TECHNICAL REPORT 039

Relative Impact of Aspen Competition and Soil Factors on the Performance of Lodgepole Pine and Hybrid White Spruce in North-central British Columbia

2007

BRITISH COLUMBIA

Ministry of Forests and Range
Forest Science Program

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Craig DeLong

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Library and Archives Canada Cataloguing in Publication Data
DeLong, C.
Relative impact of aspen competition and soil factors on the performance of lodgepole pine and hybrid white spruce in north-central British Columbia

(Technical report ; 039)

Includes bibliographical references: p.
ISBN 978-0-7726-5697-1

1. Lodgepole pine - British Columbia - Nechako Plateau - Growth. 2. White spruce - British Columbia - Nechako Plateau - Growth. 3. Populus tremuloides - British Columbia - Nechako Plateau - Growth. 4. Lodgepole pine - Soils - British Columbia - Nechako Plateau. 5. White spruce - Soils - British Columbia - Nechako Plateau. 6. Forest soils - British Columbia - Nechako Plateau. 7. Forest site quality - British Columbia - Nechako Plateau. I. British Columbia. Forest Science Program. II. Title. III. Series: Technical report (British Columbia. Forest Science Program) ; 39.

SD397.P585D44 2007 634.9'7510971182 C2007-960041-7

Citation
DeLong, C. 2007. Relative impact of aspen competition and soil factors on the performance of lodgepole pine and hybrid white spruce in north-central British Columbia. B.C. Min. For. Range, Res. Br., Victoria, B.C. Tech. Rep. 039.
<http://www.for.gov.bc.ca/hfd/pubs/Docs/Tr/Tr039.htm>

Prepared by
Craig DeLong
B.C. Ministry of Forests and Range
5th Floor, 1011 4th Avenue
Prince George, BC
V2L 3H9

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ABSTRACT

Releasing conifers from the competition effects of aspen (*Populus tremuloides* Michx.) is a key focus of plantation management in sub-boreal and boreal forests, often at considerable cost. However, other factors affect early plantation performance. This study investigates the relative influence of aspen competition and soil factors on the performance of planted lodgepole pine (*Pinus contorta* Dougl. *ex* Loud.) and hybrid white spruce (*Picea glauca* [Moench] Voss × *engelmannii* Parry *ex* Engelm.) in north-central British Columbia. Plots were established across a gradient of natural aspen competition levels that resulted from a test of aspen control treatments at one site. Within these plots, 240 of each of the target conifer species were measured and their immediate soil and vegetative environment quantified. Regression trees and regression analysis were used to examine the importance of aspen competition relative to other factors in determining target conifer size. Soil factors generally provided the best partitioning of height growth differences for lodgepole pine and hybrid white spruce, whereas a mix of vegetation competition and soil factors provided the best partitioning of diameter growth differences. Regression models accounted for 19–28% of spruce size and 24–33% of lodgepole pine size. The single variable explaining the most variability in lodgepole pine size was aspen competition, whereas it was humus depth for hybrid white spruce. Practices should be altered to alleviate soil-induced growth reductions, particularly for hybrid white spruce.

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1 INTRODUCTION

Trembling aspen (*Populus tremuloides* Michx.), considered a serious competitive threat in coniferous plantations, is the focus of significant and expensive control efforts (Lieffers et al. 1996). Given the increasing mandate to manage for all resource values, it seems appropriate to ensure that vegetation control treatments directed at aspen be justifiable.

A wide variety of wildlife use aspen for such functions as shelter, food, hiding cover, thermal protection, and perching. Aspen also provides rapid visual screening due to its fast growth rate and variation in colour and texture, which are important attributes in visual management. Conifers growing in mixtures with aspen may reduce frost damage, evaporative stress, and the effects of planting check (Marsden et al. 1996; Man and Lieffers 1997; DeLong 2000).

Forest vegetation management is the practice of efficiently channelling limited site resources into forest products rather than into non-commercial plant species. However, with the increase in aspen utilization throughout the sub-boreal and boreal forest, aspen is no longer considered a non-commercial plant species. In addition, increased public concern over herbicide application means that we need to clearly demonstrate the requirement for aspen control to meet conifer production goals.

Currently, there is little published research information from British Columbia on the competitive interactions between aspen and conifers. Information for Canada's boreal forest includes numerous studies that examine growth and/or release of white spruce beneath aspen (e.g., Steneker and Jarvis 1963; Yang 1991; Lieffers et al. 1996). Navratil and MacIsaac (1993, 1996) investigated the effects of aspen competition on the growth of both lodgepole pine and white spruce in the boreal forest in Alberta. A report by Newsome et al. (2003) for drier climatic areas in south-central British Columbia indicates that densities of over 1000 stems per hectare can decrease lodgepole pine performance in the Horsefly variant of the dry warm Sub-Boreal Spruce biogeoclimatic zone (SBSdw1) (Steen and Coupé 1997). This information estimates the increase in conifer productivity that can be expected by controlling aspen. However, these studies do not compare the effects of aspen competition to other factors influencing tree growth, such as competition from other species, soil and humus conditions, site preparation, and topographic features. Soil factors that affect the soil volume exploitable by roots have a major impact on the productivity of both lodgepole pine and white spruce (Gale et al. 1991; Szwaluk and Strong 2002). Moisture availability within the same climatic regime largely determines forest site productivity (Kozlowski 1982). If results from a productivity experiment are to be extrapolated to other sites on similar ecotypes, the various effects of different site factors affecting productivity must be isolated.

Quantifying the relative influence of factors other than aspen competition on conifer performance can offer insight about which sites may benefit the most from treatments such as aspen control.

The objective of this study was to examine the relative influence of competing vegetation, particularly trembling aspen, and soil factors on the growth of lodgepole pine (*Pinus contorta* Dougl. *ex* Loud.) and hybrid white spruce (*Picea glauca* [Moench] Voss × *engelmannii* Parry *ex* Engelm.) to develop potential management strategies to minimize the impact of these factors on plantation performance.

2 METHODS

The study site was approximately 60 km northwest of Prince George on the Nechako Plateau at 54°25´N and 123°28´W and 760 m elevation. The site is within the Mossvale variant of the moist cool Sub-Boreal Spruce biogeoclimatic zone (SBSmk1) (DeLong et al. 1993) and situated on a rolling plateau with dominant slopes < 10% gradient. Original forest cover consisted of patches of mature aspen scattered throughout a lodgepole pine–dominated mature forest.

During the summer of 1986, four permanent macroplots were established in each of three 20- to 30-ha subunits of a proposed clearcut harvest area. The subunits were related to treatment of aspen stems. One subunit was a control; in the others, all live aspen stems were treated with glyphosate using the hack and squirt method. In one subunit, stems were treated 1 year before logging and in the other, treatment immediately followed harvest. The subunits were laid out as operational trial units (i.e., no replication). Within each subunit, two of the 20 × 20 m macroplots were located in an area of relatively low density before harvest while the other two were located in areas of relatively high aspen density. The layout of these macroplots was designed to cover the range in aspen density that was likely to occur over the study area and not to test for aspen–stem treatment effect. Site, soil, and vegetation information was collected at each macroplot before logging, following methods outlined by Luttmerding et al. (1990). Slope position was described as crest, upper slope, middle slope, lower slope, or level (flat). Aspect (°) and slope (%) were measured with a compass and clinometer, respectively. Soil moisture regime was determined in the field using topographic and soil morphological properties (see DeLong et al. 1993). Soil texture was determined in the field using information presented by Luttmerding et al. (1990). The total number of pre-harvest aspen stems was also recorded at each macroplot. The opening was clearcut after sampling in 1986. Selected site, soil, stand, and silvicultural treatment characteristics for each macroplot are summarized in Table 1.

In the spring of 1988, 60 seedlings each of lodgepole pine and white spruce were planted in each of the 12 macroplots for a total of 1440 seedlings. The seedlings were planted in five rows of 12 seedlings each in alternate rows at 2.5-m spacing.

TABLE 1 *Selected macroplot characteristics*

Plot[a]	Soil particle size class[b]	Moisture regime[c]	Aspect (°)	Year 5 aspen density (sph)
C1	1	Mesic	Level	2 450
C2	2	Mesic	Level	32 175
C3	2	Mesic	Level	24 100
C4	2	Mesic	Level	4 900
PT1	1	Subhygric	58	3 200
PT2	3	Subhygric	30	5 875
PT3	3	Submesic	Level	2 300
PT4	3	Submesic	Level	2 875
ST1	4	Mesic	Level	5 150
ST2	4	Mesic	Level	18 850
ST3	2	Mesic	304	3 575
ST4	1	Mesic	92	7 025

a Macroplot treatment where C# = plots where no treatment was done to aspen, PT# = plots where live aspen were treated by hack and squirt method with glyphosate 1 year before harvest, and ST# = plots where standing aspen were treated by hack and squirt methods with glyphosate immediately following harvest.

b Soil particle size class within effective rooting zone where 1 = sandy loam over loamy sand with < 30% coarse fragments, 2 = sandy loam with < 30% coarse fragments, 3 = sandy loam with > 30% coarse fragments, 4 = silt loam with no coarse fragments.

c Relative moisture regime assessed according to methods outlined by Luttmerding et al. (1990).

2.1 Main Study

In August 1988, 20 randomly located tree-centred vegetation competition plots (1.26-m radius) were sampled for each tree species within each macroplot. This plot size had been successfully used in the past to quantify shrub/herb competition (DeLong 1991). A total of 240 plots (12 macroplots × 20 plots) were sampled for each tree species. At each plot, information on surrounding vegetation was collected for each species whose cover was at least 5% of the plot and at least as tall as the midpoint of the seedling's crown. The measurements included percent cover, average height of the top of the canopy in centimetres, and canopy proximity. An ocular estimate of percent cover was determined as the proportion of plot covered if leaf area of the species was projected vertically onto the ground. Proximity was determined as the distance from the tree stem to the inner edge of foliage of the closest clump or individual as long as that clump or individual covered at least 1% of the plot (i.e., the species canopy could be closer than the proximity estimate as long as it accounted for < 1% cover). Proximity was recorded to the nearest decimetre. From these measurements, the Light Interception Index (LII) (DeLong 1991) was calculated as:

$$LII = \sum_i \left(C_i \cdot H_i\right)/P_i$$

where i = each non-crop species that is > 5% cover and > 50% crop tree height, C = percent ground cover, H = average height (cm) of competing species, and P = proximity (dm) of competing species to crop tree.

Height and stem diameter (at base) were recorded for the tree at plot centre. All measurement trees were staked and resampled in 1989, 1990, 1991, 1992, 1994, and 1997. In 1990, vegetation competition was measured and the humus depth was assessed at four locations, near the middle of each quadrant of the 1.26-m circular plot. If mineral soil had been displaced within the plot, then the location value was recorded as a negative number. The value used in analyses was the average of the four values recorded. Density of all aspen stems within the entire 20 × 20 m macroplot was recorded for every measurement year.

2.2 Biomass Study

Consistently poorer growth of both lodgepole pine and white spruce in two of the macroplots where the aspen competition level was average indicated that factors other than aspen competition were responsible. These particular macroplots (ST1 and ST2) both occurred on finer-textured soils than the others. In 1990, a more detailed study was conducted between one of the fine-textured macroplots (ST1) and a coarser-textured macroplot (C1) with similar aspen competition levels (Table 1). Within these macroplots 10 lodgepole pine and 10 white spruce trees were randomly selected from trees not within permanent sample plots. Each tree was carefully excavated to maintain as much of the root biomass as possible. Excavation went to the total depth of fine roots (1–2 mm) and included as much of the very fine roots (< 1 mm) as possible. In the laboratory, trees were separated into above- and below-ground portions, dried at 70°C until weight was constant, and weighed.

2.3 Analysis

Standard regression analysis and regression trees were used to examine relationships between various factors expected to influence tree performance (independent variables) and tree growth (dependent variables). Independent variables examined included both categorical and continuous variables. The categorical variables were moisture regime (MR), soil particle size class (SC), and aspect (Table 1). Aspect classes were level, north for azimuth 315–345°, and east for azimuth 45–135°. Since macroplot aspen density was the same for up to 20 plots (trees), it was also treated as a categorical variable. For the first analysis run, the plots within the lowest aspen density macroplot were coded as 1 for a dummy variable called low aspen density class (ALD). In subsequent analyses, plots from the macroplot with the next lowest aspen density were added in to ALD as 1's. This procedure was continued until either all but one of the macroplots were included and this independent variable was not significant (e.g., $p < 0.15$) or until r^2 was maximized. The continuous variables were: humus depth (HU); Light Interception Index (LII), calculated as LII for all species except aspen; and aspen competition (AC), calculated as LII of aspen only.

To partition the relative influence of different factors on height and diameter growth, regression trees (Breiman et al. 1984) were developed. It was felt that regression trees could be particularly useful at establishing break points (levels at which response is very different above and below) for independent variables, which could be used to set decision thresholds for management (e.g., competition level requiring a brushing treatment).

Regression trees are built through binary recursive partitioning, an iterative process of repeatedly splitting the data into two parts. Once samples have been split off, they remain separate in subsequent partitions. We used the TREES module in SYSTAT 11 (SYSTAT Software, Inc. 2004), which draws on algorithms from Breiman et al. (1984). Tree construction was based on least squared loss, which minimizes the sum of the squared deviations from the mean in the separate parts at each split. We used as stopping criteria: (1) 5 for maximum number of splits, (2) 0.05 for the minimum proportion reduction in error (PRE) required for the tree at any split, and (3) 0.05 for the minimum split value allowed at any node (Wilkinson 2004).

The standard regression analysis was conducted using the general linear model procedure (SYSTAT Software, Inc. 2004). All categorical variables (moisture regime, aspect, soil particle size class) were coded as dummy variables where the one class was coded as 1 and all others as 0.

Multiple regression models were developed to predict tree growth (height and diameter) after 7 and/or 10 growing seasons using the individual tree-centred plot as the experimental unit. Growth-environment relationships were examined for linearity and homogeneous variance on continuous variables including LII, AC, and HU. Logarithmic transformations of LII and AC were used sometimes to improve model fit. The backward stepwise procedure was used initially in selecting independent variables at a significance level of $p < 0.15$. Final models were selected based on the equation that maximized the adjusted R^2, had unbiased residuals, and required the fewest independent variables.

Differences in root and shoot biomass of trees excavated from coarse- and fine-textured sites were tested using a 2-sample *t* test.

3 RESULTS

Soil-related factors were responsible for the major partitions of tree height growth according to the regression tree analyses. When examining the regression tree results, note that for second and third splits the sample trees included are only those included in the side of the split that occupies the same row. For instance, the second split for height after seven growing seasons, based on HU, includes only the 193 sample trees on sites that do not have silty soils (i.e., SC = 1, 2, or 3) (Table 2). For lodgepole pine height at the end of three, four, and seven growing seasons, trees growing in silt loam soils with no coarse fragments had lower height growth than on all other SCs (Tables 1 and 2). By year 7, trees growing on silt loam soils were on average 47 cm shorter than trees growing on other SCs. An additional partition relating to humus depth above and below 4 cm (better height growth below 4 cm) occurred for height at end of the seventh growing season (Table 2). Height at the end of the 10th growing season had three partitions. The first partition was related to humus depth above and below 3 cm (height of 401 vs. 454 cm, respectively). The second and third partitions further divided the trees growing in deeper humus (i.e., $\geq$ 3 cm) and were related to aspen competition surrounding the tree and macroplot aspen density (Table 2). In year 10, the shortest average tree height (n = 5, mean = 252 cm) was for those growing on sites with humus depth $\geq$ 3 cm and LII of aspen $\geq$ 1170, while the tallest average tree height (n = 6, mean = 530 cm) was for those on sites with humus depth $\geq$ 3 cm, LII of aspen < 1170, and macroplot aspen density > 32 175 stems per hectare (sph) (Table 2). The average diameter of these tallest pines was just under the average of all lodgepole pine trees in year 10 (76.6 vs. 78.6 cm). Height growth over time for lodgepole pine growing on sites with SC = 4 versus those on sites with SC $\geq$ 4 and HU < 3 cm is shown in Figure 1.

TABLE 2 *Summary of output for regression tree for lodgepole pine height*

Variable	First split	Second split	Third split	PRE[a]
H3	SC = 4 **64.8** (16.9) ***39***			
	SC < 4 **79.3** (16.1) ***200***			**0.10**
H4	SC = 4 **99.7** (24.0) ***39***			
	SC < 4 **121.5** (23.2) ***199***			**0.11**
H7	SC = 4 **223.2** (46.4) ***35***			
	SC < 4 **270.2** (49.3) ***193***	HU ≥ 4 **240.9** (57.9) ***44***		0.11
		HU < 4 ***278.9*** (43.0) ***149***		**0.19**
H10	HU < 3 **454.4** (76.1) ***150***			
	HU ≥ 3 **401.1** (99.6) ***72***	AC3 ≥ 1170 **251.6** (168.7) ***5***		0.08
		AC3 < 1170 **412.3** (84.5) ***67***	AD5 < 32 175 **400.8** (76.7) ***61***	0.15
			AD5 ≥ 32 175 **529.3** (74.6) ***6***	**0.20**

Note: Mean is shown in bold, standard deviation in brackets, and sample size in bold italic. H*n* = height at end of *n* growing seasons, SC = soil particle size class according to Table 1, HU = Depth (cm) above (+) or below (–) mineral soil/humus surrounding planted seedling (cm), AC3 = Light Interception Index of aspen measured at end of 3rd growing season, AD*n* = macroplot aspen density measured at end of *n*th growing season.

a PRE = proportional reduction in error; numbers are cumulative and boldface numbers are totals.

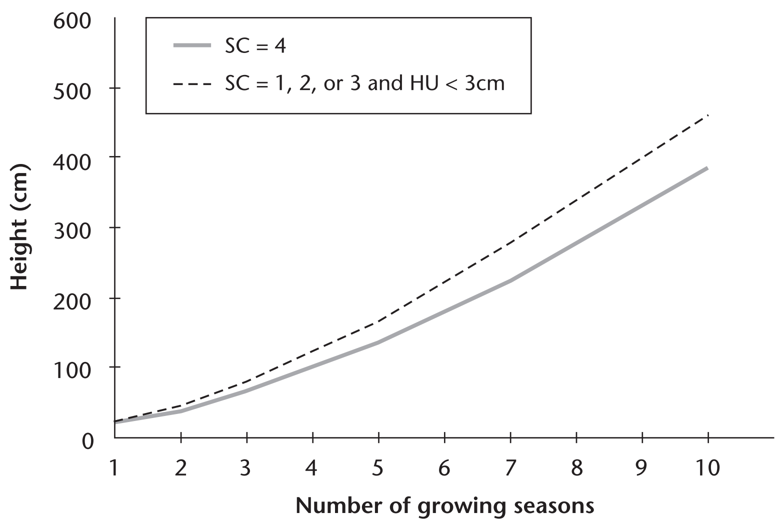

FIGURE 1 *Height growth of lodgepole pine over time for trees growing on sites with coarse fragment–free silt loam soils (i.e., SC = 4) versus trees growing on soils with other particle size classes (i.e., SC = 1, 2, or 3) with humus depth surrounding the tree < 3 cm (includes microsites with displaced soil).*

Soil displacement (i.e., HU < 0) at depths below 0, –1, and –2 were responsible for the main partitioning of hybrid spruce height growth (Table 3). Height was reduced by an average of 40 cm/yr for trees growing on sites with soil displacement of > 1 cm (i.e., HU < –1). Trees growing on sites above the soil displacement cutoff were further partitioned by SC for height at the end of 4, 7, and 10 growing seasons (Table 3). By year 10, trees growing on silt loam–textured soils with no coarse fragments were on average 77 cm shorter than ones growing on sandy loam soils with > 30% coarse fragments. Height growth over time for hybrid white spruce growing on sites with HU < –1 cm versus those on sites with HU ≥ – 1 cm and ST = 3 is shown in Figure 2.

Vegetation competition factors were responsible for most of the major partitions in tree diameter according to the regression tree analyses. For lodgepole pine diameter at the end of three growing seasons, the only partition related to macroplot aspen density measured after the first growing season was at a threshold of 1650 sph (Table 4). For diameter at the end of 4, 7, and 10 growing seasons, the first partitions were related to LII at thresholds of 518 (seven growing seasons), 715 (four growing seasons), and 718 (10 growing seasons) (Table 4). In year 10, diameter was reduced on average by 18 mm for trees growing on microsites with LII ≥ 718. Further partitions relating to SC and aspen density occurred for diameter at the end of 4, 7, and 10 growing seasons (Table 4). In year 10, the trees with the smallest average diameter (n = 16, mean = 51.5 mm) were those at LII ≥ 718 and macroplot aspen density ≥ 24 100 and the trees with the largest average diameter (n = 50, mean = 89.9 mm) were those at LII < 718 growing on sandy loam soils with < 30% coarse fragments (i.e., ST = 1). Figure 3 compares diameter growth over time for the aforementioned groups of trees.

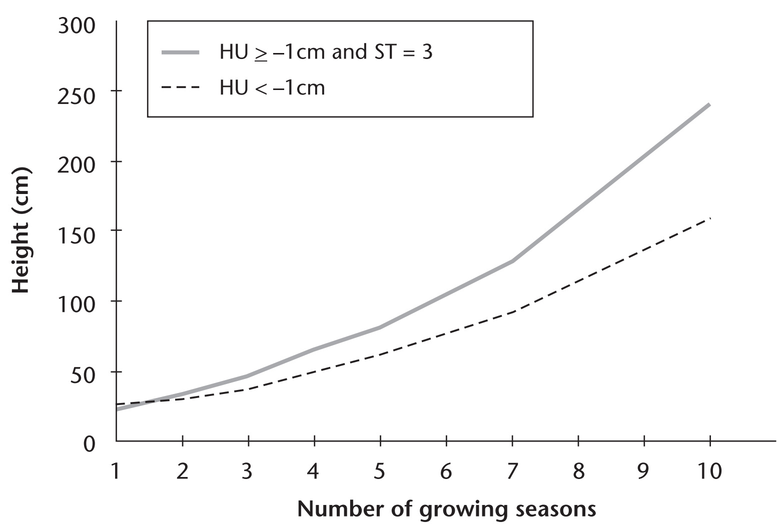

FIGURE 2 *Height growth of hybrid white spruce over time for trees growing on sites with soils displaced by > 1 cm (i.e., HU < –1cm) versus trees growing on soils with HU ≥ –1 cm and soil particle size sandy loam with > 30% coarse fragments (i.e., SC = 3).*

TABLE 3 *Summary of output for regression tree for hybrid white spruce height*

Variable	First split	Second split	Third split	PRE[a]
H3	HU < 0 **36.9** (7.8) ***65***			
	HU ≥ 0 **44.0** (9.6) ***173***			**0.11**
H4	HU < −2 **46.8** (11.5) ***39***			
	HU ≥ −2 **58.6** (15.4) ***199***	SC = 4 **50.1** (12.9) ***38***		0.08
		SC < 4 **60.6** (15.2) ***161***		**0.14**
H7	HU < −1 **91.7** (29.5) ***54***			
	HU ≥ −1 **111.1** (30.8) ***182***	SC = 4 **90.5** (29.3) ***37***		0.07
		SC < 4 **116.4** (29.0) ***145***		**0.15**
H10	HU < −1 **159.2** (51.0) ***53***			
	HU ≥ −1 **199.7** (60.2) ***181***	SC = 4 **164.8** (60.0) ***36***		0.08
		SC < 4 **208.3** (57.5) ***145***	SC < 3 **199.3** (54.4) ***114***	0.14
			SC = 3 **241.5** (57.1) ***31***	**0.19**

Note: Mean is shown in bold, standard deviation in brackets, and sample size in bold italic. H*n* = height at end of *n* growing seasons, HU = depth (cm) above (+) or below (−) mineral soil/humus surrounding planted seedling (cm), SC = soil particle size class according to Table 1.

a PRE = proportional reduction in error; numbers are cumulative and boldface numbers are totals.

TABLE 4 *Summary of output for regression tree for lodgepole pine diameter*

Variable	First split	Second split	PRE[a]
D3	AD1 ≥ 1650 **14.2** (3.2) ***179***		
	AD1 < 1650 **16.3** (3.6) ***60***		**0.08**
D4	LII ≥ 715 **20.3** (4.8) ***48***		
	LII < 715 **24.6** (5.4) ***190***	SC = 4 **20.8** (4.3) ***34***	0.10
		SC < 4 **25.4** (5.2) ***156***	**0.18**
D7	LII ≥ 518 **46.8** (11.7) ***67***		
	LII < 518 **56.8** (10.6) ***161***	SC > 1 **54.7** (9.7) ***115***	0.15
		SC = 1 **62.3** (10.8) ***46***	**0.20**
D10	LII ≥ 718 **64.1** (18.5) ***42***	AD5 ≥ 24 100 **51.5** (19.7) ***16***	0.18
		AD5 < 24 100 **71.8** (12.9) ***26***	0.24
	LII < 718 **82.0** (14.4) ***180***	SC > 1 **78.9** (13.7) ***130***	
		SC = 1 **89.9** (13.0) ***50***	**0.31**

Note: Mean is shown in bold, standard deviation in brackets, and sample size in bold italic. D*n* = basal diameter at end of *n* growing seasons, AD*n* = macroplot aspen density measured at end of *n*th growing season, LII = Light Interception Index (DeLong 1991), SC = soil particle size class according to Table 1.

a PRE = proportional reduction in error; numbers are cumulative and boldface numbers are totals.

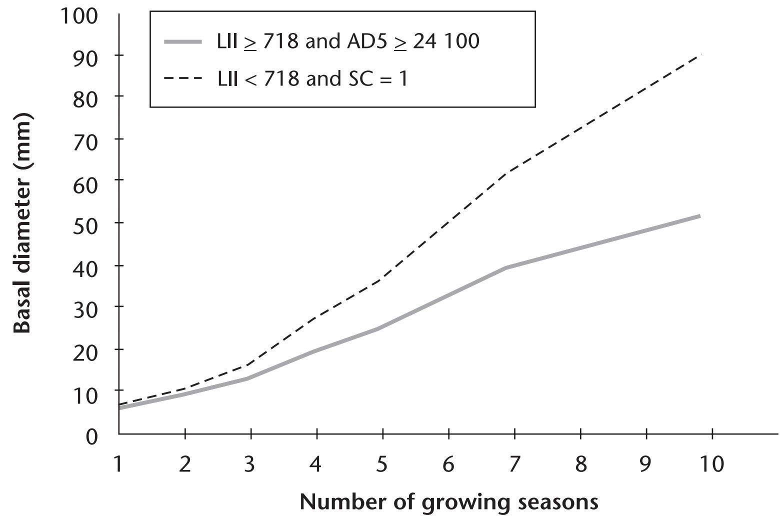

FIGURE 3 *Diameter growth of lodgepole pine over time for trees growing on sites with LII ≥ 718 and macroplot aspen density ≥ 24 100 versus trees growing on sites with LII < 718 and soil particle size sandy loam over loamy sand with < 30% coarse fragments (i.e., SC = 1).*

For hybrid white spruce, diameter at the end of three growing seasons was partitioned by HU (< or ≥ 0) and further by AC (< or ≥ 56) (Table 5). For diameter at the end of the fourth and seventh growing seasons, the first partition was related to macroplot aspen density. Further partitions were related to HU for year 4 and AC and HU for year 7 (Table 5). In year 10, the spruce trees with the smallest average diameter (n = 64, mean = 29.2 mm) were on sites with AC ≥ 41 and the trees with the largest average diameter (n = 120, mean = 38.7 mm) were on sites with AC < 41 and HU ≥ 0. Diameter growth over time for the aforementioned groups is compared in Figure 4.

Trembling aspen density of the plot, interspecific neighbourhood competition (i.e., LII or AC), soil type, humus/displacement depth, moisture regime, and aspect were all significant factors in the regression models for lodgepole pine and white spruce size (Tables 6–8). Only the individual factor FS (fine soil type indicator) was significant in all regressions, but factors representing interspecific competition were also present in all regressions (Tables 6–8). The models accounted for 24–33% of lodgepole pine size and 19–28% of spruce size (Tables 7 and 8). Fine-textured soils, aspen competition, submesic soil moisture regime, humus depth (year 7 stem diameter only), mesic moisture regime (year 7 stem diameter and year 10 height), LII (year 7 and year 10 stem diameter), and moderate aspen macroplot density (year 10 height only) all negatively influenced lodgepole pine growth (Tables 6 and 7). Low aspen macroplot density (year 7 and year 10 stem diameter) and east aspect (year 10 height only) positively influenced lodgepole pine growth (Tables 6 and 7). Fine-textured soils, LII (year 10 diameter and height), and aspen competition (year 7 and year 10 diameter) negatively influenced hybrid spruce growth while low macroplot aspen densities, humus depth, mesic and subygric moisture regime (year 10

TABLE 5 *Summary of output for regression tree for hybrid white spruce diameter*

Variable	First split	Second split	Third split	PRE[a]
D3	HU < 0 **8.2** (1.8) ***65***			
	HU ≥ 0 **9.7** (2.4) ***173***	AC < 56 **10.2** (2.4) ***122***		0.08
		AC ≥ 56 **8.7** (2.1) ***51***		**0.14**
D4	AD1 ≥ 4425 **12.4** (2.8) ***116***			
	AD1 < 4425 **14.6** (4.3) ***120***	HU ≥ 0 **15.5** (4.3) ***120***		0.13
		HU < 0 **12.2** (3.8) ***34***		**0.19**
D7	AD5 < 2875 **30.0** (9.0) ***40***			
	AD5 ≥ 2875 **22.3** (6.3) ***196***	AC3 ≥ 44.4 **19.6** (4.7) ***61***		0.15
		AC3 < 44.4 **23.6** (6.6) ***135***	HU ≥ 0 **25.1** (6.2) ***93***	0.20
			HU < 0 ***20.1*** (5.9) ***42***	**0.26**
D10	AC3 ≥ 41 **29.2** (8.3) ***64***			
	AC3 < 41 **36.5** (10.5) ***170***	HU ≥ 0 **38.7** (9.9) ***120***		0.10
		HU < 0 **31.1** (10.1) ***50***		**0.18**

Note: Mean is shown in bold, standard deviation in brackets, and sample size in bold italic. D*n* = basal diameter at end of *n* growing seasons, HU = depth (cm) above (+) or below (–) mineral soil/humus surrounding planted seedling (cm), AC = Light Interception Index (DeLong 1991) for aspen only, AD*n* = macroplot aspen density measured at end of *n*th growing season.

a PRE = proportional reduction in error; numbers are cumulative and boldface numbers are totals.

TABLE 6 *Abbreviations and definitions of the independent variables included in the regression equations*

Variable (*x*)	Definition
HU	Depth (cm) above (+) or below (–) mineral soil/humus surrounding planted seedling in cm
FS	Fine soil type indicator where soil textures with > 60% silt and clay content = 1 and others = 0
SM	Submesic relative soil moisture regime indicator where submesic sites = 1 and others = 0
ME	Mesic relative soil moisture regime indicator where mesic sites = 1 and others = 0
SH	Subhygric relative soil moisture regime indicator where subhygric sites = 1 and others = 0
EA	East aspect indicator where sites of >10% slope and azimuth 45–135° = 1 and others = 0
LII	Light Interception Index measured at end of third growing season
AC	Light Interception Index calculated for aspen competition only
ALD	Aspen density < 2500 sph
AMD	Aspen density ≥ 2500 sph but < 24 100

TABLE 7 *Regression equations for describing the stem diameter (mm) after 7 and 10 growing seasons and height (cm) after 10 growing seasons for lodgepole pine*

Independent variable (x)[a]	**Dependent variable (y)**		
	Year 7 stem diameter (mm)	**Year 10 stem diameter (mm)**	**Year 10 height (cm)**
	Regression coefficients (B_i)		
Constant	64.85 (se 2.55)	92.27 (se 2.90)	533.32 (se 19.24)
HU	−0.56 (se 0.19)	–	–
FS	−3.67 (se 2.00)	−8.89 (se 2.65)	−36.78 (se 16.11)
SM	−6.48 (se 2.51)	−8.24 (se 2.76)	−75.97 (se 19.21)
ME	−4.12 (se 1.93)	–	−38.26 (15.72)
EA	–	–	76.26 (se 15.72)
Ln (LII)	−1.07 (se 0.37)	−1.63 (se 0.49)	–
AC	–	–	−0.06 (se 0.01)
Ln (AC)	−1.47 (se 0.29)	−3.24 (se 0.39)	–
ALD	8.71 (se 2.02)	9.41 (se 2.77)	–
AMD	–	–	−66.52 (se 14.60)
	Regression statistics		
F-ratio	14.87	22.93	12.35
Total adjusted R^2	0.30	0.33	0.24
SEE	9.92	13.69	76.82
Number of trees	221	227	222

a See Table 6 for definitions of independent variables. All independent variables significant at $p < 0.07$.

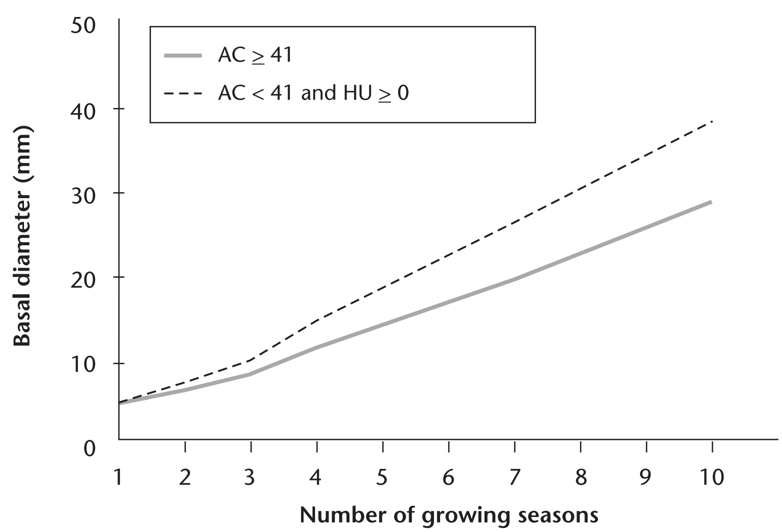

FIGURE 4 *Diameter growth of hybrid white spruce over time for trees growing on sites with LII of aspen ≥ 41 versus trees growing on sites with LII of aspen < 41 and non-displaced humus (i.e., HU ≥ 0).*

TABLE 8 *Regression equations for describing the stem diameter (mm) after 7 and 10 growing seasons and height (cm) after 10 growing seasons for white spruce*

Independent variable (*X*)[a]	**Dependent variable (*Y*)**		
	Year 7 stem diameter (mm)	**Year 10 stem diameter (mm)**	**Year 10 height (cm)**
	Regression coefficients (B_i)		
Constant	23.75 (se 0.59)	31.58 (se 1.75)	158.56 (se 10.58)
HU	0.52 (se 0.10)b	0.85 (0.16)	4.73 (se 0.96)
FS	–3.30 (se 1.12)	–5.37 (1.79)	–36.95 (se 10.8)
ME	–	3.89 (se 1.88)	33.03 (se 11.18)
SH	–	7.73 (se 2.29)	68.22 (se 13.73)
LII	–	–0.002 (se 0.001)	–0.010 (se 0.004)
Ln (AC)	–0.73 (se 0.16)	–0.68 (se 0.31)	–
ALD	6.08 (se 1.14)	8.80 (se 1.81)	41.66 (se 10.81)
	Regression statistics		
F-ratio	24.02	12.70	10.22
Total adjusted R^2	0.28	0.26	0.19
SEE	6.27	9.00	54.44
Number of trees	234	236	234

a See Table 6 for definitions of independent variables.
b All independent variables significant at $p < 0.05$.

diameter and height) positively influenced it (Tables 6 and 8). The trend in growth related to moisture regime was for subhygric sites to be the most productive, followed by mesic and submesic sites (Tables 7 and 8).

As a single factor, interspecific competition from aspen had the largest influence on lodgepole pine growth with 24% of the variability of diameter after 10 growing seasons being accounted for by the natural log of AC ($n = 222$, F-ratio = 69.363, $p = 0.000$, $r^2 = 0.236$). If all lodgepole pine where AC = 0 (i.e., no aspen competition recorded) were removed from the analysis, the r^2 increased to 0.42. Conversely, natural log of AC could explain only about 9% of the variability of white spruce diameter after 10 growing seasons ($n = 234$, F-ratio = 23.798, $r^2 = 0.089$). The only other significant single independent continuous variable for predicting spruce growth was HU. It accounted for 4.5% of the variability in spruce diameter after seven growing seasons ($n = 236$, F-ratio = 11.952, $p = 0.001$, $r^2 = 0.045$).

Overall, there was a low positive correlation between HU and competition as measured by LII ($n = 413$, $p = 0.219$) but high levels of competition were associated with deeper humus and lower levels with soil displacement (Figure 5). Competition levels over 1000 were rarely (2 of 202) present when soil was displaced (HU < 0), whereas they were more common (43 of 311) where soil was not displaced.

Lodgepole pine above- and below-ground biomass and white spruce below-ground biomass were all significantly lower after two growing seasons for saplings excavated from sites with silty soils versus those with sandy soils (Table 9).

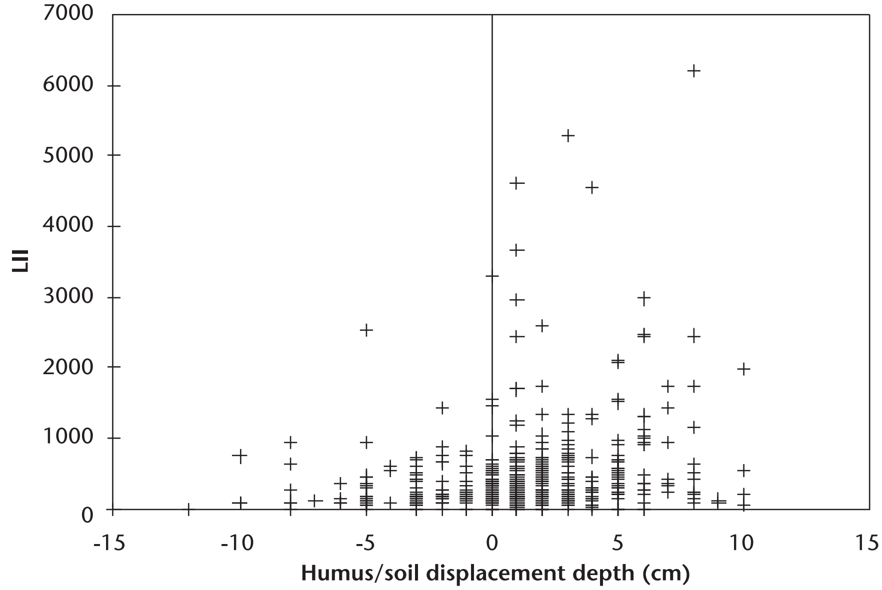

FIGURE 5 *Relationship between humus/soil displacement depth and Light Interception Index (LII).*

TABLE 9 *Above- and below-ground biomass of lodgepole pine and white spruce, after two growing seasons, growing on coarse versus fine soils for sites with moderate aspen competition*

Variable	Coarse (g)	Fine (g)	T	*p*
Pl above ground biomass	112.58	65.3	–2.996	0.008
Pl below ground biomass	33.40	21.62	–2.667	0.016
Sw above ground biomass	35.98	22.09	1.755	0.092
Sw below ground biomass	28.22	15.53	2.840	0.011

4 DISCUSSION

The results of this study indicate that soil factors can significantly affect height growth of both lodgepole pine and hybrid white spruce. Height growth of both species is negatively influenced by soils with a higher silt content, whereas deeper humus depths appear to negatively influence lodgepole pine height growth but positively influence hybrid white spruce height growth. The negative influence of silty soils on lodgepole pine height growth supports the finding of Szwaluk and Strong (2002), who observed a negative relationship with silt content and lodgepole pine site index for 78- to 146-year-old stands in southwestern Alberta. They also found that humus depth negatively influenced lodgepole pine site index, which was supported by the regression tree analysis. Decreases in site index with relative decreases in estimated soil aeration (often associated with soils with higher silt or clay content) were found by Wang (1992) for lodgepole pine and by Gale et al. (1991) and Wang and Klinka (1996) for white spruce.

Both regression tree and standard multiple regression analyses indicated a significant influence of vegetation competition on tree diameter growth. The significant effect of aspen interspecific competition on the diameter growth of lodgepole pine is consistent with recent work by Newsome et al. (2003) within the SBS. In their study, density of aspen as tall or taller than the pine explained 48–64% of the variation in pine stem diameter in the dry warm subzone of the SBS (Meidinger et al. 1991). Their recommendation of a threshold of 1000 sph of aspen is lower than the macroplot aspen density of 2500 sph (i.e., ALD) suggested by the regression analyses for lodgepole pine diameter growth. However, this result may reflect the difference between total stem count used in this study and the density of stems as tall or taller than the pine used in the Newsome et al. (2003) study. The higher sensitivity of lodgepole pine to interspecific competition compared to white spruce corresponds with the findings of Wright et al. (1998) for sites in the boreal and sub-boreal, which indicate a more linear decrease of diameter growth for lodgepole pine versus white spruce with decreasing light levels. The inclusion of soil moisture regime in the models for both lodgepole pine and hybrid white spruce and the trend of higher productivity with increasing moisture are consistent with previous studies (Gale et al. 1991; Wang 1992; Wang and Klinka 1996).

Height of the target conifer has often been included in competition indices to account for influences of tree size and past performance on tree response to current competitive conditions and generally greatly improves r^2 values (Brand 1986; Comeau et al. 1993; Simard et al. 2004). The finding that soil factors, rather than interspecific competition, primarily influenced height of white spruce indicates that using tree height in the index may be artificially inflating the apparent influence of competition since soil factors also influence diameter growth. At the very least it indicates that soil factors should also be included where possible when examining the effects of vegetation competition on tree performance.

5 MANAGEMENT IMPLICATIONS

The Light Interception Index (LII), either calculated for all vegetation or just for aspen, appears to be helpful for identifying levels at which microsite brushing may be useful to apply. For lodgepole pine diameter growth, a significant threshold at an LII value of about 700 (equivalent to 14% cover with a mean height of 100 cm with less than 1% of the cover within 20 cm of the apex of the response tree) measured after the third growing season was indicated. For hybrid white spruce diameter growth, a significant threshold at an aspen competition (i.e., LII for aspen only) value of about 50 (equivalent to 5% cover of aspen with a mean height of 100 cm with less than 1% cover within 100 cm of the apex of the response tree) measured after the third growing season was indicated. However, when dealing with aspen competition, microsite competition may be less influential than general stand aspen density (i.e., macroplot aspen density in this study) at controlling longer-term growth of conifers (Lieffers et al. 2002). An aspen density threshold of 2500 sph (measured after five growing seasons) was suggested by regression analysis as a threshold above which optimum growth of both lodgepole pine and hybrid white spruce may not be achieved.

That some of the tallest lodgepole pine trees, which had average diameters compared to the total sample, were located in the highest density macroplot indicates that acceptable growth could occur in areas of high aspen density as long as the aspen trees were not near the pine trees (i.e., within natural or managed gaps within the aspen stand). However, deleterious effects on growth, especially diameter, may be expected beyond 10 years.

Displacement of soil tended to reduce maximum shrub/herb competition level but at the same time reduced tree growth. This finding indicates that reducing competition by aggressive site preparation (e.g., blading with a tractor) may be counterproductive. Avoiding displacement of soil during harvest and site preparation activities appears to be an important consideration especially when the site is intended to be planted with hybrid white spruce. Lodgepole pine should be planted on sites where soil displacement does occur.

Increasing the performance of both lodgepole pine and hybrid white spruce on finer-textured soils may be possible by planting seedlings whose root systems place a higher proportion of roots in the upper portions of the soil horizon where better aerated soils exist. A study by Campbell et al. (2003) showed that copper treatment of stock, which promotes lateral rooting at the top of the root system, improved the performance of lodgepole pine seedlings planted on fine-textured soils.

The findings of this study suggest that reducing trembling aspen competition is important for increasing the diameter growth of lodgeople pine and hybrid white spruce. It also shows that avoiding soil displacement and forest floor reduction may be as important as, or more important than, reducing trembling aspen competition for increasing overall growth of hybrid white spruce.

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