University of Alberta

Competition effects on growth of five conifer species in southwestern British Columbia and northern Alberta

by

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Abstract

I examined the effects of N-fixing and non N-fixing woody vegetation on the growth of conifers with different levels of shade tolerance. At a site near Maple Ridge (BC), I examined the effects of red alder (*Alnus rubra* Bong.) and paper birch (*Betula papyrifera* Marsh.) on western redcedar (*Thuja plicata* Donn), western hemlock (*Tsuga heterophylla* Sarg.) and Douglas-fir (*Pseudotsuga menziesii* Franco). In an area south of Grande Prairie (AB), I examined the effects of green alder (*Alnus crispa* (Ait.) Pursh.) and other competitors on white spruce (*Picea glauca* (Moench) Voss) and lodgepole pine (*Pinus contorta* Dougl. ex. Loud.). At Maple Ridge red alder improved nitrate availability, while at Grande Prairie relationships between green alder and nitrates were not significant. Among the competition measures tested, light availability (DIFN) was generally best correlated with conifer growth, although the strength of the competition indexes was highly dependent on the species analyzed.

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1 General introduction

"The management of competing vegetation has evolved with forest management over the past half century and is now an integral part of modern forestry practice in many parts of the world. The wood yield gains from the management of competing vegetation in Pacific north-western forests range from 4 to 11800 per cent" (Wagner et al. 2006).

Conifer plantations are extremely susceptible to competing vegetation during early stages of their establishment, since crop trees are small and slow growing (Shropshire et al. 2001). Interspecific competition from woody and herbaceous vegetation is dynamic and forest managers are likely to achieve the greatest gain in tree growth from managing vegetation during the first years after planting (Wagner and Radosevich 1998).

In North American forests herbaceous species such as *Calamagrostis canadensis* (Michx.) Beauv. and fireweed (*Epilobium angustifolium*) are widely distributed and can seriously inhibit growth of conifer seedlings (Lieffers et al. 1993; Maundrell and Hawkins 2004). Also tall shrubs and other tree species such as green alder (*Alnus crispa* (Ait.) Pursh.), Sitka alder (*Alnus crispa* ssp. *sinuata*), red alder (*Alnus rubra* Bong.), willow (*Salix* spp.), trembling aspen (*Populus tremuloides* Michx.) and paper birch (*Betula papyrifera* Marsh.) can be aggressive competitors in conifer stands (Walstad and Kuch 1987). During early stages of stand development in boreal forests herbaceous species seem to be more effective at intercepting light than woody competititors; however after the third growing season the situation is reversed (Shropshire et al. 2001).

Results, from long-term studies documenting gains in wood yield associated with managing vegetation (primarily using herbicides) in forests around the world, show that substantial gains can be obtained when competing vegetation is effectively managed (Wagner et al. 2006). In the Washington and Oregon Coast Ranges early removal of competing vegetation around Douglas-fir can double stem volume compared to untreated plots after a 10-year period (Harrington et al. 1995; Monleon at al. 1999). Nonetheless, there is still a lack of general principles for forest vegetation management regarding the strategies to apply to conserve floristic diversity while maximizing desired tree survival and growth (Balandier et al. 2006).

In forestry, competition is often considered as a limiting factor in the process to maximize the yield of selected crop trees, but "unwanted" vegetation can also bring positive effects in relation to available nutrients (Simard et al. 1997), and can offer protection from extreme weather conditions (Stathers and Spittlehouse 1990; Pritchard and Comeau 2004). Before we can predict stand dynamics and future growth, it is important to understand intra- and interspecific interactions among trees.

An important beneficial effect of competing vegetation is the ability that species such as alder (*Alnus* spp.) have to fix nitrogen. As many studies have shown, alder can enrich the soil in nitrogen (and other nutrients such as calcium) (Binkley 1983; Binkley et al. 1992; Bormann and Sidle 1990; Bormann et al. 1994; Radwan et al. 1984; Swanson and Myrold 1997;), in pure red alder stands the rate of nitrogen fixation can be as high as 200 kg ha^{-1} y^{-1} (Binkley et al. 1994), whereas Sitka alder can fix nitrogen at rates ranging from 2 to 15 kg ha^{-1} $year^{-1}$ (Mead and Preston 1992; Sanborn et al. 2002). Also paper birch stands support populations of free-living nitrogen-fixing bacteria, and the ectomycorrhizal fungi linking birch and conifer roots have beneficial effects on the crop trees (Simard et al. 1997).

Many studies have shown how light levels, crown radius and cover of competitors are correlated with the growth of the subject tree (Biging and Dobbertin 1992, Comeau et al. 2003; Wagner and Radosevich 1991; Lorimer 1983). For instance, measures of vegetation cover and basal area of birch (Betula spp.), aspen or red alder are usually strongly related to light levels (Comeau et al. 1993; Comeau 2001; Comeau and Heineman 2003).

Competition indexes are widely used to characterize competition in plantations. The strength of the correlation between any particular competition index and observed growth appears to be heavily dependent upon the species (Lorimer

1983). Popular competition indexes utilize simple measurements which can be collected quickly and consistently in the field.

In summary, our ability to estimate the influence of different tending practices on stand development depends on our understanding of the key factors such as competition that influence growth, development and dynamics of mixedwood stands and their component species (Comeau et al. 2003).

This thesis analyzes various aspects of the competitive effects of woody deciduous competition on the growth of conifers in northern Alberta and south-western British Columbia. Chapter 2 presents results from a study designed to evaluate the effects of red alder and paper birch on Douglas-fir (*Pseudotsuga menziesii* Franco), western hemlock (*Tsuga heterophylla* Sarg.) and western redcedar (*Thuja plicata* Donn) in south-western British Columbia. A second study, initiated in 2006 to examine effects of willow and green alder on white spruce (*Picea glauca* (Moench) Voss), and lodgepole pine (*Pinus contorta* Dougl. ex. Loud.) is summarized in chapter 3. Chapter 4 summarizes the major conclusions from these studies.

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Effects of red alder and paper birch competition on growth of young conifers in Southwestern British Columbia

2.1 Introduction

Red alder (*Alnus rubra* Bong.), paper birch (*Betula papyrifera* Marsh.) and bigleaf maple (*Acer macrophyllum* Pursh) can be aggressive competititors with regenerating conifers in forests of coastal British Columbia (Walstad and Kuch 1987; Shainsky et al. 1994). However, there is also a potential to increase yield by mixing red alder and paper birch with shade tolerant conifers (Comeau 1996). There is substantial interest in finding species mixtures and tending regimes that balance the beneficial and detrimental effects of the various interactions that occur in broadleaf-conifer mixtures. Our ability to estimate the likely influences of different stand tending practices on stand development depends on our understanding of key factors influencing growth, development, and dynamics of these mixedwood stands and their component species (Comeau et al. 2003).

Among conifer species, western redcedar (*Thuja plicata* Donn) is extremely tolerant of broadleaf-induced shade, its seedlings need only 10% of full sunlight to survive (Wang et al. 1994) and the maximum growth rates occur at 30 % of full sunlight (Drever and Lertzman 2001). Douglas-fir (*Pseudotsuga menziesii* Franco) seedling mortality occurs at light levels lower than 20% of full sunlight but at least 40% is necessary for continued growth (Mailly and Kimmins 1997).

The growth of Douglas-fir saplings increases steadily with increasing light with no clear plateau at high light levels (Drever and Lertzman 2001). Western hemlock (*Tsuga heterophylla* Sarg.) is intermediate in shade tolerance between Douglas-fir and western redcedar (Peterson et al. 1996; Harrington 2006) and mortality is evenly distributed along the light gradient (Mailly and Kimmins 1997).

Red alder is present along the entire coast of British Columbia and the best sites to grow alder are in the Coastal Western Hemlock Biogeoclimatic Zones (DeBell and Wilson 1978). Red alder is a common early successional species on sites that have experienced major disturbances such as clearcuts, and/or landslides, in British Columbia red alder can be found in pure stands or in stands with a component of conifers such as: Douglas-fir, western hemlock, western redcedar, and Sitka spruce (*Picea sitchensis* Carr.) (Peterson et al. 1996).

Red alder can improve site productivity through symbiotic nitrogen fixation and can provide shelter for shade tolerant species. The ability to fix nitrogen (N) is due to alder's root system, which is generally extensive and has symbiosis with N-fixing *Frankia* spp. Alder root nodules are permanent and grow continuously (Peterson et al. 1996). Alders are particularly suited to soils damaged by disturbance such as erosion or repeated fires. The highest rates of nitrogen fixation are observed on young, nitrogen-poor soils that have abundant weatherable minerals. Alders in general, but especially red alder, have among the highest rates of symbiotic fixation of atmospheric nitrogen. Healthy alder trees can fix large amount of nitrogen (Binkley et al. 1994). Much of this fixed N becomes generally available within the stand as it is incorporated in the large volume of alder litterfall. Cycling of N is three to eight times faster in mixed red alder stands than in pure conifer stands (Binkley et al. 1992).

In mixed stands nitrogen fixation ranges between 50 and 100 kg N ha^{-1} y^{-1} and in pure stands it can reach rates of 200 kg N ha^{-1} y^{-1} (Binkley et al. 1994). In coastal British Columbia, red alder stands can contribute approximately 65 kg N ha^{-1} y^{-1} of nitrogen, but on sites where nitrogen is generally available this amount is usually smaller (Binkley 1983). Alder detritus is a net source of nitrogen, most of which remains primarily in the top 5 cm of soil (Swanson and Myrold 1997).

Alder litter is also important because it enriches the soil in nutrients such as calcium, magnesium, potassium and phosphorus. The litter decomposes easily, contributing to nutrient cycling. In mixedwood stands, the rate of cycling of P, S, Ca, Mg and K is two to ten times greater than in a pure conifer stand (Radwan et al. 1984). Studies also indicate that litter of other trees also decomposes faster when mixed with nutrient-rich alder litter (Fyles and Fyles 1993). Red alder produces large quantities of nutrient-rich litter every year which can increase the soil organic content, these processes aid in the acceleration of soil development for longer lived species (Bormann and Sidle 1990).

Earthworms seem to prefer litter of alder and other species that fix nitrogen, as they feed at the soil surface and transport litter into the mineral soil. This activity may partially explain high rates of organic matter incorporation and aggregation under alder (Bormann et al. 1994). As a result alder increases soil aggregation and thus decreases bulk density and these factors are thought to influence ecosystem productivity.

Mixedwoods experiments include Douglas-fir and alder, which competes with Douglas-fir for both moisture and light (Shainsky and Radosevich 1992, Shainsky et al. 1994). Studies suggest that the optimal initial density (alder plus Douglas-fir) can vary from 750 to 1250 trees ha^{-1}, with the most favorable density for alder between 50 and 250 trees ha^{-1} (Comeau and Sachs 1992, Hibbs and DeBell 1994). Even in mixtures with a shade tolerant conifer, such as western redcedar, more than about 400 alder per hectare may result in substantial reductions in conifer growth (Comeau and Sachs 1992). Studies on long-term forest succession have shown that Douglas-fir would be virtually absent unless it develops concurrently with the alder in openings within the alder stand (Newton et al. 1968).

Paper birch is generally present across the boreal forests of North America; it is adapted to a wide range of climates and tolerates a wide range of precipitation and temperature. In B.C. paper birch has the greatest growth rates within the Interior Cedar Hemlock (ICH) Biogeoclimatic Zone and is generally associated with dominant genera of *Picea, Abies, Larix, Pinus, Populus*, *Pseudotsuga,* and *Thuja* also occur with birch (Peterson et al. 1997).

Paper birch stands also support significant populations of free-living nitrogen-fixing bacteria (Peterson et al. 1997). Ectomycorrhizal fungi provide mycelial conduits to exploit a range of microenvironments and to link birch and conifer roots. The connecting mycelium can exchange nutrients, carbon and water between trees. In mixed stands, Douglas-fir seedlings have shown to share many ectomycorrhizal fungi over a high proportion of their roots (Simard et al. 1997). Paper birch litter also decomposes rapidly contributing to accelerated nutrient cycling.

A study conducted in a 33-year-old mixed stand of paper birch and conifers indicates that 600 birch ha^{-1} seems to be the optimal density to ensure good protection from wind and sunscald to understorey spruce, while also improving their growth (Comeau et al. 2003). Simard (1990) suggests that 1200-1600 stems ha^{-1} of paper birch have little effect on the long-term growth of associated conifers. Another study on birch-conifer mixtures in southern British Columbia has shown that reducing birch density from 2500 to ≤ 50 stems ha^{-1} significantly improved the growth of 8-year old spruce (Simard and Hannam 2000).

Light levels, crown radius and cover of competitors have been shown to be correlated with subject tree growth (Biging and Dobbertin 1992, Comeau et al.

2003, Wagner and Radosevich 1991, Lorimer 1983). Measures of vegetation cover and basal area of birch, aspen or alder are closely related to light levels (Comeau et al. 1993, Comeau 2001, Comeau and Heineman 2003). Competition indexes have been widely used to characterize competition effects and are useful for predicting effects of competition on tree growth. The strength of the correlation between any particular competition index and observed growth appears to be heavily dependent upon the species (Lorimer 1983). Each species responds to stress from competition differently and competition should be viewed as dynamic, since it will change over time as well (Burton 1993).

Hegyi (1974) developed a distance-dependent competition index for Jack pine (*Pinus banksiana* Lamb.), which has also been widely used for other species:

$$\mathbf{CI_{Hegyi} = \sum (D\mathit{j} / D\mathit{i}) / DIST\mathit{ij}}$$

where D = DBH

$DISTij$ = distance between the tree i and competitor j

Competitors were considered to be all trees within 3.05 m radius of the subject tree. Studies with Hegyi's competition index, on Loblolly pine (*Pinus taeda L.*) and its competitors, have shown strong correlations with annual increments in height and diameter (Daniels 1976). One limitation to the use of diameter-distance indexes is the difficulty in interpreting the change in the value of the index over time. When competitors are selected within a fixed radius from the subject tree, competition will appear to decrease over time as the number of stems per unit area decreases and the distances between trees increases (Lorimer 1983).

A study in a young Douglas-fir plantation by Wagner and Radosevich (1991) showed strong correlations between growth and cover of competing vegetation equal or taller in height than the subject tree within a 2.1m radius, the models predicting Douglas-fir growth were not improved by accounting for the distance between plants. However, the authors suggest that if the neighborhood radius used is larger than the optimum, the best competition index should be distance-dependent (Wagner and Radosevich 1991). Another study of distance-dependent indexes in conjunction with growth models of height and diameter has shown good predictive capability for mixed conifer species in northern California (Biging and Dobbertin 1992). Indixes with additional data such as competitor crown parameters show better relationships to crop tree growth. This study also suggests that competitors should be selected using a height angle gauge rather than DBH angle gauge.

Lorimer's Index is a simple distance-independent index, which considers only the diameter of selected tree and competitors, it has been found to be well correlated with subject tree growth:

$$\mathbf{CI}_{Lorimer} = \sum (\mathbf{D}_j / \mathbf{D}_i)$$

Where D_j = DBH competitor j

D_i = DBH selected tree i

This index works well in dense and uniformly spaced stands where densities are closely correlated with inter-tree distances. The lack of importance of inter-tree distances is understandable in row plantations and dense stands since there is so little variability in spacing (Lorimer 1983).

A study on loblolly pine using both distance-dependent and distance-independent indexes has shown that the best distance-dependent indexes had little if any advantage over the best distance-independent indexes (Daniels et al. 1986). Mugasha (1989) also tested both distance-dependent and distance-independent competition indexes in a young stand with jack pine (*Pinus banksiana* Lamb.) and trembling aspen (*Populus tremuloides* Michx.), and found that the distance-dependent competition indexes (based on Daniels' 1976 competition index) were better correlated with volume increment than distance-independent indexes (based on Lorimer's 1983 competition index). Another study on a mixed conifer forest in Northern California tested numerous distance-dependent and distance-independent indexes and the results show that distance-independent indexes performed as well as or slightly better than the distance-dependent indexes (Biging and Dobbertin 1995). A study by Alemdag (1978) on competition indexes to predict diameter increment in planted white spruce (*Picea glauca*) showed poor correlations, likely because variations in tree diameter were small in the white spruce plantations which were selected.

In stands that are well stocked, distance independent indexes appear to work well, whereas, distance dependent indexes should work better when competitor densities are relatively low such as in plantations where red alder is mixed with conifers or where there is spatial variability in tree distribution (Comeau et al. 2003).

A concern with several of these indexes is that inclusion of crop tree size measurements (diameter or height) may artificially inflate the correlation between growth and competition index. For this reason it may be desirable to utilize indexes that do not include subject tree size. To account for the influence of tree size and relative stature of the crop plants to the competitors it may be preferable to include size and stature measurements as separate independent variables or as covariates. For this study, most of the selected competition indexes differ from the formulas that are typically used since they do not include subject tree dimensions, in order to avoid creation of spurious correlations between annual increment and the competition index.

2.2 Objectives

The focus of this study is on examining and comparing the influence of red alder and paper birch on growth of young conifers (Douglas-fir, western hemlock and western redcedar). Competitive effects of these broadleaf spp. are measured using 10 competition indexes (5 distance-independent and 5 distance-dependent indexes) and diffuse non intercepted light (DIFN) and the effectiveness of these indexes is compared. Another objective of this study is to examine the influence of broadleaf species and density on nutrient availability in soil and conifer foliage. Analyzing the effects of red alder and paper birch on light, conifer growth and on nutrient availability will assist in interpreting net effects of these competitors on conifer growth.

2.3 Questions

1- Are the beneficial effects on soil fertility of paper birch and red alder similar?

2- Are different competition measures of equal value in predicting conifer growth (which one is more effective)?

3- Do the 3 conifers have the same response to competition?

4- Are the competitive effects of paper birch and red alder similar?

2.4 Hypotheses

1- Red alder will have stronger influences on soil characteristics than paper birch. Soil N accumulation and soil fertility in general are related to density and broadleaf species.

2- Distance-dependent indexes will perform better than the distance-independent indexes in low density mixtures.

3- Following differences in shade tolerance of selected conifers, red cedar will be the least affected by competition and Douglas-fir the most influenced. Western hemlock has an intermediate shade tolerance and will show an intermediate response.

4- Red alder will have a grater influence than paper birch on light available for conifer growth due to its more rapid growth and larger size.

2.5 Site description

This study is part of a long-term experiment established in south-western British Columbia near Maple ridge (Malcolm Knapp Research Forest Installation 1999) in the Submontane Very Wet Maritime variant of the Coastal Western Hemlock zone (mean annual precipitation 2140 mm). The trees were planted in April 1999 on a Humo-Ferric Podzol derived from colluvium and glacial till. The soils are a loamy sand with coarse fragment content of 20 to 50 %, and the site has a westerly aspect with a moderate slope. This study is designed to look at effects of alder and birch densities on growth of Douglas-fir, western redcedar and western hemlock, thus red alder and paper birch were planted at fixed densities as shown in Table 2.1. The experiment used a randomized block design, with two blocks (plots *a-j*; plots *k-t*) 120 m apart and treatments were randomly assigned to plots within each block (Figure 2.1).

Table 2.1. Broadleaf densities used in this experiment

Treatment	Trees per hectare
1	0 Broadleaves
2	277 Dr
3	556 Dr
4	1150 Dr
5	277 Ep
6	556 Ep
7	1150 Ep
8	277 Ep+Dr
9	556 Ep+Dr
10	1150 Ep+Dr
Dr=red alder	**Ep**=paper birch

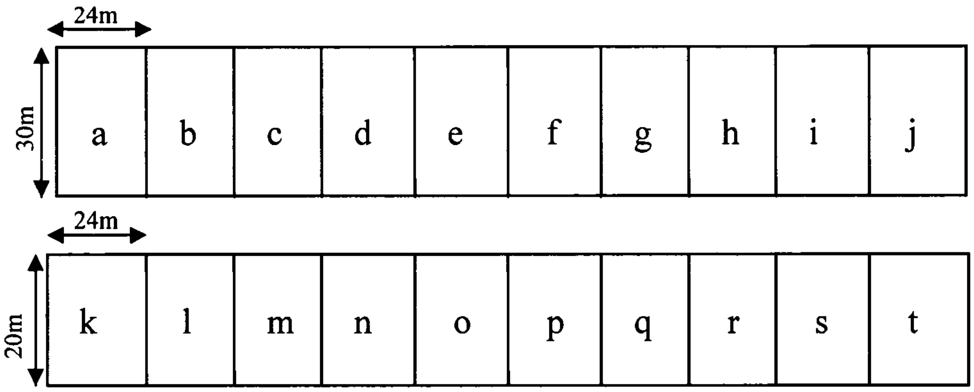


Figure 2.1. Block design of the study (2 blocks with 10 plots in each block).

Treatment plots *a* to *j* are 30 x 24 m, in these plots 10 rows of conifers were planted parallel to the long axis of this strip of plots. Douglas-fir (Fd), western redcedar (Cw), and western hemlock (Hw) were planted alternately at 3 m spacing. Treatment plots *k* to *t* are 20 x 24 m, in these plots 6 rows of conifers were planted parallel to the long axis of this strip of plots. Fd, Cw, and Hw were planted alternately at 3 m spacing. For this study, 4 conifers of each species (Fd, Cw, and Hw) were selected for each plot. With 12 selected trees per plot the total population is 240 conifers and competition effects were measured within 5.64 m radius around each selected conifer.

Plot *o* was not used in the study due to the presence of a large number of stumps, but was replaced by another plot (#7) from an adjacent study with red alder planted at density of 800 tph. In plot 7, 4 Fd and 4 Hw were selected. A delay in the brushing treatment after planting resulted in abundant natural regeneration of paper birch and, in the wetter areas, of red alder. Plots were brushed to treatment density between the two measured growing seasons.

Vexar® tubes were applied at planting (1999) for each western redcedar to protect the trees from browsing since a large population of deer is present on the area.

2.6 Methods and analysis

2.6.1 Characterization of soil structure, soil and foliar sampling

This component of the project examines effects of broadleaf species and density on nutrient availability. Five soil pits were excavated and described (visual analysis) within the studied area (3 in the upper block and 2 in the lower one), to provide information on major soil characteristics such as structure and horizon depth (Figure 2.2).

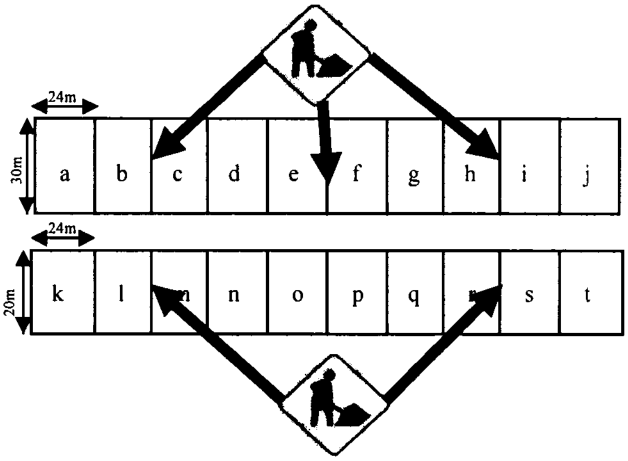


Figure 2.2. Location of the soil pits

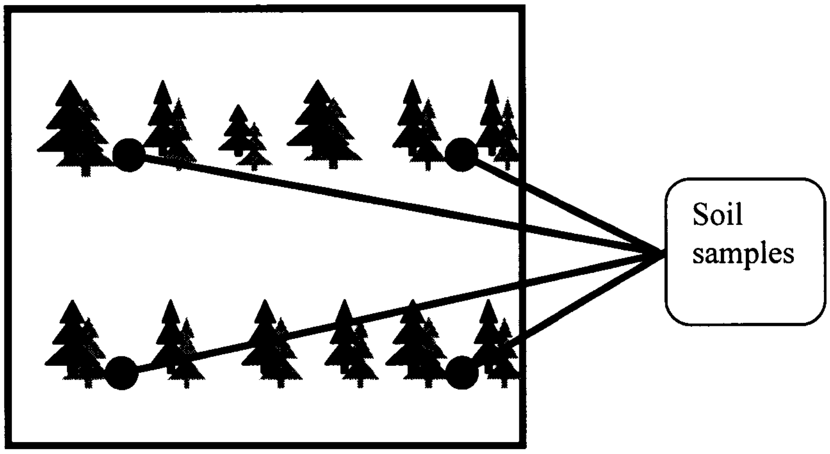


Figure 2.3. Location of soil samples within each plot.

Soil samples were collected at four locations in each plot (2 in the upper row and 2 in the lower one) to a depth of 30 cm and 5 cm in diameter (Figure 2.3). Samples were dried, sieved and analyzed in the lab to determine content of total nitrogen (N), carbon (C) and pH. Total N and C in the soil were measured by dry combustion using a Carlo Erba instrument (Gregorich and Ellert 1993). Soil pH was measured using a Fisher AR20 pH meter with glass and calomel reference electrodes calibrated to buffer pH 4 and 7 (Kalra 1994).

Available nitrogen was measured in the field using ion-exchange membranes (IEM, Plant Root Simulator™-probes). One set of PRS™-probes was installed in the upper mineral horizon (with top of probe flush with the top of the A horizon) of the soil in each treatment plot (0-15 cm depth). Each set consists of four pairs of PRS™-probes (i.e. four cation-exchange and four anion-exchange probes) for a total of 160 PRS™-probes (20 plots x 4 pairs of PRS™-probes x two types). The

4 pairs of PRS™-probes were installed on the 2 rows of selected conifers, 2 pairs on each row. Each pair was located between the conifers as shown in Figure 2.4. Probes were installed in mid-June of 2005, and retrieved after being in place for 2 months and analyzed by Western Ag Innovations Ltd.

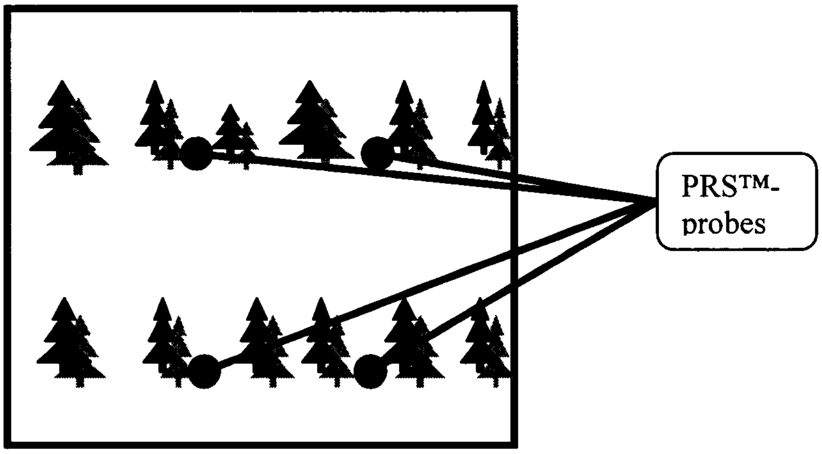


Figure 2.4. Location of the PRS™-probes within each plot.

In late October 2005, 3-4 small branches of the last growing season were collected from the upper third of the crown for every conifer (240 trees). The samples were analyzed to determine foliage macronutrient concentrations (N, P, K and Ca). Total nitrogen, phosphorus, calcium and potassium were measured following the methods by Carter (1993).

For Douglas-fir and western hemlock, needles were separated from woody material for the analysis and dry weight and surface area of a sample of 50 needles were determined. The surface area of 50 needles was determined using a scanner and WINFOLIA™ software (Régent Instruments, Québec, QC, Canada).

2.6.2 Tree growth

In order to quantify 2 annual increments of the selected conifers, the trees were measured: a) before the beginning of the growing season in March 2005, b) at the end of the growing season in October 2005, and, c) in the fall of 2006. For each tree the following were measured:

- Total height and height to crown base
- Root Collar Diameter (RCD) and Diameter at Breast Height (DBH at 1.3 m)
- Crown radius in 4 cardinal directions (North, East, South and West)
- Diffuse non intercepted light at 2 heights (mid-crown and top-height) using LAI-2000 plant canopy analyzer (LI-COR Inc., Lincoln, Neb.) (Comeau et al. 1998)

In addition, 60 conifers (20 for each species) were selected using stratified random sampling (using RCD classes <5 cm, 5-10 cm, 10-15 cm, 15-20 cm etc. as strata). For the 60 selected conifers, diameter was measured every 50 cm along their height to provide equations for calculating actual stem volume.

Every broadleaf within a 5.64 m radius around each conifer was measured for:

- Total height and height to crown base
- RCD and DBH

- Crown radius in 4 cardinal directions (North, East, South and West)
- Distance from the related conifer

These measurements provided the data for calculation of the competition indexes listed in Table 2.2.

Table 2.2. List of competition measures.

Competition Measures	Formula	Values
BA - Basal Area	$BA = \sum BA_j.$	BA_j = competitor basal area (RCD^2)
*HF - Height Factor**	$HF = \sum \frac{Ht_j}{ht_i}.$	Ht_j = competitor height ht_i = selected species ht
DS - Diameters' Sum	$DS = \sum D_j.$	D_j = competitor diameter (RCD)
TN - Trees Number	$TN = \sum N_j.$	N_j = competitor number
CSA - Crown Surface Area	$CSA = \sum CSA_j.$	CSA_j = competitor projected crown area
DDR - Diameter Distance Ratio	$DDR = \sum \frac{D_j}{dist_{ij}}.$	D_j = competitor diameter $dist_{ij}$ = distance
*SFI - Spacing Factor Index**	$SFI = \sum \frac{dist_{ij}}{htdiff_{ij}}.$	$dist_{ij}$ = distance $htdiff_{ij}$ = differential height (competitor - selected species)
*SFI/TN - Spacing Factor Index per Number of Trees**	$SFI/TN = \sum \frac{dist_{ij}}{htdiff_{ij}} \Big/ N_j.$	$dist_{ij}$ = distance $htdiff_{ij}$ = differential ht N_j = competitor number
*MBA - Modified Braathe Index**	$MBA = \sum \frac{htdiff_{ij}}{dist_{ij}}.$	$dist_{ij}$ = distance $htdiff_{ij}$ = differential ht
*VI - View Index**	$VI = \sum \arctan\left(\frac{htdiff_{ij}}{dist_{ij}}\right).$	$dist_{ij}$ = distance $htdiff_{ij}$ = differential ht
DIFN – Diffuse non-Intercepted Light	$= DIFN.$	

* Indexes also tested without the conifer's parameter in the formula (i.e. HFm,VIm)

Data analysis was completed using SAS software version 9.1 (SAS Institute, Cary, NC). Linear and non-linear regressions were used to explore relationships between dependent and independent variables. Dependent variables are the increments of each tree in stem volume (SVI), root collar diameter (RCDI), height (HTI) and basal area (BAI). Independent variables are the competition indexes (CI); diffuse non intercepted light (DIFN), and initial crown surface area (CSAi) of the crop tree.

Preliminary analysis tested linear and non-linear regressions such as power and exponential functions. The best results were given by exponential functions for competition indexes and power functions on *CSAi* as reported by Comeau et al. (2003):

$$Y = a + b_1 * e^{(b_2 * X_1 + b_3 * X_2)} * CSAi^c + \epsilon$$

Where Y is the conifer increment (SVI, RCDI, HTI or BAI), X the competition value (CI) and the other independent variable *CSAi* is the initial crown surface area of the crop tree. The competition indexes were calculated separately for red alder (X_1) and paper birch (X_2) to quantify the effect that each broadleaved component has on the conifers growth.

For DIFN the best results were given by power functions:

$$Y = a + b_1 * X^{(b_2)} * CSAi^c + \epsilon$$

Where Y is the conifer increment (SVI, RCDI, HTI or BAI), X the diffuse non intercepted light (DIFN) and the other independent variable is $CSAi$.

Competition indexes that included the height of the crop tree in their formula were also tested without crop tree height and a small "m" beside their code characterizes them (i.e. HFm).

DIFN has also been tested as a dependent variable against the competition indexes; the model is similar to those presented above:

$$Y = a + b_1 * e^{(b_2 * X_1 + b_3 * X_2)} + \epsilon$$

Where Y is diffuse non intercepted light and, X is the competition index calculated separately for red alder (X_1) and paper birch (X_2).

During the first growing season, DIFN was measured at top-crown and at mid-crown; preliminary analysis showed that top-crown measurements had the best relationship with the conifers increments. Therefore, during the second growing season DIFN measurements were taken only at the top and the mean value of both years' measurements of DIFN at the top of the tree was used in the statistical analysis.

2.7 Results

2.7.1 Characterization of soil structure, soil and foliar sampling

The excavated soil profiles showed the typical characteristic of the Podzolic soil order where the B horizons have an accumulation of amorphous material composed largely by humified organic matter mixed in varying degrees with Al and Fe. The *great group* to which the soil belongs is the Humo-Ferric Podzol that is common under coniferous, mixedwoods or deciduous stands and usually occurs on humid sites, the pH of these soils is generally low (CSSC 1978). The 5 soil profiles (described in detail in Appendix 2.1, pp:84-88) are within the Orthic Humo-Ferric and the Gleyed Humo-Ferric Podzol subgroups, cause of a B horizon thicker than 10 cm and the presence of a L, F, H or Ae horizon. Soil pits# 2, 3 and 4 have distinct or prominent mottles (by the Bf horizon) indicative of gleying, which classifies them as Gleyed Humo-Ferric Podzols, while the lack of mottles in soil pits # 1 and 5 characterizes them as Orthic Humo-Ferric Podzols (Figure 2.5).

A B

Figure 2.5. Picture A shows soil pit #5 (Orthic Humo-Ferric Podzol) and picture B shows soil pit #2 (Gleyed Humo-Ferric Podzols).

Table 2.3. Results of soil samples analysis for the studied area. Dr is red alder and Ep is paper birch.

Plot	Wt. % N	Wt. % C	pH	Dr (tph)	Ep (tph)
A	0.34	8.87	6.11	0	1150
B	0.26	6.95	5.12	556	0
C	0.40	10.12	5.42	0	277
D	0.35	9.21	5.43	0	0
E	0.35	9.17	5.52	277	0
F	0.39	10.15	5.57	278	278
G	0.35	9.82	5.64	1150	0
H	0.35	6.95	5.77	575	575
I	0.55	12.37	5.79	0	556
J	0.35	8.10	5.81	138	139
K	0.40	8.41	5.83	278	278
L	0.47	11.53	5.96	0	277
M	0.24	5.08	6.02	575	575
N	0.41	10.35	6.04	1150	0
P	0.33	7.88	6.09	0	0
Q	0.26	5.95	6.09	0	1150
R	0.34	8.28	6.27	0	556
S	0.34	9.48	6.28	277	0
T	0.58	13.12	6.38	556	0
#7	0.47	10.82	6.46	800	0
Mean Value	0.38	9.13	5.88		
σ	0.09	2.04	0.35		

Analysis of soil samples indicates an average content of total nitrogen and total carbon of 0.38 and 9.13 percent, respectively (Table 2.3). Further analysis, testing broadleaf densities and the concentration of N and C, did not show significant relationships ($p>0.73$ for N and $p>0.41$ for C). In the same way, statistical analysis did not show significant relationships between pH and broadleaf densities ($p>0.86$), the mean pH value for the analyzed samples is 5.88 (Table 2.3).

Results from analysis of available nitrogen obtained from the PRS probes improved after dropping plot “I”, since the original density of the plot (556 Ep/ha) was compromised by abundant natural regeneration of alder. The amount of total nitrogen and its components, nitrate (NO_3^-) and ammonium (NH_4^+) ions were tested against the broadleaf densities using a polynomial regression model: $y=a+bx+cx^2+\varepsilon$; where y is the nitrogen availability and x is alder density. In two cases for red alder the relationships were statistically significant ($p<0.05$) unlike paper birch that was not correlated to nitrogen levels. Red alder density was significantly correlated with total nitrogen ($p<0.001$) with an adjusted R^2 of 0.53 (n=19; RMSE 22.86326; a=11.19451, b=0.10391 and c=-0.00003772), and with nitrates ($p<0.001$) the adjusted R^2 was 0.52 (n=19; RMSE 20.90784; a=6.37922, b=0.09455 and c=-0.00003417). However, for ammonium (NH_4^+) the correlation with red alder density was not significant ($p<0.13$) (Figure 2.5).

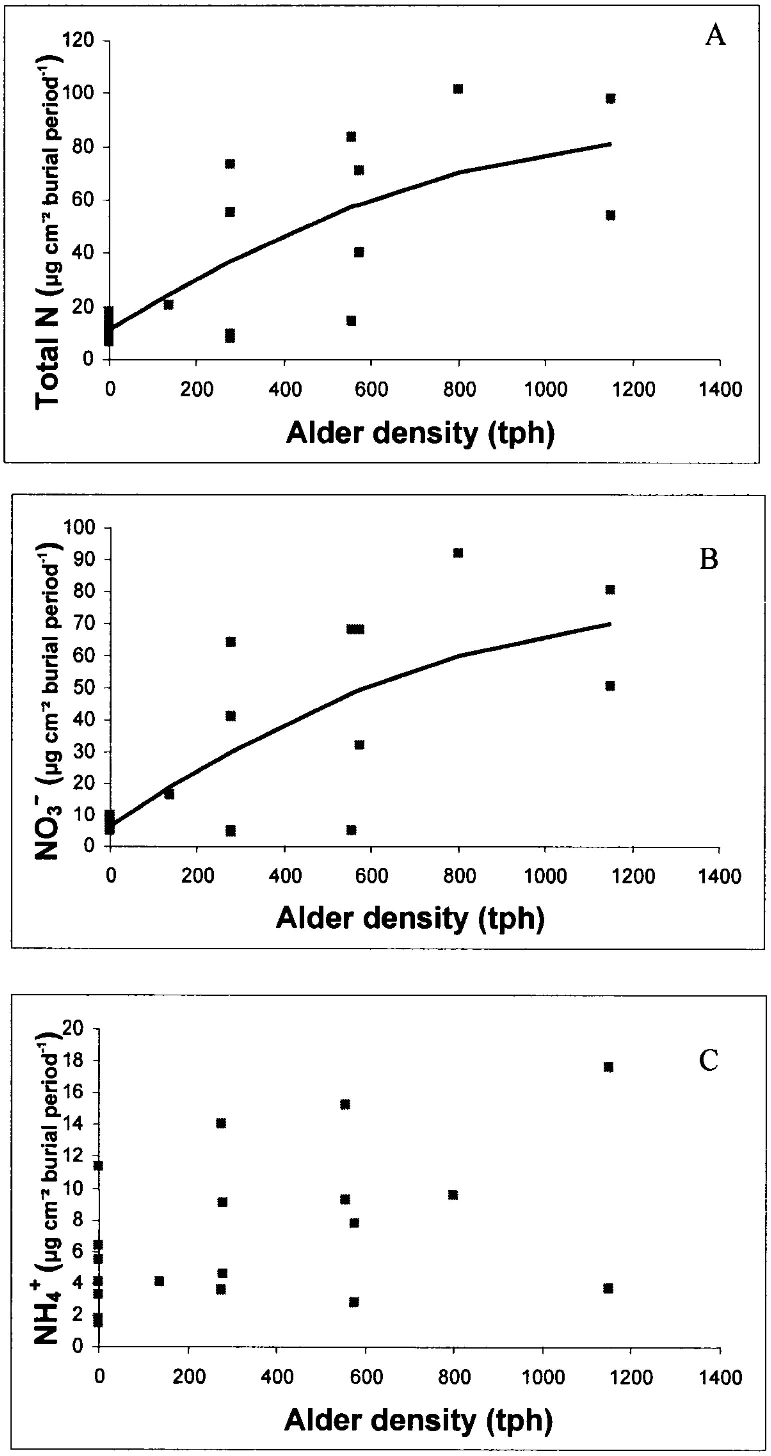


Figure 2.5. Relationships between soil nitrogen and alder density. For the significant relationships, such as total N and nitrates (graphs A and B), the polynomial regression model is: $y=a+bx+cx^2+\varepsilon$; where y is nitrogen availability and x is alder density.

The regression model used for foliar macronutrient (N, Ca, P or K) concentration with broadleaf density is: $Y = a + b_1X_1 + b_2X_1^2 + c_1X_2 + c_2X_2^2$; where Y is the percent of each macronutrient, X_1 is red alder density (tph) and X_2 is paper birch density (tph). Foliar N concentration in Douglas-fir was related to broadleaf density ($p<0.001$) with an adjusted R^2 of 0.42 (n=20, RMSE=0.20611, a=1.44626, b_1=0.00051285, c_1=0.00103 and c_2=-6.75156E-7). Foliar Ca concentration was significantly related to plot treatments ($p<0.002$) with an adjusted R^2 of 0.57 (n=20, RMSE=0.02913, a= 0.26505, b_1=-0.00008179, b_2=1.513623E-7, c_1= 0.00009271 and c_2= -2.3187E-8) (Figure 2.6). In the model the parameters related to red alder were statistically significant ($p<0.005$) for N and Ca, unlike the parameters related to paper birch. The other macronutrients such as phosphorus and potassium did not have significant relationships with the broadleaf densities for Douglas-fir, likewise no relationships between broadleaf densities and foliar macronutrients were found for redcedar or western hemlock.

For Douglas-fir and western hemlock, I investigated use of dry weight and surface area of 50 needles, in order to convert macronutrient percentage into units per gram and units per square millimeter, respectively. The adjusted values based on dry weight, showed some improvement in the R^2 for Douglas-fir but only for N and K and only in relation to total broadleaf density. The adjusted values based on surface area of 50 needles did not show consistent improvements in relationships between foliage macronutrients and plot treatments. For western hemlock the relationships between macronutrients and broadleaf density remained non-significant after the adjustments by weight and surface area of 50 needles.

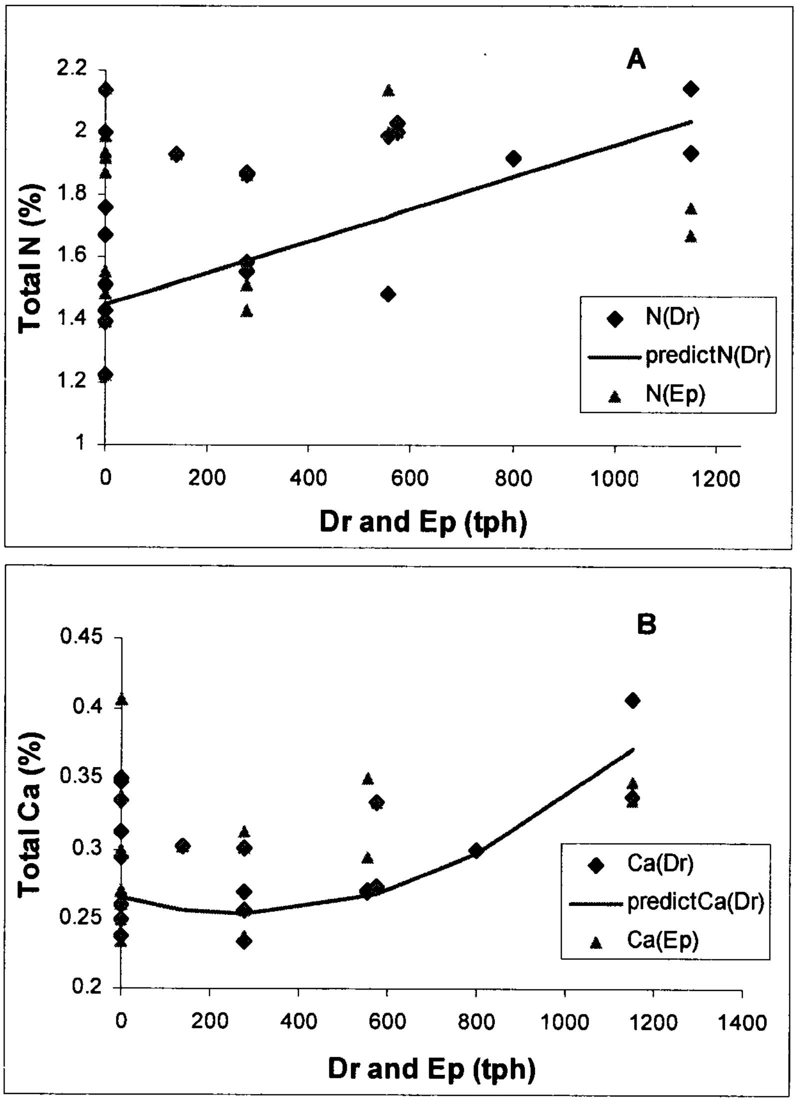


Figure 2.6. Relationships between total nitrogen (graph A) and total calcium (graph B) in foliage samples and broadleaf density. For graph A, the model is: $Y= a+b_1X_1+c_1X_2+ c_2X_2^2+ \epsilon$, where Y is total N, X_1 is Dr (tph) and X_2 is Ep (tph). For graph B, the model is: $Y =a+b_1X_1+ b_2X_1^2 + c_1X_2 + c_2X_2^2+ \epsilon$, where Y is total Ca, X_1 is Dr (tph) and X_2 is Ep (tph). In the graphs the predicted values are calculated keeping the Ep density at zero.

2.7.2 Tree growth

Values for top height in 2005 show a broad range of values (from 73 to 900 cm) and high variability in the average height of the 5 species (232-578 cm) (Table 2.4).

Table 2.4. Height range and average height of measured trees as of October 2005. Cw is western redcedar, Fd is Douglas-fir, and Hw is western hemlock.

Spp.	Height Range (cm)	Average Height (cm)
Cw	94-388	232
Fd	73-621	350
Hw	97-599	394
Dr	120-900	578
Ep	135-864	358

Diameter measurements at several heights collected for a sample of 60 conifers provided data to calculate stem volume and to develop an equation for estimating stem volume from root collar diameter. The equation that best fitted the data to estimate the stem volume (SV, cm^3) from stem height (HT, cm) and root collar diameter (RCD, cm) is similar to Honer's equation (Honer et al. 1983, Pitt et al. 2004):

$$SV = \frac{RCD^a}{b + \frac{c}{HT}}$$

Where a, b, and c are parameters calculated using non-linear least squares. For red cedar the parameters are a=1.2243, b=-0.00196, and c=2.0936 with an adjusted R^2=0.992 and n=17. For Douglas-fir the parameters are a=1.7985, b=-0.00036, and c=3.0862 with an adjusted R^2=0.995 and n=20. For western hemlock the parameters are a=1.5819, b=-0.0041, and c=4.125 with an adjusted R^2=0.981 and n=23. These equations provided local equations for stem volume of the measured conifers.

The data collected over the growing seasons of 2005 (7th growing season) and 2006 (8th growing season) provided values for 2 annual increments. I tested each annual increment separately as well as both growing seasons together. The results show that the best relationships with the competition indexes and DIFN were given by the sum of both annual increments (Table 2.5).

Table 2.5. Comparison of adjusted R^2 values obtained using 2005, 2006 and both years of measurement for examining relationships between tree growth and competitors basal area. The adjusted R^2 are for stem volume increment and competition index Basal Area (BA), the model is:

$$Y = a + b_1 * e^{(b_2 * BAdr + b_3 * BAep)} * CSAi^c + \epsilon.$$

Tree spp.	Obs. #	Year 2005	Year 2006	Years2005+2006
		Adj R^2	Adj R^2	Adj R^2
Cw	69	0.674	0.823	0.734
Fd	66	0.845	0.678	0.851
Hw	55	0.629	0.650	0.752

Competitors within a radius of 5.64 m from the crop tree were measured in 2005 and the data used to calculate the competition indexes selecting the competitors by their height. To evaluate the influence of competitor height, relative to conifer height, calculations were done using competitors taller than 50%, 75% and 100% of subject conifer height. Results show slightly greater adjusted R^2 values for competition indexes that included competitors taller than the crop tree, although the differences in adjusted R^2 are small (Table 2.6).

Table 2.6. Comparison of adjusted R^2 values obtained using competitors taller than 50%, 75% and 100% of subject conifer height for examining relationships between tree growth and competitors' basal area. The adjusted R^2 are for stem volume increment and competition index Basal Area (BA), the model is: $Y = a * e^{(b * BA)} + \epsilon$.

Tree Spp.	Cutoff	Obs. #	Adj. R^2
Cw	50%	72	0.525
Fd	50%	70	0.578
Hw	50%	63	0.508
Cw	75%	72	0.525
Fd	75%	70	0.573
Hw	75%	63	0.523
Cw	100%	72	0.522
Fd	100%	70	0.574
Hw	100%	63	0.570

As far as R^2 values are concerned, stem volume increments for the three species have the best relationships with the competition measures, followed by basal area and height increments, while root collar diameter increments have weaker correlations. The conifer species show different responses to competition and the index which works best varies among the 3 conifer species.

For stem volume increment, Douglas-fir had the best relationship with the distance-independent competition index CSA (Figure 2.9) with an adjusted R^2=0.863 and n=66, and DIFN (Figure 2.7) had the lowest adjusted R^2 among the competition measures (R^2=0.775; n=73) (Table 2.10). For western hemlock and western redcedar the best relationships was between stem volume increment and DIFN (Figure 2.7) with an adjusted R^2=0.805 (n=66) and R^2=0.825 (n=80), respectively, following that the best competition indexes are the distance-dependent SFIm/TN (R^2=0.758; n=55) and DDR (R^2=0.768; n=69) (Figure 2.10), respectively (Table 2.11; 2.9).

To quantify the broadleaf influence, the 95% confidence interval of the parameter values related to red alder or paper birch were examined. The parameter is considered to be significantly different from zero when the range does not include 0. For Douglas-fir the best competition indexes have the parameter related to red alder constantly different from zero, unlike the parameter value for paper birch. For western hemlock parameters for both alder and birch do not differ from zero, while for western redcedar parameter values for both alder and birch are different from zero.

Simple distance-independent indexes such as the sum of the competitors' height (HFm) (Figure 2.11), total number of competitors (TN) (Figure 2.13) and, competitors' basal area (BA) (Figure 2.8) did not perform much worse than the best competition index of each species. For Douglas-fir the difference between the adjusted R^2 of the best competition index (CSA) and HFm is 0.007 and 0.012 for TN and BA. For western hemlock the difference in R^2 between the best competition index (SFIm/TN) and TN is 0.002, 0.004 for HFm and 0.006 for BA. For western redcedar DDR is better than HFm by 0.025, by 0.033 for TN and, by 0.034 for BA.

The values of the parameters, their confidence interval and the adjusted R^2 of the relationships were used to rank the broadleaf influence on conifer species. A larger parameter value indicates a stronger effect (steeper slope); western redcedar has the highest values followed by Douglas-fir and western hemlock. Parameter values for red alder are bigger than the ones related to paper birch except for western hemlock. For western redcedar, the confidence intervals are mostly different from zero for red alder and paper birch, for Douglas-fir only the parameter related to red alder differs from zero and for western hemlock none of the parameters were significant. These results indicate that the broadleaf effect is greater for western redcedar, moderate for Douglas-fir, and least for western hemlock (Figure 2.14 and 2.15).

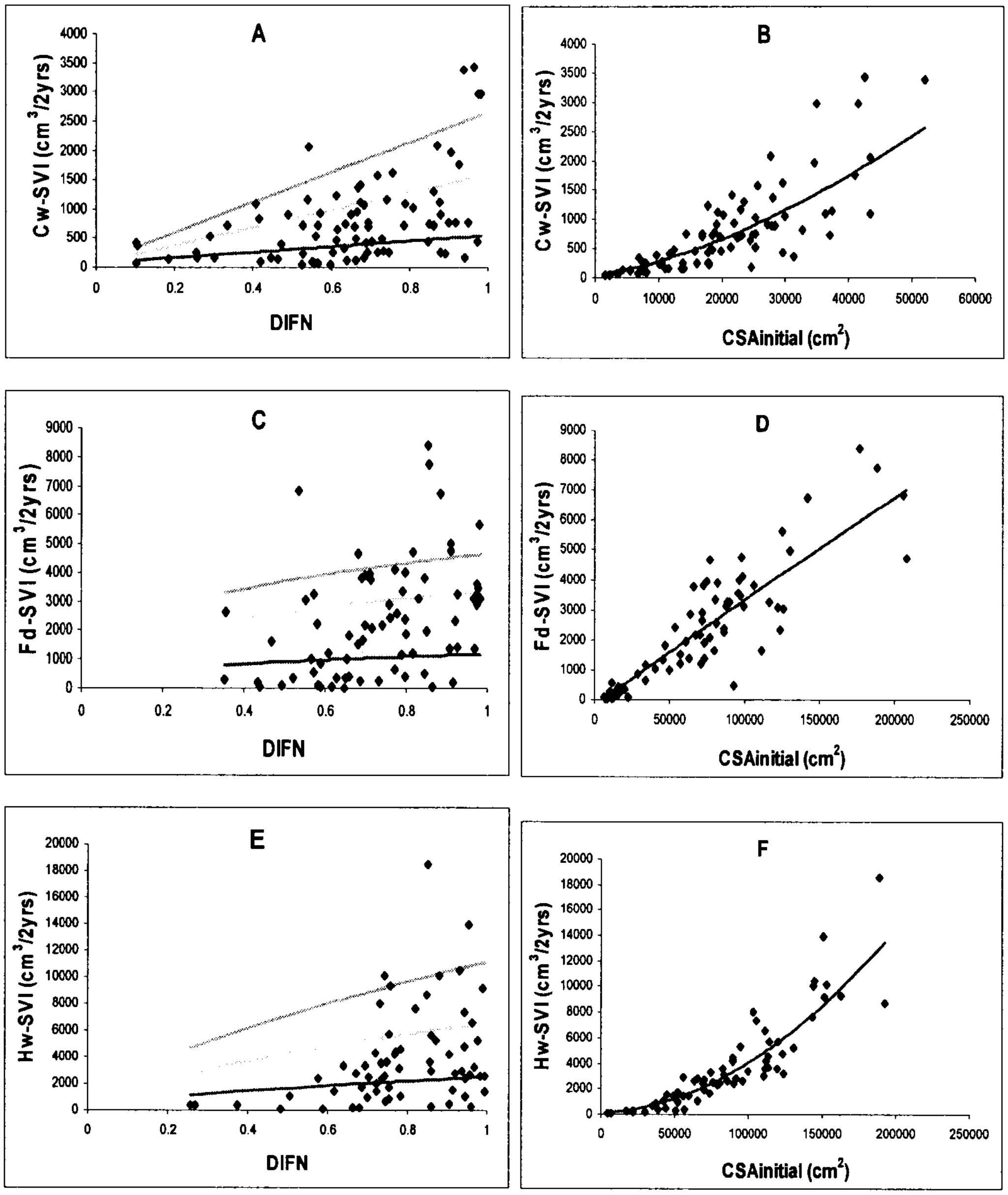


Figure 2.7. Relationships between stem volume increment and DIFN, the model is: $Y = a + b_1 * X^{(b_2)} * CSAi^c$ + €. Graph A and B are for redcedar, graph C and D for Douglas-fir and graph E and F for western hemlock. Graph A, C and E each show three different curves calculated for three levels (low-medium-high) of initial crown surface area (CSAi). Graph B, D and F each show a curve calculated using the mean value of DIFN of each species. Parameter values and statistical information for each trendline are provided in Tables 2.9, 2.10 and 2.11.

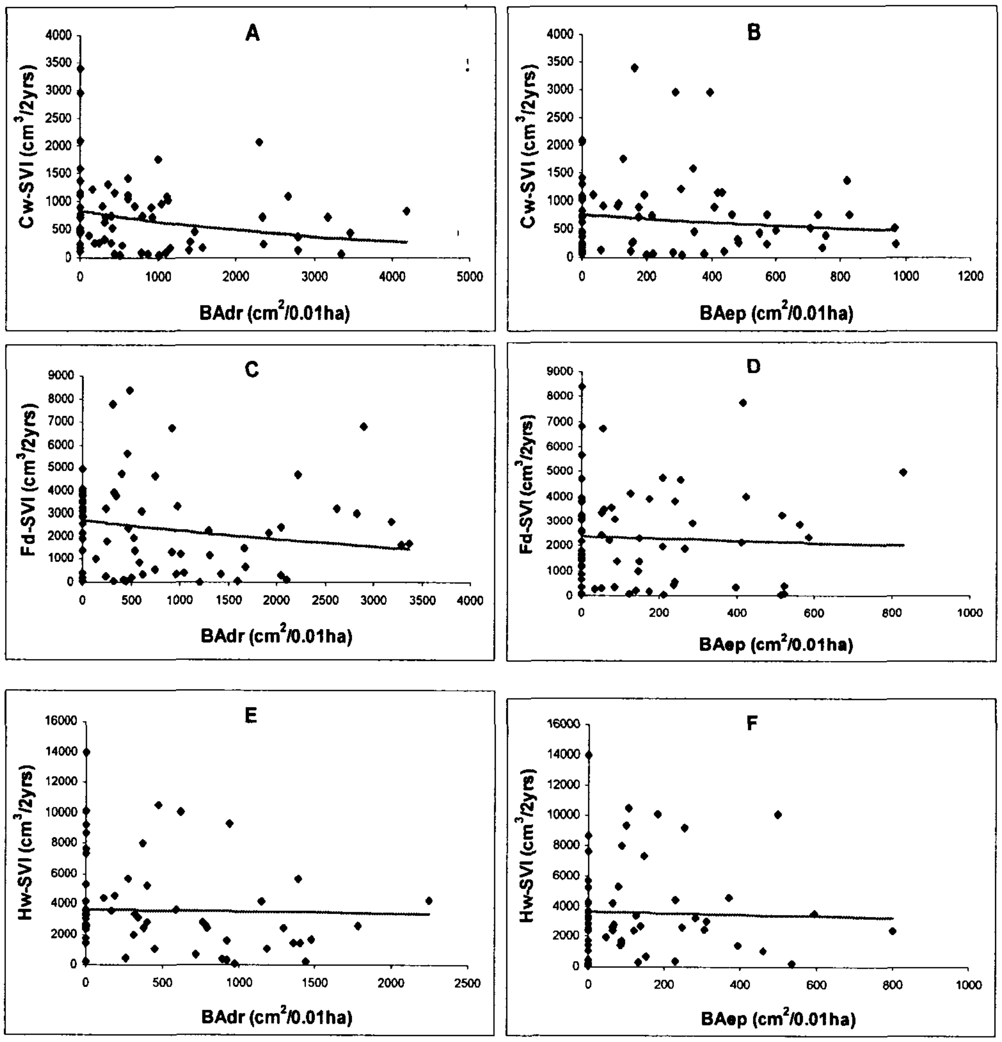


Figure 2.8. Relationships between stem volume increment and broadleaf Basal Area (BA), the model is: $Y = a + b_1 * e^{(b_2 * BAdr + b_3 * BAep)} * CSAi^c$ + €. Graph A and B are for redcedar, graph C and D for Douglas-fir and graph E and F for western hemlock. Graph A, C and E each show curves calculated using the mean value of BA for the birch component (BAep) and the mean value of initial crown surface area (CSAi) for each species. Graph B, D and F show curves calculated using the mean value of BA for the red alder component (BAdr) and the mean value of initial crown surface area (CSAi) for each species. Parameter values and statistical information for each trendline are provided in Tables 2.9, 2.10 and 2.11.

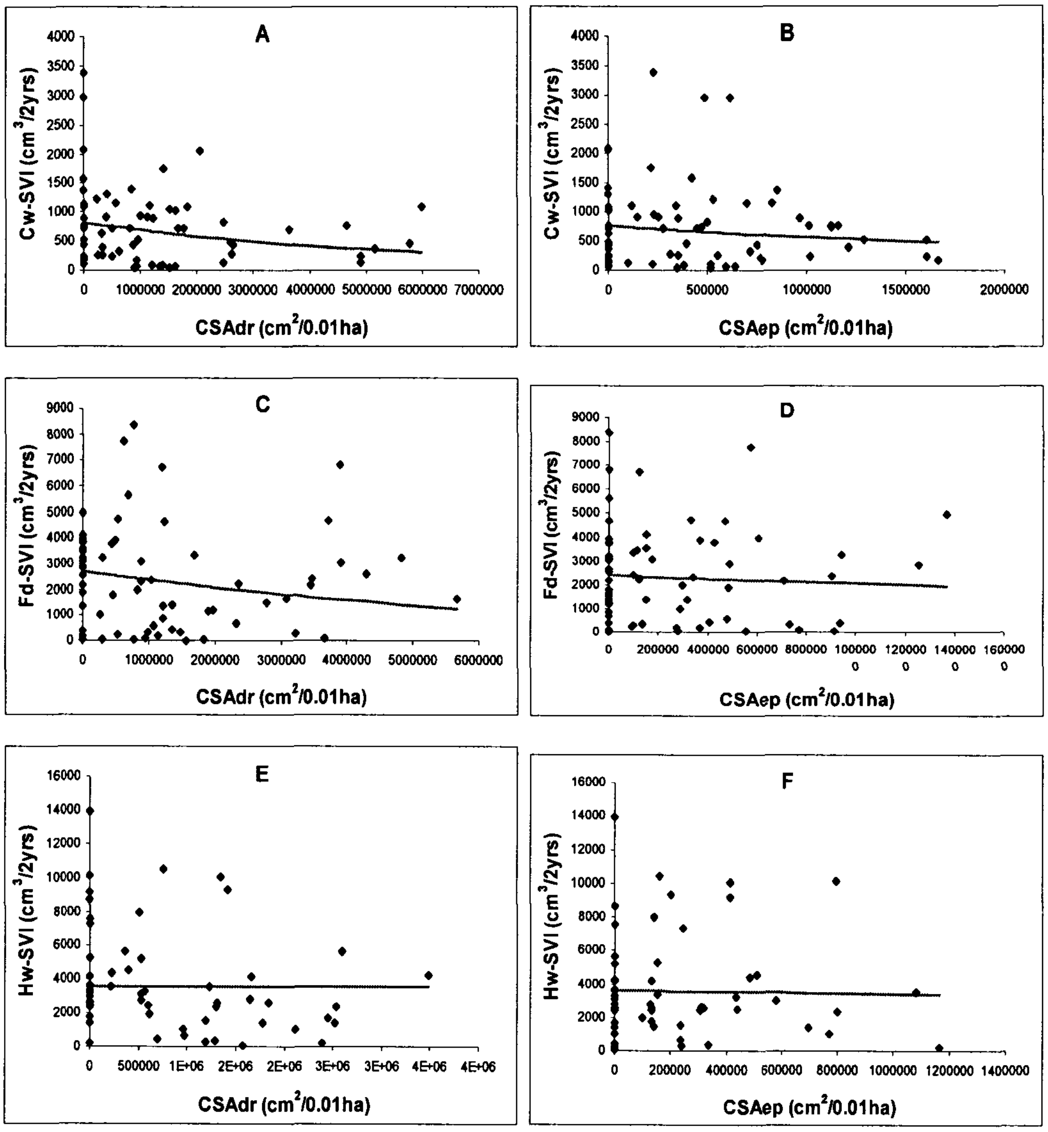


Figure 2.9. Relationships between stem volume increment and broadleaf Crown Surface Area (CSA), the model is: $Y = a + b_1 * e^{(b_2 * CSAdr + b_3 * CSAep)} * CSAi^c + \in$. Graph A and B are for redcedar, graph C and D for Douglas-fir and graph E and F for western hemlock. Graph A, C and E each show curves calculated using the mean value of CSA for the birch component (CSAep) and the mean value of initial crown surface area (CSAi) for each species. Graph B, D and F show curves calculated using the mean value of CSA for the red alder component (CSAdr) and the mean value of initial crown surface area (CSAi) for each species. Parameter values and statistical information for each trendline are provided in Tables 2.9, 2.10 and 2.11.

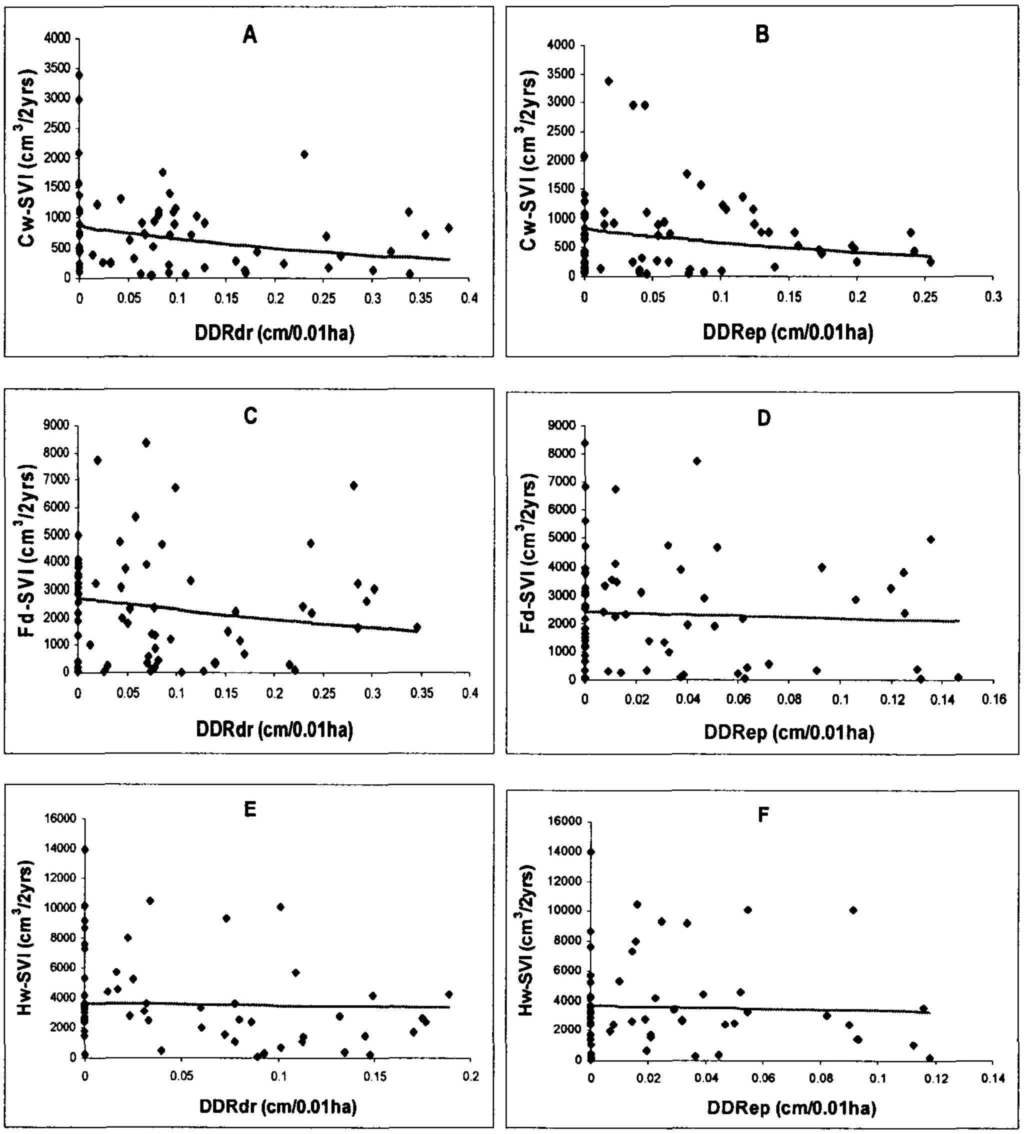


Figure 2.10. Relationships between stem volume increment and broadleaf Diameter Distance Ratio (DDR), the model is: $Y = a + b_1 * e^{(b_2*DDRdr + b_3*DDRep)} * CSAi^c + €$. Graph A and B are for redcedar, graph C and D for Douglas-fir and graph E and F for western hemlock. Graph A, C and E each show curves calculated using the mean value of DDR for the birch component (DDRep) and the mean value of initial crown surface area (CSAi) for each species. Graph B, D and F show curves calculated using the mean value of DDR for alder (DDRdr) and the mean value of CSAi for each species. Parameter values and statistical information for each trendline are provided in Tables 2.9, 2.10 and 2.11.

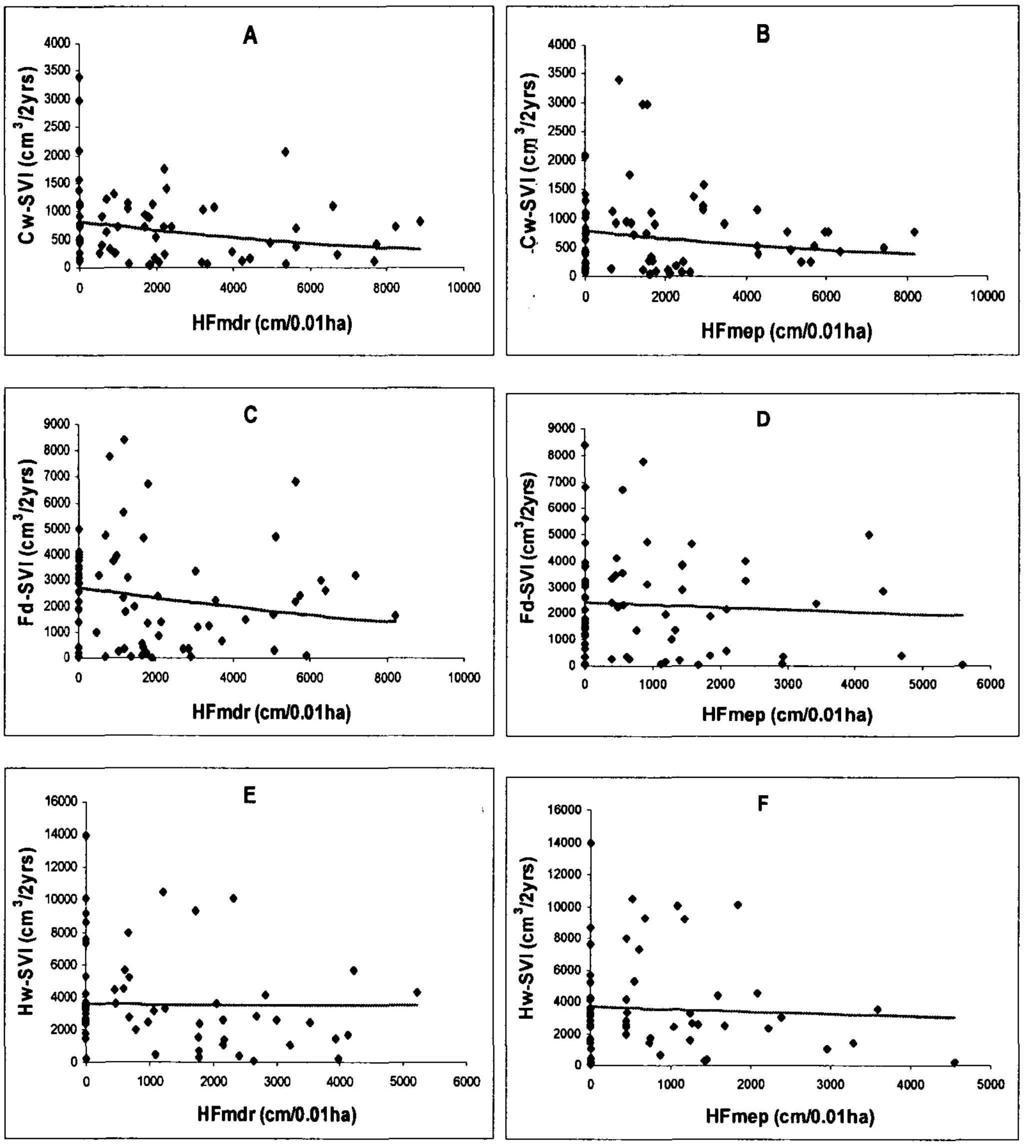


Figure 2.11. Relationships between stem volume increment and broadleaf Height Factor without selected conifers height (HFm), the model is: $Y = a + b_1 * e^{(b_2*HFmdr+b_3*HFmep)} * CSAi^c$ + €. Graph A, C and E each show curves calculated using the mean value of HFm for the birch component (HFmep) and the mean value of initial crown surface area (CSAi) for each species. Graph B, D and F show curves calculated using the mean value of HFm for the red alder component (HFmdr) and the mean value of initial crown surface area (CSAi) for each species. Parameter values and statistical information for each trendline are provided in Tables 2.9, 2.10 and 2.11.

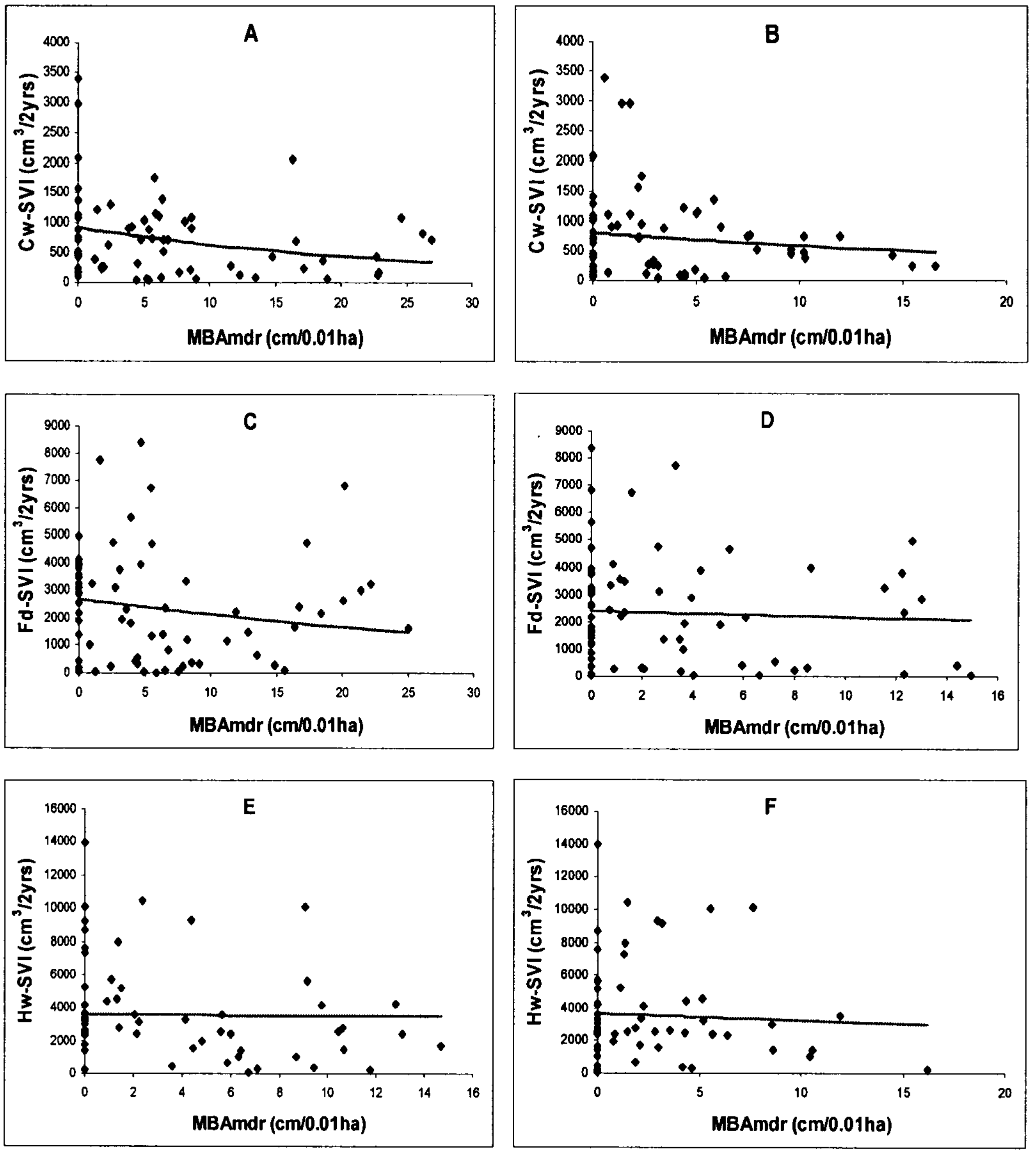


Figure 2.12. Relationships between stem volume increment and broadleaf Modified Braathe Index without selected conifers height (MBAm), the model is: $Y = a + b_1 * e^{(b_2*MBAmdr+b_3*MBAmep)} * CSAi^c + \epsilon$. Graph A, C and E each show curves calculated using the mean value of MBAm for the birch component (MBAmep) and the mean value of initial crown surface area (CSAi) for each species. Graph B, D and F show curves calculated using the mean value of MBAm for alder (MBAmdr) and the mean value of CSAi for each species. Parameter values and statistical information for each trendline are provided in Tables 2.9, 2.10 and 2.11.

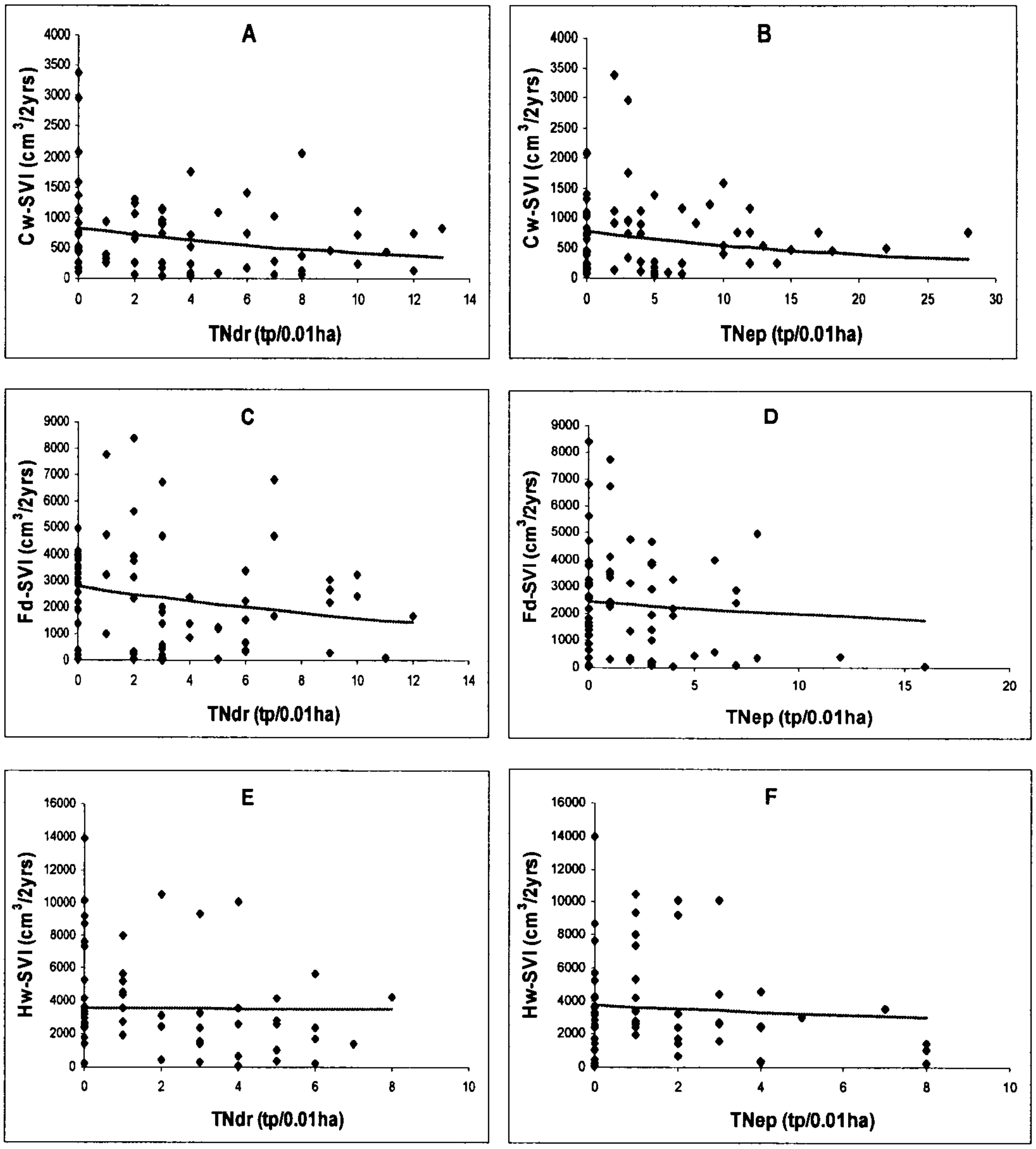


Figure 2.13. Relationships between stem volume increment and Total Number of broadleaves (TN), the model is: $Y = a + b_1 * e^{(b_2 * TNdr + b_3 * TNep)} * CSAi^c + \epsilon$. Graph A, C and E each show curves calculated using the mean value of TN for the birch component (TNep) and the mean value of initial crown surface area (CSAi) for each species. Graph B, D and F show curves calculated using the mean value of TN for the red alder component (TNdr) and the mean value of CSAi for each species. Parameter values and statistical information for each trendline are provided in Tables 2.9, 2.10 and 2.11.

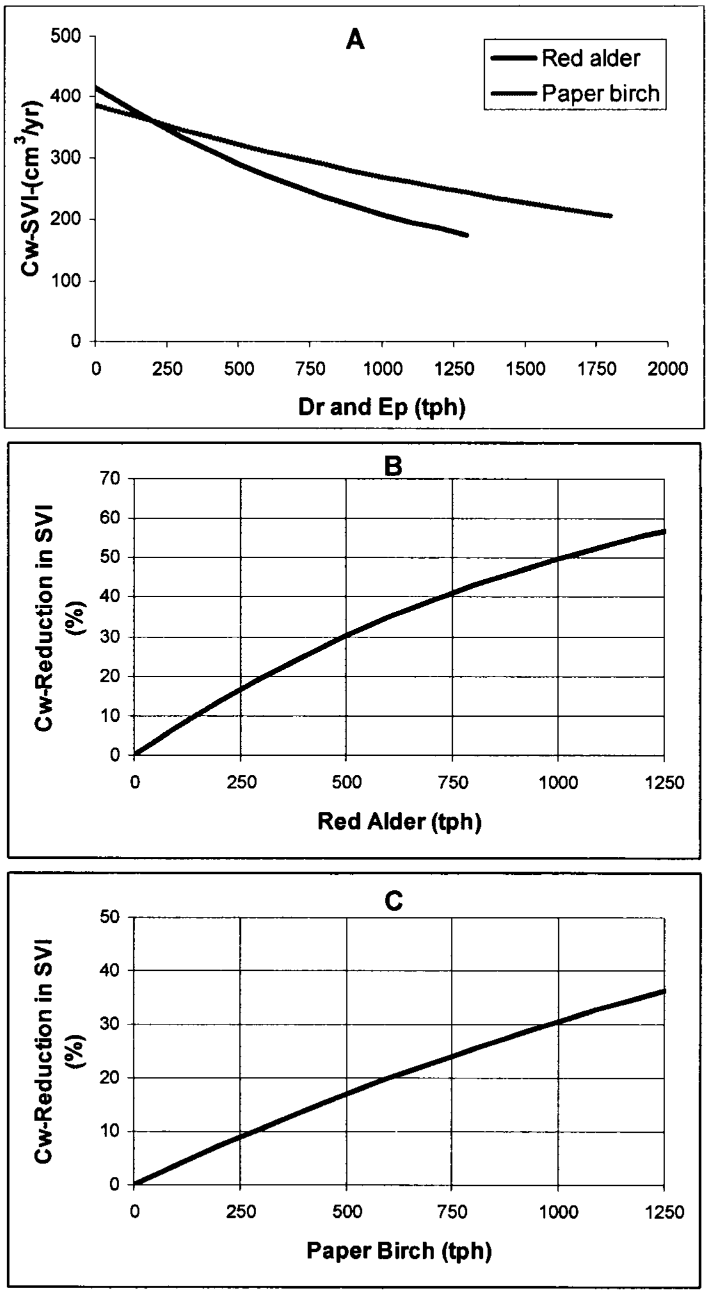
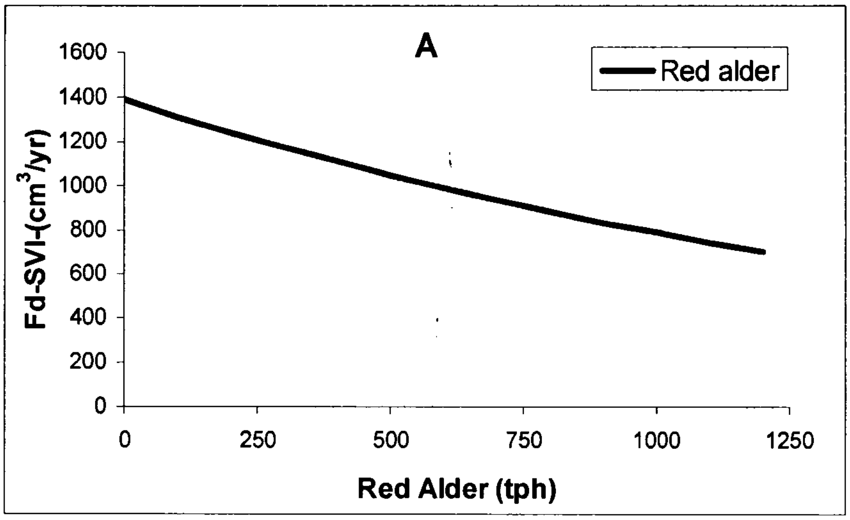


Figure 2.14. Relationships between Cw stem volume increment and broadleaf density (TN*100), using the model shown in Figure 2.13. Graph A shows two curves: calculated using the mean value of TNep for Dr and TNdr for Ep and the mean value of CSAi. Parameter values and statistical information for the trendline are provided in Table 2.9. Graphs B and C show the reduction of predicted SVI (%) calculated using this model.



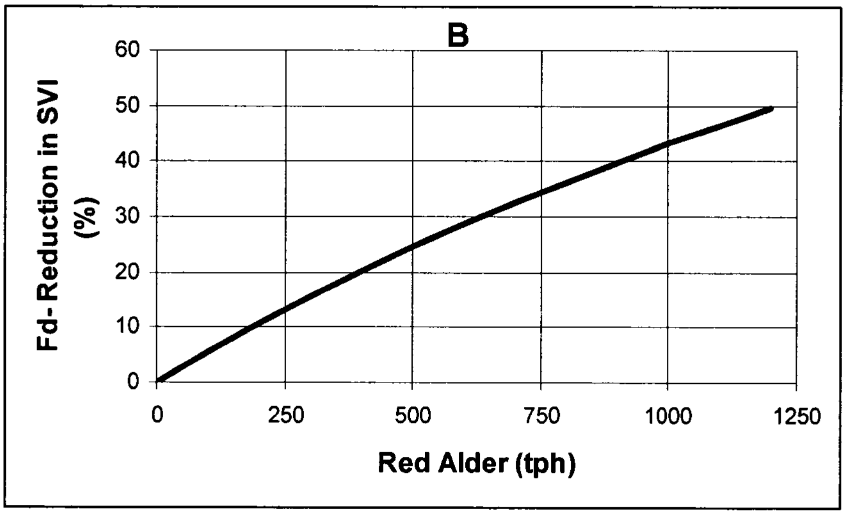


Figure 2.15. Relationships between Fd stem volume increment and broadleaf density (TN*100), using the model shown in Figure 2.13. Graph A shows two curves: calculated using the mean value of TNep for Dr and the mean value of CSAi. Parameter values and statistical information for the trendline are provided in Table 2.9. Graphs B shows the reduction of predicted SVI (%) calculated using this model.

Table 2.9. Parameter values and statistical information for non-linear models of western redcedar stem volume increment. The table shows: number of observations (obs. #), adjusted R^2 (Adj. R^2), root mean square error (RMSE) and equation parameters (A, B1, B2, B3 and C), where B2 is related to red alder and B3 to paper birch for the competition indexes. Parameter values which are significantly different from zero are shown in bold type. The model used for relationships with competition indexes is: $Y = a + b_1 * e^{(b_2 * X_1 + b_3 * X_2)} * CSAi^c + \text{€}$ and for relationships with DIFN is: $Y = a + b_1 * X^{(b_2)} * CSAi^c + \text{€}$.

Cw SVI	obs #	Adj R^2	RMSE	A	Range +/-	B1	Range +/-	B2	Range +/-	B3	Range +/-	C	Range +/-
DifnTop	80	0.825	311.836	62.564	176	0.000347	1.20E-03	**9.85E-01**	3.39E-01			**1.493**	0.3249
DDR	69	0.768	336.862	53.27	214	0.00077	3.21E-03	**-3.0373**	1.17E+00	**-3.6888**	2.1833	**1.42**	0.3897
MBA	69	0.767	337.426	91.579	198	0.000588	2.46E-03	**-6.75E-02**	2.77E-02	**-0.0754**	0.0485	**1.4397**	0.3909
MBAm	69	0.764	339.585	70.404	210	0.000523	2.25E-03	**-0.0415**	1.65E-02	**-3.47E-02**	2.16E-02	**1.4537**	4.01E-01
VI	69	0.757	344.975	92.9	206	0.000507	2.23E-03	**-0.1063**	4.42E-02	**-0.0947**	0.0635	**1.4547**	0.4103
HF	69	0.750	349.716	142.7	189	0.000331	1.48E-03	**-0.0358**	1.55E-02	**-0.0266**	0.01874	**1.4944**	0.4192
VIm	69	0.748	351.436	92.501	213	0.000323	1.50E-03	**-8.29E-02**	3.47E-02	**-0.0532**	0.0373	**1.4984**	0.4312
HFm	69	0.743	354.741	92.698	213	0.000198	9.22E-04	**-1.30E-04**	5.00E-05	**-0.00011**	0.00008	**1.5445**	0.4354
DS	69	0.742	355.331	81.507	217	0.000227	1.05E-03	**-0.00972**	4.22E-03	**-0.0109**	0.00841	**1.5334**	0.4325
TN	69	0.735	360.272	119.4	211	0.000179	8.81E-04	**-0.087**	3.81E-02	**-0.0447**	0.0346	**1.5529**	0.4578
BA	69	0.734	361.061	54.909	226	0.000206	0.000954	**-0.0003**	0.00014	**-0.00053**	0.00052	**1.5391**	0.4339
CSA	69	0.733	361.791	65.162	223	0.000167	0.000785	**-1.85E-07**	8.65E-08	-3.19E-07	3.24E-07	**1.5574**	0.4393
SFIm	69	0.700	383.112	177.2	209	0.000036	0.000204	**-0.1339**	0.0679	-0.0384	0.04075	**1.6977**	0.5282
SFI	69	0.681	395.354	178	219	0.000016	0.000099	**-0.0665**	0.0365	-0.00921	0.01245	**1.768**	0.5679
SFIm/TNm	69	0.660	407.955	76.184	274	0.000176	0.001054	-0.0481	0.3945	**0.3578**	0.2819	**1.4989**	0.551
SFI/TN	69	0.648	415.226	72.254	281	0.000267	0.001633	-0.0177	0.1753	**0.1087**	0.0858	**1.4623**	0.5654

Table 2.10. Parameter values and statistical information for non-linear models of Douglas-fir stem volume increment. The table shows: number of observations (obs. #), adjusted R^2 (Adj. R^2), root mean square error (RMSE) and equation parameters (A, B1, B2, B3 and C), where B2 is related to red alder and B3 to paper birch for the competition indexes. Parameter values which are significantly different from zero are shown in bold type. The model used for relationships with competition indexes is:

$Y = a + b_1 * e^{(b_2 * X_1 + b_3 * X_2)} * CSAi^c + \epsilon$ and for relationships with DIFN is: $Y = a + b_1 * X^{(b_2)} * CSAi^c + \epsilon$.

Fd SVI	obs #	Adj R^2	RMSE	A	Range +/-	B1	Range +/-	B2	Range +/-	B3	Range +/-	C	Range +/-
CSA	66	0.863	736.405	-25.351	499.85	0.00591	0.01819	**-1.33E-07**	5.67E-08	-1.53E-07	1.95E-07	**1.1731**	0.259
HFm	66	0.856	753.549	-81.885	535.98	0.0132	0.0407	**-0.00008**	0.00004	-0.00004	0.000066	**1.1031**	0.2571
DS	66	0.853	761.760	-78.2	538.1	0.0129	0.0399	**-0.00581**	0.00273	-0.00409	0.00637	**1.1053**	0.2584
Vlm	66	0.853	762.712	-91.452	547.45	0.0173	0.0535	**-0.0499**	0.0236	-0.0196	0.034	**1.0796**	0.2567
MBAm	66	0.852	765.129	-94.4	543.8	0.0124	0.0388	**-0.023**	0.0109	-0.0092	0.01754	**1.1072**	0.2597
Vl	66	0.851	766.136	-29.617	530.42	0.0172	0.0526	**-0.084**	0.0408	-0.0405	0.0735	**1.0777**	0.2541
TN	66	0.851	766.789	-89.685	552.68	0.0219	462.9781	**-0.0543**	0.0261	-0.0199	0.0333	**1.0598**	0.2563
BA	66	0.851	767.677	-66.489	534.99	0.00827	0.02643	**-0.00018**	0.00009	-0.0002	0.000331	**1.1426**	0.2685
MBA	66	0.849	771.563	-26.435	536.04	0.0188	0.0576	**-0.0615**	0.0309	-0.024	0.0545	**1.0686**	0.2547
HF	66	0.848	774.481	27.3785	507.52	0.0233	0.069	**-0.0331**	0.0166	-0.0139	0.02369	**1.0511**	0.2464
DDR	66	0.848	775.615	-96.897	550.4	0.0124	0.0388	**-1.6295**	0.8077	-0.975	1.744	**1.108**	0.2626
SFlm	66	0.842	789.507	-88.566	577.27	0.0399	0.1239	**-0.0931**	0.0495	-0.0248	0.0451	**1.0073**	0.258
SFl	66	0.835	806.420	-156.9	618.1	0.0238	0.0788	**-0.0275**	0.0158	-0.00131	0.00717	**1.0504**	0.2748
SFl/TN	66	0.800	888.796	-291.5	758	0.0645	0.2395	0.0391	0.0746	0.0315	0.0375	**0.9452**	0.3018
SFlm/TNm	66	0.795	899.922	-337	792.1	0.0665	0.2541	0.00697	0.24813	0.1225	0.199	**0.9483**	0.3108
DifnTop	73	0.775	924.838	-224.6	699	0.0539	0.1887	0.319	0.3719			**0.9725**	0.289

Table 2.11. Parameter values and statistical information for non-linear models of western hemlock stem volume increment. The table shows: number of observations (obs. #), adjusted R^2 (Adj. R^2), root mean square error (RMSE) and equation parameters (A, B1, B2, B3 and C), where B2 is related to red alder and B3 to paper birch for the competition indexes. Parameter values which are significantly different from zero are shown in bold type. The model used for relationships with competition indexes is: $Y = a + b_1 * e^{(b_2 * X_1 + b_3 * X_2)} * CSAi^c + €$ and for relationships with DIFN is: $Y = a + b_1 * X^{(b_2)} * CSAi^c + €$.

Hw	obs	Adj	RMSE	A	Range	B1	Range	B2	Range	B3	Range	C	Range
SVI	#	R^2			+/-		+/-		+/-		+/-		+/-
DifnTop	66	0.805	1566.816	192	1010.5	1.84E-06	1.12E-05	0.6623	0.8306			**1.8781**	2.3751
SFIm/TNm	55	0.758	1525.720	-237	1540.2	0.000023	0.000178	0.1268	0.2414	0.0968	0.2705	**1.6517**	0.6484
SFI	55	0.757	1529.490	-439	1626	0.000255	0.001775	0.000936	0.019764	-0.0102	0.0211	**1.4573**	0.5704
SFIm	55	0.757	1529.655	-407	1604.6	0.000233	0.001647	0.00149	0.06811	-0.0402	0.0841	**1.4647**	0.5804
HF	55	0.756	1533.249	-428	1603	0.000254	0.001766	-0.00253	0.02663	-0.0184	0.0401	**1.4584**	0.5718
TN	55	0.756	1533.921	-467	1642.7	0.000248	0.001762	-0.00108	0.04428	-0.0246	0.0554	**1.4603**	0.5816
MBA	55	0.755	1535.687	-431	1609.8	0.000281	0.001939	-0.0168	0.0642	-0.0426	0.1053	**1.45**	0.5688
VI	55	0.755	1535.836	-458	1629.7	0.00027	0.00189	-0.0141	0.0785	-0.0529	0.1242	**1.4535**	0.5755
VIm	55	0.755	1536.066	-483	1655.2	0.000245	0.001735	-0.00188	0.04348	-0.0227	0.0541	**1.4618**	0.5817
HFm	55	0.754	1538.192	-475	1657.8	0.000221	0.001579	-1.5E-06	7.15E-05	-0.00004	0.000105	**1.4701**	0.586
MBAm	55	0.754	1539.453	-482	1657.5	0.000228	0.001612	-0.00178	0.02348	-0.0105	0.0284	**1.4675**	0.5815
DDR	55	0.754	1540.435	-503	1680.9	0.000283	0.002007	-0.3318	1.7458	-0.8989	2.6802	**1.4498**	0.5815
DS	55	0.754	1540.493	-491	1676	0.00025	0.00179	-0.00047	0.00521	-0.00347	0.01001	**1.4599**	0.5869
SFI/TN	55	0.753	1542.483	-270	1585.3	0.000047	0.000367	0.00964	0.05546	0.0177	0.0637	**1.593**	0.6377
BA	55	0.752	1544.145	-484	1685.1	0.000234	0.001676	-0.00003	0.000184	-0.00013	0.000513	**1.4652**	0.5894
CSA	55	0.751	1546.914	-431	1660.2	0.00015	0.00109	2.01E-09	1.11E-07	-4.47E-08	3.136E-07	**1.5006**	0.598

For basal area increment Douglas-fir had the best relationship with the distance-dependent competition indexes SFI/TN and SFI with adjusted R^2=0.665 (n=66) and DIFN (Figure 2.16) had the lowest adjusted R^2 among the competition measures (R^2=0.559; n=73) (Table 2.13). In contrast, western hemlock and western redcedar had the best relationships with DIFN (R^2=0.559, n=66 and R^2=0.73, n=80, respectively) (Figure 2.16). The best competition indexes were: a) for western hemlock the distance dependent SFIm/TN (R^2=0.477; n=55); and b) for western redcedar MBA (R^2=0.665; n=69) (Table 2.12 and 2.14). As far as broadleaf influence is concerned, for Douglas-fir the 2 competition indexes with the highest R^2 had only the parameter related to paper birch constantly different from zero, while the rest of the indexes only showed the parameter for the alder component different from zero. For western hemlock the range of the broadleaf related parameters included zero, while the first 4 indexes for western redcedar had parameters for both red alder and paper birch different from zero.

For height increment, Douglas-fir had the best relationship with the distance-dependent competition index SFI/TN with adjusted r^2=0.631 (n=66) and DIFN (Figure 2.17) had the lowest adjusted R^2 among the competition measures (R^2=0.548; n=73) (Table 2.16). Western hemlock and western redcedar had the best relationships with the light measure DIFN (Figure 2.17) with an adjusted R^2=0.494 (n=66) and R^2=0.678 (n=80), respectively, and the best competition indexes for western hemlock and western redcedar were distance-dependent SFI (R^2=0.318; n=55) and MBA (R^2=0.566; n=69), respectively (Table 2.15 and

2.17). As far as broadleaf influence is concerned, for Douglas-fir and western hemlock none of the parameters for red alder and paper birch had a range that did not include zero, while for western redcedar the parameter related to red alder was different from zero for most of the indexes.

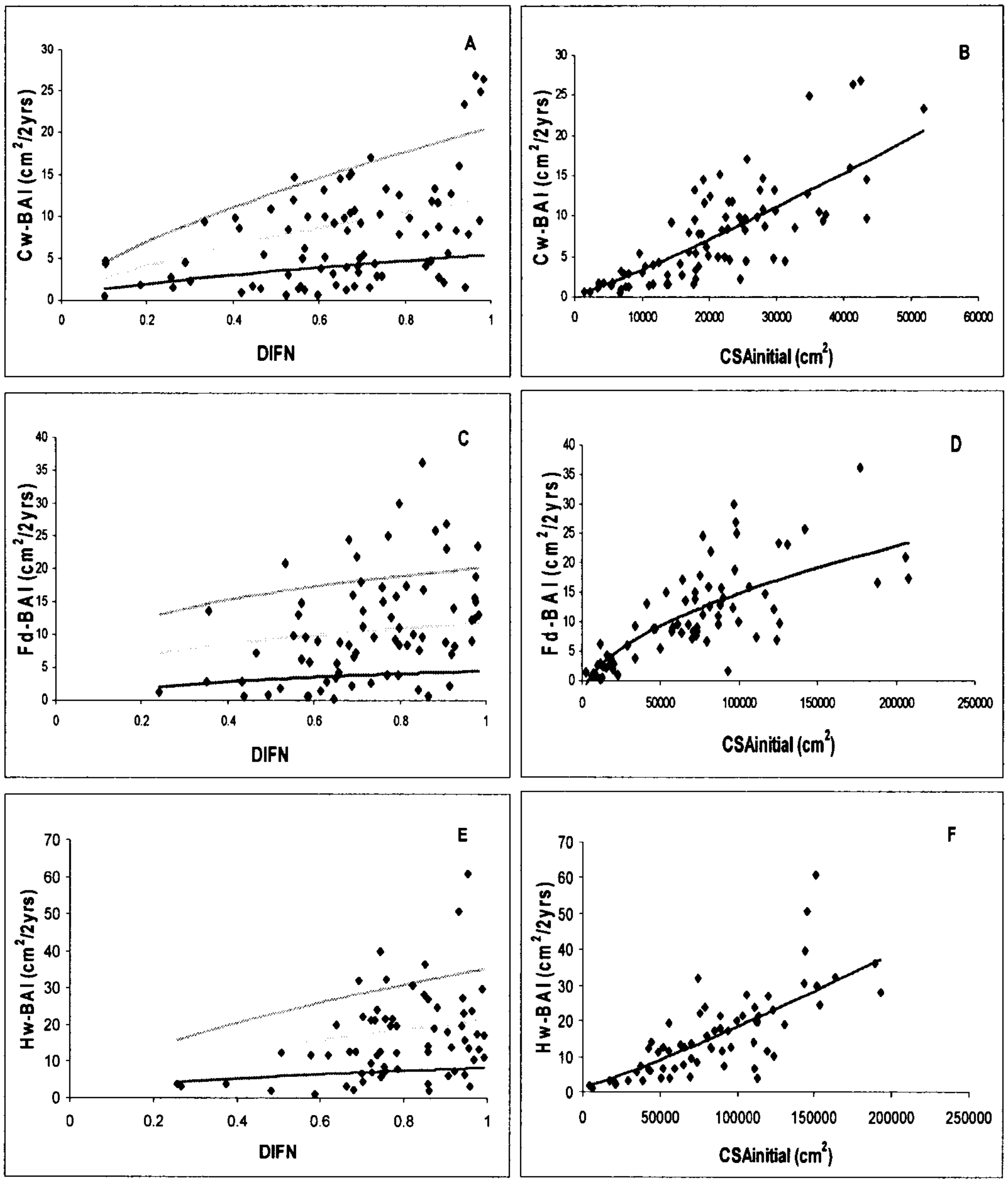


Figure 2.16. Relationships between basal area increment and DIFN, the model is: $Y = a + b_1 * X^{(b_2)} * CSAi^c$ + €. Graphs A and B are for redcedar, graph C and D for Douglas-fir and graph E and F for western hemlock. Graph A, C and E each show three different curves calculated for three levels (low-medium-high) of initial crown surface area (CSAi). Graph B, D and F each show a curve calculated using the mean value of DIFN of each species. Parameter values and statistical information for each trendline are provided in Tables 2.12, 2.13 and 2.14.

Table 2.12. Parameter values and statistical information for non-linear models of western redcedar basal area increment. The table shows: number of observations (obs. #), adjusted R^2 (Adj. R^2), root mean square error (RMSE) and equation parameters (A, B1, B2, B3 and C), where B2 is related to red alder and B3 to paper birch for the competition indexes. Parameter values which are significantly different from zero are shown in bold type. The model used for relationships with competition indexes is: $Y = a + b_1 * e^{(b_2 * X_1 + b_3 * X_2)} * CSAi^c + \epsilon$ and for relationships with DIFN is: $Y = a + b_1 * X^{(b_2)} * CSAi^c + \epsilon$.

Cw BAI	obs #	Adj R^2	RMSE	A	Range +/-	B1	Range +/-	B2	Range +/-	B3	Range +/-	C	Range +/-
Difn Top	80	0.730	3.141	0.289	2.3573	0.000112	0.000439	**0.6959**	0.33			**1.1425**	0.3631
MBA	69	0.665	3.369	0.4126	2.8845	0.000375	0.001775	**-0.0507**	0.0286	**-0.0478**	0.04134	**1.0259**	0.4418
DDR	69	0.662	3.387	0.04	3.1628	0.000398	0.001922	**-2.2654**	1.2365	**-2.3995**	2.0001	**1.0252**	0.4496
MBAm	69	0.661	3.393	0.181	3.1038	0.000328	0.001622	**-0.0313**	0.0174	**-0.0223**	0.01924	**1.0412**	0.4582
VI	69	0.655	3.423	0.3869	3.0091	0.000337	0.001673	**-0.0788**	0.0453	**-0.0591**	0.05418	**1.0365**	0.4613
BA	69	0.645	3.469	-0.0739	3.2205	0.000239	0.001201	**-0.00022**	0.00013	-0.00037	0.000451	**1.0701**	0.4645
CSA	69	0.644	3.474	0.0646	3.1519	0.000204	0.001036	**-1.42E-07**	8.73E-08	-2.28E-07	2.83E-07	**1.0839**	0.4704
HFm	69	0.644	3.475	0.315	3.1052	0.000203	0.001057	**-0.0001**	0.00006	-0.00006	6.45E-05	**1.0848**	0.4818
HF	69	0.643	3.478	0.9247	2.6283	0.000255	0.001245	**-0.0251**	0.01532	-0.0153	0.01552	**1.0594**	0.4575
DS	69	0.643	3.481	0.1926	3.1646	0.000227	0.001173	**-0.00702**	0.00423	-0.00666	0.00729	**1.0755**	0.4774
VIm	69	0.643	3.482	0.3505	3.1382	0.000242	0.001268	**-0.0602**	0.0356	-0.0317	0.032072	**1.0682**	0.4858
TN	69	0.627	3.555	0.5207	3.1448	0.000181	0.000999	**-0.0598**	0.0378	-0.0234	0.02812	**1.0928**	0.5111
SFIm/TN	69	0.602	3.674	-0.5241	4.1072	0.00031	0.00183	0.1341	0.2952	**0.3445**	0.2495	**0.9987**	0.5298
SFI/TN	69	0.599	3.690	-0.7532	4.3411	0.000781	0.004509	0.0728	0.1248	**0.1089**	0.0779	**0.914**	0.5185
SFIm	69	0.592	3.718	0.6895	3.2727	0.000115	0.000703	**-0.0742**	0.0594	-0.011	0.0269	**1.1273**	0.5662
SFI	69	0.574	3.802	0.6731	3.4421	0.000081	0.000524	**-0.0335**	0.03138	-0.0019	0.0086	**1.1568**	0.6001

Table 2.13. Parameter values and statistical information for non-linear models of Douglas-fir basal area increment. The table shows: number of observations (obs. #), adjusted R^2 (Adj. R^2), root mean square error (RMSE) and equation parameters (A, B1, B2, B3 and C), where B2 is related to red alder and B3 to paper birch for the competition indexes. Parameter values which are significantly different from zero are shown in bold type. The model used for relationships with competition indexes is: $Y = a + b_1 * e^{(b_2*X_1+b_3*X_2)} * CSAi^c + \epsilon$ and for relationships with DIFN is: $Y = a + b_1 * X^{(b_2)} * CSAi^c + \epsilon$.

Fd BAI	obs #	Adj R^2	RMSE	A	Range +/-	B1	Range +/-	B2	Range +/-	B3	Range +/-	C	Range +/-
SFI/TN	66	0.665	4.701	-1.0983	5.9863	0.00421	0.02249	0.00106	0.08424	**0.08**	0.05	**0.7058**	0.4275
SFI	66	0.665	4.703	-2.334	7.3673	0.0116	0.0598	-0.016	0.01933	**0.0102**	0.0072	**0.6396**	0.4137
CSA	66	0.642	4.858	-1.3387	6.4003	0.00552	0.02948	**-1.08E-07**	9.23E-08	-3.37E-08	2.63E-07	**0.71**	0.4385
HFm	66	0.641	4.865	-1.9972	7.248	0.00981	0.05239	**-0.00006**	5.68E-05	0.000022	0.000076	**0.6591**	0.4331
BA	66	0.638	4.891	-1.66	6.7965	0.00733	0.03937	**-0.00015**	0.00014	-5.00E-05	0.000444	**0.6858**	0.4404
DS	66	0.637	4.893	-2.13	7.4481	0.0116	0.0616	**-0.00415**	0.0041	0.00184	0.00762	**0.6456**	0.4321
TN	66	0.637	4.893	-2.1646	7.5716	0.0119	0.0638	**-0.0361**	0.0371	0.0173	0.0378	**0.6413**	0.4313
VIm	66	0.637	4.897	-2.2617	7.6817	0.0126	0.0674	-0.0341	0.034467	0.0149	0.0397	**0.6378**	0.4334
MBAm	66	0.634	4.915	-2.4178	7.8332	0.0131	0.071	-0.0164	0.016529	0.00561	0.02089	**0.6352**	0.4372
SFIm	66	0.634	4.917	-1.9221	7.2591	0.0106	0.0557	-0.0595	0.0641	0.0281	0.0466	**0.6494**	0.4242
VI	66	0.629	4.947	-1.8063	7.3804	0.0146	0.0769	**-0.0621**	0.06061	-0.00442	0.08492	**0.6251**	0.4259
DDR	66	0.629	4.948	-2.5296	8.0156	0.0147	0.0795	-1.1358	1.1995	0.4242	2.0794	**0.6262**	0.4382
MBA	66	0.627	4.959	-1.8291	7.4872	0.0164	0.0858	-0.0448	0.044903	-0.00152	0.06252	**0.6146**	0.4235
HF	66	0.627	4.962	-1.0584	6.3573	0.0101	0.0506	-0.023	0.02381	4.84E-03	0.02356	**0.6516**	0.4057
SFIm/TN	66	0.618	5.021	-2.3597	8.0978	0.0104	0.0608	-0.1274	0.2875	0.2416	0.27	**0.643**	0.467
Difn Top	73	0.559	5.291	-3.2478	9.582	0.0444	0.2384	0.2545	0.4513			**0.5289**	0.4257

Table 2.14. Parameter values and statistical information for non-linear models of western hemlock basal area increment. The table shows: number of observations (obs. #), adjusted R^2 (Adj. R^2), root mean square error (RMSE) and equation parameters (A, B1, B2, B3 and C), where B2 is related to red alder and B3 to paper birch for the competition indexes. Parameter values which are significantly different from zero are shown in bold type. The model used for relationships with competition indexes is: $Y = a + b_1 * e^{(b_2 * X_1 + b_3 * X_2)} * CSAi^c + \text{€}$ and for relationships with DIFN is: $Y = a + b_1 * X^{(b_2)} * CSAi^c + \text{€}$.

Hw BAI	obs #	Adj R^2	RMSE	A	Range +/-	B1	Range +/-	B2	Range +/-	B3	Range +/-	C	Range +/-
Difn Top	66	0.559	7.786	1.3943	8.0056	0.000036	0.000291	0.622	1.0072			**1.1479**	0.6689
SFlm/TN	55	0.477	8.503	3.0833	9.5198	3.35E-07	4.54E-06	0.2516	0.427	0.1064	0.4464	**1.5189**	1.1063
MBAm	55	0.475	8.514	1.7645	10.4952	6.68E-06	7.83E-05	0.00468	0.03682	-0.0238	0.051	**1.2841**	0.9543
SFlm	55	0.473	8.531	2.46	10.1327	1.48E-06	1.85E-05	0.052	0.1127	-0.0133	0.1339	**1.4021**	1.0455
HFm	55	0.472	8.540	2.2567	10.2478	2.99E-06	3.7E-05	0.000031	0.000115	-0.00006	0.000187	**1.3477**	1.0033
Vlm	55	0.472	8.540	2.1348	10.3302	3.77E-06	4.62E-05	0.0164	0.0703	-0.0328	0.0953	**0.0625**	2.2591
DDR	55	0.472	8.541	1.5275	10.9282	0.00001	0.000118	0.0875	2.6968	-2.0438	4.7335	**1.2505**	0.9565
TN	55	0.472	8.544	2.3736	10.1589	2.55E-06	3.15E-05	0.0223	0.073	-0.0263	0.0964	**1.3599**	1.0136
MBA	55	0.471	8.550	2.1555	10.0679	6.19E-06	7.18E-05	0.000152	0.098348	-0.0772	0.1884	**1.2893**	0.9512
SFl	55	0.471	8.551	2.1135	10.531	5.22E-06	6.28E-05	0.0106	0.0327	-0.00812	0.03372	**1.299**	0.9771
Vl	55	0.470	8.553	2.1918	10.1721	4.33E-06	5.17E-05	0.0133	0.1225	-0.0818	0.2203	**1.3185**	0.9825
CSA	55	0.470	8.557	1.937	10.6013	4.37E-06	5.26E-05	3.525E-08	1.74E-07	-1.7E-07	5.53E-07	**1.3172**	0.9878
DS	55	0.468	8.569	2.0223	10.6157	4.38E-06	5.36E-05	0.00165	0.00835	-0.00461	0.01731	**1.3163**	1.0027
HF	55	0.468	8.575	2.2251	10.458	3.02E-06	3.8E-05	0.01	0.0418	-0.0139	0.067	**1.3463**	1.0204
BA	55	0.466	8.592	1.7658	10.9747	6.55E-06	7.95E-05	0.000024	0.000286	-0.00022	0.000879	**1.2838**	0.9927
SFl/TN	55	0.462	8.620	1.6894	11.2973	6.63E-06	8.34E-05	0.00548	0.08962	0.00997	0.09663	**1.2795**	1.0304

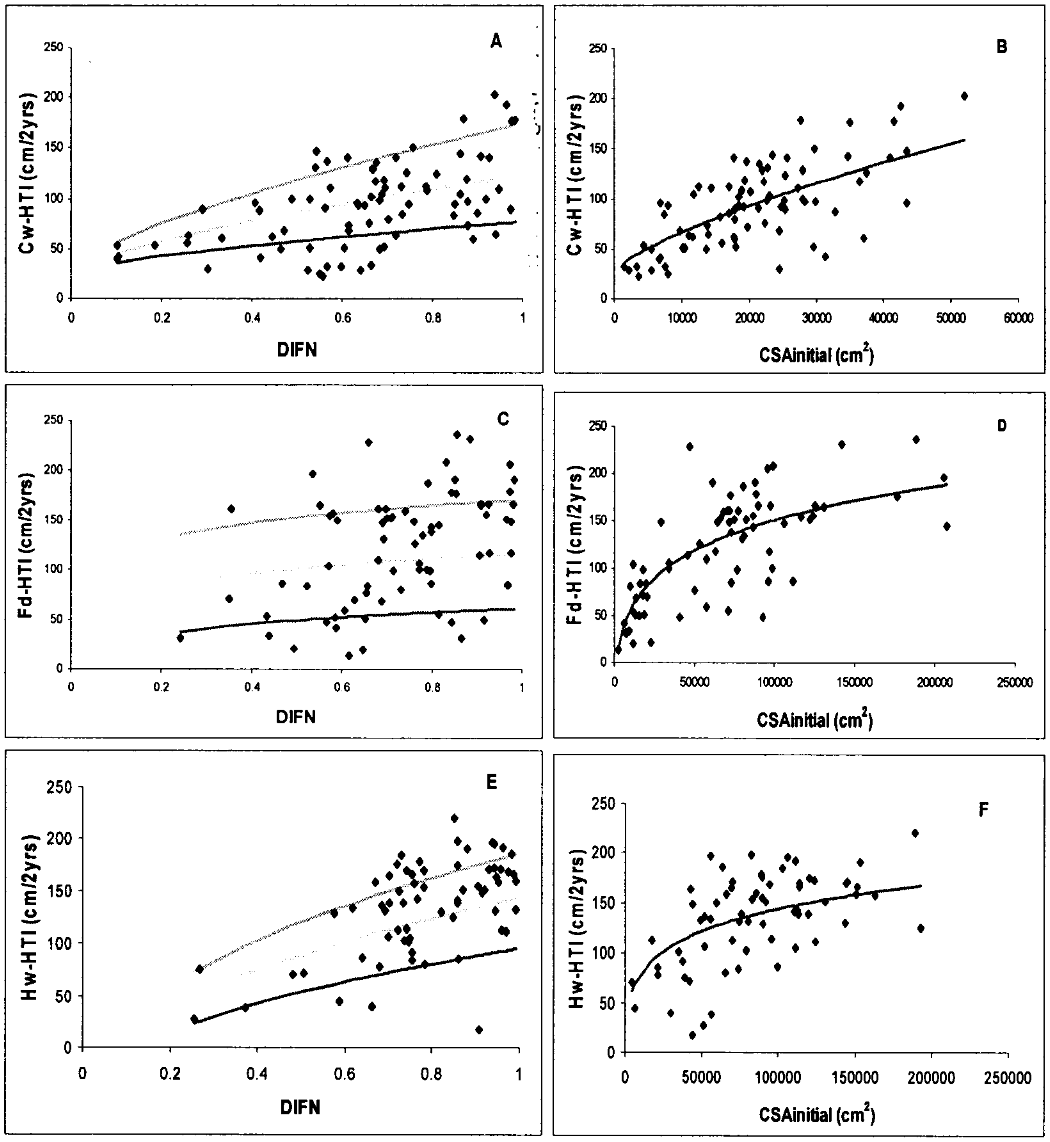


Figure 2.17. Relationships between height increment and DIFN, the model is: $Y = a + b_1 * X^{(b_2)} * CSAi^c$ + €. Graphs A and B are for redcedar, graph C and D for Douglas-fir and graph E and F for western hemlock. Graph A, C and E each show three different curves calculated for three levels (low-medium-high) of initial crown surface area (CSAi). Graph B, D and F each show a curve calculated using the mean value of DIFN of each species. Parameter values and statistical information for each trendline are provided in Tables 2.15, 2.16 and 2.17.

Table 2.15. Parameter values and statistical information for non-linear models of western redcedar height increment. The table shows: number of observations (obs. #), adjusted R^2 (Adj. R^2), root mean square error (RMSE) and equation parameters (A, B1, B2, B3 and C), where B2 is related to red alder and B3 to paper birch for the competition indexes. Parameter values which are significantly different from zero are shown in bold type. The model used for relationships with competition indexes is: $Y = a + b_1 * e^{(b_2 * X_1 + b_3 * X_2)} * CSAi^c + \epsilon$ and for relationships with DIFN is: $Y = a + b_1 * X^{(b_2)} * CSAi^c + \epsilon$.

Cw HTI	obs #	Adj R^2	RMSE	A	Range +/-	B1	Range +/-	B2	Range +/-	B3	Range +/-	C	Range +/-
DifnTop	80	0.678	23.717	24.7272	28.4139	0.0897	0.3113	**0.6726**	0.3694			**0.6999**	0.318
MBA	69	0.566	27.366	31.0931	33.6038	0.0432	0.2313	**-0.0509**	0.0365	-0.0284	0.03568	**0.7599**	0.4923
DDR	69	0.566	27.372	25.859	39.3892	0.0626	0.3386	**-2.2726**	1.5867	-1.5862	1.7957	**0.7317**	0.4938
BA	69	0.563	27.461	26.341	37.4405	0.0392	0.211	**-0.00024**	0.00017	-0.00035	0.000439	**0.7755**	0.4946
MBAm	69	0.559	27.593	26.3063	39.7896	0.0561	0.3149	**-0.0302**	0.02201	-0.0121	0.01634	**0.739**	0.5125
CSA	69	0.557	27.653	27.6375	36.7874	0.0335	0.1849	**-1.48E-07**	1.1E-07	-1.79E-07	2.64E-07	**0.7873**	0.5069
VI	69	0.546	28.005	28.8255	37.6171	0.0486	0.2765	**-0.0732**	0.0555	-0.0291	0.0454	**0.749**	0.5206
DS	69	0.542	28.132	27.0481	39.3165	0.0422	0.2421	**-0.00666**	0.00513	-0.00382	0.00644	**0.765**	0.5244
HFm	69	0.540	28.178	26.7945	40.0032	0.0439	0.2561	**-0.00009**	0.00007	-0.00003	0.000058	**0.7594**	0.5326
VIm	69	0.533	28.410	26.5424	41.4044	0.0494	0.2951	**-0.0532**	0.0422	-0.0123	0.0262	**0.7476**	0.544
HF	69	0.530	28.482	**36.4828**	28.5777	0.0249	0.1361	**-0.0233**	0.01838	-0.00669	0.01344	**0.8049**	0.5054
TN	69	0.517	28.869	26.3223	42.8387	0.0486	0.3023	**-0.0492**	0.04214	-0.00537	0.02147	**0.746**	0.564
SFIm	69	0.487	29.766	24.9765	47.2607	0.0514	0.3458	-0.0517	0.05752	0.00443	0.01917	**0.7339**	0.6068
SFI/TN	69	0.485	29.819	8.7588	76.4458	0.318	2.1407	0.0286	0.1084	0.0812	0.0865	0.55	0.5743
SFIm/TN	69	0.479	30.003	12.2275	70.1467	0.1624	1.1336	0.0216	0.2516	0.2218	0.2553	**0.613**	0.6014
SFI	69	0.472	30.203	20.21	56.9698	0.0871	0.6109	-0.0211	0.02844	0.00221	0.00627	**0.6844**	0.6263

Table 2.16. Parameter values and statistical information for non-linear models of Douglas-fir height increment. The table shows: number of observations (obs. #), adjusted R^2 (Adj. R^2), root mean square error (RMSE) and equation parameters (A, B1, B2, B3 and C), where B2 is related to red alder and B3 to paper birch for the competition indexes. Parameter values which are significantly different from zero are shown in bold type. The model used for relationships with competition indexes is: $Y = a + b_1 * e^{(b_2 * X_1 + b_3 * X_2)} * CSAi^c + \text{€}$ and for relationships with DIFN is: $Y = a + b_1 * X^{(b_2)} * CSAi^c + \text{€}$.

Fd HTI	obs #	Adj R^2	RMSE	A	Range +/-	B1	Range +/-	B2	Range +/-	B3	Range +/-	C	Range +/-
SFI/TN	66	0.631	33.486	918.6	5433.4	-1439.1	4127.7	-0.00836	0.06086	0.00306	0.02284	-0.0549	0.3682
SFI	66	0.627	33.654	-557.9	3538.6	333.6	3005.2	-0.00122	0.00679	-0.00125	0.00654	0.0675	0.3591
CSA	66	0.626	33.706	-718	5879	470.6	5243.6	-6.53E-09	4.6E-08	-8.4E-09	6.77E-08	0.0549	0.3918
MBAm	66	0.624	33.808	-683.6	5452.9	443.3	4834.1	-0.00131	0.0089	-0.0009	0.00669	0.0566	0.391
HFm	66	0.623	33.833	-756.2	6460.6	509.6	5832.6	-3.78E-06	2.78E-05	-2.8E-06	2.18E-05	0.0516	0.3868
DDR	66	0.623	33.856	-657.1	5095.4	420.4	4486.2	-0.094	0.6229	-0.1002	0.7245	0.0585	0.3905
SFIm/TN	66	0.623	33.860	3405.5	91348.1	-3849.8	90137.5	-0.00612	0.17142	-0.00122	0.03412	-0.0145	0.4021
DS	66	0.622	33.898	-686.3	5469.2	448.4	4863.3	-0.00028	0.00193	-0.00034	0.00249	0.0559	0.3858
BA	66	0.621	33.932	-685.2	5390.6	441.2	4767	-8.63E-06	5.86E-05	-0.00001	0.000107	0.0571	0.3888
VIm	66	0.621	33.940	-844.2	7951.3	593.1	7309.1	-0.00197	0.01617	-0.00131	0.01141	0.0463	0.3874
MBA	66	0.621	33.959	-2221.5	47879.2	1923.6	47122.9	-0.00078	0.01578	-0.00008	0.0025	0.0187	0.3838
VI	66	0.620	33.990	-1517.3	23215.6	1233.6	22495.3	-0.00153	0.02153	-0.00029	0.00535	0.0269	0.3843
TN	66	0.618	34.062	-774.6	6818.8	532.6	6204.2	-0.00195	0.01495	-0.00123	0.01009	0.0494	0.3821
HF	66	0.616	34.189	-643.7	5022.5	426.7	4471.1	-0.00083	0.00579	-0.00037	0.00319	0.0552	0.3693
SFIm	66	0.612	34.355	-823.4	7409.9	577	6799.1	-0.00155	0.01285	-0.00087	0.00777	0.0465	0.3705
DifnTop	73	0.548	37.856	-161	670.1	52.2244	349.6756	0.0791	0.2465			0.1574	0.401

Table 2.17. Parameter values and statistical information for non-linear models of western hemlock height increment. The table shows: number of observations (obs. #), adjusted R^2 (Adj. R^2), root mean square error (RMSE) and equation parameters (A, B1, B2, B3 and C), where B2 is related to red alder and B3 to paper birch for the competition indexes. Parameter values which are significantly different from zero are shown in bold type. The model used for relationships with competition indexes is: $Y = a + b_1 * e^{(b_2 * X_1 + b_3 * X_2)} * CSAi^c + €$ and for relationships with DIFN is: $Y = a + b_1 * X^{(b_2)} * CSAi^c + €$.

Hw HTI	obs #	Adj R^2	RMSE	A	Range +/-	B1	Range +/-	B2	Range +/-	B3	Range +/-	C	Range +/-
DifnTop	66	0.494	32.468	-63.2767	342.0767	35.6322	178.8678	0.4431	0.9207			0.1623	0.475
SFI	55	0.318	34.486	**209.9**	165.8	-6533.5	37353.3	0.0128	0.0398	0.0114	0.0253	-0.4114	0.7357
SFIm/TN	55	0.298	34.999	-671.5	10570.4	432.1	9291.5	0.0196	0.2639	0.00708	0.10422	0.0544	0.7315
MBAm	55	0.296	35.050	246.2	353.1	-2375.1	11378.1	0.0128	0.0516	0.00875	0.03965	-0.281	0.738
DDR	55	0.296	35.053	256.5	404.6	-2234.6	10708.4	0.7483	3.2591	1.0294	4.4789	-0.2669	0.7507
SFI/TN	55	0.295	35.078	244.2	308.2	-3678.4	20709.5	0.0186	0.0908	0.0303	0.1074	-0.3218	0.7803
BA	55	0.290	35.209	350.5	1023.8	-1413.7	4751.2	0.000011	0.000116	0.00011	0.000621	-0.1697	0.7318
MBA	55	0.289	35.229	333.9	916.2	-1188.4	3273.5	0.0102	0.0571	0.0066	0.0451	-0.162	0.6601
SFIm	55	0.288	35.258	305.2	749.6	-1617.4	6969.4	0.0028	0.0438	0.0111	0.0625	-0.203	0.7873
DS	55	0.287	35.275	345.2	1016.4	-1413.1	4919.6	0.000272	0.003418	0.00168	0.01022	-0.1718	0.7502
VIm	55	0.287	35.280	290.7	622.4	-1707.6	7319.7	0.00851	0.05239	0.011	0.0598	-0.2174	0.7548
TN	55	0.286	35.296	292.6	646.1	-1710.5	7481.4	0.00622	0.04528	0.00999	0.05531	-0.2159	0.7701
HF	55	0.283	35.362	419.2	1839.2	-1291.6	4102.4	-0.00052	0.01037	0.00108	0.01102	-0.1351	0.8486
CSA	55	0.283	35.365	559.1	3510.4	**-1196**	531.8	-3.19E-09	3.67E-08	8.33E-09	1.16E-07	-0.0923	0.7277
VI	55	0.283	35.374	388.4	1415.9	-1208.5	2914.4	0.00482	0.04428	0.00617	0.05553	-0.1404	0.7141
HFm	55	0.282	35.385	432.9	1874.5	-1212.1	2367.7	1.034E-06	3E-05	5.34E-06	5.27E-05	-0.1257	0.7349

Further analysis investigated the relationships between DIFN values and the competition indexes, showing that for Douglas-fir the competition index with the highest adjusted R^2 was MBA ($R^2=0.344$; $n=70$) (Figure 2.18) and both parameters related to red alder and paper birch were different from zero (Table 2.19). For western hemlock SFI was the best index ($R^2=0.247$; $n=61$), followed by MBA (Figure 2.18) with a similar adjusted R^2 ($R^2=0.243$; $n=61$), in these cases the broadleaf parameter values were not significantly different from zero (Table 2.20). For western redcedar, the competition index better related to DIFN was MBA ($R^2=0.459$; $n=72$) (Figure 2.18), but parameters values for red alder and paper birch were not different from zero (Table 2.18).

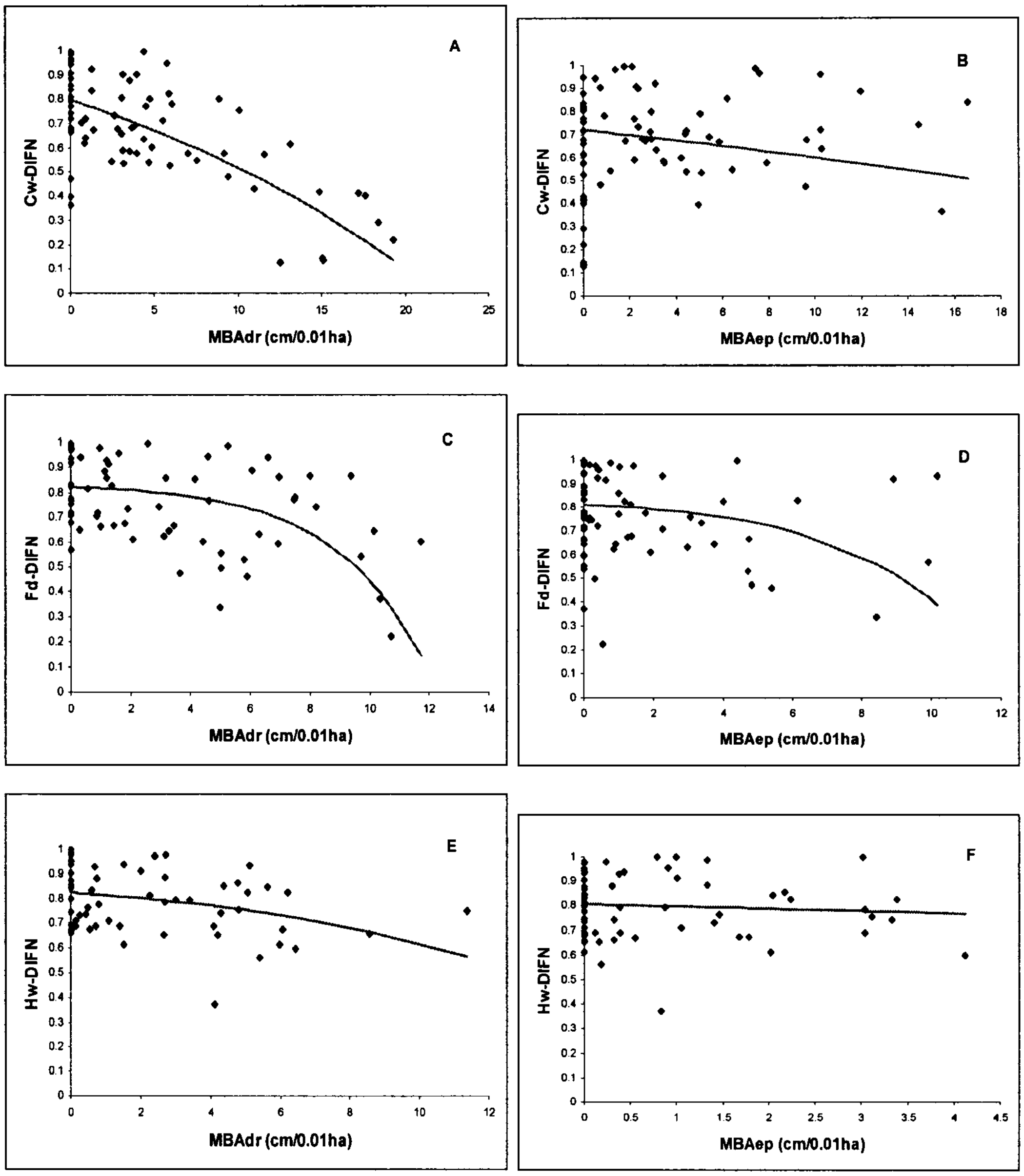


Figure 2.18. Relationships between DIFN value and competition index Modified Braathe Index (MBA), the model is: $Y = a + b_1 * e^{(b_2*MBAdr+b_3*MBAep)}$ + €. Graphs A and B are for redcedar, graphs C and D for Douglas-fir and graphs E and F for western hemlock. Graphs A, C and E each show curves calculated using the mean value of MBA for the birch component (MBAep). Graphs B, D and F show curves calculated using the mean value of MBA for the red alder component (MBAdr). Parameter values and statistical information for each trendline are provided in Tables 2.18, 2.19 and 2.20.

Table 2.18. Parameter values and statistical information for non-linear models of western redcedar DIFN values. The table shows: number of observations (obs. #), adjusted R^2 (Adj. R^2), root mean square error (RMSE) and equation parameters (A, B1, B2, B3), where B2 is related to red alder and B3 to paper birch for the competition indexes. Parameter values which are significantly different from zero are shown in bold type. The model used for relationships with competition indexes is: $Y = a + b_1 * e^{(b_2*X_1+b_3*X_2)}$+€.

Cw DIFNtop	obs #	Adj R^2	RMSE	A	Range +/-	B1	Range +/-	B2	Range +/-	B3	Range +/-	P(<0.05)
MBA	72	0.459	0.156	1.3769	1.9404	-0.5472	1.8828	0.0395	0.0981	0.0169	0.0482	**<.0001**
DDR	72	0.434	0.159	1.7895	4.9108	-0.9555	4.8474	1.2832	5.2692	0.4552	2.0214	**<.0001**
MBAm	72	0.407	0.163	1.6916	4.3034	-0.8594	4.236	0.0193	0.0756	0.00558	0.02362	**<.0001**
VI	72	0.360	0.169	1.4201	2.776	-0.6054	2.7133	0.0568	0.1932	0.0145	0.0564	**<.0001**
DS	72	0.331	0.173	1.1329	1.275	-0.3588	1.2264	0.00739	0.01741	0.000299	0.005171	**<.0001**
CSA	72	0.319	0.175	-1.9072	28.8506	2.7316	28.7852	-3.59E-08	4.16E-07	-3.06E-08	3.49E-07	**<.0001**
HF	72	0.313	0.175	-0.5003	4.2873	1.2972	4.2469	-0.00818	0.03268	-0.00065	0.00412	**<.0001**
HFm	72	0.312	0.175	1.3499	2.7747	-0.5584	2.707	0.000076	0.000276	0.000013	0.000057	**<.0001**
VIm	72	0.311	0.175	1.2022	1.742	-0.4082	1.6768	0.0601	0.1751	0.00717	0.02903	**<.0001**
TN	72	0.272	0.181	**0.9334**	0.5894	-0.1659	0.5308	0.1052	0.196	0.00107	0.04523	**<.0001**
BA	72	0.269	0.181	**0.4541**	0.1508	**0.4445**	0.1818	**-0.00087**	0.000867	-0.00075	0.000895	**<.0001**
SFI	72	0.097	0.201	**0.5553**	0.1925	**0.2053**	0.199	-0.2253	0.538	0.000997	0.015503	**0.0194**
SFI/TNm	72	0.079	0.203	**0.6234**	0.0591	0.0787	0.1975	-21.9473	1450.947	0.6873	2.3437	**0.0356**
SFIm	72	0.075	0.203	**0.623**	0.0592	**0.1444**	0.138	-14.778	280.078	0.00516	0.06224	**0.0402**
SFI/TN	72	0.075	0.203	**0.623**	0.0591	0.1571	0.2166	-12.7323	302.7323	-0.014	0.5239	**0.0405**

Table 2.19. Parameter values and statistical information for non-linear models of Douglas-fir DIFN values. The table shows: number of observations (obs. #), adjusted R^2 (Adj. R^2), root mean square error (RMSE) and equation parameters (A, B1, B2, B3), where B2 is related to red alder and B3 to paper birch. Parameter values which are significantly different from zero are shown in bold type. The model used for relationships with competition indexes is: $Y = a + b_1 * e^{(b_2 * X_1 + b_3 * X_2)}$+€.

Fd DIFNtop	obs #	Adj R^2	RMSE	A	Range +/-	B1	Range +/-	B2	Range +/-	B3	Range +/-	P(<0.05)
MBA	70	0.344	0.141	**0.8378**	0.0697	-8.92E-03	0.02402	**0.3341**	0.237	**0.2831**	0.1987	**<.0001**
HF	70	0.287	0.148	0.1393	1.6739	0.7421	1.6418	-0.0205	0.0611	-0.00688	0.02068	**<.0001**
VI	70	0.212	0.155	**0.896**	0.2672	-0.0546	0.2105	0.2386	0.4194	0.1824	0.3478	**0.0003**
SFIm	70	0.209	0.156	6.4664	266.6336	-5.6002	266.5002	0.00722	0.33488	0.00149	0.06921	**0.0003**
TN	70	0.148	0.161	-0.3834	16.286	1.2525	16.2125	-0.0216	0.3152	-0.00971	0.14271	**0.0035**
SFI/TNm	70	0.142	0.162	0.035	5.8963	0.8811	5.7626	-0.2863	2.3935	-0.1257	1.0752	**0.0043**
VIm	70	0.120	0.164	0.2487	3.7882	0.6208	3.7133	-0.0446	0.3462	-0.0278	0.2158	**0.0095**
MBAm	70	0.104	0.165	**0.6655**	0.1261	**0.2172**	0.1475	-0.1804	0.3205	-0.0464	0.1001	**0.0165**
DDR	70	0.103	0.166	**0.6485**	0.1735	**0.2376**	0.1735	-9.7605	19.1236	-5.328	11.1151	**0.0168**
DS	70	0.100	0.166	1.068	1.9857	-0.2242	1.9026	0.00721	0.04349	0.00988	0.06072	**0.0190**
HFm	70	0.089	0.167	**0.6859**	0.0936	**0.1972**	0.1439	-0.00082	0.001396	-0.00014	0.000356	**0.0089**
SFI	70	0.084	0.167	**0.7189**	0.0504	**0.1598**	0.1309	-1.9365	11.3858	-0.0167	0.0629	**0.0325**
CSA	70	0.067	0.169	**0.7014**	0.0798	**0.1637**	0.1416	-1.79E-06	3.68E-06	-4.00E-07	1.48E-06	0.0554
BA	70	0.061	0.169	**0.7073**	0.072	**0.1651**	0.1488	-0.00349	0.00714	-0.00094	0.00295	0.0669
SFI/TN	70	-0.024	0.177	**0.747**	0.053	0.00165	0.01865	1.4643	3.9699	-4.6052	679.5052	0.7123

Table 2.20. Parameter values and statistical information for non-linear models of western hemlock DIFN values. The table shows: number of observations (obs. #), adjusted R^2 (Adj. R^2), root mean square error (RMSE) and equation parameters (A, B1, B2, B3), where B2 is related to red alder and B3 to paper birch. Parameter values which are significantly different from zero are shown in bold type. The model used for relationships with competition indexes is: $Y = a + b_1 * e^{(b_2 * X_1 + b_3 * X_2)} + \epsilon$.

Hw DIFNtop	obs #	Adj R^2	RMSE	A	Range +/-	B1	Range +/-	B2	Range +/-	B3	Range +/-	P(<0.05)
SFI	61	0.247	0.128	**0.7997**	0.0339	-6.46E-12	3.38E-10	1.2709	2.6399	0.233	0.5586	**0.0002**
MBA	61	0.243	0.128	**0.9027**	0.2255	-0.0737	0.1936	0.1276	0.1469	0.0785	0.2466	**0.0003**
CSA	61	0.227	0.130	**0.8118**	0.0471	-0.00094	0.00507	1.09E-06	9.26E-07	4.03E-06	4.16E-06	**0.0005**
DDR	61	0.224	0.130	**0.8845**	0.1853	-0.0575	0.1505	5.516	5.9399	1.5661	5.5547	**0.0006**
BA	61	0.216	0.130	**0.8576**	0.1464	-3.89E-02	0.1128	0.000626	0.000654	0.000124	0.000278	**0.0007**
SFIm	61	0.209	0.131	**0.8253**	0.0655	-0.00836	0.02716	**0.5074**	0.3983	0.0419	0.2317	**0.0009**
DS	61	0.207	0.131	**0.8371**	0.0945	-0.0164	0.0536	**0.0281**	0.0266	0.0185	0.032	**0.0010**
VI	61	0.207	0.131	**0.7975**	0.0354	-7.57E-07	1.78E-05	1.3335	2.3333	2.1502	4.4194	**0.0010**
HFm	61	0.180	0.133	**0.8024**	0.0404	-0.00007	0.000621	0.0011	0.00115	0.00173	0.00242	**0.0025**
TN	61	0.179	0.133	**0.8236**	0.0693	-0.00608	0.02528	**0.3446**	0.3351	0.1779	0.33	**0.0025**
MBAm	61	0.179	0.133	**0.836**	0.0982	-0.0158	0.0565	0.1281	0.1339	0.0841	0.2252	**0.0025**
HF	61	0.164	0.135	1.1302	1.9609	-0.3031	1.9298	0.0195	0.0945	-0.00178	0.02158	**0.0041**
VIm	61	0.158	0.135	**0.8416**	0.1079	-0.0152	0.06	0.2557	0.3058	0.189	0.3791	**0.0049**
SFI/TNm	61	0.129	0.137	1.1261	2.3224	-0.2455	2.2354	0.4141	2.8289	0.2447	1.5982	**0.0124**
SFI/TN	61	0.015	0.146	**0.8013**	0.0615	-0.00215	0.02005	-0.2313	0.689	0.7229	1.5833	0.2835

2.8 Discussion

2.8.1 Characterization of soil structure, soil and foliar sampling

Soil analysis indicates: a concentration of total nitrogen of 0.38%, a content of total carbon of 9.13%, an average pH of 5.88 (Table 2.3). These results, in comparison to the average values for the MKRF installation, show that nitrogen and carbon are not scarce and the pH of the soil is higher than the average value for the area, probably because red alder has not been on the site long enough to acidify the soil (Klinka and Krajina 1983).

The results of the PRS probes show that soil nitrogen availability is related to red alder density (Figure 2.5). In particular, the amount of available nitrate (NO_3^-) is significantly related to red alder density, due to the high mobility of nitrates in the soil, unlike the ammonium ion (NH_4^+) component (Pritchett 1979). The relationships between available nitrogen in the soil and paper birch density were not significant. Red alder has the ability to fix nitrogen (N) due to a symbiosis with N-fixing *Frankia* spp. As many studies have shown healthy stands can fix large amount of nitrogen (up to 200 kg ha^{-1} y^{-1} in pure stands), which becomes available within the stand (Binkley et al. 1994, Binkley et al. 1992, Swanson and Myrold 1997). Paper birch stands also sustain populations of free-living nitrogen-fixing bacteria, but this study suggests that the influence of red alder on nitrogen availability in the soil is greater than the influence of paper birch. Red alder in particular has the capability to enrich the soil with nutrients (N, P, S, Ca, Mg and K) as a result of the rapid decomposition of their high quality litter, which also contributes in accelerated nutrient cycling (Radwan et al. 1984, Fyles and Fyles 1993; Simard et al. 1997).

The foliage samples showed significant relationships between broadleaf density and nitrogen or calcium concentrations for Douglas-fir only. For N concentration in the needles the parameter related to red alder density is statistically significant ($p<0.005$), unlike the parameter related to paper birch and a similar result is shown by the concentration of Ca in the needles (Figure 2.6). Foliar concentration of other macronutrients (K and P) was not significantly related to broadleaf density for any of the conifers. The results were not improved by accounting for nutrient content in relation to dry weight or the surface area of 50 needles for Douglas-fir and western hemlock. For Douglas-fir the concentration of nitrogen and calcium in the needles is not considered deficient (Carter 1992). This study suggests that Douglas-fir, which has the highest growth rates among the conifers, can benefit from increased nitrogen and calcium availability, which red alder is able to supply even on a nutrient rich site.

2.8.2 Tree growth

DIFN and competition indexes show different capability in predicting conifer growth. For Douglas-fir competition indexes perform consistently better than

DIFN, whereas for western hemlock and western redcedar DIFN was more predictive. This outcome is probably related to species shade-tolerance characteristics and the size of the trees at the time of the measurements. Douglas-fir top height is in a range of 73-621 cm (average height 350 cm), which makes it generally as tall as, or taller than the surrounding broadleaf vegetation. For this reason competition indexes are probably better predictors of tree increments because they take into account the actual size of the competing broadleaves and may account for factors other than competition for light. Some studies suggest red alder competes with Douglas-fir for both moisture and light (Shainsky and Radosevich 1992; Shainsky et al. 1994; Cole and Newton 1986; Balandier et al. 2006). Variation in the light response might also be a consequence of the nutritional benefits of alder. The benefits related to N availability may balance light reduction or competition for water.

The more shade tolerant western redcedar (average height 232 cm) is mostly growing below the main broadleaf canopy and light availability is probably the main factor limiting their growth; therefore the best relationships are with the DIFN values. Western hemlock is growing at high rates and shows weak relationships with competition measures (average height 394 cm). For the three conifers, it is important to mention that the differences in adjusted R^2 between DIFN and the best competition index is quite small and it ranges between 0.088 (Fd) and 0.047 (Hw).

Comparing competition indexes, 2 distance-independent indexes (CSA and HFm) have the best relationships with Douglas-fir stem volume growth, while for western hemlock and western redcedar the best 4 indexes are distance-dependent. For Douglas-fir, it is important to point out that the differences in adjusted R^2 values among the two groups of indexes are very small (adj. $R^2 = 0.009$). As Lorimer (1983) and Burton (1993) observed, the strength of the correlation between any particular competition index and growth is heavily dependent upon the species, because each species responds differently to stress from competition.

Douglas-fir is growing together with alder in the main canopy and distance-independent competition indexes have the best relationships with stem volume growth. In some cases, if Douglas-fir is overtopped by competitors such as red alder, height growth can increase over a short period of time (Cole and Newton 1987, Wagner 2000). Western redcedar is growing under the main canopy level and it has in distance-dependent indexes their best relationships with stem volume increments. For western hemlock parameter values for red alder and paper birch were not significant. For smaller trees at the low density of broadleaf of this study (0-1150 tph), the distance between crop tree and competitors is an important factor to account for the competition index , whereas in stands that are well stocked, distance independent indexes appear to work well (Comeau et al. 2003).

As studies on distance-dependent and distance-independent indexes have shown, the differences in effectiveness are often small and results are not consistently better for one group of indexes over the other one (Daniels et al. 1986, Mugasha

1989, Biging and Dobbertin 1995). In fact, simple indexes such as the sum of the competitors' height (HFm) (Figure 2.11), total number of competitors (TN) (Figure 2.13) and, competitor basal area (BA) (Figure 2.8) performed quite well. The difference in adjusted R^2 between the best competition index for Douglas-fir (CSA) and HFm is only 0.007 and for TN and BA it is 0.012. For western hemlock and western redcedar the difference in R^2 ranged between 0.002 and 0.034.

The parameter values of each species (strongest negative parameter value) suggest that western redcedar is the most affected by competition, followed by Douglas-fir and, with western hemlock the least affected (Figure 2.14 and 2.15). The literature suggests that western hemlock and western redcedar have similar shade-tolerance and Douglas-fir is not shade-tolerant, thus the broadleaf influence should follow this gradient with Douglas-fir being the most affected by competition (Peterson et al. 1996; Harrington 2006).

However, western redcedar is most affected by broadleaf competition likely due to its small size. At this stage (7-8 years old), top height of western redcedar is lower than top height of Douglas-fir and western hemlock, respectively. External factors, such as the Vexar® tubes installed around western redcedar at the time of planting, browsing by ungulates and natural regeneration of broadleaves, may also influence western redcedar growth. At ground level, the reduction in percentage of full sunlight, caused by red alder and paper birch, is substantial and light levels can drop below 30%, which is the minimum required by western redcedar for optimal growth (Drever and Lertzman 2001). Douglas-fir is growing primarily at the top canopy level where light is generally above 40%, which is the threshold for its continued growth (Mailly and Kimmins 1997). Western hemlock, having a lower nitrogen (nitrate) demand, together with its shade-tolerant characteristics, shows overall high growth rates, so that it is less affected by competition.

The relationships between DIFN and competition indexes clearly show the different influences that red alder and paper birch have on available light for conifer growth. The parameter values for DIFN against the competition indexes (calculated for each broadleaf component), are bigger (steeper slope) for red alder compared to the ones for paper birch (Figure 2.18 and Table 2.18, 2.19, 2.20). This result indicates that red alder has a stronger influence in reducing light levels compared to paper birch. Red alder average height is 578 cm while the average height of paper birch is 358 cm, the shape of the crown and its thicker leaves lead to more light reduction by alder than birch. Results suggest that paper birch can be retained at higher densities than red alder in mixture with conifers.

Even on a nutrient non-limiting site, such as the one where this study took place, results suggest that red alder can enhance nutrient availability (i.e., increases conifer foliar nitrogen), this is in contrast to what Cole and Newton (1986) demonstrated on a 5-year-old Douglas-fir plantation in the Oregon Coast Range.

For my study, the benefit to soil nitrogen and calcium content is contributing to a weaker relationship between growth and DIFN for Douglas-fir.

Microsite and microclimate variations and the topography of the site might have caused differences between the experimental units. Abundant natural regeneration of paper birch and shrubs was present in some plots before the measurements of the 7th growing season, due to the nutrient rich site. The site was brushed between the 7th and the 8th growing season, but the unwanted vegetation might have affected the growth of some conifers.

2.9 Conclusions

The characteristics of the soil for the investigated area did not indicate major problems in structure and fertility. Nonetheless, planted red alder improved nitrate availability in the soil, and an increase in the number of alder resulted in increased nitrogen availability.

Competition indexes performed slightly better when only competitors taller than the crop tree were considered, but the differences in adjusted R^2 were small. DIFN was the best predictor of western redcedar and western hemlock growth, and for Douglas-fir the competition index Crown Surface Area was the best predictor of its growth. Distance-dependent competition indexes performed better than distance-independent indexes for western hemlock and western redcedar, and for

Douglas-fir there was little difference between the two groups. It is important to mention that the differences in adjusted R^2 between distance-dependent and distance-independent indexes were small.

Western redcedar is the most affected by competition, followed by Douglas-fir and, with western hemlock being the least affected. Height of each species at the time of the measurement appears to play a more important role than shade tolerance. The models suggest that red alder affects conifer growth more than paper birch. Red alder is not only taller, but also the crown shape and the thickness of the leaves make it more effective in intercepting sunlight.

It appears that the nutritional benefits of red alder on soil N is contributing to a weaker relationship between growth and DIFN for Douglas-fir than in the case for the other conifer species.

The growth model for western redcedar indicates that a significant reduction in stem volume (30%) occurs with red alder density around 500 tph and with paper birch density around 1000 tph. Likewise, the growth model for Douglas-fir shows important reduction in annual volume increments with red alder density between 500 and 750 tph, whereas paper birch did not significantly affect Douglas-fir at this stage.

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Appendix 2.1

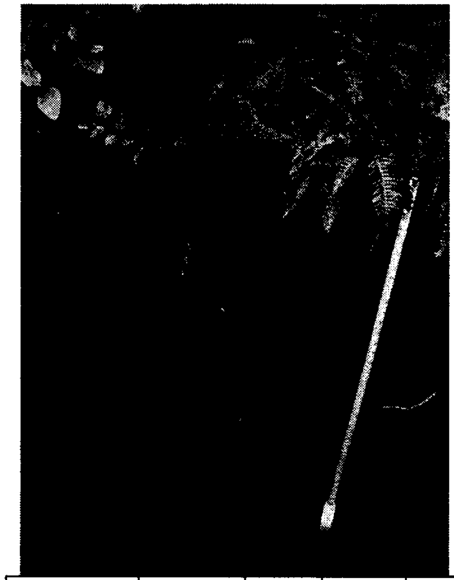
Soil descriptions for Malcolm Knapp Research Forest 1997-23 – "B" Study –

Pit #: 1 Soil Drainage: Moderately Well

Horizon	Depth	min	max	Gravel%	Cobble%	Stones%	Soil Texture	Structure Class& Kind	Mottles	Comments
L	18-15	0	3							
Wood	15-0	10	30							
Ahe	0-5	0	10	10	5	5	SL			
Ae	5-17	0	15	10	5	5	SL	C-PL		
Bf	18-85	?		30	10	10	LS	C-ABK	none	
Ck	85+									

Miscellaneous comments: C "k" horizon – cemented light grey colored; rooting depth=60 cm

Completed by: Phil Comeau June 17, 2005



Pit #: 2
Soil Drainage: Moderately Well

Horizon	Depth	min	max	Gravel%	Cobble%	Stones%	Soil Texture	Structure Class& Kind	Mottles	Comments
L	3-0	0	4							
BF1	0-36	20	40	20	10	5	SL	C-ABK		
BFg	36-96			30	10	5	SL	C-ABK	Distinct grey and red mottles	
BC	96+									

Miscellaneous comments: Grey and orange/red banding and splotching. Soil has mottles, but may also comprise mixed layers of Ae and B horizon which may have resulted from wind-throw and movement of soil into burned out root channels. Charcoal in the soil in various places.

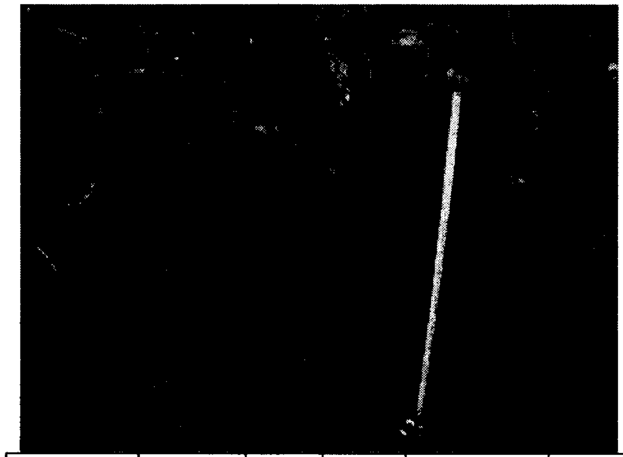
Completed by: Phil Comeau June 17, 2005

Pit #: 3
Soil Drainage: Moderately Well

Horizon	Depth	min	max	Gravel%	Cobble%	Stones%	Soil Texture	Structure Class& Kind	Mottles	Comments
L	17-15	0	3							
F	15-12	1	3							
H	12-0	5	20							
Aej	0-3	0	4	20	5	5	SL	C-PL		
BFj	3-52	15	60	20	5	5	L	C-ABK		
BFg	52-70			20	10	5	L	C-ABK	Many large distinct mottles	
Water	70+									

Miscellaneous comments: soil appears to have been mixed in upper 70 cm perhaps due to wind-throw, there are grey bands that look like Ae at depth, often overlain by layers of charcoal – which could be old surface or could be burned roots.

Completed by: Phil Comeau June 17, 2005

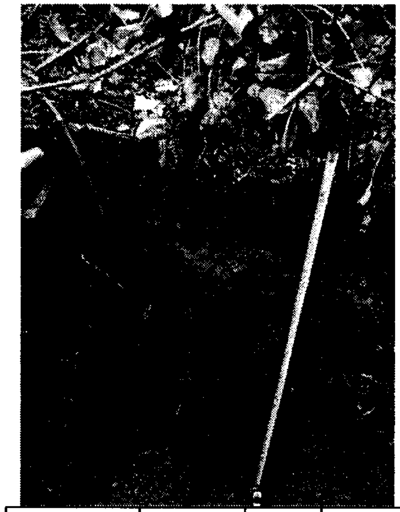


Pit #: 4
Soil Drainage: Moderately Well

Horizon	Depth	min	max	Gravel%	Cobble%	Stones%	Soil Texture	Structure Class& Kind	Mottles	Comments
LFH	0	0								
AB	0-20	5	40	20	10	5	L	M-SBK		Mixed due to harvesting disturbance
Bf1	20-48	10	40	25	10	5	SL	C-ABK		
Bf2	48-85			25	10	5	SL	C-ABK	Many medium sized mottles	
Water	85+									

Miscellaneous comments: Salmonberry-sword fern ecosystem.

Completed by: Phil Comeau June 17, 2005



Pit #: 5
Soil Drainage: Moderately Well

Horizon	Depth	min	max	Gravel%	Cobble%	Stones%	Soil Texture	Structure Class& Kind	Mottles	Comments
L	8-7	0	2							
F	7-5	0	4							
H	5-0	0	10							
Bf1				20	5	5	SL	C-PL		Discontinuous, probably result of wind-throw mixing soil
Ae	0-25	0	30	20	5	5	SL	C-ABK		
Bf2	25-42			20	5	5	SL	C-ABK		
Bf3	42-60			20	5	5	SL	C-ABK		
BC	60-95			30	10	5	SL	C-ABK		
Ck	95+									Cemented horizon

Completed by: Phil Comeau June 17, 2005

Appendix 2.2

Parameter values and statistical information for non-linear models of western redcedar root collar diameter increment. The table shows: number of observations (obs. #), adjusted R^2 (Adj. R^2), root mean square error (RMSE) and equation parameters (A, B1, B2, B3 and C), where B2 is related to red alder and B3 to paper birch for the competition indexes. Parameter values which are significantly different from zero are shown in bold type. The model used for relationships with competition indexes is: $Y = a + b_1 * e^{(b_2 * X_1 + b_3 * X_2)} * CSAi^c +$ € and for relationships with DIFN is: $Y = a + b_1 * X^{(b_2)} * CSAi^c +$ €.

Cw RCDI	obs #	Adj R^2	RMSE	A	Range +/-	B1	Range +/-	B2	Range +/-	B3	Range +/-	C	Range +/-
DifnTop	80	0.637	0.457	-0.0336	0.7822	0.00466	0.01834	**0.4192**	0.2919			**0.6029**	0.3538
DDR	69	0.557	0.506	-0.2907	1.5095	0.0168	0.0929	**-1.2611**	1.2321	-1.0799	1.3768	**0.4893**	0.4817
BA	69	0.556	0.506	-0.2097	1.3143	0.01	0.0547	**-0.00014**	0.000136	-0.00024	0.00034	**0.5355**	0.4815
MBA	69	0.554	0.507	-0.1641	1.3143	0.0136	0.0741	**-0.0272**	0.02696	-0.018	0.02551	**0.5025**	0.4792
MBAm	69	0.548	0.511	-0.2567	1.4984	0.0143	0.0824	-0.0166	0.016816	-0.00776	0.01204	0.5013	0.5027
CSA	69	0.541	0.514	-0.1262	1.2296	0.00692	0.03928	-8.19E-08	8.24E-08	-1E-07	2.01E-07	**0.5653**	0.5038
VI	69	0.538	0.516	-0.1575	1.3269	0.011	0.0625	**-0.0403**	0.041279	-0.0182	0.0328	**0.5217**	0.5007
DS	69	0.537	0.517	-0.1771	1.3353	0.00929	0.05321	-0.00375	0.003865	-0.00236	0.00477	**0.5393**	0.5048
HFm	69	0.532	0.520	-0.1596	1.3341	0.00839	0.04951	-0.00005	5.33E-05	-0.00001	0.000038	**0.5463**	0.5192
VIm	69	0.528	0.522	-0.1931	1.414	0.0102	0.0606	-0.029	0.03145	-0.00691	0.01901	**0.529**	0.5224
HF	69	0.526	0.523	0.0764	0.9189	0.00498	0.02632	-0.0122	0.013088	-0.00325	0.00965	**0.5858**	0.4743
SFI/TN	69	0.523	0.525	-0.5948	2.3183	0.0328	0.2093	0.0399	0.0882	0.0592	0.0739	0.409	0.5184
SFIm/TN	69	0.522	0.525	-0.5106	2.0882	0.0177	0.1173	0.0773	0.1984	0.176	0.22	0.4645	0.5456
TN	69	0.519	0.527	-0.2022	1.4482	0.00998	0.06102	-0.0257	0.03063	-0.00169	0.01539	0.5286	0.5337
SFIm	69	0.508	0.533	-0.2522	1.5796	0.0109	0.0695	-0.0243	0.0394	0.00482	0.01418	0.5172	0.5545
SFI	69	0.498	0.538	-0.371	1.8843	0.0165	0.1089	-0.0092	0.01913	0.00189	0.00481	0.4801	0.5644

Parameter values and statistical information for non-linear models of Douglas-fir root collar diameter increment. The table shows: number of observations (obs. #), adjusted R^2 (Adj. R^2), root mean square error (RMSE) and equation parameters (A, B1, B2, B3 and C), where B2 is related to red alder and B3 to paper birch for the competition indexes. Parameter values which are significantly different from zero are shown in bold type. The model used for relationships with competition indexes is: $Y = a + b_1 * e^{(b_2 * X_1 + b_3 * X_2)} * CSAi^c + \epsilon$ and for relationships with DIFN is: $Y = a + b_1 * X^{(b_2)} * CSAi^c + \epsilon$.

Fd RCDI	obs #	Adj R^2	RMSE	A	Range +/-	B1	Range +/-	B2	Range +/-	B3	Range +/-	C	Range +/-
SFI	66	0.439	0.477	-0.7733	4.4525	0.1772	1.3969	-0.00798	0.02078	0.00606	0.01194	0.2262	0.5251
SFI/TN	66	0.436	0.478	-0.4194	3.3949	0.0968	0.8133	-0.00424	0.06684	0.0464	0.0862	0.2567	0.5727
BA	66	0.429	0.481	-4.7866	48.9611	2.8709	41.019	-0.00003	0.00023	-0.00001	0.000144	0.0718	0.5938
CSA	66	0.428	0.482	-4.0842	38.7251	2.2851	31.0387	-2.1E-08	1.51E-07	-5.3E-09	8.29E-08	0.0818	0.607
HFm	66	0.425	0.483	-4.2249	39.9007	2.4	32.3106	-0.00001	0.000088	1.16E-06	2.18E-05	0.0792	0.5903
DS	66	0.425	0.483	-5.6822	64.4729	3.6761	56.3546	-0.00074	0.00677	-0.00003	0.0016	0.0613	0.5799
MBAm	66	0.422	0.484	-6.483	81.8707	4.298	72.7173	-0.00269	0.02809	0.000455	0.006255	0.0563	0.6052
VIm	66	0.422	0.484	-10.7968	202.2968	8.3915	192.5085	-0.00359	0.05969	0.000051	0.004619	0.035	0.593
VI	66	0.421	0.484	19.2328	489.3672	-22.18	478.08	0.00376	0.10284	0.00121	0.03339	-0.0207	0.5585
DDR	66	0.421	0.485	-11.0916	212.3916	8.6085	202.0915	-0.1249	2.131	0.00509	0.26721	0.0347	0.6032
TN	66	0.419	0.486	-7.395	102.072	5.2723	93.6179	-0.00512	0.05972	-0.00003	0.00534	0.0479	0.5735
MBA	66	0.417	0.486	-232	81478.3	229.4	81468.2	-0.00019	0.06719	-0.00003	0.01093	0.00161	0.56429
HF	66	0.415	0.487	-2.319	16.0106	1.3606	12.2425	-0.00563	0.02703	-0.00124	0.0083	0.0948	0.4415
SFIm	66	0.405	0.491	-2.428	17.0185	1.162	11.8686	-0.0163	0.0766	0.000848	0.014252	0.1106	0.5325
SFIm/TN	66	0.385	0.499	-0.8515	5.1745	0.2052	1.7659	-0.0532	0.225	0.0881	0.2597	0.2142	0.5619
DifnTop	73	0.336	0.516	-3.436	32.7598	2.0643	26.7327	0.0668	0.4971			0.0779	0.564

Parameter values and statistical information for non-linear models of western hemlock root collar diameter increment. The table shows: number of observations (obs. #), adjusted R^2 (Adj. R^2), root mean square error (RMSE) and equation parameters (A, B1, B2, B3 and C), where B2 is related to red alder and B3 to paper birch for the competition indexes. Parameter values which are significantly different from zero are shown in bold type. The model used for relationships with competition indexes is: $Y = a + b_1 * e^{(b_2 * X_1 + b_3 * X_2)} * CSAi^c + \epsilon$ and for relationships with DIFN is: $Y = a + b_1 * X^{(b_2)} * CSAi^c + \epsilon$.

Hw RCDI	obs #	Adj R^2	RMSE	A	Range +/-	B1	Range +/-	B2	Range +/-	B3	Range +/-	C	Range +/-
DifnTop	66	0.301	0.733	-0.1303	2.761	0.0274	0.239	0.4725	1.0191			0.384	0.6567
MBAm	55	0.213	0.784	-26.4367	1175.537	22.0801	1148.72	-0.0012	0.0497	-0.00114	0.04774	0.0225	0.9479
DDR	55	0.212	0.785	-42.2262	2856.226	37.4744	2826.526	-0.0567	3.6646	-0.0718	4.6489	0.0147	0.9623
MBA	55	0.206	0.788	-11.1574	236.2574	8.0478	219.0522	-0.00567	0.10427	-0.0046	0.0863	0.0434	0.8179
VI	55	0.195	0.793	-6.6311	97.0931	3.6217	78.8151	-0.0087	0.1002	-0.00766	0.09186	0.0762	0.9228
SFI/TN	55	0.195	0.793	-10.9268	205.4268	6.5526	177.9474	-0.00567	0.09037	-0.00113	0.01883	0.0595	0.9861
VIm	55	0.193	0.794	-6.6643	98.2119	3.4151	77.3643	-0.00492	0.05602	-0.00347	0.04097	0.0817	0.9923
SFIm/TN	55	0.191	0.795	-0.5055	5.5471	0.024	0.3596	0.0654	0.319	0.0879	0.3502	0.3962	1.0889
CSA	55	0.190	0.796	-2.8471	26.6561	0.7655	12.9594	-1.7E-08	1.09E-07	-4.6E-08	3.15E-07	0.1614	0.9993
SFI	55	0.188	0.796	-5.9946	77.7749	2.6361	56.2084	-0.00208	0.02068	0.000036	0.004204	0.0966	1.0087
HFm	55	0.188	0.796	-3.6665	38.0497	1.2284	22.2496	-9.2E-06	6.72E-05	-8.4E-06	7.04E-05	0.1336	0.9951
BA	55	0.188	0.797	-3.2729	31.4806	0.9687	16.7038	-0.00002	0.000163	-0.00004	0.000338	0.1478	0.9831
DS	55	0.188	0.797	-4.0964	44.1515	1.4674	27.3025	-0.00063	0.00488	-0.00058	0.00559	0.1243	0.9914
TN	55	0.187	0.797	-5.4421	68.9741	2.3821	49.3817	-0.00423	0.04013	-0.00146	0.01896	0.0993	0.9989
HF	55	0.186	0.797	-1.5949	12.5298	0.3048	4.0608	-0.00368	0.02488	-0.00113	0.02183	0.2144	0.86
SFIm	55	0.186	0.798	-2.7633	23.8296	0.6162	10.2704	-0.00298	0.03448	0.00518	0.04512	0.1766	1.0075

Evaluation of competitive effects of green alder, willow and other tall shrubs in Northern Alberta

3.1 Introduction

Management of competing vegetation is of primary importance for the successful growth and survival of desired tree species in the northern regions of North America (Wagner et al. 2006; Walstad and Kuch 1987). There are numerous cases that show evidence of the benefits of vegetation control to enhance tree growth, but there is still a lack of general principles for forest vegetation management regarding the strategies to apply to conserve floristic diversity while maximizing desired tree survival and growth (Balandier et al. 2006). In the first stages of their establishment, conifer plantations are extremely susceptible to competing vegetation since crop trees are relatively small and slow growing (Shropshire et al. 2001). The importance of interspecific competition from woody and herbaceous vegetation is dynamic and forest managers are likely to achieve the greatest tree growth gain from managing vegetation during the first years after planting (Wagner and Radosevich 1998).

Lodgepole pine (*Pinus contorta* Dougl. ex. Loud.) and white spruce (*Picea glauca* (Moench) Voss) are common components in boreal forests of western Canada and they usually grow together with numerous tall shrubs such as green alder (*Alnus crispa* (Ait.) Pursh.) (as the most widespread), and willow (*Salix* spp.) (Burns and

Honkala 1990). Lodgepole pine is very intolerant of shade and competition from other plant species, whereas white spruce is intermediate in its tolerance to shade (Burns and Honkala 1990).

In the boreal forests of North America, herbaceous species such as *Calamagrostis canadensis* (Michx.) Beauv. are widely distributed and can seriously inhibit growth of white spruce seedlings (Lieffers et al. 1993), or lodgepole pine. After clear-cuting, *C. canadensis* will spread rapidly and be present in almost every square meter, unless it is killed using herbicides or a deep burn (Lieffers et al. 1993). Tall shrubs and non-crop trees such as green alder, willow (*Salix* spp.), trembling aspen (*Populus tremuloides* Michx.) and paper birch (*Betula papyrifera* Marsh.) can also be aggressive competitors with conifers.

By virtue of their height, tall shrubs can compete for light with slower growing conifers for a longer period of time than lower growing shrubs, herbs and grasses. In a study comparing effects of woody and herbaceous plant species on light attenuation in the boreal forest, results show that during early stages of stand development herbaceous species intercept more light than woody competititors. However after the third growing season the situation was reversed (Shropshire et al. 2001), and light levels at a height of 20 cm can be lower than 10 % of open sky values (Shropshire et al. 2001).

During the last decades of the 19th and the first decades of the 20th century in North America, forests were being exploited without any silvicultural prescription resulting in concern about the future state of Canada's forests (Armson 2005). Since 1966, establishment surveys have been required in Alberta in an attempt to ensure stand regeneration. From the early 1990's, legislative requirements for forest regeneration were amended and during the last 20 years regeneration surveys have been important management tools in order to determine forest condition. The Regeneration Survey Task Force consisting of both industry and government, worked together to realize the "2000 Regeneration Standards" that became effective in May 2000, and amended in 2003 (Alberta Sustainable Resource Development 2003). The main purposes of the Regeneration Standards are to achieve: "rapid reforestation following harvest, acceptable stocking, suitable growth rates and survival, and last but not least, a level of performance that emulates natural yields found in Alberta's forests". Moreover, the Free-To-Grow (FTG) standards of the Performance Survey were changed to allow retention of greater levels of vegetation adjacent to conifer crop trees that are growing well.

In the Province of Alberta, regeneration surveys are conducted on all public lands to meet the obligations under the Timber Management Regulation. The strata that forest operators are expected to reforest are: coniferous (C), coniferous-deciduous (CD), deciduous-coniferous (DC), and deciduous (D). In this study the focus is on FTG standards for pure stands with conifers (C strata) such as white spruce or lodgepole pine. The Regeneration Standard consists of two independent surveys: an Establishment Survey 4 to 8 years after harvesting and a Performance Survey completed 8 to 14 years after harvesting. The Establishment Survey verifies stocking (SR) ensuring no areas over 4 hectares in size are unstocked (NSR) based on: stocking amount (percent), and the early growth of regenerated trees. The Performance Survey measures the same parameters as the Establishment Survey but also deems if coniferous crop trees meet the Free-To-Grow standard.

Coniferous seedlings must meet the FTG standards in order to be considered as an acceptable crop tree. For performance surveys conducted 8 to 11 years after harvest, tree or shrub broadleaved vegetation is considered a competitor if it is within 1.78 m (stem to stem) of the conifer crop tree and it is equal or greater than 2/3 of the crop tree height. For surveys conducted 12 to 14 years after harvest broadleaved vegetation is considered a competitor if it is within 1.78 m, it is equal or greater than the crop tree height and the base diameter is ≥ 70% of the crop tree root collar diameter. For blocks classified as mixedwood stands, competing vegetation can occupy only one quadrant within the 1.78m plot. Minimum coniferous height requirements for a FTG crop tree vary depending on the drainage class and ecosite. For white spruce the minimum height is either 80 or 100 cm and for lodgepole pine is 130 or 150cm. In order to pass the regeneration standard 70% of the plots established in a survey block must have one FTG conifer crop tree (A.S.R.D. 2003).

Passing these standards typically requires complete removal of tall shrubs from conifer blocks, since 70% of the plots established in a block must have a free-to-grow conifer. This results in "administrative" brushing treatments which are done to pass the standards but which may not have biological or growth benefits. Tall shrubs and broadleaved vegetation can have beneficial effects on conifer growth and many studies are trying to better understand these interactions. For example, Sitka alder can fix nitrogen at rates ranging from 2 to 15 kg ha^{-1} $year^{-1}$ (Mead and Preston 1992; Sanborn et al. 2002), and conifers can benefit from the increased nitrogen in forest soils, although alder might compete with them for moisture, light or other nutrients (Simard 1990). On some sites, the presence of tall shrubs may also provide protection from growing season frost (Stathers and Spittlehouse 1990; Pritchard and Comeau 2004) and winter desiccation due to Chinook injury (Krasowski et al. 1993). Willow and alder are also important browse species for ungulates and, therefore, maintenance of a component of these and other species on harvested areas is generally desirable.

Simard (1990) reports that Sitka alder cover of up to 35% had little effect on growth of 6 to 10 year old lodgepole pine. Simard and Heineman (1996) report an improvement in pine growth when alder cover was reduced from 22% to 15%. Brockley and Sanborn (2003) found that growth of lodgepole pine over a 6 year period was not reduced until alder cover exceeded 45%. Even under very high cover of alder, pine height and diameter growth over a 6 year period was reduced by only 12% and 10%, respectively, compared to situations without alder

(Brockley and Sanborn 2003). Another study with Sitka alder and lodgepole pine sets the alder cover threshold between 10 and 40% (average 33%), at which point competition intensity for shared resources increases to the detriment of conifer growth, but alder removal beyond this minimum threshold also could influence conifer performance negatively through depletion of ecosystem (Simard et al. 2004). Another study shows that conifer growth increases with increasing intensity of broadleaf tree reduction. All vegetation management improved conifer competitive status but root disease such as *Armillaria ostoyae* increased mortality in the greatest reductions in broadleaves (Simard et al. 2005). Simard et al. (2006) suggest that allowing Sitka alder and herbs to grow together with pine provides protection against extreme microclimate conditions and herbivores and can build soil nitrogen levels over the long term. Variation in results from these different studies suggests that responses may be species and site specific.

In a study comparing green alder, willow and other species, Shropshire et al. (2001) found that alder, willow and birch intercepted more light than other species, and that levels of light reduction were greater on moister/richer sites than on poorer/drier sites. While very low (<10%) light levels may be encountered at a height of 20 cm, Shropshire et al. (2001) found that light levels were above 60% of open sky values at heights above 1 m.

Competition changes over time and components such as light levels, crown radius and cover of competitors are related to subject tree growth (Biging and Dobbertin

1992; Comeau et al. 2003; Wagner and Radosevich 1991; Lorimer 1983). Competition indexes are a commonly used as tools to predict effects of competition on tree growth. Several studies indicate that visual estimates of cover can provide equal or even better estimates of interspecific competitive effects on conifers growth, in comparison to other plant abundance measures (Bell et al. 2000; Simard 1990; Wagner and Radosevich 1991). The strength of the relationship between a competition index and growth is heavily dependent upon the species, since every species responds differently to stress from competition (Lorimer 1983; Burton 1993).

A better understanding of the competitive effects of tall shrubs, particularly of alder and willow, is required to serve as a basis for evaluating, and, if appropriate, for refining regeneration standards. In addition to an understanding of the competitive effects of these species, the growth patterns of tall shrubs and the effects of site need to be documented and examined.

During 2006, field studies were established in white spruce and lodgepole pine plantations to examine the competitive effects of different densities and arrangements and the growth of tall shrubs, with a focus on green alder and willow.

3.2 Objectives

This study was designed to examine the following questions:

1) Do relationships between growth and competition vary from one geographic location (cut-block) to another?
2) How well do different measures ("competition indexes") work for describing tall shrub competition in young white spruce and pine plantations in western Alberta?
3) How does abundance (assessed in terms of number of clumps, number of individual stems, height and % cover) of tall shrubs influence light and influence the growth of lodgepole pine and white spruce between ages 10 and 20?
4) Are there beneficial/detrimental effects on soil fertility from alder and willow?

3.3 Study design

A neighborhood approach was used to examine effects of tall shrubs on light and on growth of lodgepole pine and white spruce. This approach involves selecting individual crop conifers and collecting data on the abundance and stature of vegetation around each of these crop seedlings.

Previous research (Comeau unpubl., Howard and Newton 1984) suggests that the radius of these crop tree centered plots should equal the distance between mid-crown height of the crop tree and the top height of the neighboring non-crop vegetation.

3.3.1 Selected blocks

For both lodgepole pine (Pl) and white spruce (Sw), we selected 10 blocks (5 for each species) during 2006 with a range of tall shrub densities, that are between 10 and 20 years old. The selected blocks are located within areas being managed by Canadian Forest Products Ltd. (CANFOR), and Weyerhaeuser Co. Ltd, and are described in table 3.1.

Blocks were selected from locations surveyed using enhanced performance survey methodology in 2004 and 2005, where surveys indicated that tall shrubs were present in various amounts across the block (with several blocks not meeting current performance standards). Each block was stratified into areas having high, medium, and low densities of tall shrubs. Within each of these strata, 25 conifers (spruce or pine) located at least 6m apart were selected. We selected one tree for each density level as we moved in a line through the block. In this way, we obtained a representative sample of low, medium and high densities of tall shrubs throughout the block. This provided a total of 75 conifer trees per block. Numbered tags were attached to the lower branches of each subject tree and the GPS location of each tree was recorded. A total of 750 trees were tagged during 2006.

Table 3.1. Location information for blocks selected for measurement.

Company	**Block ID**	**Block Area (ha)**	**Conifer spp.**	**Year of Plantation**	**GPS Location**
Canfor	G31041	20.5	Sw and Pl	1993 and 1994	N54 35.405 W118 09.956
Canfor	G33033	21.7	Sw	1993	N54 37.030 W118 12.265
Weyerhaeuser	61045044	26.54	Sw and Pl	1993 and 1995	N54 14.560 W118 35.345
Weyerhaeuser	64050029	17.60	Sw	1993	N54 31.434 W118 42.782
Weyerhaeuser	60050040	35.49	Pl	1993	N54 11.269 W118 42.814
Weyerhaeuser	60050046	53.78	Pl	1996	N54 10.342 W118 44.834
Weyerhaeuser	64050063	38.60	Pl	1992 (natural regeneration)	N54 33.273 W118 42.783
Weyerhaeuser	64050076	22.55	Sw	1993	N54 34.004 W118 42.432

3.3.2 Conifer measurements

During 2006, 45 conifers were measured in each of 10 blocks for diameter at 15 cm above ground-line, diameter (DBH) at 1.3 m, top height, height increment over each of the previous 5 years, and crown radius in each of 4 cardinal directions. Condition and damage were recorded for each tree following the Alberta SRD/LFD tree condition codes (PSP manuals 2005).

In each block 21 tagged trees (7 from each of the 3 strata) were selected for destructive sampling to determine past diameter growth. A disk was cut at 15 cm and at 1.3 m for measurement of radial increment. Diameter measurements were taken every 50cm along the stem to provide data for development of localized stem volume equations. Diameter and volume increment over each of the past 5 years was measured. Disks were kept refrigerated to keep their size stable. Disks were sanded and the tree rings measured with a Velmex "TA" tree ring measurement system (Velmex Inc. Bloomfield NY) which consists of a VELMEX Unislide attached to an Acu-Rite Encoder (Acu-Rite, Jamestown NY), a Quick-Check QC-1000 digital encoder linked to a personal computer running MeasureJ2X software (VoorTech Consulting, NH USA). A stereomicroscope was used to view the discs to ensure accurate measurement of ring-width.

3.3.3 Competition measurements

Assessments of cover of alder, willow, other shrubs, herbs and other trees were completed using a plot radius of 3.99 m at each of the 45 measured tagged conifers in each block. Within each competition plot, percent cover and modal height were recorded for each component species or layer (herbs, shrubs and trees). Top height, distance from tree stem to leaf edge and to the nearest stems was also recorded for each of the alder and willow clumps within the plot. Where shrubs overtop the conifer, this overtopping distance was recorded as a negative value indicating the distance over which overtopping occurs. In addition, the diameter of each "clump" (i.e. individual plant) of alder and willow was measured in two cardinal directions for each clump found inside a 3.99 m radius plot.

3.3.4 Light measurements

Light levels were measured in mid-summer at 2/3 of the distance between crown base and the top of the tree for each of the 450 selected conifers using LAI-2000 plant canopy analyzer sensors. The readings were taken with sensor heads fitted with 180 degree view restrictors and measurements taken in 2 cardinal directions pointing away from the crop tree. The open sky readings (usually in a clearing) were taken in a nearby clearing located less than 1 km from the block.

3.3.5 Nutrients

To evaluate relationships between shrub density and nitrogen availability, a set of four Plant Root Simulator™-probes (IEM) probes were installed next to three selected conifer in each of the 3 shrub density classes, at each site (9 trees per site). Probes were installed with the membrane centered at approximately 10 cm depth from the top of the mineral soil. The probes were located in the soil at the edge of the crown drip-line of the subject tree. PRS™-probes were installed in

June and removed in Mid-August of 2006 and analyzed by Western Ag Innovations Ltd, as detailed by Hangs et al. (2004).

In fall 2006, 3-4 small branches of the last growing season were collected from the upper third of the crown from each of the 9 selected trees in the fall of 2006. The samples were oven-dried for 72 hours at 75° Celsius and analyzed to determine macronutrient concentrations (N, P, K and Ca). Total nitrogen, phosphorus, calcium and potassium were measured following the methods by Carter (1993).

Needles were separated from woody material for the analysis and dry weight and surface area of a sample of 50 needles were determined. The surface area was determined using a scanner and WINFOLIA™ software (Régent Instruments, Québec, QC, Canada).

Table 3.2. Competition measures.

Competition measures	**Formula**	**Values**
HF - Height Factor	$HF = \sum \frac{Ht_j}{ht_i}.$	Ht_j = competitor height ht_i = selected specie height
MBA-Modified Braathe Index	$MBA = \sum \frac{htdiff_{ij}}{dist_{ii}}.$	$dist_{ij}$ = distance $htdiff_{ij}$ = differential height (competitor - selected specie)
VI - View Index	$VI = \arctan\left(\sum \frac{htdiff_{ij}}{dist_{ii}}\right).$	$dist_{ij}$ = distance $htdiff_{ij}$ = differential height (competitor – selected specie)
Com.I- Comeau Index	$Com.I = \frac{\sum(ci \times Ht_j)}{ht_i}$	ci = % cover (size related) Ht_j = competitor ht ht_i= selected specie ht
VC,VC and VCm-*[1] *Visual Cover*	$VC = \sum ci$	ci = %cover (visually measured)
VCHT- Visual Cover times Height	$VCHT = \sum(ci \times Ht_j)$	ci = % cover (visually measured) Ht_j=competitor ht
DIFN- Diffuse non intercepted light	=DIFN	

[1] VC was also tested with the measured (size calculated) cover of alder and willow separately (VC*) and for measured total shrubs (VCm)

3.4 Data analysis

Diameter measurements at several heights collected for a sample of 210 conifers provided data to calculate stem volume and to develop an equation for estimating stem volume from diameter at 15 cm. The equation that best fit the data to estimate the stem volume (SV, cm^3) from stem height (HT, cm) and, diameter at 15 cm (D15, cm) is similar to Honer's equation (Honer et al. 1983, Pitt et al. 2004):

$$SV = \frac{D15^a}{b + \frac{c}{HT}}$$

Where a, b, and c are parameters calculated using non-linear least squares. Stem volume increments were calculated using the ring increment (D15) and height increment values for the past 5 years of growth (2001-2006). Tree volume was calculated as a stack of cylinders.

Data analysis was completed using SAS software version 9.1 (SAS Institute, Cary, NC). Linear and non-linear regressions were used to explore relationships between dependent and independent variables. Relationships between levels of shrub competition (ie. competition index values) and - a) light levels; b) soil N availability; c) foliar nutrient concentrations and d) stem volume growth – were explored using regression analysis. A variety of competition indexes (Table 3.2) were tested, including height factor (ratio of shrub height to crop tree height), cover (% cover of shrubs), and proximity measurements (distance weighted cover, sky view fraction). Relationships between conifer growth and light levels were also examined.

Preliminary analysis tested linear and non-linear regressions such as power and exponential functions. Among the possible covariates available for use in the model the height of the crop tree in 2006 was the one that showed the best relationships with crop tree growth. The best results were given by exponential functions for competition indexes and power functions on height at 2006 as reported by Comeau et al. (2003):

$$Y = a + b_1 * e^{(b_2 * X_1 + b_3 * X_2)} * HT2006^c + \epsilon$$

Where Y is the conifer stem volume increment for the past 3 years, X is the competition value (CI) and the other independent variable HT2006 is the height of the crop tree in 2006. The competition indexes were calculated separately for alder (X_1) and willow (X_2) to quantify the effect that each species has on the conifer growth.

For visual cover indexes (VC, VCm and VCHT) the model is:

$$Y = a + b_1 * e^{(b_2 * X_1 + b_3 * X_2 + b_4 * X_3)} * HT2006^c + \epsilon$$

Where Y is the conifer stem volume increment for the past 3 years, X is the competition value (CI) and the other independent variable HT2006 is the height of the crop tree in 2006. The competition indexes were calculated separately for total shrub cover (X_1), tree cover (X_2) and herb cover (X_3), to quantify the effect that each broadleaved component has on conifer growth.

For the index Visual Cover (VC*), the following model was also tested using the measured values (size related) for alder and willow:

$$Y = a + b_1 * e^{(b_2 * X_1 + b_3 * X_2 + b_4 * X_3 + b_5 * X_4)} * HT2006^c + \epsilon$$

Where Y is the conifer stem volume increment for the past 3 years, X is the competition index (VC*) and the other independent variable HT2006 is the height of the crop tree in 2006. The competition indexes were calculated separately for shrub cover (X_1 and X_2), tree cover (X_3) and herb cover (X_4).

For diffuse non intercepted light (DIFN) the model is:

$$Y = a + b_1 * X_1^{b_2} * HT2006^c + \epsilon$$

Where Y is the conifer stem volume increment for the past 3 years, X_1 is DIFN value and the other independent variable HT2006 is the height of the crop tree in 2006.

The models presented above were also tested with DIFN as the dependent variable and the competition indexes as independent variables, in order to explore the effectiveness of the competition indexes for predicting light availability.

3.5 Results

3.5.1 Tree growth

Stem volume equations using a model similar to Honer's equation showed high adjusted R^2 when the cutblocks were pooled together. For white spruce the adjusted R^2 is 0.991 ($n=105$, $a=1.5878$, $b=-0.0012$, and $c=1.9771$) and for lodgepole pine the adjusted R^2 is 0.993 ($n=105$, $a=1.5543$, $b=-0.0004$, and $c=1.4327$) (Figure 3.1), which are consistent with the results obtained by Pitt et al. (2004).

Top height in 2006 shows a broad range of values (from 73 to 900 cm) and high variability in the average height of the 4 species (90-560 cm) (Table 3.3).

Measurements of diameter increments before 2003 were difficult and showed substantial variability for these small trees. For this reason diameter and stem volume growth of white spruce and lodgepole pine was calculated only for the past 3 years (2003, 2004 and 2005).

The competition indexes were calculated selecting the competitors by their height. To evaluate the influence of competitor height relative to conifer height I tested the effect of different minimum height values in the calculations of competition. Calculations were done using competitors taller than 66%, 75%, and 100% of subject conifer height and also using all the competitors. For the analysis, measured cover (size related) of the shrub layer (MCshrubs) was used. For white spruce (Table 3.4) results show no differences in adjusted R^2 among the cut-off heights (adjusted R^2=0.755, n=101), and for lodgepole pine very little variation among the adjusted R^2 was observed (adjusted R^2 range= +/-0.013, n=103). Since there is little or no difference between the cut-off levels, every measured competitor has been included for the calculation of the competition indexes in the rest of this study.

At this stage, the sample size in each block is insufficient (21 trees/block) to allow between block comparison of growth-competition relationships to evaluate objective 1. Attempts to fit appropriate non-linear models resulted in most models not converging and making it impossible to effectively evaluate between site differences. Thus, data for each conifer species were pooled across all measured sites. For white spruce, preliminary analysis suggested that block G33033 (Canfor, 21.7 ha) differed substantially from the other spruce blocks when a simple model relating growth to tall shrub cover was evaluated and was therefore not included together with the other blocks. Block G33033 is located in a low-lying and swampy area which may result in changes in growth-competition relationships.

Relationships between growth and light (DIFN) are illustrated in Figure 3.2 for both white spruce and lodgepole pine. These models, which also use tree height in

2006 as a second independent variable, explain 85% of the variation in white spruce growth (Table 3.5) and 76% of the variation in pine growth (Table 3.6). Both light and height are significant variables in these models.

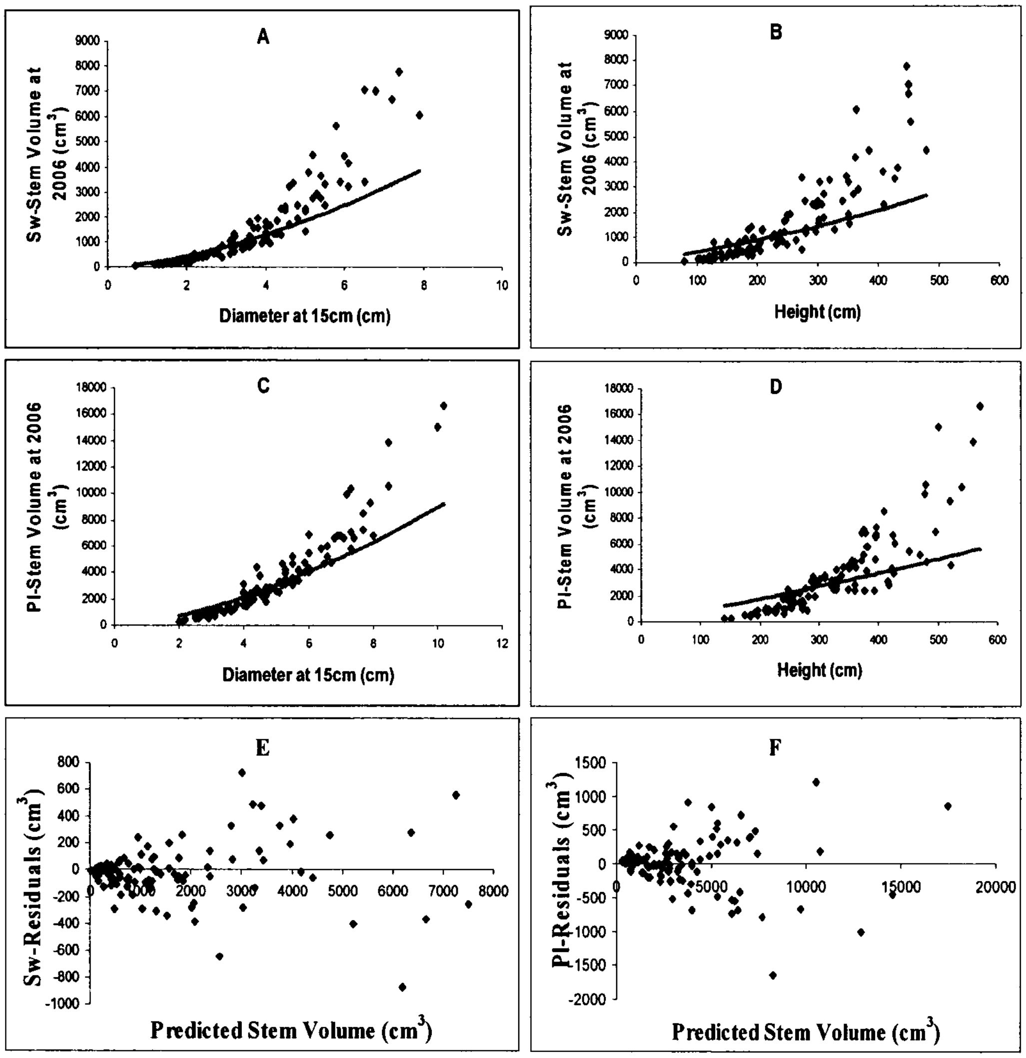


Figure 3.1. Relationships between measured stem volume (SV) and diameter or height, and between residuals and predicted SV. The model is: $SV = D15^{a}/(b + c/HT) + \epsilon$. Graphs A, B and E are for white spruce (Sw) and graphs C, D and F for lodgepole pine (Pl). Graphs A and C show predicted SV calculated using the mean value of top height (HT). Graphs B and D show predicted SV calculated using the mean value of diameter at 15 cm (D15). Graphs E and F show residuals versus predicted SV.

Table 3.3. Height range and modal height of measured trees as at 2006.

Spp.	Height Range (cm)	Average Height (cm)
Sw	105-480	242
Pl	150-560	322
Green alder	100-500	250
Willow spp.	90-550	225

Table 3.4. Comparison of adjusted R^2 values obtained using competitors taller than 66%, 75% and 100% of subject conifer height for examining relationships between tree growth and measured shrub cover (MCshrub). The adjusted R^2 are for stem volume increment and measured shrub cover (MCshrub), the model is: $Y = a * b_1 * e^{(b_2 * MCshrub)} * HT2006^c + \epsilon$.

Tree Spp.	**Cutoff**	**Obs. #**	**Adj. R^2**
Sw	100%	101	0.755
Pl	100%	103	0.683
Sw	75%	101	0.755
Pl	75%	103	0.674
Sw	66%	101	0.755
Pl	66%	103	0.671
Sw	None	101	0.755
Pl	None	103	0.670

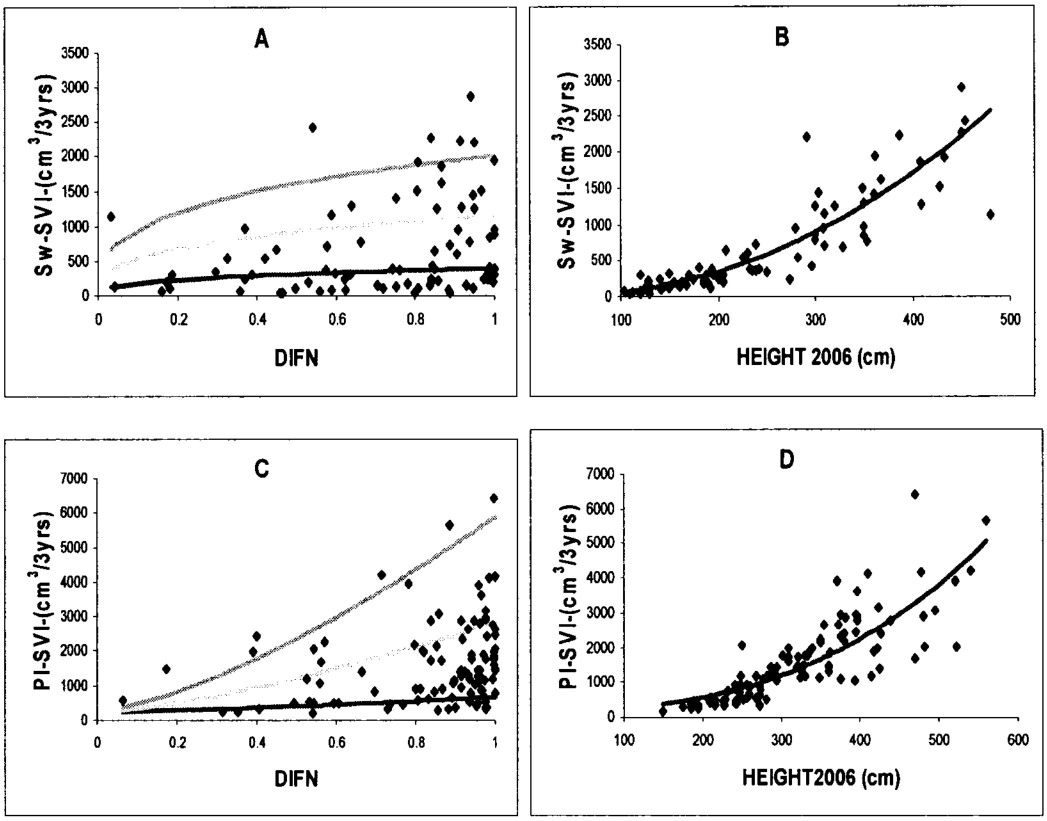


Figure 3.2. Relationships between stem volume increment and DIFN, the model is: $Y = a + b_1 * X_1^{b_2} * HT2006^c + €$. Graphs A and B are for white spruce and graphs C and D for lodgepole pine. Graphs A and C show three different curves calculated for three levels (low-medium-high) of height at 2006 (HT2006). Graphs B and D show a curve calculated using the mean value of DIFN of each species. Parameter values and statistical information for each trendline are provided in Table 3.5 and 3.6.

For white spruce the competition measure with the highest adjusted R^2 is the visual cover estimate times the height of the competitor (VCHT) (adjusted $R^2=0.886$, n=80) (Figure 3.3), followed by VC (adjusted $R^2=0.881$, n=80). The modified Braathe index (MBA; with actual measured values (size related cover) of the competing shrubs) (adjusted $R^2=0.859$, n=80) ranked in third place of all indexes tested for white spruce followed by DIFN (adjusted $R^2=0.850$, n=80) (Figure 3.2). The measured cover index (VC*), which included the measured cover of alder and willow as separate independent variables, has a slightly higher adjusted R^2 than VCm, which used the sum of measured cover of alder and willow as a single independent variable. In VC* willow cover was non-significant (as indicated by the fact that the 95% confidence interval around the B3 parameter includes 0.0) (Table 3.5).

To quantify the competitors influence, the 95% confidence interval of the parameter values related to competition measures were examined. The parameter is considered to be significantly different from zero when the range does not include 0. For the competition indexes VCHT and VC, the parameters related to total shrub cover (%), tree cover (%) and herb cover (%) were different from zero with the parameter for tree cover bigger than herb cover and shrub cover, which implies a steeper slope. For MBA and VI the parameters related to alder and willow are different from zero, with alder having a steeper slope (Table 3.5). For Com.I only the parameter related to alder is significant, and for HF neither alder or willow values are significant. In the model using VC* the parameter values for willow and for herbs are not different from 0, while the parameters for alder and for trees are different from 0, with tree cover having a significantly steeper slope than alder cover. Tree and herbaceous cover are also significant parameters in model types 3 and 4 for VCHT, VC and VC*.

Taken in combination these results for white spruce indicate that while alder is a slightly stronger competitor than willow there is little merit to separating cover of the two species in describing relationships between volume increment and competition. Results also indicate that consistent visual estimates of cover can work better than cover derived from measurements of crown area and that tree and herbaceous cover needs to be considered when examining relationships between spruce growth and shrub competition.

For lodgepole pine, DIFN is the best competition measure with an adjusted R^2 of 0.762 (n=103) (Figure 3.2). The best competition index is VCHT (adjusted R^2=0.729, n=103) (Figure 3.3), followed by the view index (VI) (adjusted R^2=0.727, n=103) and the Comeau Index (Com.I.) (adjusted R^2=0.701, n=103) (Figure 3.4).

For the competition index VCHT the parameter related to total shrub cover (%) is different from zero but tree and herb cover are not significant (Table 3.6). For lodgepole pine, herbaceous cover was significant only in the model that used VCm for the tall shrubs. For VI both parameters related to alder and willow are different from zero and have similar slope values (i.e. they do not differ significantly). Only with the Com.I., alder and willow have significantly different parameter values, and in this case willow is not significantly different from 0.0. VCm, did not improve the ability to predict stem volume increments (adjusted R^2=0.688, n=103) compared to VC which was based on visual cover estimates and in the model using VC* only the willow and the initial size variables were significant.

In summary, results for pine suggest that while size and light are significantly related to growth, the best index for the characterizing competition uses the combined cover of tall shrubs in the VCHT index, and that tree and herbaceous competition is not significant for the measured lodgepole pine on these sites.

To examine the relationship between light levels and competition, diffuse non intercepted light (DIFN) was also tested as a dependent variable against each competition index. The results show that the visual cover estimate times the height of the competitor (VCHT) has the highest adjusted R^2 values for white spruce (adjusted R^2 =0.406, n=80), and lodgepole pine (adjusted R^2=0.412, n=103) (Figure 3.5). Parameters values are not different from zero except for shrub cover for lodgepole pine (Table 3.7 and 3.8).

3.5.2 Nutrient availability

Relationships between nitrogen availability in the soil (PRS probes) and shrub cover (alder and willow) were explored using polynomial regression models (i.e.: $y=a+bx+cx^2+\varepsilon$). The results did not show any significant relationship ($P>0.05$) between nitrogen availability and cover of alder and willow (Figure 3.6).

The relationships between foliar nitrogen, phosphorus, potassium and calcium concentrations and shrub cover (alder and willow) were explored using polynomial regression models (i.e.: $y=a+bx+cx^2+\varepsilon$). Figure 3.7 shows the scatter of data points for the plots of foliar N concentration against alder cover and total shrub cover. While the scatter plots suggests a trend for white spruce, results did not show any significant relationships ($P>0.05$) between foliar nutrient concentrations and cover of alder and willow. Further investigations using the adjusted values based on needle dry weight (nitrogen content per g of needle) and the adjusted values based on surface area (nitrogen content per cm^2) did not show consistent improvements in relationships between foliage macronutrients and cover.

The average values of foliar nutrient concentrations (N, P, K, and Ca) of each site (9 trees/block) were compared to the deficiency ranges calculated by Carter (1992) (Tables 3.9, 3.10, 3.11 and 3.12). The comparison indicates that white spruce is deficient in nitrogen on all sites, and average levels of P are in the slightly deficient range in some cases, while K and Ca are not deficient. Lodgepole pine average concentration in N is generally low, both P and K are slightly deficient in every block and Ca concentration is adequate.

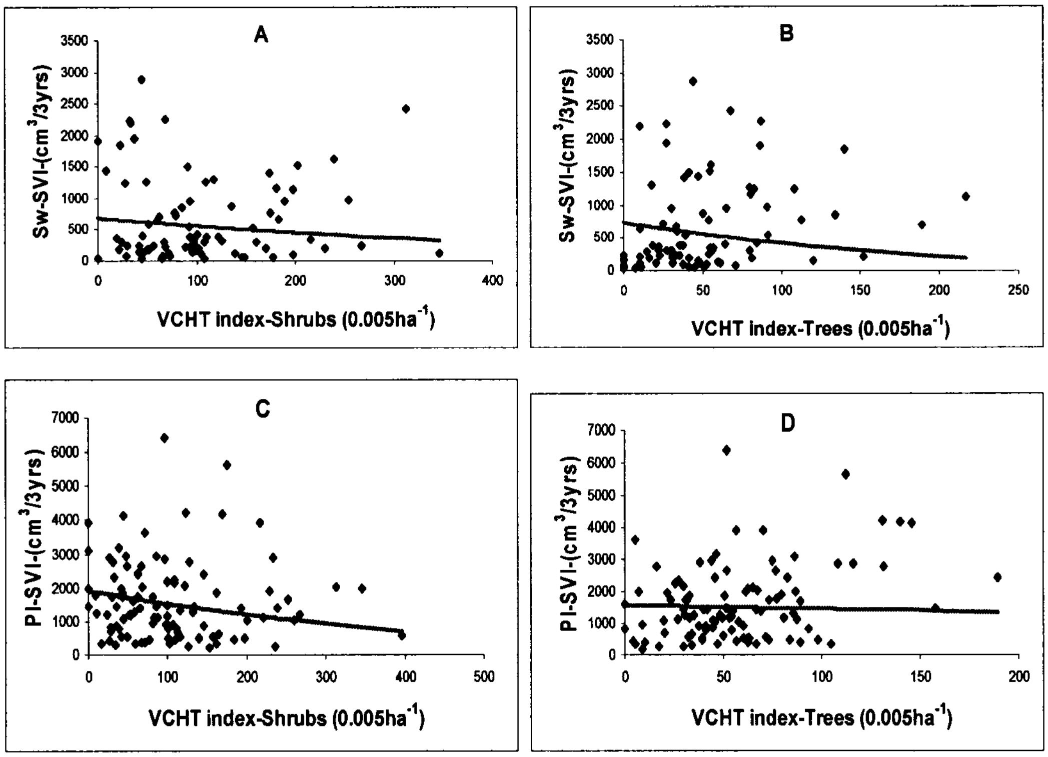


Figure 3.3. Relationships between stem volume increment and VCHT Index. The model is: $Y = a + b_1 * e^{(b_2 * VCHTshrubs + b_3 * VCHTtrees + b_4 * VCHTherbs)} * HT2006^c +$ €. Graphs A and B are for white spruce and graphs C and D for lodgepole pine. Graphs A and C show curves calculated using the mean value of VCHT for the trees component (VCHTtrees), for the herbs component (VCHTherbs) and the mean value of height at 2006 (HT2006) for each species. Graphs B and D curves calculated using the mean value of VCHT for the shrubs component (VCHTshrubs), for the herbs component (VCHTherbs) and the mean value of height at 2006 (HT2006) for each species. Parameter values and statistical information for each trendline are provided in Tables 3.5 and 3.6.

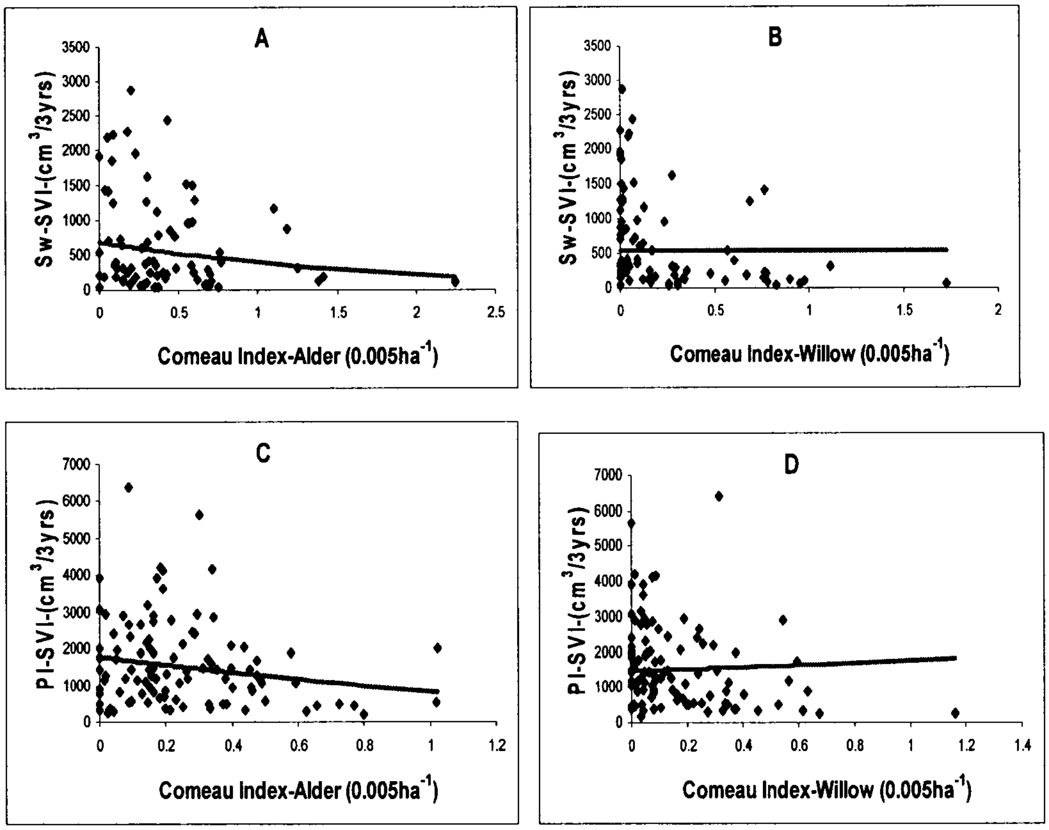


Figure 3.4. Relationships between stem volume increment and Comeau Index (Com.I.). The model is: $Y = a + b_1 * e^{(b_2 * Com.I.alder + b_3 * Com.I.willow)} * HT2006^c +$ €. Graphs A and B are for white spruce and graphs C and D for lodgepole pine. Graphs A and C show curves calculated using the mean value of Com.I. for the alder component (Com.I.willow) and the mean value of height at 2006 (HT2006) for each species. Graphs B and D curves calculated using the mean value of Com.I. for the alder component (Com.I.alder) and the mean value of height at 2006 (HT2006) for each species. Parameter values and statistical information for each trendline are provided in Tables 3.5 and 3.6.

Table 3.5. Parameter values and statistical information for non-linear models of white spruce stem volume increment. The table shows: competition measure (Comp.Meas.), number of observations (obs. #), adjusted R^2 (Adj. R^2), root mean square error (RMSE) and equation parameters (A, B1, B2, B3, B4, B5 and C).Parameter values which are significantly different from zero are shown in bold type. The 4 models used are listed below (α=0.05).

	Comp. Meas.	obs #	Adj R^2	RMSE	A	Range +/-	B1	Range +/-	B2	Range +/-	B3	Range +/-	B4	Range +/-	B5	Range +/-	C	Range +/-
3	VCHT	80	0.886	227.603	-100.8	180.665	6.22E-03	0.01868	**-0.0018**	0.00075	**-0.0047**	0.00162	**-0.0029**	0.00276			**2.2165**	0.499
3	VC	80	0.881	233.923	-131.5	200.501	3.83E-02	0.1101	**-1.1331**	0.4018	**-2.3444**	0.7687	**-0.8549**	0.5076			**2.0308**	0.49
2	MBA	80	0.859	253.031	-10.276	151.876	9.07E-03	0.02643	**-0.0834**	0.0239	**-0.0385**	0.0196					**1.9991**	0.4713
1	DIFN	80	0.850	261.089	-22.057	174.157	3.50E-03	0.0122	**0.3158**	0.153							**2.2062**	0.573
4	VC*	80	0.846	270.184	-34.896	196.596	3.30E-03	0.0132	**-0.5827**	0.5233	-0.1427	0.6225	**-2.1688**	0.9611	0.0613	0.7233	**2.296**	0.6419
3	VCm	80	0.841	272.872	-15.77	188.27	3.25E-03	0.01275	**-0.5401**	0.5286	**-2.4499**	1.0156	-0.0409	0.7436			**2.3187**	0.6363
2	VI	80	0.837	273.928	-51.47	191.57	3.23E-02	0.1034	**-0.1484**	0.0587	**-0.0772**	0.07681					**1.7912**	0.5182
2	Com.I.	80	0.800	305.629	-99.359	253.359	3.79E-02	0.1434	**-0.4613**	0.3497	0.00678	0.38512					**1.8141**	0.6148
2	HF	80	0.774	320.797	-160.7	323.4	4.22E-02	0.193	-0.008	0.06512	0.0193	0.0565					**1.7781**	0.7321

1- $Y = a + b_1 * X_1^{b_2} * HT2006^c + \in$

2- $Y = a + b_1 * e^{(b_2 * X_1 alder + b_3 * X_2 willow)} * HT2006^c + \in$

3- $Y = a + b_1 * e^{(b_2 * X_1 shrubs + b_3 * X_2 trees + b_4 * X_3 herbs)} * HT2006^c + \in$

4- $Y = a + b_1 * e^{(b_2 * X_1 alder + b_3 * X_2 willow + b_4 * X_3 trees + b_5 * X_4 herbs)} * HT2006^c + \in$

Table 3.6. Parameter values and statistical information for non-linear models of lodgepole pine stem volume increment. The table shows: competition measure (Comp.Meas.), number of observations (obs. #), adjusted R^2 (Adj. R^2), root mean square error (RMSE) and equation parameters (A, B1, B2, B3, B4, B5 and C).Parameter values which are significantly different from zero are shown in bold type. The 4 models used are listed below (α=0.05).

	Comp. Meas.	obs #	Adj R^2	RMSE	A	Range +/-	B1	Range +/-	B2	Range +/-	B3	Range +/-	B4	Range +/-	B5	Range +/-	C	Range +/-
1	DIFN	103	0.762	577.269	238.9	384.9	4.89E-04	0.00205	**1.4123**	0.6287							**2.5843**	0.675
3	VCHT	103	0.729	616.166	-592.8	1002.2	9.98E-02	0.5057	**-0.0017**	0.00104	-0.0005	0.0015	-0.0023	0.00305			**1.775**	0.8204
2	VI	103	0.727	618.198	-205	847.2	4.27E-02	0.2322	**-0.0504**	0.0391	**-0.0539**	0.05141					**1.8158**	0.8428
2	Com.I.	103	0.701	646.327	-550.8	1080.6	1.92E-01	0.9589	**-0.512**	0.432	0.1302	0.3593					**1.6254**	0.7788
3	VC	103	0.698	649.836	-790.3	1374	4.74E-01	2.5547	-0.3595	0.3822	-0.009	0.55168	-0.0635	0.3931			**1.503**	0.8585
4	VC*	103	0.695	653.204	-780.1	1398.5	3.63E-01	2.008	-0.0519	0.3529	**0.3078**	0.2781	0.366	0.5541	0.2363	0.3768	**1.4755**	0.8364
2	MBA	103	0.689	659.758	-773	1463.9	6.15E-01	3.4663	**-0.0051**	0.00437	-0.0019	0.00504					**1.4219**	0.859
3	VCm	103	0.688	660.607	-812.1	1469.7	4.41E-01	2.4801	0.1869	0.2322	0.4777	0.5707	**0.4227**	0.3686			**1.4143**	0.8298
2	HF	103	0.671	678.009	-820.7	1603.4	4.26E-01	2.6647	0.0131	0.0537	0.0295	0.0618					**1.4826**	0.9525

1- $Y = a + b_1 * X_1^{b_2} * HT2006^c + \epsilon$

2- $Y = a + b_1 * e^{(b_2 * X_1 alder + b_3 * X_2 willow)} * HT2006^c + \epsilon$

3- $Y = a + b_1 * e^{(b_2 * X_1 shrubs + b_3 * X_2 trees + b_4 * X_3 herbs)} * HT2006^c + \epsilon$

4- $Y = a + b_1 * e^{(b_2 * X_1 alder + b_3 * X_2 willow + b_4 * X_3 trees + b_5 * X_4 herbs)} * HT2006^c + \epsilon$

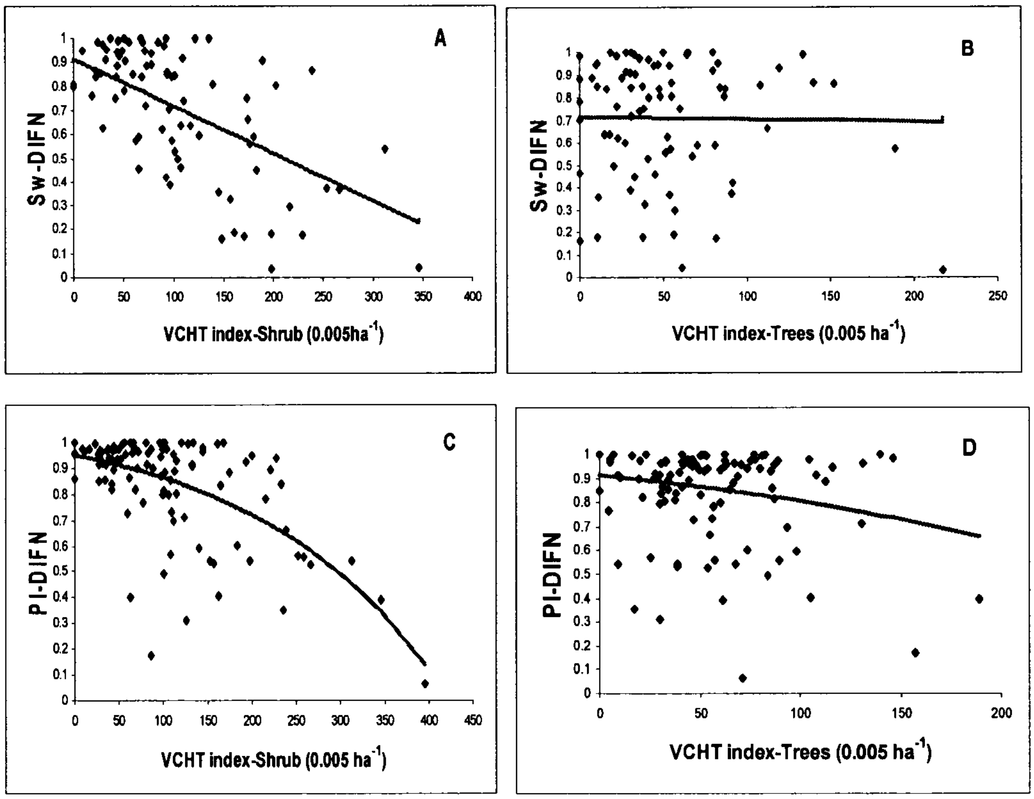


Figure 3.5. Relationships between DIFN value and competition index VCHT. The model is: $Y = a + b_1 * e^{(b_2*VCHTshrubs+b_3*VCHTtrees+b_4*VCHTherbs)} * HT2006^c + €$. Graphs A and B are for white spruce and graphs C and D for lodgepole pine. Graphs A and C show curves calculated using the mean value of VCHT for the trees component (VCHTtrees), for the herbs component (VCHTherbs) and the mean value of height at 2006 (HT2006) for each species. Graphs B and D curves calculated using the mean value of VCHTshrubs, VCHTherbs and HT2006 for each species. Parameter values and statistical information for each trendline are provided in Tables 3.7 and 3.8.

Table 3.7. Parameter values and statistical information for non-linear models of white spruce DIFN values. The table shows: competition index (Comp. Index), number of observations (obs. #), adjusted R^2 (Adj. R^2), root mean square error (RMSE) and equation parameters (A, B1, B2, B3, B4 and B5). Models that are statistically significant and parameter values which are significantly different from zero are shown in bold type. The 3 models used are listed below ($\alpha=0.05$).

	Comp. Index	obs #	Adj R^2	RMSE	A	Range +/-	B1	Range +/-	B2	Range +/-	B3	Range +/-	B4	Range +/-	B5	Range +/-	P(<0.05)
2	VCHT	80	0.406	0.205	13.5529	433.147	-1.27E+01	433.145	0.00015	0.00512	7.46E-06	0.00026	-0.0002	0.00575			<.0001
2	VC	80	0.395	0.207	1.5301	2.2107	-5.94E-01	2.0297	0.8633	2.1047	0.1824	0.7627	-0.0966	0.6354			<.0001
3	VC*	80	0.236	0.235	28.7705	3663.63	-2.85E+01	3663.2	0.00398	0.51892	-0.0033	0.42487	-0.0091	1.19594	-0.0252	3.2909	0.0003
2	VCm	80	0.217	0.236	-0.6958	10.2395	1.03E+00	9.922	-0.0228	0.2455	0.1358	1.0665	0.502	3.7227			0.0002
1	Com.I.	80	0.194	0.235	1.4114	2.5369	-0.5617	2.4466	0.3474	1.0627	0.2475	0.8432					<.0001
1	HF	80	0.024	0.260	**0.7222**	0.0616	-7.65E-06	0.00015	-0.0452	1.0624	1.0843	1.7741					0.1217
1	VI	80	0.009	0.264	**0.782**	0.244	-5.84E-02	0.2449	-0.1868	0.7364	0.457	1.044					0.2973
1	MBA	80	-0.027	0.267	**0.7155**	0.0837	-1.36E-03	0.04706	0.1132	1.7832	0.1534	1.0814					0.5847

1- $Y = a + b_1 * e^{(b_2 * X_1 alder + b_3 * X_2 willow)} + \epsilon$

2- $Y = a + b_1 * e^{(b_2 * X_1 shrubs + b_3 * X_2 trees + b_4 * X_3 herbs)} + \epsilon$

3- $Y = a + b_1 * e^{(b_2 * X_1 alder + b_3 * X_2 willow + b_4 * X_3 trees + b_5 * X_4 herbs)} + \epsilon$

Table 3.8. Parameter values and statistical information for non-linear models of lodgepole pine DIFN values. The table shows: competition index (Comp. Index), number of observations (obs. #), adjusted R^2 (Adj. R^2), root mean square error (RMSE) and equation parameters (A, B1, B2, B3, B4 and B5). Models that are statistically significant and parameter values which are significantly different from zero are shown in bold type. The 3 models used are listed below (α=0.05).

	Comp. Index	obs #	Adj R^2	RMSE	A	Range +/-	B1	Range +/-	B2	Range +/-	B3	Range +/-	B4	Range +/-	B5	Range +/-	P(<0.05)
2	VCHT	103	0.412	0.154	**1.0897**	0.241	-0.078	0.1493	**0.00485**	0.00325	0.00465	0.00519	0.00833	0.00847			<.0001
2	VC	103	0.292	0.169	**0.9919**	0.1503	-3.66E-03	0.01396	**3.5938**	2.6304	3.1379	3.1632					<.0001
1	Com.I.	103	0.194	0.180	1.7117	3.1487	-7.52E-01	3.0845	0.3709	1.2239	0.3562	1.1259					<.0001
3	VC*	103	0.063	0.194	**0.8465**	0.0397	-1.82E-07	6.2E-06	17.3897	44.9798	10.8068	32.1278	-29.155	125.058	3.929	39.5087	0.0456
2	VCm	103	0.049	0.197	**0.8454**	0.04	-2.59E-07	7.4E-06	18.6876	39.7605	-11.285	30.8715	-8.9923	28.402			0.0938
1	MBA	103	0.021	0.198	**0.8931**	0.1591	-6.40E-02	0.1758	0.00721	0.08919	0.0825	0.1095					0.166
1	HF	103	0.017	0.199	-6.5513	1861.35	7.40E+00	1861.3	0.00386	0.97294	-0.0052	1.30909					0.1988
1	VI	103	0.016	0.199	**0.7651**	0.2698	4.36E-02	0.2412	-0.1562	0.4805	-0.2668	0.8188					0.2038

1- $Y = a + b_1 * e^{(b_2 * X_1 alder + b_3 * X_2 willow)} + \epsilon$

2- $Y = a + b_1 * e^{(b_2 * X_1 shrubs + b_3 * X_2 trees + b_4 * X_3 herbs)} + \epsilon$

3- $Y = a + b_1 * e^{(b_2 * X_1 alder + b_3 * X_2 willow + b_4 * X_3 trees + b_5 * X_4 herbs)} + \epsilon$

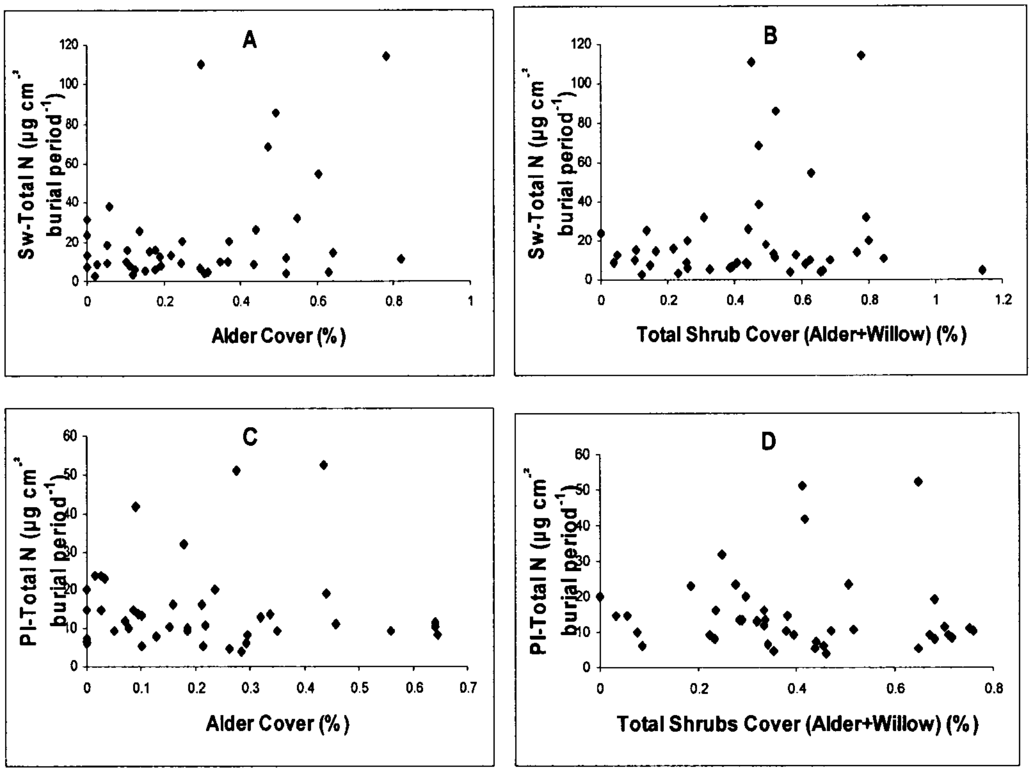


Figure 3.6. Soil available nitrogen and shrub cover. Graphs A and B are for white spruce and graphs C and D for lodgepole pine. Graphs A and C show the values for total available nitrogen and alder cover. Graphs B and D show the values for total available nitrogen and total shrub cover.

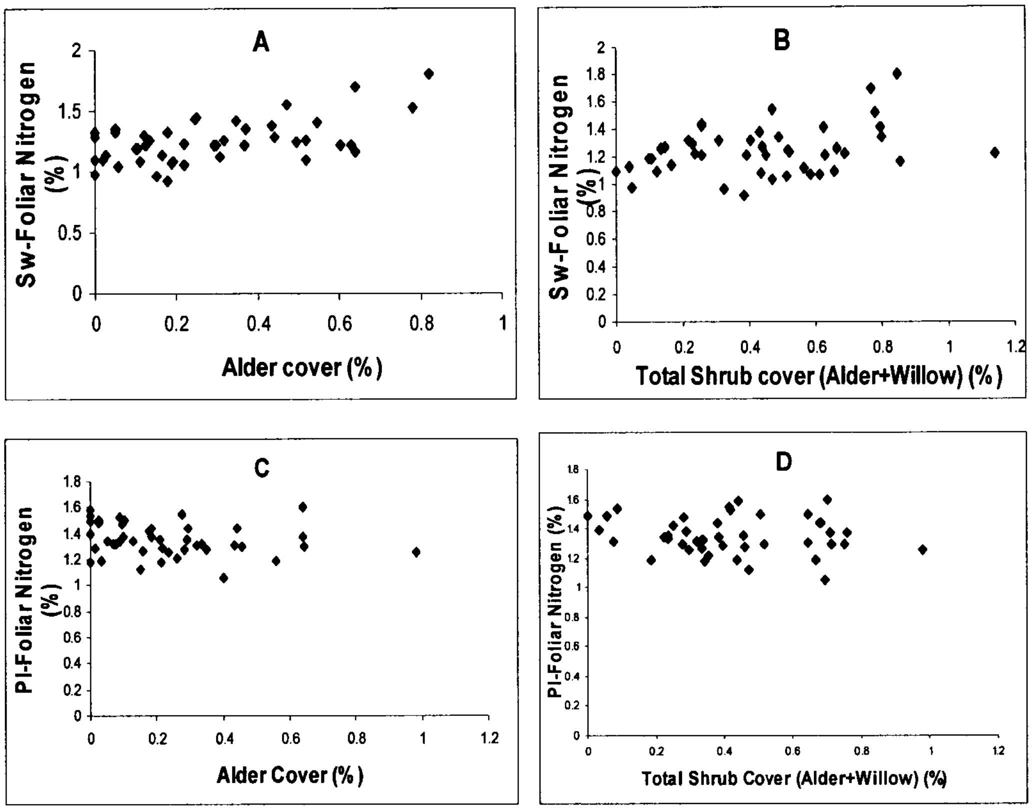


Figure 3.7. Foliar nitrogen and shrub cover. Graphs A and B are for white spruce and graphs C and D for lodgepole pine. Graphs A and C show the values for foliar nitrogen and alder cover. Graphs B and D show the values for foliar nitrogen and total shrub cover.

Table 3.9. Interpretation of macronutrient concentrations (%) in current year foliar samples of white spruce for: nitrogen (N), phosphorus (P), potassium (K) and calcium (Ca), in comparison to standard range values from Carter (1992). Average values and standard deviation (in parenthesis), are shown for each block (9 trees/block).

Site	N %	Critical value for N	P %	Critical value for P	K %	Critical value for K	Ca %	Critical value for Ca
A	1.10	1.05-1.25	0.16	0.14-0.16	0.50	0.30-0.50	0.38	>0.20
	(0.14)	Moderate to severe deficiency	(0.02)	Slightly deficient	(0.07)	Slight to moderate deficiency	(0.08)	Adequate
B	1.26	1.26-1.45	0.17	>0.16	0.80	>0.50	0.34	>0.20
	(0.19)	Slight to moderate deficiency	(0.03)	Adequate	(0.21)	Adequate	(0.09)	Adequate
C	1.22	1.05-1.25	0.20	>0.16	0.66	>0.50	0.39	>0.20
	(0.11)	Moderate to severe deficiency	(0.02)	Adequate	(0.14)	Adequate	(0.12)	Adequate
D	1.34	1.26-1.45	0.17	>0.16	0.66	>0.50	0.43	>0.20
	(0.22)	Slight to moderate deficiency	(0.04)	Adequate	(0.12)	Adequate	(0.07)	Adequate
E	1.30	1.26-1.45	0.17	>0.16	0.73	>0.50	0.38	>0.20
	(0.15)	Slight to moderate deficiency	(0.03)	Adequate	(0.17)	Adequate	(0.08)	Adequate

A (block ID #:G33033), B (block ID #:G31041), C (block ID #:64050040), D (block ID #:61045044) and E (block ID #:64050076)

Table 3.10. Interpretation of macronutrient concentrations (%) in current year foliar samples of white spruce for: nitrogen (N), phosphorus (P), potassium (K) and calcium (Ca), in comparison to standard range values from Carter (1992). For each site, the numbers of trees in each deficiency class are shown.

	Foliar concentration (% dry mass basis)		Number of trees per class at each site				
Element	White Spruce	Interpretation	A	B	C	D	E
Nitrogen	<1.05	Very severely deficient	3			1	
	1.05-1.25	Moderate to severe deficiency	5	6	4	2	5
	1.25-1.45	Slight to moderate deficiency	1	2	5	5	2
	>1.45	Adequate		1		1	2
Phosphorus	<0.10	Severely deficient					
	0.10-0.14	Moderately deficient	2	2		2	1
	0.14-0.16	Slightly deficient	2	1		2	4
	>0.16	Adequate	5	6	9	5	4
Potassium	<0.25	Very severely deficient					
	0.25-0.30	Moderate to severe deficiency					
	0.30-0.50	Slight to moderate deficiency	5				
	>0.50	Adequate	4	9	9	9	9
Calcium	<0.10	Severely deficient					
	0.10-0.15	Moderate to severe deficiency					
	0.15-0.20	Slight to moderate deficiency					
	>0.20	Adequate	9	9	9	9	9

A (block ID #:G33033),B(block ID #:G31041),C(block ID #:64050040),D(block ID #:61045044) and E(block ID #:64050076)

Table 3.11. Interpretation of macronutrient concentrations (%) in current year foliar samples of lodgepole pine for: nitrogen (N), phosphorus (P), potassium (K) and calcium (Ca), in comparison to standard range values from Carter (1992). Average values and standard deviation (in parenthesis), are shown for each block (9 trees/block) (site B has 8 samples).

Site	N %	Critical value for N	P %	Critical value for P	K %	Critical value for K	Ca %	Critical value for Ca
B	1.36	>1.35	0.13	0.12-0.15	0.51	0.40-0.55	0.20	>0.10
	(0.13)	Adequate	(0.02)	Slightly deficient	(0.11)	Slight to moderate deficiency	(0.04)	Adequate
F	1.40	>1.35	0.15	0.12-0.15	0.56	>0.55	0.18	>0.10
	(0.11)	Adequate	(0.03)	Slightly deficient	(0.07)	Adequate	(0.04)	Adequate
D	1.39	>1.35	0.13	0.12-0.15	0.57	>0.55	0.24	>0.10
	(0.14)	Adequate	(0.01)	Slightly deficient	(0.08)	Adequate	(0.07)	Adequate
G	1.37	>1.35	0.14	0.12-0.15	0.53	0.40-0.55	0.15	>0.10
	(0.11)	Adequate	(0.01)	Slightly deficient	(0.07)	Slight to moderate deficiency	(0.03)	Adequate
H	1.24	1.15-1.35	0.12	0.12-0.15	0.53	0.40-0.55	0.13	>0.10
	(0.09)	Slight to moderate deficiency	(0.01)	Slightly deficient	(0.07)	Slight to moderate deficiency	(0.04)	Adequate

B (block ID #:G31041), F (block ID #:60050040), D (block ID #:61045044), G (block ID #:60050046) and H (block ID #:64050063)

Table 3.12. Interpretation of macronutrient concentrations (%) in current year foliar samples of lodgepole pine for: nitrogen (N), phosphorus (P), potassium (K) and calcium (Ca), in comparison to standard range values from Carter (1992). For each site, the numbers of trees in each deficiency class are shown (site B has 8 samples instead of 9).

	Foliar concentration (% dry mass basis)		Number of trees per class at each site				
Element	Lodgepole pine	Interpretation	B	F	D	G	H
Nitrogen	<1.00	Very severely deficient					
	1.00-1.15	Moderate to severe deficiency					
	1.15-1.35	Slight to moderate deficiency	4	5	4	4	9
	>1.35	Adequate	4	4	5	5	
Phosphorus	<0.09	Severely deficient					
	0.09-0.12	Moderately deficient	1		1	1	6
	0.12-0.15	Slightly deficient	6	7	8	6	3
	>0.15	Adequate	1	2		2	
Potassium	<0.35	Very severely deficient					
	0.35-0.40	Moderate to severe deficiency					
	0.40-0.55	Slight to moderate deficiency	7	4	5	6	6
	>0.55	Adequate	1	5	4	3	3
Calcium	<0.06	Severely deficient					
	0.06-0.08	Moderate to severe deficiency					
	0.08-0.10	Slight to moderate deficiency					
	>0.10	Adequate	8	9	9	9	9

B (block ID #:G31041), F(block ID #:60050040), D(block ID #:61045044), G (block ID #:60050046) and H (block ID #:64050063).

3.6 Discussion

Lodgepole pine stem volume growth was reduced more strongly than white spruce by decreasing light levels. For lodgepole pine, the slope of the growth versus DIFN curve is more than 4 steeper than for white spruce. This outcome illustrates the differences between the shade intolerant lodgepole pine and the moderately shade tolerant white spruce. Other studies have shown that shading inhibits plant development and survival more for lodgepole pine than for white spruce (Burns and Honkala 1990; Kobe and Coates 1997; Wright et al. 1998).

The fact that light measurements are more strongly correlated with tree growth than other measures of competition reaffirms the potential to utilize light measurements as an objective technique for assessing competition as suggested by other studies (DeLong 1992; Jobidon 1992; Comeau et al. 1993; Ter-Mikalean et al. 1999). The main limitation in measuring light in the field using tools such as LAI-2000 plant canopy analyzers (Li-Cor Inc., Lincoln, NB) is the cost of the equipment and the limited time for field measurements (6-8 weeks during the summer).

For both lodgepole pine and white spruce the VCHT index ,which incorporates visual cover estimate of shrubs, trees and herbs and their modal height, worked better than other indexes, including those based on cover derived from measurements of crown area. The other competition indexes (HF, MBA, VI, and

Com.I.), calculated only for shrub cover using size related values, showed weaker relationships against conifer growth. Hamilton and Yearsley (1998) also found that this crown volume index was effective for characterizing competition. Brand (1996) and Wagner and Radosevich (1991) found that simple indexes that characterize cover around conifer crop seedlings worked better than more complicated measurements of competing plant size and location. Including height as a multiplier in the non-linear model with VCHT used in this study provides a combined representation of vegetation cover, vegetation height and crop tree height in a fashion that approximates the Comeau competition index.

Visual estimates of cover perform as well as or better than direct measurements of crown areas in the various indexes (VC, VC* and VCm) using "measured" cover values, although differences in adjusted R^2 are small. Other studies found that visual cover estimates are as effective as other abundance measures of competing vegetation (Bell et al. 2000; Simard 1990; Wagner and Radosevich 1991). This is likely related to the difficulty in objectively and accurately quantifying cover using measurements of crown dimension. It should also be noted that cover in this study was estimated by one individual. Problems with standardization of cover when several individuals are providing estimates could result in some potential benefits to using measured crown areas to determine cover, but these must be weighed against the cost of measurements.

Size of the crop trees is an important variable in the models of tree growth presented in this study. Size is related to the stature and position of the crop trees in relation to the surrounding competition and will influence the amount of light and other resources available to the trees (Comeau et al. 1993). Size is also related to the leaf or crown surface area of the seedlings, which has a strong influence on the amount of carbon seedlings can fix through photosynthesis (Comeau et al. 1993). In addition, size reflects the history of past tree growth, because cumulative growth will have been influenced by the range of factors controlling and influencing growth, including (but not exclusively) competition (Morris et al. 1990). Due to logistical issues the height of conifers at the end of the growth period was used in this study (and height in 2003 and height in 2006 were found to be very highly correlated). Future measurements of these trees will allow evaluation of growth using size at the beginning of the growth period.

Tall shrub, tree and herbaceous cover all exert influences on the growth of white spruce. However, for lodgepole pine, results indicate that tall shrubs are the major competitors, with herbaceous cover only appearing as a significant variable in one model. Possible reasons for differential effects of shrub, tree and herbaceous cover on the two crop species include: differences in the height of the spruce and pine, and differences in vegetation cover and height on the spruce and pine blocks. The fact that herbaceous cover is having more effect on white spruce than lodgepole pine may be related to both their height and differences in rooting depth. Lodgepole pine roots extend to some depth in the soil and it has commonly taproots and vertical sinkers, while white spruce is shallow rooted (Burns and Honkala 1990). For this reason, white spruce root system is probably competing for water and nutrients with the root system of *Calamagrostis canadensis* and other herb layer vegetation.

Our results also indicate that taller conifers have a stronger competitive effect than tall shrubs, with their effect on white spruce being larger than that on lodgepole pine. Comparison of the effects of alder and willow indicates that both species are having negative effects on growth of pine and spruce on these sites with green alder having a stronger influence on spruce than pine due in part to the smaller size of the spruce. These results are consistent with results presented by Bell et al. (2000).

Foliar nutrient concentration values suggest that white spruce is deficient in nitrogen and slightly deficient for phosphorus, while lodgepole pine is slightly deficient for nitrogen, phosphorus and potassium (Carter 1992). These results confirm that these boreal forest ecosystems, and in particular pine forests, may be experiencing nutrient limitations (Vogel and Gower 1998). Although a weak relationship between foliar N and alder density is apparent for white spruce, relationships between soil N and alder abundance and between foliar N and alder abundance were non-significant. This contrasts with results presented for lodgepole pine by Brockley and Sanborn (2003) who found that Sitka alder improved foliar nitrogen and growth of lodgepole pine on the sites examined in their study. Also Vogel and Gower (1998) found that mature boreal jack pine (*Pinus banksiana* Lamb.) forests with green alder showed higher N content of the overstory biomass components (i.e.: branch and foliage) than jack pine stands without alder. In boreal region stands, Matsushima and Chang (2006) found that white spruce would not benefit from N fertilization unless the grass layer (*Calamagrostis canadensis* (Michx.) Beauv.) is removed. Low rates of nitrogen fixation by green alder on my study sites and possibly higher soil nutrient availability and other factors, such as the small size of green alder and high grass abundance, may result in alder having little nutritional benefit.

Green alder is similar in shape and morphological characteristics to Sitka alder, which can fix 2 to 15 kg ha^{-1} year^{-1} of nitrogen (Mead and Preston 1992; Sanborn et al. 2002), while red alder stands can contribute approximately 65 kg ha^{-1} y^{-1} of nitrogen (Binkley 1983). The different N-fixing rates, together with other factors mentioned above, may explain why in the Maple Ridge project we found significant increments in nitrogen availability at increasing levels of red alder density, while for the Grande Prairie study green alder did not significantly improve N availability.

3.7 Conclusions

Results from this study indicate that simple measures of competition based on visually estimated cover and height of the vegetation and height of the crop conifers are as effective as more complicated measurements of competition. However, we are challenged to develop repeatable and auditable measurements of competition that can be used in regeneration surveys. Measurement of light is a potentially useful and objective method but its use is limited to a narrow time frame (of 6 to 8 weeks) in the summer and requires the use of expensive equipment. Models are presented which can be useful in estimating effects of competitors on the growth of lodgepole pine and white spruce. Further ongoing studies at these sites will evaluate the potential to utilize more simplified competition measures such as the number of quadrants which are occupied by tall shrubs.

Tall shrub, tree and herbaceous cover all exert influences on the growth of white spruce. However, for lodgepole pine results indicate that tall shrubs are the major competitors. Further exploration of the factors underlying these differences is warranted to determine if they are related to crop species, site differences or other factors.

Results obtained from this first year and from retrospective measurements of tree growth indicate that tall shrubs are competitors and provide little evidence to indicate strong beneficial effects in relation to soil nutrition or frost protection at this stage.

The regeneration standards for pure conifer stands require no competing vegetation within a 1.78 m radius and for mixedwood stands only one quadrant can be occupied by competing vegetation. My study suggests that these standards may be overestimating the effect that competing vegetation has on conifer growth. Significant growth reduction occurs only at high shrub density suggesting that in pure conifer stands the growth of the crop trees will not be dramatically reduced if one quadrant is occupied by competing vegetation. Likewise allowing 2 quadrants to have some competing vegetation would not dramatically reduce conifer growth. The results also suggest that a larger radius (3.99 m) might be a better indicator of the amount of competing vegetation, but more generally the regeneration standards need to find a more accurate way to quantify the competition effects of non-crop vegetation.

Ongoing remeasurement of trees in these blocks will provide additional information on differences in relationships between blocks and further resolution of differences in the effects of green alder, willow, and other vegetation and to further evaluate simpler and more objective measures of competition. These measurements will also be useful in developing and evaluating models for estimating future tree growth based on tree and neighborhood characteristics.

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4 Syntheses

I examined the effects of N-fixing and non N-fixing woody competition on the growth of conifers with different levels of shade tolerance. At a site near Maple Ridge (BC), I examined the effects of red alder and paper birch on the growth of western redcedar, western hemlock and Douglas-fir. I utilized an experiment established in 1999 where trees were planted at fixed densities in 10 treatments/plots with 2 replications. Within the experiment, 240 conifers were selected. Readings of light availability (DIFN) were taken at each conifer and competition was measured within a 5.64 m radius around each crop tree. Soil pits, soil samples, foliar samples and PRS-probes were used to explore nutrients availability.

A second component of my study examined the effects of green alder and other competitors on the growth of white spruce and lodgepole pine. In an area south of Grande Prairie (AB), I selected and tagged 750 trees at 8 locations that were up to 35 km apart. A sample of the tagged trees (210) was cut in order to provide an estimate of the past increments. Readings of light availability (DIFN) were taken at each conifer and competition was measured within a 3.99 m radius around each crop tree. Foliage samples and PRS-probes were used to explore nutrient availability.

At Maple Ridge, red alder improved soil nitrate availability and Douglas-fir showed higher levels of foliar nitrogen and calcium as red alder density increased. Although soils at the study site near Grande Prairie developed on a less fertile substrate (typical of the area), weak and not significant relationships were found between green alder and nitrate availability in the soil. The shrubby characteristic of green alder, compared to the tree-like nature of red alder, results in green alder being 5-6 times less efficient than red alder in fixing nitrogen (Binkley 1983; Mead and Preston 1992; Sanborn et al. 2002).

Among the competition measures tested on both projects, light availability (DIFN) was generally best correlated with conifer growth. The strength of the various competition indexes calculated was highly dependent on the species analyzed. For the Maple Ridge project, distance-dependent indexes performed just slightly better than distance-independent indexes, thus the extra cost related to the additional measurement (distance) might not be justified. The slightly better outcome of distance dependent competition indexes is probably a consequence of the low competitor tree density of the stand.

The study near Grande Prairie suggests that visual estimates can perform as well as if not better than cover estimates calculated using the measured size of the competitors. The lack of accuracy for cover related to crown-size measurements is probably due to the measuring process. The required measurements such as crown radius, modal height and shape of the crown lead to possibly large errors. The visual estimate is highly dependent on the operator skills, but it has the benefit of being the result of only one “reading”. Also in this case (as for the Maple Ridge project for the distance-independent indexes), a more straight forward analysis such as the visual cover estimate can be preferable than a more complex estimate.

Competition is a dynamic factor, thus shade-tolerance characteristics of each species and conifer size in relation to the surrounding vegetation at the moment of measurements play a key role and must be considered in growth models. In general, more shade tolerant species such as western hemlock and white spruce grow better under competition than shade intolerant species such as Douglas-fir and lodgepole pine, unlike western redcedar that regardless of its shade tolerant characteristics was highly affected by the surrounding vegetation. For western redcedar this outcome is a consequence of other external factors (slow initial growth, small size, natural regeneration of broadleaves, browsing, Vexar® tubes etc.) that resulted in stronger growth reduction.

In Alberta the regeneration standards for pure conifer stands require no competing vegetation within a 1.78m radius and for mixedwood stands only one quadrant can be occupied by competing vegetation. My study near Grande Prairie suggests that the standards may be overestimating the effect that competing vegetation has on conifers growth therefore a higher shrub retention might be allowed.

My two studies were able to address only some of the questions related to competitive/facilitative relationships between crop trees and surrounding vegetation. For a better understanding of the possible interactions, due to their variability and complexity, it is necessary to enlarge the tree sample and it would be recommended to build growth models for reasonably small areas. For the Grande Prairie project, for example, a larger sample size is required to allow analysis on a site-based scale.

For both projects, the selected trees will be measured again in future years, and for the project near Grande Prairie the sample size will be enlarged so that site-specific growth models can be calculated.

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