers (Steneker 1964; Bella 1975;

Huffman 1999; and Penner et al. 2001). However, one must realize the shortfalls to thinning aspen. Thinning aspen is only considered beneficial with good clones and on good sites, otherwise the volume lost to thinning is never regained (Bella and Yang 1991; Penner et al. 2001). It is too soon to speculate whether any of the thinned sites in this study will regain the volumes lost to thinning or if the time required for the remaining aspen to product peeler or pulp logs.

Competition by herbs, woody shrubs and deciduous trees has been well documented (Eis 1980; Brand 1985; Kolb et al. 1989; Hogg and Lieffers 1991; Groot 1999) and has been described as the greatest obstacle to plantation success (Delong 1991) in the interior of British Columbia. In aspen/spruce mixedwood forests where aspen has been removed or treated to release spruce, the understory herbaceous vegetation may respond and create a new competitor to the spruce. Changes in light, temperature and moisture that are considered favorable to seedling growth (Lieffers et al. 1993) may also favor herbaceous vegetation growth. Bluejoint grass and fireweed are two common herbaceous competitors to white spruce plantations (Lieffers and Stadt 1993).

Partial removal of the aspen canopy increased the cover of both species. On this site, bluejoint and fireweed increased in cover with increasing light at similar rates at the low light levels. At higher light levels fireweed's rate of increase declined more than bluejoint. At the higher light levels bluejoint appeared to be out-competing fireweed and in fact suppressing fireweed. Therefore, when planning to open a canopy to allow greater light availability, full canopy removal can shift competition from aspen to understory grasses and herbaceous vegetation. The key issue becomes at what age and height can removal of the canopy take place to eliminate competition to the understory coniferous crop. I suggest that at the time of treatment the height of the crop tree must be equal to or greater than the anticipated height of the competition two years after treatment. This will ensure crop trees are not overtopped by competition and the mechanical damage of vegetation press is eliminated.

Nitrogen

Nitrogen has been identified as the soil nutrient most limiting to plant growth in forest ecosystems (Vitousek et al. 1979; Flanagan and Van Cleve 1983; Weetman et al. 1988; Courtin et al. 1988; Lodhiyal and Singh 1993; Klinka et al. 1994; Lundell 2001). Examination of the inorganic nitrogen content of the soil over a three-year period found time and moisture as the controlling variables. There was an increase in available nitrogen over the growing season in all years. This can be explained by an increase in microbial activity during the growing season and a readily available organic nitrogen pool supplied by past and present litter accumulation. Aspen litter is readily decomposable and has a half-life of from 1.8 to 2.1 years (Van Cleve 1971; Bartos and DeByle 1981).

The amount of litter produced also plays an important role. Aspen typically produces greater quantities of litter than conifer. Greater quantities combined with higher quality litter all lend to increased productivity without the advent of anthropogenic augmentation of the nutrient pool. Therefore, it can be adventitious to maintain a component of aspen on these sites to contribute to soil productivity.

6. FUTURE RESEARCH AND POTENTIAL BENEFITS

Boreal mixedwoods are still poorly understood and demand more of our attention as their importance as a source of wood supply increases. Succession trends in Boreal mixedwoods need to be understood if we are to manage these systems to the best of our ability. Increasing our knowledge of natural succession patterns will help our long-term planning scenarios. I believe studying aspen/spruce mixedwoods in a chronological sequence will provide the greatest understanding regarding the structure of future stand composition when managing clear-cut scenarios or other silviculture systems.

We also need to gain a better understanding of the timing of growth and physiological response of understory conifers to changes in their environment. Opening the stand to increase sunlight will unquestioningly increase growth of understory spruce. However, quantifying mechanical damage that may occur from mixedwood management also needs to be explored. This is, of course, important when determining inventory and cut control measures. Without a clear understanding, the stands we are managing may be over or under estimated in volume. Neither scenario is beneficial to the public, government or industry, as we need to know what we are planning for and how long it will take to get there, if at all.

The mechanism of vegetation damage to crop trees needs further investigation. Implementing the right pest management plan is contingent on knowing how vegetation affects the crop tree not just that it affects the crop tree. Without this knowledge, blanket prescriptions will be produced that are indiscriminate and will inflict a substantial amount of collateral damage.

Can mixedwood management increase productivity? More research is needed to answer this question. The two-pass system proposed by Navratil (1996) may work, but more research needs to be conducted regarding the health of the spruce understory (physiological shock, windthrow) and aspen regeneration. Growing two or more species that utilize available resources in a manner that limits interspecific competition should increase productivity. However, the degree to which competition limits productivity of each species needs further investigation. Resource availability by way of nutrients, light, water, soil temperature, and pest management all need to be factored into the equation.

McDougall (1988), in his keynote address to the symposium on northern mixedwoods held at Edmonton Alberta in 1988, stressed how difficult it is to return mixedwood stands to mixedwood. Past experience has demonstrated that mixedwood stands are resilient and reestablish even when efforts are intended to eliminate them. The difficulty is exacerbated by the aggressive colonization of species such as aspen resulting in hardwood dominated stands immediately following disturbance.

Inclusion of the mixedwood landbase in the inventory can increase total landbase utilization. When both hardwoods and softwoods are utilized, additional landbase is employed which was previously underutilized. This has the potential to increase merchantable volumes at time of harvest while reducing road building and harvesting costs. By taking full advantage of the landbase, product diversity increases, and consequently greater industry stability and employment. As the industry diversifies, there could be reductions in total hectares harvested each year because greater return is generated from each hectare.

Harvesting in mixedwoods

Mixedwood development assumes aspen and white spruce will be grown on the same land base. Based on the successional characteristics (i.e. vertically stratified with aspen over spruce) of aspen-spruce stands, Brace and Bella (1988) proposed a two-pass tending and harvesting system. In the first pass, aspen 60-80 years old and any spruce greater than 25 cm diameter (dbh) would be harvested. Sixty years later, all remaining species would be harvested. The focus of their work followed the trend of placing greater priority on spruce, then other species.

This two-pass model depends on spruce understory densities and structure, prior to aspen removal. Aspen may fill in available space unoccupied by spruce if conditions, such as soil temperature, allow. Yield at second harvest depends on age and structure (i.e. distribution) of the understory spruce, as there is an emphasis to retain this resource, and the amount of aspen that has reestablished.

Harvesting trials in Alberta showed 40% - 80% of white spruce understories are destroyed or damaged during harvest when high and medium precautions were taken. Damage to understory is related to density, harvest equipment, operational technique, and level of planning and supervision (Navratil 1996). Selecting the appropriate site, harvest mechanism and training is as important as attempting to protect understory. The size and density of understory spruce that would minimize damage must be quantified. Harvesting in aspen mixedwoods, where a sufficient understory exists for protection, needs further investigation.

Mechanisms of benefits

In British Columbia, mixedwoods represent a substantial component of the productive forest landbase (6.4%). In northeast B.C. the mixedwood component is even higher (21.5% in Fort St. John and Dawson Creek Forest Districts) and 36.9% in Fort Nelson Forest District (Cuthbert 1991). This high component of mixedwood can lend itself to a balanced management approach based on the following potential benefits (Comeau 1996):

- mixedwoods occur naturally;
- they provide a valuable visual resource;
- they are diverse and support a diversity of organisms;
- mixedwood stands may reduce impacts from forest pests and diseases, and reduce risks of volume loss;
- broadleaf species can serve as a valuable nurse crop for conifers;
- improved nutrient availability in mixed stands;
- mixedwood stands may improve wood yield over pure stands;
- growing mixedwood stands may be more readily sustainable;
- cost savings can occur by less intensive silviculture management;

- mixedwood stands may provide greater economic returns; and
- mixedwood stocking standards may require management of mixtures.

The mechanisms most likely affected by maintaining an aspen canopy are more favorable soil temperature and moisture regimes during germination and seedling establishment. Potential benefits of mixedwood management may be enhanced nutrient recycling rates and protection from windfall and disease.

Furthermore, there may be greater volume production on mixedwood stands. Over a natural rotation of 140 years, the aspen component is greatly reduced due to mortality and replacement by white spruce. By removing aspen at age 50 to 60 years, not only is the aspen component utilized, but spruce yield is also increased because it is released earlier.

Other benefits include the reduction in disease, insect and frost damage. Monocultures can be subjected to heavy insect and disease damage because they provide optimal habitat for pathogens. Mixedwood stands tend to break or disrupt the pathogens habitat, creating barriers or obstacles that effectively reduce damage. Further benefits can be the elimination or reduction of understory competitors such as bluejoint and fireweed. A partial cut allowing 40 % light transmission may result in only 20 % competition cover improving the probability of seedling survival.

7. CONCLUSION AND RECOMMENDATIOINS

Aspen and spruce mixedwood stands can be managed in concert to take advantage the attributes of both species. In young juvenile stands, where aspen forms a well constructed canopy over spruce, the canopy can be opened to allow more light for the growth of understory spruce. However, opening the canopy prior to spruce reaching a height of one to one and a half-meters may subject them to severe competition from understory herbs. The aspen canopy can perform two important functions: Firstly, it can control vegetation competition, and secondly, the litter produced will act as a long-term source of inorganic nitrogen. The recommended degree of opening is based on the following assumptions:

1) Spruce require between 40 and 50 percent full sunlight for maximum height growth;
2) Understory competition can be adequately suppressed at 40 percent full light; and
3) Aspen has the ability to maintain soil productivity through litter deposition at a basal area of $15m^2$, and based on this study this corresponds to about 40% light; based on this study.

Opening the canopy of a 45-year old aspen and spruce mixedwood stand to a targeted aspen basal area of $15\ m^2$ will achieve the objectives of managing understory competition, ensuring long-term productivity is maintained, and increasing growth of spruce and aspen.

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