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Early Effects of Manipulating Aspen Density and Spatial Arrangement on Lodgepole Pine Performance, Aspen Sucker Production, and Stand Development in an 11-Year-Old Stand in the SBPSxc Subzone of South-central British Columbia

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Ministry of Forests and Range
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ABSTRACT

The Clusko aspen removal study, established in 2001 in an 11-year-old lodgepole pine–trembling aspen stand in the SBPSxc subzone, investigates the effects of five levels of aspen removal on target pine, neighbourhood competitive interactions, and stand development. Treatments include: (1) an untreated control; (2) complete aspen removal; broadcast retention of (3) 1000 and (4) 2500 aspen stems ha^{-1}; and (5) a spatial treatment that removed aspen within a 1-m radius around target pine.

Two years after treatments were applied, 2001–2003 target pine stem diameter increment was significantly larger in the 0, 1000, and 2500 stems ha^{-1} removal treatments than in the uncut control. In 2003, target pine stem diameter was significantly larger in the complete aspen removal treatment than in the control, and height:diameter ratio was smaller. Aspen removal treatments had no significant effect on lodgepole pine height, leader length, or crown width within 2 years of treatment.

Regression analysis showed that when the stand was 13 years old, lodgepole pine stem diameter growth decreased with increasing density of aspen that were at least as tall as the target pine. The relationship was strongest where aspen were included within a 2.56-m radius plot, which was the largest neighbourhood examined in this study, and was not statistically significant in neighbourhoods with smaller radii. At age 13, tall aspen density accounted for a maximum of 21.2% of the variation in pine growth, with the strongest relationship occurring between 2-year pine stem diameter increment (2001–2003) and 2003 tall aspen density. At the stand level, reducing aspen density immediately changed the diameter distribution of aspen and reduced its basal area, although after 2 years aspen continued to have greater basal area than pine in all but the complete aspen removal treatment. Two years after cutting, aspen sucker density had decreased significantly with the level of aspen retention. Complete aspen removal resulted in an average density of approximately 93 000 suckers ha^{-1} after 2 years, compared with approximately 44 000 and 22 000 suckers ha^{-1} in the 1000 and 2500 stems ha^{-1} retention treatments, respectively.

ACKNOWLEDGEMENTS

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1 INTRODUCTION

Mixtures of trembling aspen (*Populus tremuloides* Michx.) and lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.) regenerate naturally throughout the Sub-Boreal Pine-Spruce (SBPS), Interior Douglas-fir (IDF), Sub-Boreal Spruce (SBS), and Interior Cedar-Hemlock (ICH) zones in the Cariboo-Chilcotin area of the Southern Interior Forest Region (Meidinger and Pojar 1991). Due to the rapid height growth and high initial sucker densities of young aspen, these stands generally require some management at the juvenile stage to meet conifer growth objectives. Strategies designed to lessen competition from young aspen have become more complex over the past decade. In light of our current understanding of the importance of broadleaf tree species to overall ecosystem health, successful management of young pine-aspen stands now requires practitioners to find a balance between removing aspen to meet lodgepole pine growth objectives and retaining as much aspen as possible to (a) preserve the ecosystem benefits conferred by broadleaf species, (b) reduce suckering, and (c) reduce silviculture treatment costs.

At low to moderate densities, many benefits are associated with the presence of aspen. Aspen can take up large amounts of nutrients, particularly calcium, and retain them within the ecosystem (Pastor 1990). It is also more resistant to Armillaria and Phellinus root rots than most conifers, and its presence slows the spread of these diseases through conifer stands (Morrison et al. 1991; Peterson and Peterson 1995; Gerlach et al. 1997). Aspen also improves the mechanical stability of stands as they mature because the communal root system (Strong and La Roi 1983) reduces windthrow among neighbouring conifers (Frivold 1985; Yang 1989). Finally, conifer seedlings may experience less frost damage under mature aspen canopies than in clearcuts (DeLong 2000) because of reductions in nighttime radiative heat loss (Stathers 1989); however, this is a more important consideration for white spruce than for lodgepole pine because of differences in frost tolerance (Farnden 1994).

Despite the potential benefits of aspen, at high densities it can compete strongly with young lodgepole pine by reducing both light and soil water to levels that limit conifer growth for at least part of the growing season (DeLong and Tanner 1996). Light availability is particularly important to shade-intolerant lodgepole pine (Klinka and Scagel 1984; Wright et al. 1998). In low-light environments, pine stem diameter growth decreases, height:diameter ratio increases, and crown width decreases (e.g., Simard et al. 2001). Mechanical "whipping" damage to pine by aspen branches is also common where stems of the two species are growing in close proximity (Lees 1966).

Aspen removal is generally done with the objective of increasing resource availability to lodgepole pine. The degree to which removal treatments stimulate aspen sucker production is also an important consideration in the management of these juvenile stands. There is ample evidence that sucker production increases with the level of aspen removal (e.g., Huffman et al. 1999). This phenomenon has been informally observed on a variety of Cariboo-Chilcotin sites, and is of concern because of the potential for suckers to grow rapidly and engender additional stand entries. The mechanisms governing aspen sucker production are not completely understood, but contributing factors include aspen basal area prior to harvesting (presumably because aspen root density increases with basal area), genetic characteristics of individual clones, changes to hormonal balances following cutting treatments, site environmental attributes, site disturbance, and season of cutting (Frey et al. 2003).

A series of experiments has been established in the Cariboo-Chilcotin to provide ecosystem-specific information about the levels of aspen that can be retained in juvenile stands before unacceptable losses of lodgepole pine survival and growth occur. This information is expected to be useful for operational silviculture planning, and has already contributed to the development of management policy for this species mix. Early results from a retrospective study suggested that, for 7- to 10-year-old pine-aspen stands, 1000 and 2000 stems ha^{-1} of aspen as tall or taller than the target pine may be retained in drier variants of the SBSdw and in the IDFdk subzones, respectively (Newsome et al. 2003), without having an unacceptable effect on pine vigour and growth. This information has already been incorporated into current free-growing guidelines for the Cariboo (B.C. Ministry of Forests 2002), and the thresholds are being further tested in experiments where aspen has been removed to specific levels on other SBS and IDF sites (Newsome et al. 2004a, 2004b). The effects of various levels of aspen retention on sucker production are also being studied in these ecosystems.

Early work associated with this project focused on the SBS and IDF zones because they are widespread and at least moderately productive. However, pine-aspen mixtures are also common in the less productive SBPS zone, which occupies 21 948 km^2 in the Cariboo-Chilcotin (Steen and Coupé 1997). Of particular interest is the SBPSxc subzone, which comprises approximately half the total SBPS area. Until relatively recently, harvesting activity was limited in the SBPSxc because of its low productivity (site index 15 on zonal sites) (B.C. Ministry of Forests 2005). Despite its large area, very little research has been done in the SBPSxc, and subzone-specific information was lacking when free-growing guidelines were revised (B.C. Ministry of Forests 2002). This report presents second-year results from the Clusko River (Clusko) study, which was established in 2001 to study the effects of variable levels of aspen removal in the SBPSxc subzone.

2 OBJECTIVES

The objectives of the Clusko variable density study are:

1. To compare vigour, survival, and growth of target lodgepole pine growing in control neighbourhoods where no aspen have been removed with that of target pine growing in neighbourhoods where aspen density was reduced to 0, 1000, and 2500 stems ha^{-1}, and where aspen were removed within a 1-m radius of target pine.
2. To study the effects of these treatments on aspen sucker production.
3. To compare aspen density thresholds for lodgepole pine growth in the SBPSxc with those that have been tentatively identified for the IDFdk and SBSdw.
4. To compare untreated pine-aspen stand structure with that of treated stands where aspen density has been reduced to 0, 1000, and 2500 aspen stems ha^{-1}, and where aspen has been removed within a 1-m radius of target pine.

5. To examine the size of the competitive neighbourhood in which neighbouring aspen and lodgepole pine affect the target pine.
6. To provide a demonstration site for variable density aspen removal treatments in a pine-aspen complex in the SBPSxc subzone.

3 METHODS

3.1 Study Areas and Site Selection

The Clusko site was selected for three reasons: first, it had a relatively homogeneous stand of 11-year-old aspen that was scheduled for operational brushing to release lodgepole pine. Second, aspen at least as tall as lodgepole pine were present at a minimum of 2500 stems ha^{-1}, which was necessary to permit random allocation of the 2500 stems ha^{-1} treatment plots. Third, the site was selected because it had good road access, which was important given its remote location.

The Clusko study is 55 km northwest of Redstone (approximately 150 km west of Williams Lake), at latitude 53°30' N and longitude 124°06' W, in the SBPSxc subzone (Sub-Boreal Pine-Spruce very dry cold subzone) (Figure 1). The SBPSxc has mean annual precipitation of 389 mm, a mean annual temperature of 1.7°C, an average of 93 frost-free days per year, and brunisolic zonal soils (Steen and Coupé 1997). The Clusko site is zonal (site series 01) in the SBPSxc, with a submesic-mesic moisture regime and medium nutrient regime. The site is gently sloping (2–10%) with a southwesterly aspect, situated across an elevational range of 1100–1150 m.

The site (mapsheet-opening 93C 060–2) was salvage logged in 1989. Mistletoe was eradicated in 1991. Aspen regenerated immediately following harvest by suckering from the existing root system, whereas pine ingress occured over several years. Post-harvest stand development is assumed to have started in 1990. It was estimated that pine ranged from 6 to 11 years old at the start of the experiment in 2001.

At the time of treatment, vegetation at the Clusko site was dominated by kinnikinnick (*Arctostaphylos uva-ursi*) and pinegrass (*Calamagrostis rubescens*). The sparse low shrub layer included common juniper (*Juniperus communis*), prickly rose (*Rosa acicularis*), and soopolallie (*Shepherdia canadensis*). Richardson's sedge and/or northwestern sedge (*Carex richardsonii* and/or *C. concinnoides*) and rough-leaved ricegrass (*Oryzopsis asperifolia*) were also common in the herb layer.

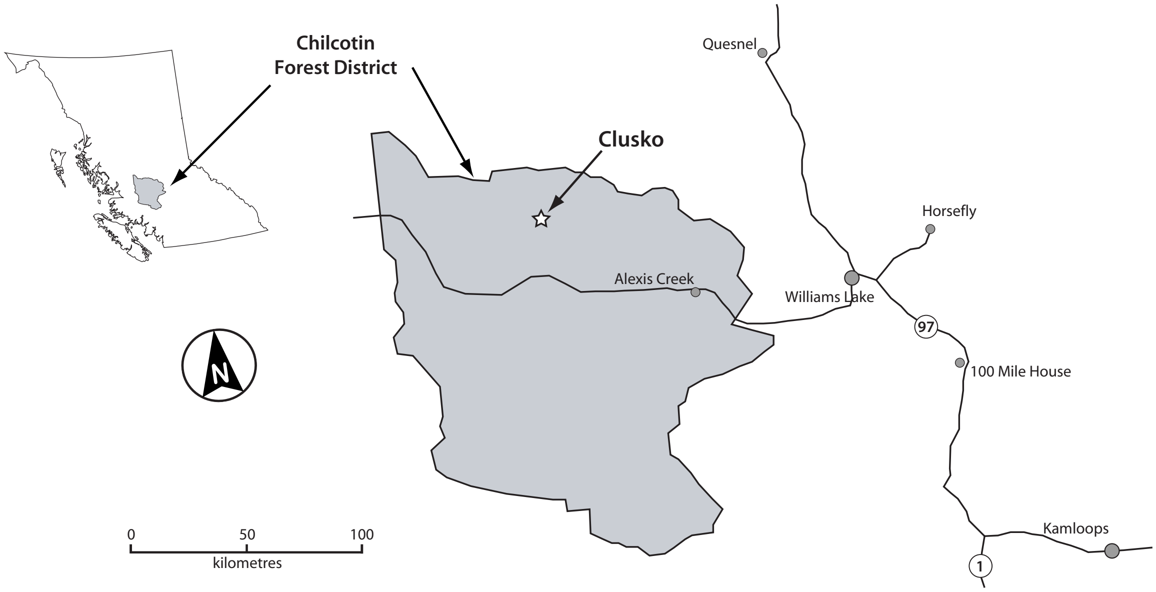


FIGURE 1 *Location of the Clusko aspen removal study.*

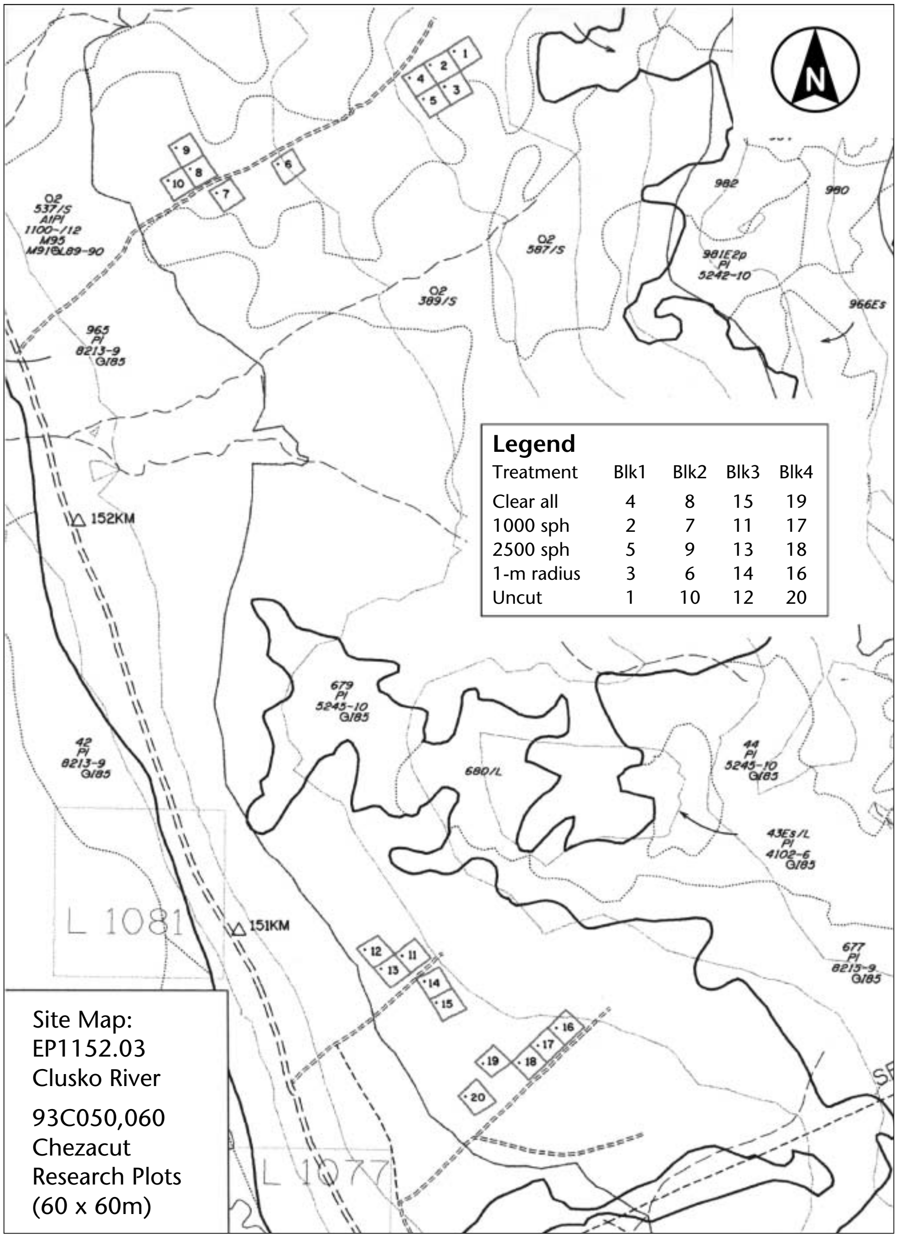
3.2 Sampling Design and Treatment

The Clusko aspen removal study used a randomized complete block design (RCBD) with four blocks and five treatments. Analysis of pre-treatment pine and aspen data showed that blocking was not necessary on the basis of height or density differences (see Section 3.4.1). However, because groups of plots were separated geographically by a distance of up to 1 km, they were blocked to account for spatial variation across the site. Each of the four blocks was randomly located in an area of the cutblock where stand conditions were homogeneous across a large enough area to accommodate five plots, and where the minimum aspen density was at least 2500 stems ha^{-1} to allow for random allocation of treatments. Blocking also ensured that replicate plots within a single treatment would be widely distributed in case of a catastrophic event such as wildfire.

The following five treatments were randomly assigned to the five treatment plots in each of the four blocks (Figure 2):

1. 0 aspen stems ha^{-1} (all aspen removed)
2. 1000 aspen stems ha^{-1}
3. 2500 aspen stems ha^{-1}
4. Aspen removal in 1-m radius
5. Control (no aspen removal)

Each treatment plot was 60 × 60 m, containing a 40 × 40 m measurement area surrounded by a 10 m buffer. A 7.5 × 7.5 m grid of 25 points was centred within the measurement area by establishing the first grid point 7.1 m from the northwest corner of the measurement area, at a bearing that was 45° from the orientation of the plot. Of the 25 grid points, numbers 9 and 17 were selected for the establishment of permanent vegetation plots where no other data would be collected so as to avoid trampling damage to the vegetation. Vegetation plots had a 3.99-m radius (50 m^2), with the grid point as plot centre. At the remaining 23 grid points, the closest healthy undamaged lodgepole pine was chosen as a potential target pine, and tall aspen (i.e., aspen as tall as



Legend

Treatment	Blk1	Blk2	Blk3	Blk4
Clear all	4	8	15	19
1000 sph	2	7	11	17
2500 sph	5	9	13	18
1-m radius	3	6	14	16
Uncut	1	10	12	20

FIGURE 2 *Plot layout at the Clusko site.*

or taller than the target pine) were counted within a 2.56-m radius (20.6 m^2) of the target pine. The first 16 potential target pine that were growing in neighbourhoods with at least 2500 tall aspen stems ha^{-1} (i.e., with at least eight tall aspen within a 2.56-m radius) were selected as target pine. These were tagged, and became centres for the sixteen 2.56-m radius subplots that would be included in the experiment.

In treatments 1, 2, and 3, aspen density was reduced on a broadcast basis to target levels of 0, 1000, and 2500 stems ha^{-1} (Figure 3). Crews were instructed to retain the tallest and most vigorous aspen stems, while keeping in mind the target density within each plot. "Leave" aspen were marked within the 2.56-m radius subplots to ensure accurate densities, but the contractor was

FIGURE 3 *An example of the 0 stems ha^{-1} treatment (complete aspen removal) next to an uncut area. The photo was taken in 2003, 2 years after treatments were applied to the 11-year-old stand.*

responsible for ensuring accurate density in the remainder of the treatment area. For treatment 4, crews removed aspen within a 1-m radius of target pine, and the remainder of the plot was untreated. Naturally established lodgepole pine in treatments 1–4 were retained unless they were closer than 50 cm to each other, in which case the least vigorous was removed by hand pulling or clipping. Aspen removal treatments were applied July 15–23, 2001, using brushsaws. Control plots (treatment 5) were left uncut.

3.3 Measurements

3.3.1 Pre-treatment Pre-treatment measurements were carried out June 4–9, 2001 to characterize each plot and to determine whether there was sufficient variation in neighbourhood aspen or pine size to warrant blocking of the experiment. The density of broadleaves as tall as or taller than the target pine within radii of 1.80 and 2.56 m was recorded in each subplot. In every fourth subplot, the total density of broadleaves ≥30 cm tall was also recorded. To obtain a representative sample of aspen and lodgepole pine heights and diameters, a random bearing was established from the plot centre to the edge of each 2.56-m radius subplot, and the 10 stems of each species closest to the line (except the target pine) were measured for height and ground-level stem diameter. Generally, all pine were measured because most plots had fewer than 10 stems of that species. Cover and modal height of all vascular and non-vascular plant species were recorded in the vegetation plots (results for individual species are not included in this report). Ground-level diameter and year 2000 and 2001 heights of target pine were also measured prior to treatment to determine whether differences existed between treatment plots.

3.3.2 Post-treatment

Target lodgepole pine The following post-treatment measurements were taken for target lodgepole pine in August of 2001 and repeated in August of 2003:

- Total height
- Leader length
- Ground-level stem diameter
- Crown width (average of N-S and E-W widths)
- Crown length
- Survival and vigour
- Type and cause of damage
- Degree of overtopping

Height:diameter ratio (HDR) and height and stem diameter increments from 2001 to 2003 were calculated. Pine survival, vigour, damage presence, damage cause, and degree of overtopping were assessed according to a standard research protocol (Appendix 1).

Stand and neighbourhood measurements In order to provide information about potential aspen growth, and to allow a known set of dominant aspen stems to be remeasured over time, the three tallest aspen in each subplot were tagged immediately following cutting so that growth of individual stems could be tracked. Henceforth, these aspen will be referred to as "tagged dominant aspen." Height and ground-level diameter were measured for the three tagged dominant aspen in each plot. Stand structure (i.e., the relative abundance and stature of all pine and aspen, including the target pine) and competition effects from neighbouring trees (i.e., the effects of surrounding pine and aspen on the target pine) were assessed in 2.56-m radius (20.6 m^2) subplots around each target lodgepole pine seedling. Height and ground-level diameter were also measured for all original broadleaf and conifer trees (i.e., not including aspen suckers that had emerged following the 2001 aspen removal treatments). These stems were painted for future identification and were remeasured in 2003. Basal area (using ground-level diameter) and density of both aspen and pine were calculated for each subplot. Quadratic mean diameter (QMD) (based on ground-level diameter) was also calculated for aspen (Equation 1). QMD puts more emphasis on the larger, and hence more competitive, stems.

$$\text{QMD} = ([\sum GLD_i^2]/n)^{-1/2} \qquad (1)$$

where QMD is quadratic mean diameter, GLD_i is ground-level diameter of an individual aspen tree, and n is the number of aspen trees in the subplot.

In 2001, stem-to-stem distance (from the outside edge of the neighbourhood tree stem to the stem centre of the target pine) and crown-to-stem distance (from the crown edge of the neighbourhood tree to the stem centre of the target pine) were recorded for all original neighbouring pine and aspen within a 2.56-m radius of each target pine. These measurements were intended to facilitate investigations into the size of the competitive neighbourhood. In 2003, stem-to-stem distances were measured for original aspen (i.e., not including suckers) and pine, but crown-to-stem distances were not measured.

In 2003, suckers (shoots that originate from adventitious buds on the established root system) and sprouts (shoots that originate from adventitious buds at the root collar of stumps) that had emerged following the 2001 thinning treatments were counted within the 2.56-m subplots. No attempt was made to differentiate between suckers and sprouts, and both will henceforth be referred to as suckers. Starting from due north and travelling clockwise, height was measured for the first 15 suckers. In 2003, ground-level stem diameter was also measured for three representative (one small, one medium, one large) suckers of the 15 that were measured for height.

3.4 Analysis

Summary statistics, including mean, standard deviation, and standard error were compiled for all continuous variables of interest (e.g., height, diameter, density, and basal area of pine and aspen). For categorical variables such as vigour and survival, numbers and percentages of trees in each class were calculated.

Analysis of variance (ANOVA) models (Table 1 and 2) were fitted, and an F-test, with the error degrees of freedom calculated by Satterthwaite's method (SAS Institute Inc. 1996), was used to test the treatment effect on pine and aspen. The statistical significance of differences between all pairs of treatment means was assessed by the Bonferroni multiple comparison test. In some cases (e.g., aspen density and basal area per hectare), a square root transformation was applied to stabilize the variance and improve the normality of the data prior to ANOVA. Where a square root transformation was used, the estimated (least-squares) treatment means and associated confidence intervals were back-transformed to the original scale (by squaring the mean, and upper and lower 95% confidence limits) to facilitate interpretation of the ANOVA results.

Treatment effects on pine were also investigated by fitting a non-linear model (Equation 2) relating pine growth to the amount of remaining aspen (i.e., density or basal area per hectare). Boxplots and probability plots were used to examine the ANOVA and regression residuals for outliers and other departures from normality. All data analyses were carried out using SAS statistical software (SAS Institute Inc. 1996, 1999). The following procedures were applied: PROC UNIVARIATE, PROC TABULATE, NLINMIX macro (Wolfinger 2000), and PROC MIXED (REML method of estimation).

3.4.1 Pre-treatment data ANOVA was used to determine whether the height or stem diameter of target lodgepole pine, or the height, diameter, or density

TABLE 1 *Sources of variation for analyzing the effects of aspen removal treatments on (a) target lodgepole pine growth and (b) stand- and neighbourhood-level pine and aspen (including suckers) variables calculated on a per-hectare basis*

Source of variation	Degrees of freedom[a,b]	Type of effect
Block (B)	3	Random
Treatment (T)	4	Fixed
B × T	12	Random
Error (tree or subplot)	n-20	Random

a The associated degrees of freedom are the maximum values assuming no mortality or missing data (n is the total number of trees or subplots).

b For analyses that do not include the 0 stems ha^{-1} treatment, degrees of freedom for treatment (T) decrease by 1 and degrees of freedom for the other terms decrease accordingly.

TABLE 2 *Sources of variation for analyzing the effects of aspen removal treatments on pine and aspen (including suckers) neighbourhood- and stand-level growth variables based on individual-tree measurements*

Source of variation	Degrees of freedom[a,b]	Type of effect
Block (B)	3	Random
Treatment (T)	4	Fixed
B × T	12	Random
Subplot	440	Random
Error (tree)	n-460	Random

a The associated degrees of freedom are the maximum values assuming no mortality or missing data (n is the total number of trees or subplots).

b For analyses that do not include the 0 stems ha^{-1} treatment, degrees of freedom for treatment (T) decrease by 1 and degrees of freedom for the other terms decrease accordingly.

of neighbourhood aspen and pine, varied significantly among treatment plots before treatments were applied. Although significant differences in pine and aspen height were found between plots, the differences were small, and the plots with taller aspen were not always the same plots where pine was taller. Stratifying plots for differences in one species would not have addressed differences in the other. In other words, there were no trends that could be addressed by blocking according to differences in productivity. However, since each of the four groups of five plots was separated geographically by up to 1 km, blocking was employed to account for any differences that resulted from this physical separation.

3.4.2 Post-treatment data Lodgepole pine responses to the aspen removal treatments were analyzed using a mixed-effects ANOVA model applied to three different, but overlapping, sets of data. Treatment effects were analyzed using the data sets that included: (a) target lodgepole pine only, (b) neighbourhood lodgepole pine (all pine within a 2.56-m radius of live target pine, but not including the target pine), and (c) stand-level pine (all live pine in a 2.56-m radius subplot, including both target and neighbourhood pine). The ANOVA model shown in Table 1 was used to analyze the following target pine variables, by year: 2001 and 2003 height, leader length, stem diameter, HDR, crown width, and 2001–2003 height and stem diameter increments, as well as neighbourhood- and stand-level variables calculated on a per-hectare basis (i.e., square root–transformed basal area and density). The ANOVA model shown in Table 2 was used to analyze neighbourhood and stand pine variables based on tree-level measurements (i.e., height and ground-level diameter).

The effects of the aspen removal treatments on aspen growth were also analyzed using a mixed-effects ANOVA model applied to four data sets: (a) tagged dominant aspen (the three aspen that were tallest in each subplot immediately following treatment), (b) neighbourhood tall aspen (aspen as tall as or taller than the target pine at each assessment date), (c) the aspen stand (all aspen 30 cm or taller with responses expressed collectively as a single value for each subplot), and (d) new aspen suckers. Subsets (b) and (c) included only residual aspen (i.e., aspen stems that were present prior to the cutting treatment and not new suckers). Tree-level responses (i.e., height and ground-level diameter of individual stems) and stand-level (subplot) responses (i.e., square root–transformed basal area and density per hectare, and quadratic mean diameter) were analyzed separately, by year, by fitting a mixed-effects ANOVA model. The ANOVA models for analyzing the stand- and tree-level responses of aspen are the same as the corresponding pine models (Table 1 and 2), except for those analyses that exclude the 0 stems ha^{-1} treatment and consequently have 3 rather than 4 degrees of freedom associated with treatment.

Regression analysis was used to examine the relationship between pine size and aspen density or aspen basal area. An exponential model was selected to allow comparison of Clusko results with previously reported results for pine-aspen stands in other Cariboo-Chilcotin ecosystems (Newsome et al. 2003, 2004a). The following model was fitted for pine diameter, diameter increment, height, and leader length:

$$y = ae^{bx} + \gamma_{\text{block}} + \delta_{\text{treatment plot (block)}} + \varepsilon \qquad (2)$$

where y is one of the pine response variables, x is the density or basal area of tall aspen (aspen at least as tall as the target pine), γ_{block}, $\delta_{\text{treatment plot (block)}}$, and ε are the random errors associated with blocks, treatment plots within blocks, and the residual (tree) error, respectively, a and b are model parameters estimated by the (non-linear) least-squares method, and e is the base of the natural log (ln) equal to 2.71828…..

To assess size of the competitive neighbourhood, the above regression analysis was done using data sets that included tall aspen within the following radii of target pine: 0.5 m, 1.0 m, 1.8 m, 2.56 m.

4 RESULTS

4.1 Target Lodgepole Pine

Target pine were considered, at the time aspen removal treatments were applied at Clusko, to have the potential to grow to a harvestable size by the end of the rotation. They differed from neighbourhood- and stand-level pine in that they were all healthy and free of damage and/or visually evident damaging agents at the start of the experiment, according to selection criteria.

4.1.1 Target pine survival and vigour In 2003, 2 years after aspen removal treatments were applied, target lodgepole pine survival was 100% in all treatments (Table 3). Vigour decreased slightly between 2001 and 2003, but the majority of stems (86–92%) continued to have good vigour in 2003. The small decrease in vigour was related mainly to a slight shift from good to fair vigour (Figure 4). Very few (≤3%) target pine had poor vigour in 2003. In that assessment, over 92% of all target pine were completely healthy and free of damage to foliage, leaders, or stems. Of the small amount of damage recorded in 2003, about half was caused by big game (probably moose) and about half was attributed to unknown causes.

TABLE 3 *Mean percent survival and vigour of target lodgepole pine in aspen removal treatments in 2001 and 2003, 11 and 13 years post-harvest*

	Aspen removal treatment				
Pine variable	**0 stems ha^{-1}**	**1000 stems ha^{-1}**	**2500 stems ha^{-1}**	**1-m radius**	**Control**
Survival (%)					
2001	100	100	100	100	100
2003	100	100	100	100	100
Good vigour (%)					
2001	100	98	97	97	100
2003	88	91	92	86	89
Fair vigour (%)					
2001	0	0	3	3	0
2003	9	9	8	12	11
Poor vigour (%)					
2001	0	2	0	0	0
2003	3	0	0	2	0

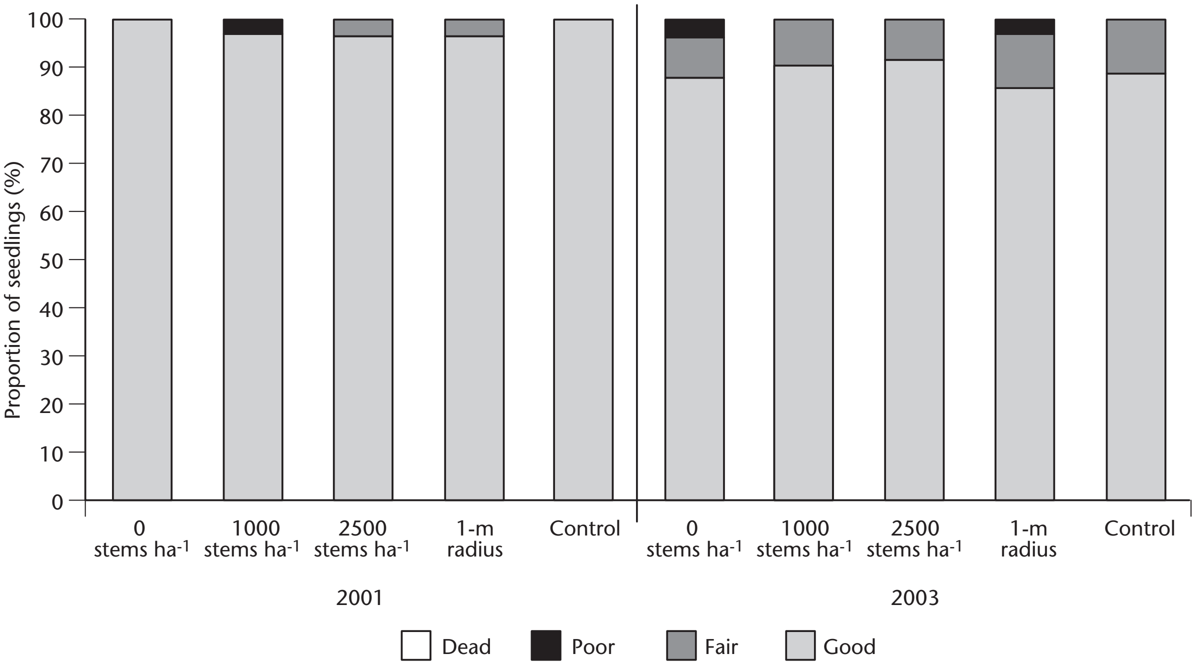


FIGURE 4 *Comparison of target lodgepole pine vigour in aspen removal treatments in 2001 and 2003, 11 and 13 years post-harvest. There was no pine mortality by 2003.*

4.1.2 Target pine growth Immediately following treatment application in 2001, there were no significant differences in target lodgepole pine height, leader length, stem diameter, crown width, or HDR among the various aspen removal treatments. Two years later, target pine stem diameter was significantly larger in the complete aspen removal treatment (0 stems ha^{-1}) than in the untreated control (p=0.0410, Table 4), and there also was a significant difference in the 2001–2003 diameter increment (p<0.0001). The diameter increment in the complete aspen removal treatment was significantly larger than in any of the other treatments, and was nearly twice as large as in the untreated control (1.01 versus 0.52 cm). Diameter increment was also significantly larger (p=0.0484) in the 2500 stems ha^{-1} treatment than in the untreated control. The difference between the 1000 stems ha^{-1} treatment and the control was marginally non-significant (p=0.0547). As of 2003, there were no significant differences in height, 2001–2003 height increment, leader length, or crown width as a result of the aspen removal treatments, but HDR was significantly lower in the 0 stems ha^{-1} treatment than in the untreated control (p=0.0111, Table 4).

TABLE 4 *Mean[a] size of target lodgepole pine[b] in aspen removal treatments in 2001 and 2003, 11 and 13 years post-harvest*

	Aspen removal treatment					
Pine variable	**0 stems ha^{-1}**	**1000 stems ha^{-1}**	**2500 stems ha^{-1}**	**1-m radius**	**Control**	**p-value[c]**
Height (cm)						
2001	74 ± 7	68 ± 7	73 ± 6	73 ± 7	70 ± 7	0.9589
2003	103 ± 7	95 ± 7	103 ± 6	99 ± 7	99 ± 7	0.9235
2001–2003 height increment (cm)	29 ± 2	27 ± 2	30 ± 2	26 ± 2	29 ± 2	0.3697
Leader length (cm)						
2001	16 ± 1	16 ± 1	17 ± 1	16 ± 1	16 ± 1	0.8674
2003	16 ± 1	14 ± 1	15 ± 1	14 ± 1	15 ± 1	0.3590
Diameter (cm)						
2001	1.37 ± 0.09	1.27 ± 0.09	1.40 ± 0.09	1.34 ± 0.09	1.34 ± 0.09	0.8613
2003	2.37 ± 0.11 a	1.99 ± 0.11 ab	2.12 ± 0.11 ab	1.98 ± 0.11 ab	1.86 ± 0.11 b	**0.0410**
2001–2003 diameter increment (cm)	1.01 ± 0.04 a	0.72 ± 0.04 bc	0.72 ± 0.04 b	0.64 ± 0.04 bc	0.52 ± 0.04 c	**<0.0001**
HDR						
2001	55 ± 2	53 ± 2	52 ± 2	54 ± 2	52 ± 2	0.8852
2003	43 ± 2 a	47 ± 2 ab	49 ± 2 ab	50 ± 2 ab	53 ± 2 b	**0.0111**
Crown width (cm)						
2001	36 ± 3	35 ± 3	37 ± 3	38 ± 3	36 ± 3	0.9754
2003	52 ± 3	52 ± 3	53 ± 3	50 ± 3	47 ± 3	0.6615

a Presented as “mean ± 1 standard error,” where the standard error is based on the ANOVA model (i.e., variances are assumed to be homogeneous for all treatments and blocks).

b The data set includes all live target pine.

c Values in **bold** are significant at p≤0.05, according to ANOVA. Means with different letters are significantly different within the given year according to the Bonferroni test.

4.1.3 Neighbourhood tree responses

Neighbourhood trees were assessed in 2.56-m radius (20.6 m^2) subplots around live target pine to investigate competitive interactions between aspen and pine.

Tagged dominant aspen Tagged dominant aspen are the three aspen in each subplot that were tallest immediately following treatment. There were no significant between-treatment differences in height or ground-level diameter of these aspen in 2001 or 2003 ($p>0.05$, Table 5). However, by 2003, the 2001–2003 diameter increment was significantly larger in the 1000 stems ha^{-1} treatment than in the 1-m radius treatment or the control ($p=0.0011$). There were no differences in 2001–2003 height increment between aspen removal treatments.

TABLE 5 *Mean[a] tagged dominant aspen[b] size and growth increments[c] in aspen removal treatments[d] in 2001 and 2003, 11 and 13 years post-harvest*

	Aspen removal treatment				
Aspen variable	**1000 stems ha^{-1}**	**2500 stems ha^{-1}**	**1-m radius**	**Control**	**p-value[e]**
Height (cm)					
2001	285 ± 27	283 ± 27	288 ± 27	299 ± 27	0.9341
2003	330 ± 33	321 ± 32	315 ± 32	326 ± 32	0.9748
2001–2003 height increment (cm)	46 ± 7	37 ± 7	29 ± 7	26 ± 7	0.2346
Diameter (cm)					
2001	3.40 ± 0.28	3.46 ± 0.28	3.28 ± 0.28	3.60 ± 0.28	0.7616
2003	4.12 ± 0.32	4.06 ± 0.32	3.70 ± 0.32	4.01 ± 0.32	0.6518
2001–2003 diameter increment (cm)	0.72 ± 0.06 a	0.57 ± 0.05 ab	0.45 ± 0.05 b	0.41 ± 0.05 b	**0.0011**

[a] Presented as "mean ± 1 standard error," where the standard error is based on the ANOVA model (i.e., variances are assumed to be homogeneous for all treatments, blocks, and subplots).

[b] The data set includes the three tallest aspen stems in each subplot immediately following treatment in 2001. The same aspen stems were measured in 2003 regardless of whether they were still the tallest in the subplot.

[c] The difference between 2001 and 2003 height or diameter values may disagree with increment values because of mortality that occurred between the two assessments.

[d] No tagged dominant aspen were present in the 0 stems ha^{-1} treatment.

[e] Values in **bold** are significant at $p \leq 0.05$, according to ANOVA. Means with different letters are significantly different within the given year according to the Bonferroni test.

Tall aspen In 2001, just after aspen removal treatments were applied, the mean height of tall aspen (aspen as tall as or taller than the target pine within a 2.56-m radius of the target pine) differed significantly between treatments ($p=0.0033$). Means followed a trend of: 1000 stems ha^{-1}>2500 stems ha^{-1}>1-m radius>control, but the Bonferroni multiple comparison test only distinguished significant height differences between only the 1000 stems ha^{-1} treatment and the control. By 2003, although tall aspen height was significant in the ANOVA model ($p=0.0193$), the Bonferroni test did not distinguish significant differences between individual treatments (Table 6). In both 2001 and 2003, ground-level diameter of tall aspen was significantly larger in the 1000 and 2500 stems ha^{-1} treatments than in the 1-m removal treatment or the untreated control.

TABLE 6 *Mean[a] tall aspen[b] height and diameter in aspen removal treatments[c] in 2001 and 2003, 11 and 13 years post-harvest*

	Aspen removal treatment				
Aspen variable	**1000 stems ha^{-1}**	**2500 stems ha^{-1}**	**1-m radius**	**Control**	**p-value[d]**
Height (cm)					
2001	285 ± 21 a	248 ± 21 ab	181 ± 20 ab	177 ± 20 b	**0.0033**
2003	306 ± 23 a	278 ± 22 a	215 ± 22 a	215 ± 22 a	**0.0193**[e]
Diameter (cm)					
2001	3.40 ± 0.21 a	3.04 ± 0.20 a	2.08 ± 0.20 b	2.11 ± 0.20 b	**0.0006**
2003	3.82 ± 0.22 a	3.50 ± 0.21 a	2.52 ± 0.20 b	2.59 ± 0.20 b	**0.0010**

a Presented as "mean ± 1 standard error," where the standard error is based on the ANOVA model (i.e., variances are assumed to be homogeneous for all treatments, blocks, and subplots).

b The data set includes neighbourhood aspen that were at least as tall as the target pine.

c No tall aspen were present in the 0 stems ha^{-1} treatment.

d Values in **bold** are significant at $p \leq 0.05$, according to ANOVA. Means with different letters are significantly different within the given year according to the Bonferroni test.

e The Bonferroni test found no differences between treatments ($p > 0.05$), even though $p \leq 0.05$ for the treatment effect in ANOVA. Differences between the 1000 stems ha^{-1} treatment and the 1-m radius treatment or the untreated control were marginally non-significant ($p < 0.06$).

Average tall aspen densities achieved by the cutting treatments in 2001 were slightly lower than target values for the 1000 and 2500 stems ha^{-1} treatments (972 and 2347 stems ha^{-1}, respectively) (Table 7). The 1-m radius treatment reduced tall aspen density to 7475 stems ha^{-1} from the untreated control density of 9934 stems ha^{-1}. No tall aspen were retained in the 0 stems ha^{-1} treatment. Between 2001 and 2003, tall aspen densities decreased by 21 and 16% in the control and 1-m radius treatments, respectively, to 7806 and 6273 stems ha^{-1}. During the same period, tall aspen densities increased in the 1000 and 2500 stems ha^{-1} by 14 and 2%, respectively, to 1109 and 2397 stems ha^{-1}. In both 2001 and 2003, tall aspen densities were significantly higher in the control and 1-m radius treatments than in the 1000 and 2500 stems ha^{-1} treatments, and were also significantly higher in the 2500 than in the 1000 stems ha^{-1} treatment ($p < 0.0001$). The difference in tall aspen density between the 1-m radius treatment and the uncut control was not significant in either year.

In both 2001 and 2003, tall aspen basal area (based on ground-level diameter) was significantly larger in the control than in the 1000 and 2500 stems ha^{-1} treatments, and was also larger in the 1-m radius treatment than in the 1000 stems ha^{-1} treatment (Table 7). Between 2001 and 2003, tall aspen basal area increased by 52, 35, 20, and 14% in the 1000 stems ha^{-1}, 2500 stems ha^{-1}, 1-m removal, and control, respectively.

TABLE 7 *Means and 95% confidence limits[a] for tall aspen[b] density and basal area in aspen removal treatments[c] in 2001 and 2003, 11 and 13 years post-harvest*

	Aspen removal treatment				
Aspen variable	**1000 stems ha^{-1}**	**2500 stems ha^{-1}**	**1-m radius**	**Control**	**p-value[d]**
Density (stems ha^{-1})					
2001					
Mean	972 a	2 347 b	7 475 c	9 934 c	**<0.0001**
Lower confidence limit	*547*	*1 653*	*6 189*	*8 442*	
Upper confidence limit	*1 518*	*3 163*	*8 883*	*11 548*	
2003					
Mean	1 109 a	2 397 b	6 273 c	7 806 c	**<0.0001**
Lower confidence limit	*698*	*1 770*	*5 226*	*6 636*	
Upper confidence limit	*1 615*	*3 119*	*7 415*	*9 070*	
Basal area (m^2 ha^{-1})					
2001					
Mean	0.90 a	1.83 ab	2.95 bc	4.19 c	**0.0005**
Lower confidence limit	*0.36*	*1.01*	*1.88*	*2.89*	
Upper confidence limit	*1.67*	*2.89*	*4.26*	*5.72*	
2003					
Mean	1.37 a	2.47 ab	3.54 bc	4.76 c	**0.0020**
Lower confidence limit	*0.65*	*1.46*	*2.31*	*3.31*	
Upper confidence limit	*2.35*	*3.74*	*5.03*	*6.47*	

a To facilitate interpretation, means and 95% confidence limits were back-transformed (by squaring) to the original scale of measurement following the analysis of square root–transformed data.

b The data set includes neighbourhood aspen that were at least as tall as the target pine.

c No tall aspen were present in the 0 stems ha^{-1} treatment.

d Values in **bold** are significant at $p \leq 0.05$, according to ANOVA. Means with different letters are significantly different within the given year according to the Bonferroni test. Both ANOVA and Bonferroni tests were conducted on square root–transformed data.

4.1.4 Neighbourhood lodgepole pine Neighbourhood pine were, on average, almost the same height as target pine (Figure 5). They also had similar stem diameter (Figure 6), although variances tended to be smaller among the target pine because of the selection criteria that had been applied at the start of the study. There were no significant differences among treatments in neighbourhood lodgepole pine height or stem diameter in 2001 or 2003 ($p>0.05$, Table 8).

There were no significant differences between treatments for density or basal area of neighbourhood lodgepole pine in either 2001 or 2003 (Table 9). In 2001, there was an average of 2277 neighbourhood lodgepole pine stems ha^{-1} within a 2.56-m radius of target lodgepole pine across all treatments, with an average basal area of 0.49 m^2 ha^{-1}. By 2003, the overall average neighbourhood pine density had decreased very slightly (0.3%) to 2270 stems ha^{-1} and average basal area had increased to 1.00 m^2 ha^{-1}. Pine density was slightly lower at the neighbourhood than the stand level because target pine were not included in the neighbourhood data set.

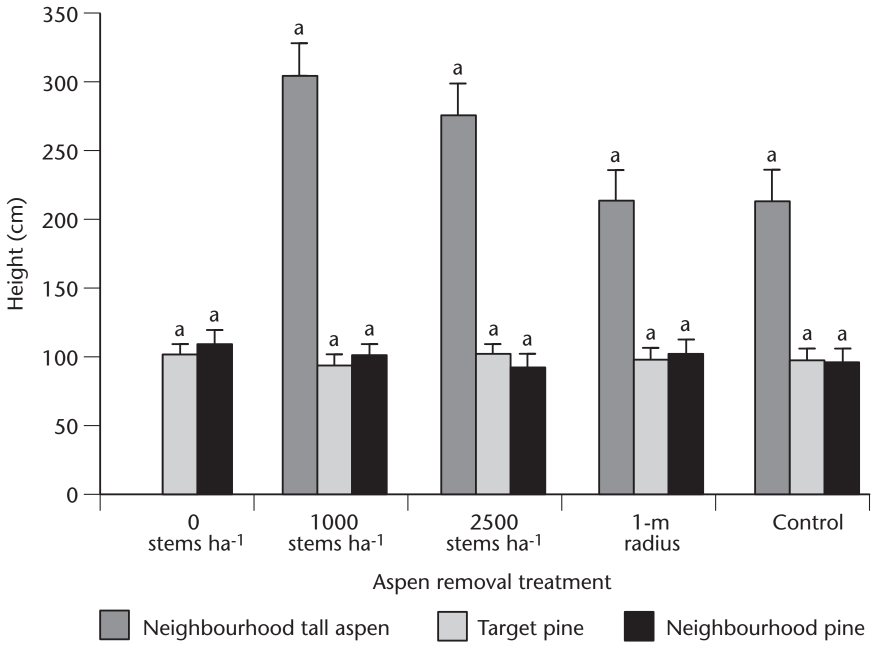


FIGURE 5 *Comparison of mean height of neighbourhood tall aspen, target lodgepole pine, and neighbourhood pine between aspen removal treatments 13 years post-harvest (2003). Error bars represent one standard error. Means with the same letter within a single category (the same shading within bars) are not significantly different according to the Bonferroni test (p>0.05). There were no tall aspen in the 0 stems ha^{-1} treatment.*

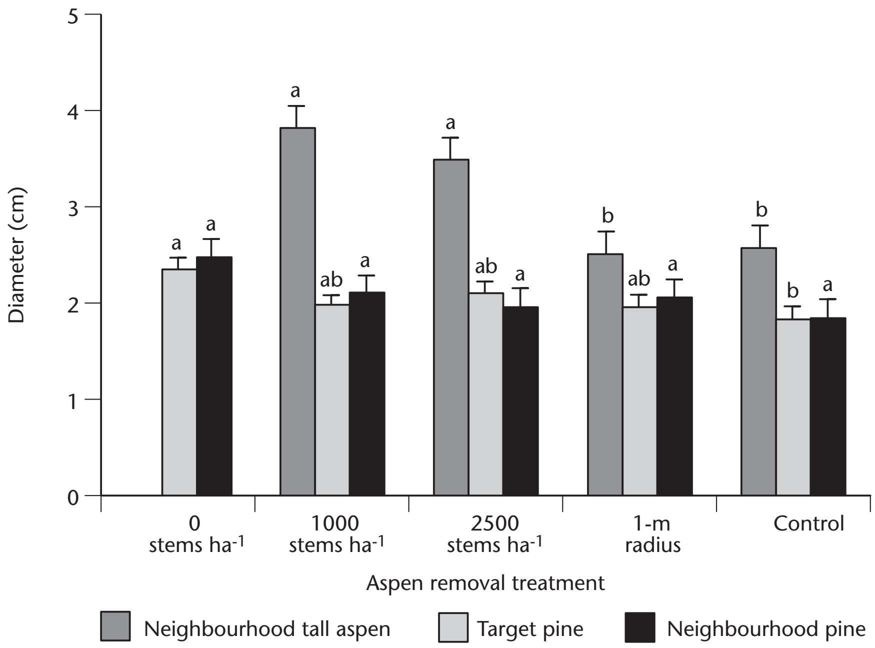


FIGURE 6 *Comparison of mean ground-level diameter of neighbourhood tall aspen, target lodgepole pine, and neighbourhood pine between aspen removal treatments 13 years post-harvest (2003). Error bars represent one standard error. Means with the same letter within a single category (the same shading within bars) are not significantly different according to the Bonferroni test (p>0.05). There were no tall aspen in the 0 stems ha^{-1} treatment.*

TABLE 8 *Mean[a] neighbourhood lodgepole pine[b] height and diameter in aspen removal treatments in 2001 and 2003, 11 and 13 years post-harvest*

	Aspen removal treatment					
Pine variable	**0 stems ha^{-1}**	**1000 stems ha^{-1}**	**2500 stems ha^{-1}**	**1-m radius**	**Control**	**p-value[c]**
Height (cm)						
2001	82 ± 8	76 ± 8	66 ± 8	78 ± 8	71 ± 7	0.3488
2003	110 ± 9	101 ± 9	93 ± 9	103 ± 9	98 ± 9	0.4151
Diameter (cm)						
2001	1.55 ± 0.15	1.46 ± 0.15	1.37 ± 0.15	1.54 ± 0.15	1.40 ± 0.15	0.8017
2003	2.48 ± 0.18	2.12 ± 0.18	1.97 ± 0.18	2.07 ± 0.18	1.86 ± 0.17	0.1023

a Presented as "mean ± 1 standard error," where the standard error is based on the ANOVA model (i.e., variances are assumed to be homogeneous for all treatments, blocks, and subplots).

b The data set includes only neighbourhood lodgepole pine (target pine were excluded).

c Values are significant at $p \leq 0.05$, according to ANOVA.

TABLE 9 *Means and 95% confidence limits[a] for neighbourhood lodgepole pine[b] density and basal area in aspen removal treatments in 2001 and 2003, 11 and 13 years post-harvest*

	Aspen removal treatment					
Pine variable	**0 stems ha^{-1}**	**1000 stems ha^{-1}**	**2500 stems ha^{-1}**	**1-m radius**	**Control**	**p-value[c]**
Density (stems ha^{-1})						
2001						
Mean	2177	2442	1907	2172	2688	0.4118
Lower confidence limit	*1505*	*1727*	*1282*	*1501*	*1935*	
Upper confidence limit	*2973*	*3281*	*2656*	*2967*	*3566*	
2003						
Mean	2170	2443	1902	2169	2667	0.4106
Lower confidence limit	*1507*	*1737*	*1286*	*1507*	*1926*	
Upper confidence limit	*2952*	*3270*	*2638*	*2951*	*3528*	
Basal area (m^2 ha^{-1})						
2001						
Mean	0.52	0.52	0.36	0.52	0.53	0.7019
Lower confidence limit	*0.26*	*0.26*	*0.14*	*0.25*	*0.26*	
Upper confidence limit	*0.88*	*0.88*	*0.66*	*0.88*	*0.89*	
2003						
Mean	1.31	1.09	0.72	0.94	0.92	0.3541
Lower confidence limit	*0.74*	*0.58*	*0.32*	*0.47*	*0.45*	
Upper confidence limit	*2.04*	*1.77*	*1.29*	*1.58*	*1.55*	

a To facilitate interpretation, means and 95% confidence limits were back-transformed (by squaring) to the original scale of measurement following the analysis of square root–transformed data.

b The data set includes only neighbourhood lodgepole pine (target pine were excluded).

c Values are significant at $p \leq 0.05$, according to ANOVA. ANOVA tests were conducted on square root–transformed data.

4.1.5 Aspen abundance as a predictor of lodgepole pine growth Relationships predicting lodgepole pine size from aspen abundance were consistently statistically significant only in the case of pine stem diameter and tall aspen density or basal area, and only in 2003 (Table 10). Models predicting 2001 pine size from 2001 tall aspen abundance were not significant or, in one case, had a negative R^2 value, indicating that the exponential model produced a poor fit for that particular pairing of variables. The lack of significant relationships in 2001 was expected because pine had not had sufficient time to respond to the altered growing environments created by the treatments. Cutting was done 1 month before the 2001 assessment. Prior to this, pine in all plots had been growing under similar conditions of aspen abundance. The predictive ability of both tall aspen density and basal area improved between 2001 and 2003, but the relationships remained relatively weak. The strongest relationship was between 2001–2003 pine stem diameter increment and 2003 tall aspen density, where tall aspen density was able to explain 21.2% of the variation in diameter increment ($R^2=0.212$) (Figure 7). In comparison, 2003 tall aspen basal area explained 10.7% of the variation in 2001–2003 diameter increment. Models using 2003 tall aspen density or basal area to predict other 2003 pine growth attributes were generally statistically non-significant and had very low R^2 values.

TABLE 10 *Regression equation parameters[a] and R^2 values for predicting target lodgepole pine growth from: a) tall aspen density and b) tall aspen basal area[b]*

Lodgepole pine growth response variable	n	a	b	R^2	RMSE[c]	p-value[d]
a) Tall aspen density						
Stem diameter 2001	320	1.500 ± 0.110	-0.0350 ± 0.0109	-0.064	0.535	**0.0056**
Stem diameter 2003	319	2.470 ± 0.142	-0.0550 ± 0.0127	0.055	0.740	**0.0008**
Stem diameter increment 2001–2003	319	0.900 ± 0.0552	-0.0730 ± 0.0167	0.212	0.307	**0.0007**
Height 2001	320	0.7370 ± 0.0309	-0.0070 ± 0.0049	0.005	0.303	0.1552
Height 2003	319	1.047 ± 0.0432	-0.0140 ± 0.0066	0.009	0.380	0.1208
Leader length 2001	320	0.1660 ± 0.0048	-0.0050 ± 0.0046	0.004	0.065	0.2463
Leader length 2003	319	0.1550 ± 0.0088	-0.0180 ± 0.0081	0.011	0.058	0.0573
b)Tall aspen basal area						
Stem diameter 2001	320	1.300 ± 0.040	0.0003 ± 0.0095	0.000	0.519	0.9749
Stem diameter 2003	319	2.190 ± 0.079	-0.0240 ± 0.0101	0.034	0.750	**0.0288**
Stem diameter increment 2001–2003	319	0.7890 ± 0.0656	-0.0370 ± 0.0158	0.107	0.327	**0.0219**
Height 2001	320	0.672 ± 0.030	0.0283 ± 0.0105	0.012	0.302	**0.0128**
Height 2003	319	0.9670 ± 0.0328	0.0113 ± 0.0079	0.008	0.381	0.1530
Leader length 2001	320	0.1570 ± 0.0053	0.0151 ± 0.0097	0.005	0.065	0.1448
Leader length 2003	319	0.1480 ± 0.0079	-0.0050 ± 0.0093	0.001	0.059	0.6292

a General form of the regression model for all variables is: $y = ae^{bx} + \gamma_{\text{block}} + \delta_{\text{treatment plot (block)}} + \varepsilon$, where y is one of the pine growth variables, x is tall aspen density or basal area, and $\gamma_{\text{block}} + \delta_{\text{treatment plot (block)}}$, and ε are random errors associated with blocks, treatment plots within blocks, and the residual error, respectively.

b Regression analysis included tall aspen within a 2.56-m radius around target lodgepole pine. Tall aspen abundance in 2001 was used to predict pine stem diameter, height, and leader length in 2001. All other pine variables were predicted using tall aspen abundance in 2003.

c Root mean square error.

d Values are in **bold** if the coefficient b is significant at $p \leq 0.05$.

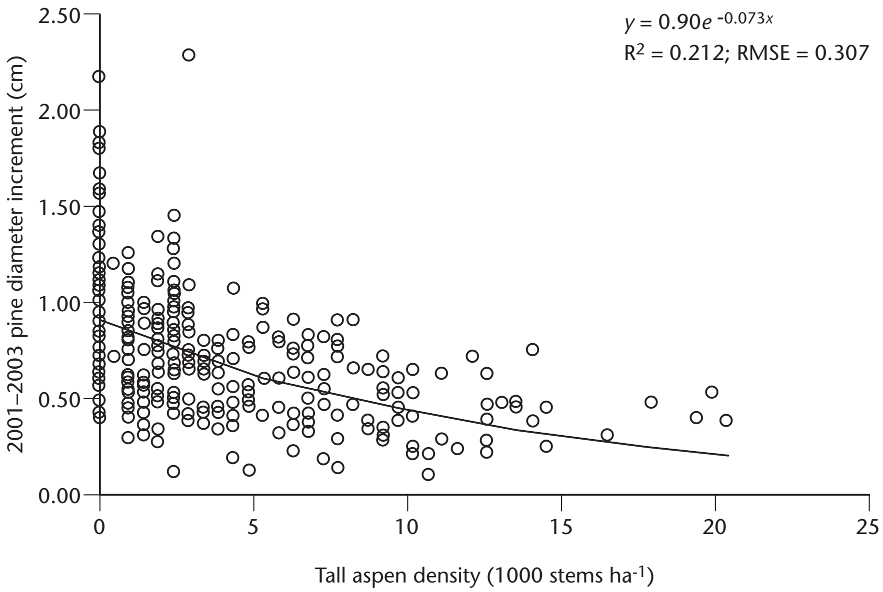


FIGURE 7 *Scatter plot with fitted non-linear regression line showing the relationship between 2001–2003 lodgepole pine stem diameter increment and 2003 tall aspen density within a 2.56-m radius plot around target pine.*

4.1.6 Size of the competitive neighbourhood Relationships between lodgepole pine size and tall aspen density or basal area within 0.5- or 1.0-m radius neighbourhoods around the target pine were not statistically significant, regardless of the pine growth attribute considered ($p>0.05$, Table 11). When the regression model included tall aspen within 1.8- or 2.56-m radii, the relationship between tall aspen density and pine stem diameter was significant. Relationships between tall aspen basal area and pine size were statistically significant only in the 2.56-m radius neighbourhoods, for 2003 stem diameter, 2001–2003 diameter increment, and 2001 height.

In 2003, when the naturally regenerated stand at Clusko was approximately 13 years old, coefficients of determination (R^2) tended to be maximized (and RMSE values were minimized) for those models where tall aspen within 2.56 m of target pine were used to predict lodgepole pine diameter increment. However, relationships were still very weak at that age: the strongest relationship was between tall aspen density and 2001–2003 pine stem diameter increment. Figure 8 illustrates that R^2 values increased with plot size and compares tall aspen density and basal area as predictors of 2-year pine diameter increment.

TABLE 11 *A comparison of the ability of (a) tall aspen density and (b) tall aspen basal area, within 0.5-, 1.0-, 1.8-, and 2.56-m radius neighbourhoods, to predict target pine size using an exponential model*[a,b,c]

		0.5 m			**1.0 m**			**1.8 m**			**2.56 m**		
	n	**R^2**	**RMSE**	**p-value**	**R^2**	**RMSE**	**p-value**	**R^2**	**RMSE**	**p-value**	**R^2**	**RMSE**	**p-value**
a) Tall aspen density													
Stem diameter 2001	320	0.002	0.518	0.4685	*0.004*	*0.517*	0.2547	-0.001	0.522	**0.0024**	-0.006	0.535	**0.0056**
Stem diameter 2003	319	0.010	0.760	0.3140	0.028	0.750	0.0506	*0.088*	*0.730*	**0.0004**	0.055	0.740	**0.0008**
Diameter increment 2001–2003	319	0.015	0.343	0.4147	0.039	0.339	0.1820	0.159	0.317	**0.0016**	*0.212*	*0.307*	**0.0007**
Height 2001	320	0.000	0.304	0.8536	0.001	0.304	0.5089	0.008	0.303	0.0842	0.005	0.303	0.1552
Height 2003	319	0.001	0.382	0.7156	0.000	0.382	0.7937	*0.011*	*0.380*	0.0874	0.009	0.380	0.1208
Leader length 2001	320	0.002	0.065	0.4531	0.000	0.065	0.8840	*0.004*	*0.065*	0.2640	*0.004*	*0.065*	0.2463
Leader length 2003	319	0.000	0.059	0.5696	0.001	0.059	0.4898	0.010	0.058	0.0827	*0.011*	*0.058*	0.0573
b) Tall aspen basal area													
Stem diameter 2001	320	0.000	0.519	0.9851	0.000	0.519	0.7405	*0.001*	*0.518*	0.6600	0.000	0.519	0.9749
Stem diameter 2003	319	0.005	0.760	0.5467	0.013	0.760	0.2188	0.029	0.750	0.0515	*0.034*	*0.750*	**0.0288**
Diameter increment 2001–2003	319	0.004	0.345	0.7009	0.016	0.343	0.4360	0.054	0.336	0.1332	*0.107*	*0.327*	**0.0219**
Height 2001	320	0.002	0.304	0.5727	0.000	0.304	0.8227	0.006	0.303	0.2242	*0.012*	*0.302*	**0.0128**
Height 2003	319	0.002	0.382	0.5115	0.002	0.382	0.5897	0.004	0.381	0.3762	*0.008*	*0.381*	0.1530
Leader length 2001	320	*0.005*	*0.065*	0.1888	0.001	0.065	0.6864	0.004	0.065	0.2237	*0.005*	*0.065*	0.1448
Leader length 2003	319	0.002	0.059	0.1956	*0.003*	*0.059*	0.1458	0.001	0.059	0.5900	0.001	0.059	0.6292

[a] General form of the regression model for all variables is: $y = ae^{bx} + \gamma_{\text{block}} + \delta_{\text{treatment plot (block)}} + \varepsilon$, where y is one of the pine growth variables, x is tall aspen density or basal area, and $\gamma_{\text{block}} + \delta_{\text{treatment plot (block)}}$, and ε are random errors associated with blocks, treatment plots within blocks, and the residual error, respectively.

[b] Tall aspen abundance in 2001 was used to predict pine stem diameter, height, and leader length in 2001. All other pine variables were predicted using tall aspen abundance in 2003.

[c] The highest R^2 and the lowest RMSE values for each pine variable are in *italics*, and significant p-values ($p \leq 0.05$) for each variable are in **bold**.

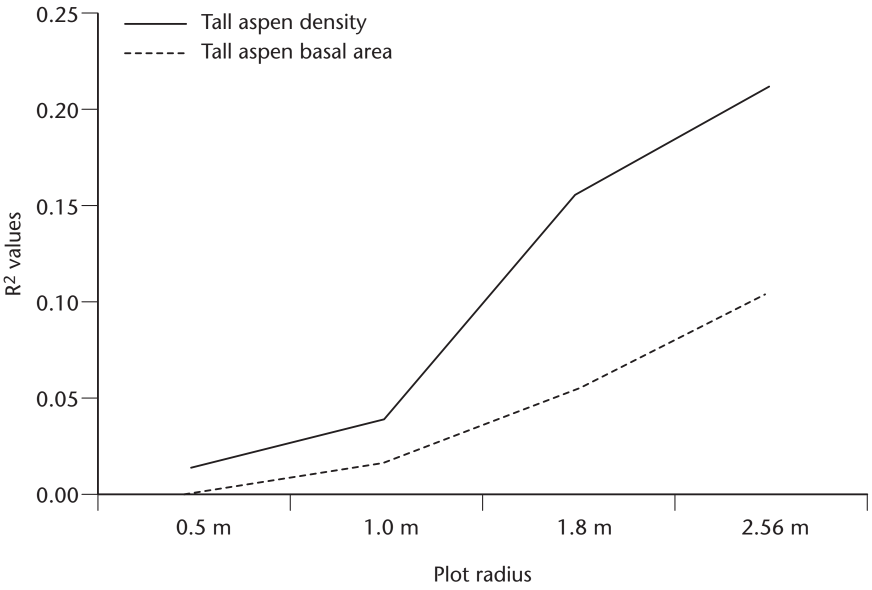


FIGURE 8 *A comparison of the R^2 values for the fitted regression models relating 2001–2003 pine stem diameter increment to 2003 tall aspen density or basal area in different-sized neighbourhoods. The R^2 value represents the proportion of the variation in the pine diameter increment that is explained by either tall aspen density or basal area.*

4.2 Stand-level Treatment Responses

Treatment effects on stand structure were assessed by considering all live aspen ≥30 cm tall (excluding new suckers or sprouts) and all live pine stems in the 2.56-m subplots.

4.2.1 Stand-level aspen

Height and diameter In the process of reducing aspen densities to the target treatment values in the 1000 and 2500 stems ha^{-1} treatments, crews removed short aspen and retained the tallest, most vigorous stems. Consequently, mean aspen height immediately became significantly larger in these treatments than in the control ($p=0.0002$, Table 12). This effect was somewhat diluted by 2003 because of the large number of short aspen stems that were released by the treatments. These stems, which had been shorter than the minimum measured height of 30 cm in 2001, had grown taller than 30 cm by 2003. Aspen stem diameter followed a similar trend, with stems in the 1000 and 2500 stems ha^{-1} treatments being significantly larger than those in the 1-m radius treatment and the control in both 2001 and 2003. Diameter distributions were created to examine stand development (Figure 9). Aspen in the cutting treatments moved into larger diameter classes more rapidly (by proportion, not absolute numbers) than aspen in the uncut control. In both 2001 and 2003, trends in differences between treatments were similar for mean diameter and quadratic mean diameter, except that quadratic mean diameter was larger in magnitude because the index gives greater weight to larger stems.

TABLE 12 *Mean[a] stand-level aspen[b] height, stem diameter, and quadratic mean diameter in aspen removal treatments in 2001 and 2003, 11 and 13 years post-harvest*

	Aspen removal treatment					
Aspen variable	**0 stems ha^{-1}**	**1000 stems ha^{-1}**	**2500 stems ha^{-1}**	**1-m radius**	**Control**	**p-value[c]**
Height (cm)						
2001	n/a	285 ± 18a	248 ± 17 a	147 ± 17 b	140 ± 17 b	**0.0002**
2003	63 ± 18 a	216 ± 16 bc	242 ± 16 b	170 ± 15 c	164 ± 15 c	<**0.0001**
Diameter (cm)						
2001	n/a	3.40 ± 0.19 a	3.04 ± 0.18 a	1.74 ± 0.17 b	1.72 ± 0.17 b	<**0.0001**
2003	0.95 ± 0.18 a	2.71 ± 0.16 b	3.06 ± 0.15 b	2.05 ± 0.14 c	2.03 ± 0.14 c	<**0.0001**
Quadratic mean diameter (cm)						
2001	n/a	3.43 ± 0.20 a	3.15 ± 0.20 a	1.99 ± 0.20 b	2.02 ± 0.20 b	**0.0002**
2003	0.96 ± 0.19 a	3.34 ± 0.18 b	3.38 ± 0.18 b	2.33 ± 0.18 c	2.35 ± 0.18 c	<**0.0001**

a Presented as "mean ± 1 standard error," where the standard error is based on the ANOVA model (i.e., variances are assumed to be homogeneous for all treatments and blocks).

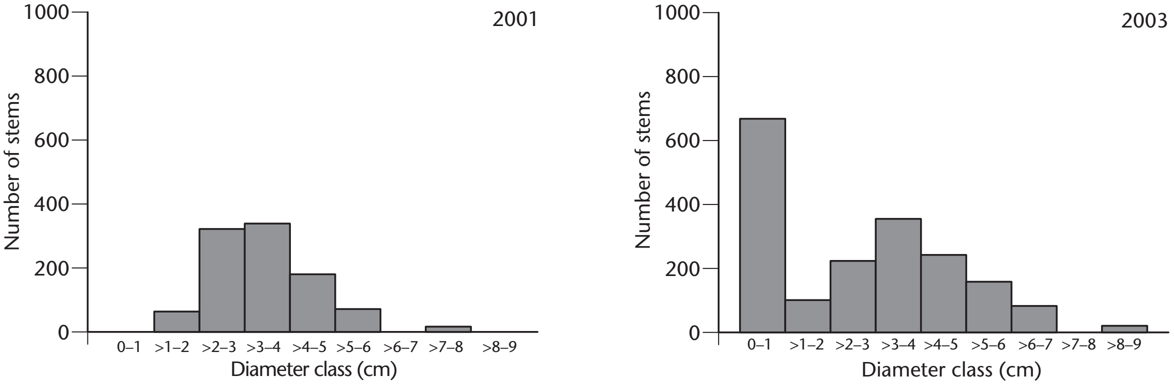
b The data set includes all aspen taller than 30 cm that were present prior to cutting, and excludes new suckers.

c Values in **bold** are significant at $p \leq 0.05$, according to ANOVA. Means with different letters are significantly different within the given year according to the Bonferroni test.

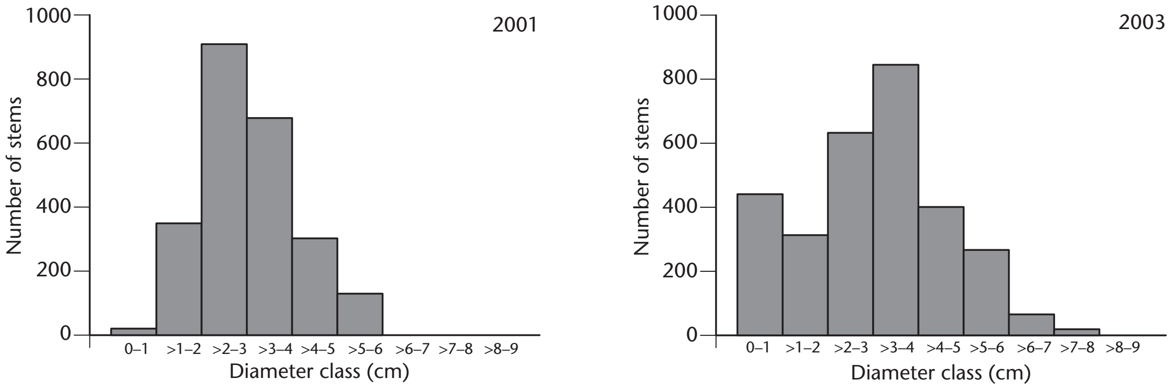
Density Aspen removal treatments applied in 2001 reduced total aspen density to 972, 2364, and 10 120 stems ha^{-1} in the 1000 stems ha^{-1}, the 2500 stems ha^{-1}, and the 1-m radius treatments, respectively (Table 13). The average aspen density in the control, which represents uncut pre-treatment conditions, was 14 185 stems ha^{-1}. Between 2001 and 2003, total aspen density in the control decreased by 1864 stems ha^{-1} as a result of self-thinning, a rate of 6.6% per year. During the same period, total aspen density in the 1-m radius treatment decreased by 5.3% per year. In contrast, between 2001 and 2003, total aspen density increased in the 2500, 1000, and 0 stems ha^{-1} treatments because many stems that had been shorter than 30 cm in 2001 were released by the treatments, and grew tall enough to be included in the 2003 data set. These numbers do not include new suckers and sprouts. Between 2001 and 2003, total aspen density in the 2500 and 1000 stems ha^{-1} treatments increased by 534 (11.3% per year) and 741 stems ha^{-1} (38.1% per year), respectively. In the 0 stems ha^{-1} treatment, all aspen were cut below 30 cm in 2001, but by 2003, 537 stems ha^{-1} had grown to at least 30 cm tall.

Basal area In 2001, the cutting treatment significantly reduced aspen basal area from the untreated control level of 4.44 m^2 ha^{-1} to 0.90 m^2 ha^{-1} in the 1000 stems ha^{-1} treatment and to 1.83 m^2 ha^{-1} in the 2500 stems ha^{-1} treatment (Table 13). The 1-m radius treatment did not significantly reduce 2001 aspen basal area from that of the control. Similar between-treatment differences were found in 2003. Between 2001 and 2003, aspen basal area increased by 18% in the control compared with increases of 23%, 38%, and 56% in the 1-m radius, 2500 stems ha^{-1}, and 1000 stems ha^{-1} treatments, respectively.

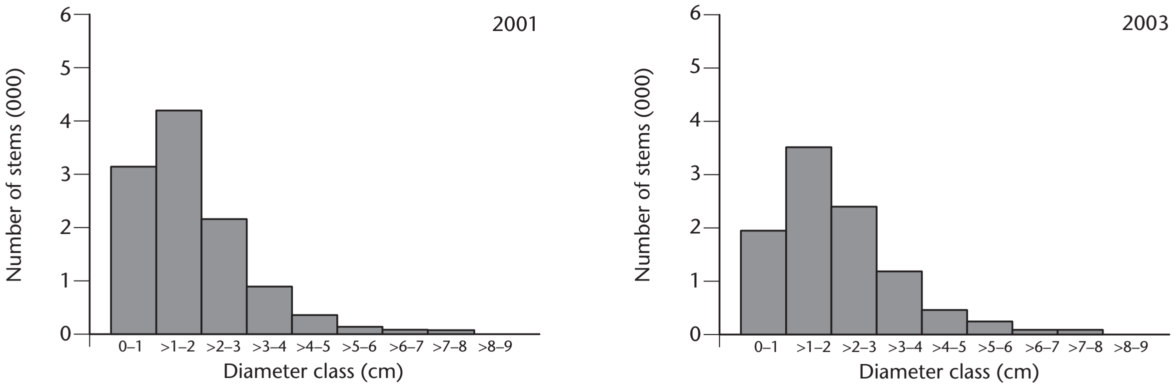
a) 1000 aspen stems ha^{-1} treatment



b) 2500 aspen stems ha^{-1} treatment



c) 1-m radius aspen removal treatment



d) Control

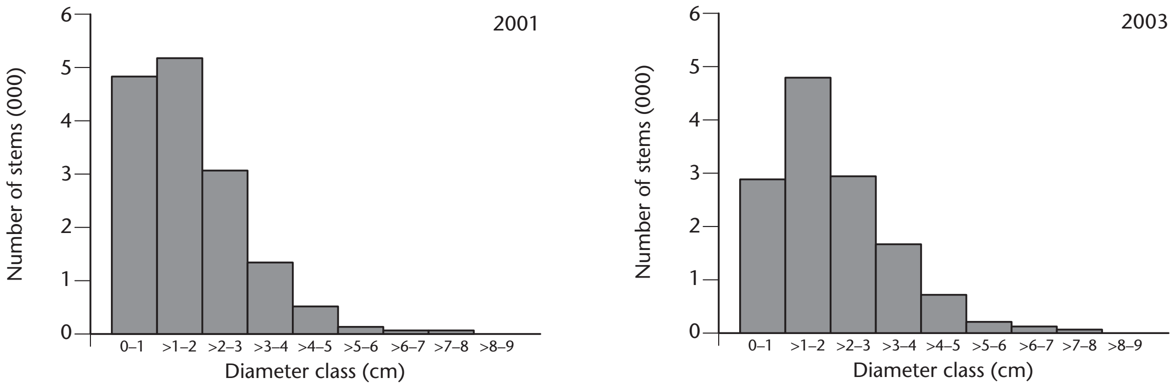


FIGURE 9 *Aspen diameter distributions in aspen removal treatments in 2001 and 2003, 11 and 13 years post-harvest. Note that y-axes have different scales.*

TABLE 13 *Means and confidence limits[a] for stand-level aspen[b] density and basal area in aspen removal treatments in 2001 and 2003, 11 and 13 years post-harvest*

	Aspen removal treatment					
Aspen variable	**0 stems ha^{-1}**	**1000 stems ha^{-1}**	**2500 stems ha^{-1}**	**1-m radius**	**Control**	**p-value[c]**
Density (stems ha^{-1})						
2001						
Mean	n/a[d]	972 a	2 364 a	10 120 b	14 185 b	**<0.0001**
Lower confidence limit		*411*	*1 424*	*8 049*	*11 710*	
Upper confidence limit	*1 769*	*3 541*	*12 429*	*16 896*		
2003						
Mean	537 a	1 713 ab	2 898 b	9 050 c	12 321 c	**<0.0001**
Lower confidence limit	*197*	*1 041*	*1 998*	*7 393*	*10 378*	
Upper confidence limit	*1 044*	*2 552*	*3 964*	*10 874*	*14 431*	
Basal area (m^2 ha^{-1})						
2001						
Mean	n/a	0.90 a	1.83 ab	3.11 bc	4.44 c	**0.0005**
Lower confidence limit		*0.34*	*0.98*	*1.96*	*3.03*	
Upper confidence limit		*1.72*	*2.95*	*4.52*	*6.10*	
2003						
Mean	0.04 a	1.40 b	2.52 bc	3.81 cd	5.24 d	**<0.0001**
Lower confidence limit	*0.02*	*0.72*	*1.57*	*2.62*	*3.82*	
Upper confidence limit	*0.28*	*2.30*	*3.69*	*5.23*	*6.88*	

[a] To facilitate interpretation, means and 95% confidence limits were back-transformed (by squaring) to the original scale of measurement following the analysis of square root–transformed data.

[b] The data set includes all aspen taller than 30 cm that were present prior to cutting, and excludes new suckers.

[c] Values in **bold** are significant at $p \leq 0.05$, according to ANOVA. Means with different letters are significantly different within the given year according to the Bonferroni test. Both ANOVA and Bonferroni tests were conducted on square root–transformed data.

[d] No aspen taller than 30 cm were present in the 0 stems ha^{-1} treatment in 2001.

Suckering In 2003, 2 years after cutting treatments were applied, there were significant differences in sucker numbers between nearly all the treatments ($p<0.0001$, Table 14). Sucker densities decreased significantly between treatments in this order: 0 stems ha^{-1}>1000 stems ha^{-1}>2500 stems ha^{-1}=1-m radius treatment>untreated control. The only statistically similar treatments were the 2500 stems ha^{-1} and the 1-m radius. In 2003, there were 93 086 aspen suckers ha^{-1} in the 0 stems ha^{-1} treatment compared with 44 184 in the 1000 stems ha^{-1} treatment and 22 410 in the 2500 stems ha^{-1} treatment (Figure 10). It was subjectively observed that suckers were not evenly distributed across the site, but dense clumps tended to occur in close proximity to cut stumps (Figure 11). Two years after cutting, sucker height also differed significantly between aspen removal treatments ($p=0.0032$, Table 15). Suckers in the 0 stems ha^{-1} treatment were significantly taller than those in the uncut control, but no other treatments differed significantly in height.

TABLE 14 *Means and 95% confidence limits[a] for sucker density in aspen removal treatments 2 years post-treatment (2003)*

	Aspen removal treatment					
Aspen variable	**0 stems ha^{-1}**	**1000 stems ha^{-1}**	**2500 stems ha^{-1}**	**1-m radius**	**Control**	**p-value[b]**
Mean	93 086 a	44 184 b	22 410 bc	14 019 c	1 406 d	<**0.0001**
Lower confidence limit	*73 688*	*31 172*	*13 469*	*7 176*	*15*	
Upper confidence limit	*114 747*	*59 460*	*33 615*	*23 131*	*5 061*	

a To facilitate interpretation, means and 95% confidence limits were back-transformed (by squaring) to the original scale of measurement following the analysis of square root–transformed data.

b Values in **bold** are significant at p≤0.05, according to ANOVA. Means with different letters are significantly different within the given year according to the Bonferroni test. Both ANOVA and Bonferroni tests were conducted on square root–transformed data.

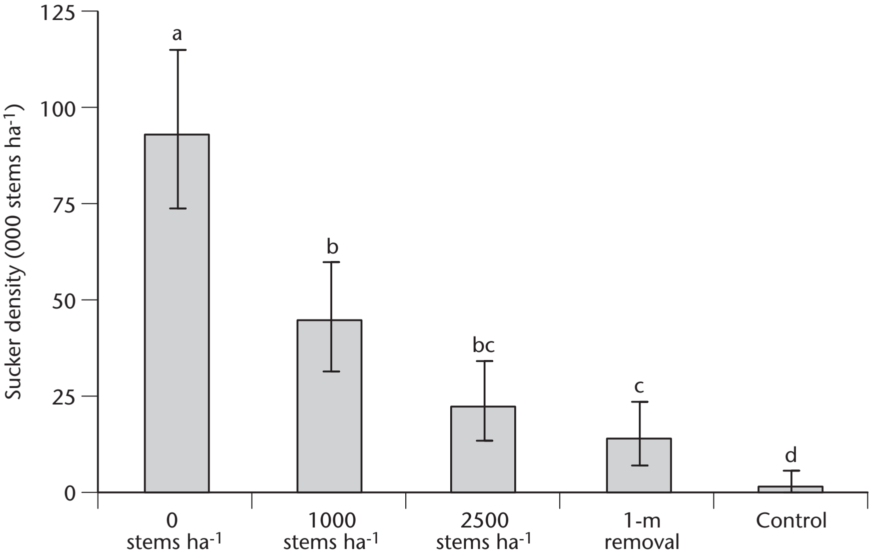


FIGURE 10 *Aspen sucker densities in 2003, 2 years after the aspen removal treatments were applied. Error bars represent approximate 95% confidence limits. Means with different letters are significantly different, according to the Bonferroni test applied to square root–transformed data (p>0.05).*

FIGURE 11 *Typical aspen sucker density, height, and clumpy distribution in the 1000 stems ha^{-1} treatment in 2003, 2 years after aspen removal treatments were applied.*

TABLE 15 *Mean[a] height of aspen suckers in aspen removal treatments 2 years post-treatment (2003)*

	Aspen removal treatment					
Aspen variable	**0 stems ha^{-1}**	**1000 stems ha^{-1}**	**2500 stems ha^{-1}**	**1-m radius**	**Control**	**p-value[b]**
Average sucker height (cm)	30 ± 2 a	25 ± 2 ab	25 ± 2 ab	23 ± 2 ab	17 ± 2 b	**0.0032**

a Presented as "mean ± 1 standard error," where the standard error is based on the ANOVA model (i.e., variances are assumed to be homogeneous for all treatments and blocks).

b Values in **bold** are significant at p≤0.05, according to ANOVA. Means with different letters are significantly different within the given year according to the Bonferroni test.

4.2.2 Stand-level lodgepole pine There were no significant between-treatment differences in stand-level lodgepole pine height or stem diameter in 2001 or 2003 (p>0.05, Table 16). In 2001, pine averaged 74 cm tall for all treatments and had average ground-level stem diameter of 1.44 cm. By 2003, pine averaged 101 cm tall with 2.09 cm stem diameter.

There were no significant differences in the stand-level density of lodgepole pine among aspen removal treatments in either 2001 or 2003 (Table 17). Average pine densities across treatments were 2842 stems ha^{-1} in 2001 and 2835 stems ha^{-1} in 2003. Average pine basal area increased from 0.58 to 1.22 m^{2} ha^{-1} between 2001 and 2003. In 2001, aspen basal area in the uncut control was 7.2 times greater than pine basal area. In comparison, aspen basal area was 5.1, 4.0, and 1.5 times that of pine in the 1-m radius, 2500, and 1000 stems ha^{-1} treatments, respectively. Between 2001 and 2003, the basal area of pine tended to increase slightly relative to aspen, so that aspen basal area was 4.8, 3.3, 2.6, and 1.1 times greater than pine basal area in the uncut control, 1-m radius, 2500, and 4000 stems ha^{-1} treatments, respectively (Figure 12).

TABLE 16 *Mean[a] stand-level lodgepole pine[b] height and stem diameter in aspen removal treatments in 2001 and 2003, 11 and 13 years post-harvest*

	Aspen removal treatment					
Pine variable	**0 stems ha^{-1}**	**1000 stems ha^{-1}**	**2500 stems ha^{-1}**	**1-m radius**	**Control**	**p-value[c]**
Height (cm)						
2001	81 ± 7	74 ± 7	68 ± 7	77 ± 7	71 ± 7	0.4752
2003	109 ± 8	100 ± 8	95 ± 8	102 ± 8	98 ± 8	0.5132
Diameter (cm)						
2001	1.51 ± 0.13	1.42 ± 0.13	1.38 ± 0.13	1.50 ± 0.13	1.39 ± 0.13	0.8589
2003	2.46 ± 0.15	2.08 ± 0.15	2.00 ± 0.15	2.04 ± 0.15	1.86 ± 0.15	0.0584

a Presented as "mean ± 1 standard error," where the standard error is based on the ANOVA model (i.e., variances are assumed to be homogeneous for all treatments and blocks).

b The data set includes both target and neighbourhood lodgepole pine.

c Values are significant at p≤0.05, according to ANOVA.

TABLE 17 *Means and 95% confidence limits[a] for stand-level lodgepole pine[b] density and basal area in aspen removal treatments in 2001 and 2003, 11 and 13 years post-harvest*

	Aspen removal treatment					
Pine variable	**0 stems ha^{-1}**	**1000 stems ha^{-1}**	**2500 stems ha^{-1}**	**1-m radius**	**Control**	**p-value[c]**
Density (stems ha^{-1})						
2001						
Mean	2711	3031	2479	2730	3260	0.4002
Lower confidence limit	*2021*	*2298*	*1821*	*2037*	*2499*	
Upper confidence limit	*3503*	*3864*	*3238*	*3524*	*4123*	
2003						
Mean	2704	3031	2474	2726	3238	0.3982
Lower confidence limit	*2024*	*2308*	*1826*	*2043*	*2489*	
Upper confidence limit	*3482*	*3851*	*3221*	*3507*	*4084*	
Basal area (m^2 ha^{-1})						
2001						
Mean	0.62	0.61	0.46	0.61	0.62	0.8147
Lower confidence limit	*0.34*	*0.33*	*0.23*	*0.34*	*0.34*	
Upper confidence limit	*0.99*	*0.97*	*0.78*	*0.98*	*0.99*	
2003						
Mean	1.60	1.30	0.97	1.14	1.09	0.3234
Lower confidence limit	*1.00*	*0.76*	*0.52*	*0.65*	*0.61*	
Upper confidence limit	*2.33*	*1.96*	*1.55*	*1.78*	*1.71*	

a To facilitate interpretation, means and 95% confidence limits were back-transformed (by squaring) to the original scale of measurement following the analysis of square root–transformed data.

b The data set includes both target and neighbourhood lodgepole pine.

c Values are significant at p≤0.05, according to ANOVA. ANOVA tests were conducted on square root–transformed data.

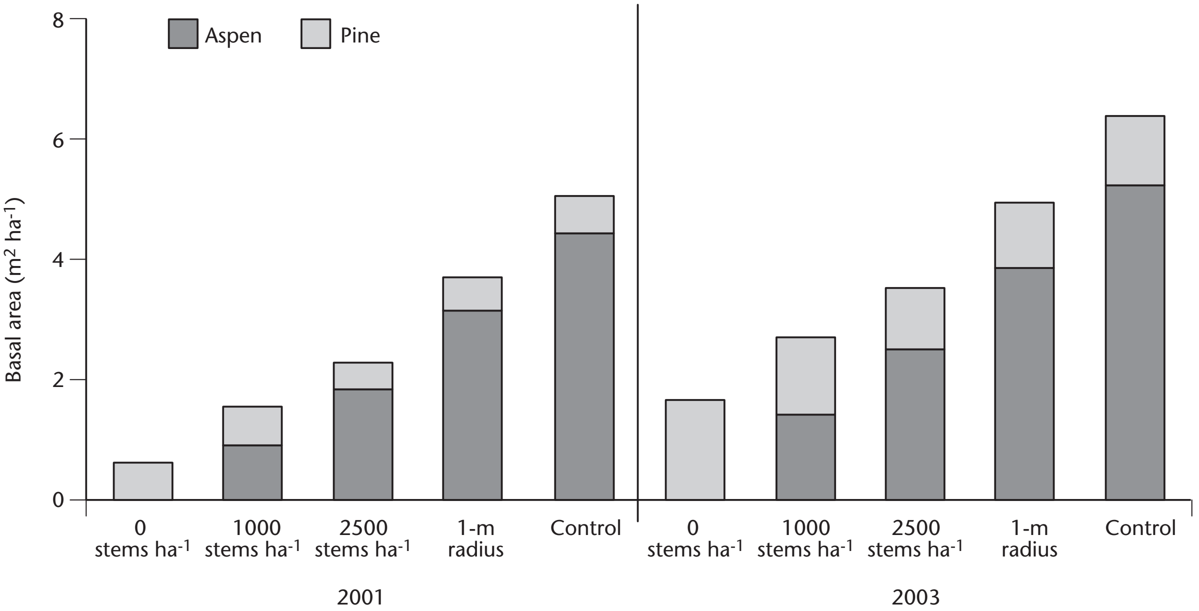


FIGURE 12 *Comparison of aspen and pine basal area in aspen removal treatments in 2001 and 2003, 11 and 13 years post-harvest (not including new suckers).*

4.2.3 Vegetation characteristics When aspen removal treatments were applied in 2001, average overall vegetation cover at Clusko was 85%, average conifer cover was 4%, and average broadleaf cover was 28%. Cover of shrubs and herbs averaged 41 and 44%, respectively. Moss cover was 2% and lichen cover was 3%. These baseline data will be compared with future assessments.

5 DISCUSSION

The Clusko aspen removal study investigates the effects of five levels of aspen removal on lodgepole pine survival and growth in the SBPSxc subzone. Treatments include an untreated control, a complete aspen removal treatment, broadcast retention of 1000 and 2500 aspen stems ha^{-1}, and a spatial treatment that removed aspen within a 1-m radius around target pine. Stand development and neighbourhood interactions between pine and aspen under the different treatment regimes are also being studied.

5.1 Target Pine Responses

Two years after aspen removal treatments were applied at the Clusko site, lodgepole pine stem diameter and stem diameter increment had significantly increased relative to the uncut control in the treatment where all aspen stems had been removed, but there was no significant height response for any of the treatments. Conifer stem diameter commonly responds more quickly than height to reductions in vegetation competition (e.g., Lanner 1985; Lanini and Radosevich 1986; Simard et al. 2001), but the response at Clusko was stronger and more rapid than had been anticipated on the basis of a similar study in the IDFxm (Newsome et al. 2004a). In the Clusko study, 2-year lodgepole pine stem diameter increment in the 0 stems ha^{-1} treatment (i.e., where all aspen had been removed) had increased relative to not only the untreated control, but also to all other aspen removal treatments. All variable density treatments (i.e., 0, 1000, and 2500 stems ha^{-1}) had significantly larger pine diameter increment than the control. In contrast, neither diameter nor any other measure of lodgepole pine growth improved within 4 years of treatment at the IDFxm site (Newsome et al. 2004a). In the present study at Clusko, the increases in diameter growth after 2 years also resulted in significantly lower HDR in the 0 stems ha^{-1} treatment than in the control. Only the 1-m radius aspen removal treatment failed to stimulate increased diameter growth of pine, which is consistent with the lack of response to a similar treatment applied in an SBSdw2 pine-aspen stand (Newsome et al. 2004b). Interestingly, the significant 2-year treatment effect on target lodgepole pine diameter at Clusko did not extend to the set of neighbourhood pine. This is likely due to greater variability among neighbourhood pine, which included both healthy and unhealthy stems, as well as a few scattered residuals. In contrast, the set of target pine included only stems that had been healthy and free of defects at the start of the study in 2001.

The faster diameter growth response of lodgepole pine in the SBPSxc than in the IDFxm is likely due to a combination of factors that differed between the two sites. These could include differences in: (a) the size of pine relative to aspen at the time of treatment, (b) soil moisture and nutrient availability, (c) the origin of pine and their age relative to aspen, and (d) pine condition at the time of treatment. The lack of lodgepole pine growth response in the related Meldrum Creek (IDFxm) study (Newsome et al. 2004a) suggests that pine were either not experiencing significant competition from aspen, or that they were unable to respond to the aspen removal treatments because other factors were more limiting. In contrast, pine in the present study at Clusko did respond to reductions in aspen abundance, which suggests that aspen were important competitors and that treatments were successful at relieving the competitive stress. However, since the experiments were designed to measure the effects of competition rather to investigate its mechanisms, we can only speculate about reasons behind the differing responses.

Lodgepole pine at the Clusko (SBPSxc) site may have been experiencing more severe competition from aspen for light, and possibly soil resources, than those at Meldrum Creek in the IDFxm (Newsome et al. 2004a). Trembling aspen can be a strong competitor for light. Numerous studies have documented lodgepole pine stem diameter growth increases in response to decreased broadleaf abundance (e.g., Simard et al. 2001; Newsome et al. 2003). However, the ability of aspen to compete for light depends on crown characteristics and the relative height of pine within the aspen canopy. Based on regression models that predict light availability from basal area on an ecosystem-specific basis (Comeau et al. 2006), understorey light levels at the time of treatment were approximately the same (60%) at both the Clusko (SBPSxc) and Meldrum (IDFxm) sites. However, lodgepole pine at Clusko were only 40% as tall as aspen and tended to be growing almost entirely beneath the canopy (Figure 13), while those at Meldrum were 65% as tall as aspen, occupying the mid-canopy. Additional models developed by Comeau et al. (2006) indicate that light availability increases rapidly with relative height in the aspen canopy, which suggests that pine at the IDFxm site were experiencing less competition for light at the time of treatment than those at the SBPSxc site.

FIGURE 13 *Lodgepole pine in the understorey beneath a dense patch of aspen at the Clusko site.*

Height differentials between pine and aspen were larger at the Clusko site than at Meldrum in the IDFxm (Newsome et al. 2004a). This is probably because the Meldrum site was planted immediately following site preparation (so that pine and aspen were the same age), whereas Clusko regenerated naturally over several years. Recruitment of naturally regenerated lodgepole pine peaks 6–8 years after harvest and site preparation (Weetman and Vyse 1990), which suggests that pine at Clusko were, on average, younger than aspen.

Lodgepole pine in the present SBPSxc study may have been experiencing more competition for soil resources, as well as for light, than those in the IDFxm study at Meldrum Creek (Newsome et al. 2004a). Both ecosystems are very dry, but the soil moisture regime at the SBPSxc site ranged from mesic to submesic, whereas it ranged from mesic to subhygric at the IDFxm site. Nutrient limitations are also more common on zonal sites in the SBPSxc than in the IDFxm (Steen and Coupé 1997). Since young aspen have high nutrient requirements (Peterson and Peterson 1995), their removal may have increased nutrient availability to lodgepole pine, stimulating the observed increase in diameter growth. In a study in the boreal where chemical brushing was applied to reduce the abundance of an aspen-dominated community, the foliar nitrogen content of white spruce (*Picea glauca* [Moench] Voss) increased relative to the untreated control within 5 years and returned to control levels by year 14 (Macadam and Kabzems 2006).

Aspen may also have been a less dominant competitor for soil water at Meldrum Creek (Newsome et al. 2004a) than in the present study at Clusko, with the result that reductions in aspen density in the IDFxm did not stimulate pine to release. A relatively abundant herb layer that included a variety of grass species was also present at the Meldrum site, which may have contributed more to moisture competition than did aspen. The more abundant herbaceous vegetation at Meldrum than Clusko is attributed to the generally moister site conditions, in combination with inherent differences in typical subzone species composition (Steen and Coupé 1997). Pinegrass, which is a strong competitor for soil water and nutrients (Haeussler et al. 1990) was a dominant species at Clusko, but due in part to the extreme climatic conditions, the lower vegetation layer was not very vigorous, and pinegrass had a mean height of only 22 cm (data not shown). Pinegrass abundance in the SBPSxc often does not increase following canopy removal (Steen and Coupé 1997).

5.2 Competition Indices

Various competition indices and measures of aspen abundance were previously investigated in a retrospective study conducted in Cariboo-Chilcotin ecosystems for their ability to predict lodgepole pine growth (Newsome et al. 2003). Tall aspen density (i.e., the density of aspen as tall as or taller than the target lodgepole pine) was consistently the best predictor of lodgepole pine stem diameter growth, and the relationship became stronger as stands aged. In that study, tall aspen density predicted 40–58% and 37–43% of the variation in pine diameter in 8- to 12-year-old naturally regenerated lodgepole pine-aspen stands in the SBSdw and IDFdk subzones, respectively. By the time those stands were 15–19 years old, tall aspen density explained 48–68% of the variation in pine stem diameter in the SBSdw and 50–63% in the IDFdk. The relationship was further tested in the 10-year-old pine plantation at Meldrum Creek in the IDFxm, and again tall aspen density proved to be the best predictor (Newsome et al. 2004a). However, the relationship was much weaker than had been indentified in the retrospective study, explaining a maximum of 14.6% of the variation in pine stem diameter increment.

The present study at Clusko compared tall aspen density and basal area in a 13-year-old pine-aspen stand in the SBPSxc, and found that for those particular stand age and site conditions, tall aspen density was again a better predictor of lodgepole pine stem diameter than was tall aspen basal area. At the Clusko site, tall aspen density accounted for 21% of the variation in 2-year lodgepole pine stem diameter increment. The weaker relationships found at Meldrum (Newsome et al. 2004a) and Clusko than in similar-aged stands in the retrospective study (Newsome et al. 2003) suggest that the competitive ability of aspen is highly variable in very young stands. While aspen density was a major limiting factor in the naturally regenerated stands in the retrospective study, planted pine in the IDFxm grew quickly enough to remain high in the aspen canopy where light availability was adequate for growth (Comeau et al. 2006). Retrospective study results also indicated that the effects of competition took longer to manifest in the slower-growing IDFdk stands than in SBSdw stands (Newsome et al. 2003), which suggests that they may take longer still to materialize in the even slower-growing SBPSxc subzone.

Tall aspen basal area has been a weaker predictor of pine growth than tall aspen density in the present study at Clusko, and in related studies in the Cariboo-Chilcotin (Newsome et al. 2003; Newsome et al. 2004a). In contrast, Comeau (2002) found that basal area was highly correlated with light availability in the aspen understorey in 10- to 30-year-old boreal stands, whereas density was poorly correlated. It is possible that the predictive ability of aspen basal area may improve on our sites as the stands age. As P.G. Comeau (pers. comm., Jan. 2006) remarked, aspen basal area, which accounts for both density and size of aspen, might eventually prove to be useful as a more general competition index, suitable for application across a range of stands of different ages, sizes, or densities within a single ecosystem (in this case the SBPSxc). Density, on the other hand, often only works well as a site- and age-specific competition index. Bravo et al. (2001) determined that basal area was most highly correlated with conifer growth where competition for soil resources predominated, a scenario that Simard and Sachs (2004) suggested becomes more common as broadleaf-conifer stands age and competition for light decreases in importance.

5.3 Size of the Competitive Neighbourhood

Regression analysis of 2003 data collected at the Clusko site suggests that, at a stand age of 13 years, aspen within a 2.56-m radius of target lodgepole pine were the main competitors. When neighbourhood sizes were compared, the highest R^2 value (0.212) was found between 2-year lodgepole pine diameter increment and tall aspen density within 2.56 m of the target pine. This relationship became weaker when aspen were included only within smaller radii of 1.8, 1.0, or 0.5 m. In contrast, regression analysis of data collected in the 10-year-old stand at Meldrum Creek in the IDFxm suggested that aspen within a 1.0-m radius of target pine were the most important competitors (Newsome et al. 2004a), while the retrospective study results showed that aspen within a 1.78-m radius of target pine were the main competitors in 15- to 19-year-old stands in the SBSdw and IDFdk (Newsome et al. 2003). The size of competitive neighbourhoods may have varied between sites because of differences in the height differential between broadleaf and conifer species. Tall individuals capture more light than shorter individuals (Keddy 1990), and they also cast shade over a greater distance. At Clusko, aspen were 2.2–3.2 times as tall as pine, compared with 1.5–1.7 times as tall at Meldrum. Consequently, pine at Clusko would have been shaded by stems growing at a greater distance, explaining the larger size of the competitive neighbourhood.

Studies involving other broadleaf-conifer mixtures have identified even larger competitive neighbourhoods. For example, Lieffers et al. (2002) found that plots less than 2 m in radius poorly represented light competition between aspen and white spruce in 10–12 m tall boreal stands, and suggest that plots of 10-m radius would be required to accurately assess understorey light conditions. In 11-year-old Douglas-fir and paper birch stands in the southern interior of British Columbia, Simard and Sachs (2004) determined that the size of the competitive neighbourhood was 3–4 m.

5.4 Stand Characteristics

Current management objectives for Cariboo-Chilcotin stands focus on softwood rather than mixedwood timber production, with the interest in aspen retention centred primarily on issues of forest health, biodiversity, and sucker reduction. However, at least one local forest company is currently utilizing aspen fibre, and interest is increasing in mixedwood management throughout northern and central British Columbia. Information about juvenile stand structure is useful for examining differences in stand development between ecosystems, and is also expected to be useful for future analyses and modelling projects.

Some differences in stand characteristics were apparent between the Clusko site (SBPSxc), described in this paper, and the Meldrum site (IDFxm) (Newsome et al. 2004a). Aspen height was similar when treatments were applied in the two studies, despite the fact that the stand at Clusko was approximately 5 years older. Mean aspen stem diameter was larger in the older stand at Clusko, and total density was lower, possibly due to more intensive self-thinning or the more extreme growing conditions. At the time of treatment, there were approximately 14 000 aspen stems ha^{-1} at Clusko compared with approximately 23 000 stems ha^{-1} at Meldrum Creek. The variable density treatments at Clusko immediately reduced tall aspen densities to

0 stems ha^{-1} and to slightly less than the target treatment values of 1000 and 2500 stems ha^{-1}, and reduced total aspen basal area in those treatments by 100, 80, and 59%, respectively, compared to the control.

Aspen diameter distributions changed relative to the control as a result of these three treatments because small stems were removed and the largest, most vigorous stems were retained. In the 2 years following treatment, diameter growth of tagged dominant aspen was significantly greater in the 1000 stems ha^{-1} treatment than in the 1-m radius treatment or control, which supports the suggestion by Peterson and Peterson (1995) that although aspen self-thin efficiently, aspen sawlog production can be enhanced by thinning treatments. The 1000 and 2500 stems ha^{-1} thinning treatments also had the effect of releasing very small aspen (<30 cm tall) that were growing in the understorey. This effect was not observed in the IDFxm, probably because small aspen were not as abundant due to the well-developed herb layer. Aspen stems shorter than 30 cm were not measured in the initial assessment, but had they been, overall pre-treatment densities at Clusko and Meldrum would likely have been similar.

Like aspen, lodgepole pine had larger diameter relative to height at Clusko in the SBPSxc than at Meldrum in the IDFxm (Newsome et al. 2004a), as demonstrated by lower HDR values of target lodgepole pine at Clusko. Differences in height growth at these two sites are likely typical for the ecosystems, since site index for lodgepole pine on zonal SBPSxc sites is 15, compared with 18 for zonal IDFdk3 sites[1] (B.C. Ministry of Forests 2005). At Clusko, lodgepole pine basal area averaged 0.6 m^2 ha^{-1} in 2001, increasing to an average of 1.2 m^2 ha^{-1} by 2003. In both 2001 and 2003, aspen basal area exceeded that of pine in all treatments except where aspen had been completely removed, although the difference between the two species was very slight in the 1000 stems ha^{-1} treatment.

5.5 Aspen Density Effects on Sucker Production

One of the anticipated benefits of retaining some aspen stems on sites that are manually brushed is a reduction in the number of suckers that are produced. This phenomenon has been documented in a variety of studies (e.g., Huffman et al. 1999; Prévost and Pothier 2003), and has been subjectively observed in the Cariboo-Chilcotin area of the Southern Interior Forest Region. At Clusko, it was clear that the number of suckers produced decreased significantly with increasing level of aspen retention. The density of suckers produced where 1000 aspen stems ha^{-1} were retained was approximately half the number that emerged following complete aspen removal (44 184 versus 93 086 suckers ha^{-1}). Retaining 2500 aspen stems ha^{-1} resulted in only about one-quarter the sucker density of complete aspen removal. Sucker production and development are also currently being studied in two related Cariboo-Chilcotin studies in the IDFxm and the SBSdw1 (Newsome et al. 2004a, 2006). At both these sites, a clear decrease in sucker production occurred with increasing density of retained aspen, although the overall sucker densities produced in the various treatments were only 25–50% as high as at Clusko in the SBPSxc. The density of aspen in the original stands may have been a determinant of sucker density (Frey et al. 2003), but we have no analysis of pre-harvest information regarding the presence of aspen that would allow us to make comparisons between sites.

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[1] We use site index values for the IDFdk3 for comparison because the Meldrum site is transitional to this variant, and because few data are available for the IDFxm.

Two-year sucker height also tended to decrease with increasing levels of aspen retention at Clusko, although the only significant between-treatment difference was for the complete removal treatment and the uncut control. Suckers produced at Clusko in the SBPSxc, despite their numbers, were considerably shorter than in other Cariboo-Chilcotin ecosystems. At Clusko, 2-year-old suckers were 25–30 cm tall, which was 40–50% shorter than suckers of the same age at the IDFxm site (Newsome et al. 2004a) and SBSdw1 sites (Newsome et al. 2006), on average. In contrast, other studies have found that sucker height is more responsive than sucker density to treatments that vary the level of aspen retention (P.G. Comeau, pers. comm., Jan. 2006).

5.6 Future Work Related to Management and Operational Recommendations

The Clusko study is one of a series of experiments currently under way in the Cariboo-Chilcotin to provide information about thresholds for aspen retention in mixed pine-aspen stands. The results will help forest managers decide whether or not it is necessary to reduce aspen density to enhance lodgepole pine survival and growth, and to prescribe an appropriate density of aspen to leave after partial brushing treatments. The Cariboo-Chilcotin aspen-pine retrospective study suggested a threshold of 2000 tall aspen stems ha^{-1} for dry IDF sites at age 15–19 (Newsome et al. 2003), and ongoing measurement of the Clusko study will help determine whether a similar threshold exists in the SBPSxc.

Suckering is being studied at the Clusko site, as well as at sites in other biogeoclimatic units of the Cariboo-Chilcotin. Further data collection is required at all sites before recommendations can be made regarding the effects of cutting treatments on sucker production, survival, and growth. Sucker densities at Clusko were far higher than in other ecosystems tested, and trends need to be assessed over time.

We intend to further investigate the effects of manipulating aspen density on stand development. Growth and yield plots will be established at the Clusko study site during the next assessment. Over the long-term, data from these plots will be used to calibrate models for predicting the long-term effects of variable density treatments on growth and yield and stand development. Much more in-depth analysis is also planned concerning the spatial aspects of competition between pine and aspen. Larger plots may be useful to determine the competitive distance between aspen and pine.

As the Clusko stand ages, data collection will be required to refine standards relating to the British Columbia provincial free-growing guidelines (B.C. Ministry of Forests 2002), and to determine whether the current guidelines are biologically appropriate for the SBPSxc subzone. The issue of refining allowable density guidelines is extremely important because of the long-term contributions that aspen can make to stand health and site quality, and because of the potential for reducing stand-tending costs. Aspen may, in some areas, contribute to future timber supply. If free-growing guidelines are based on ecosystem-specific research results, managers can be confident that they are applying brushing treatments where they are biologically necessary to meet long-term conifer growth objectives.

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Code		**Overall seedling condition**
1	Good:	Seedling shows no signs of stress, and has a vigorous growth rate and a generally healthy appearance.
2	Fair:	Seedling is under some form of stress, may have minor defects, and has a moderate growth rate.
3	Poor:	Seedling is under severe stress, may have major defects, and the growth rate is poor.
4	Moribund:	Seedling is almost dead.
5	Dead	
6	Missing	
7	Destructively sampled	

		Seedling vegetation cover codes
O	Overtopped:	The leader of the crop tree is at present overtopped by surrounding vegetation; crop tree available sunlight is greatly reduced.
T	Threatened:	The leader of the crop tree is at or near the same height of the surrounding vegetation, and/or is likely to be overtopped within two growing seasons.
F	Free growing:	The leader of the crop tree is well above the surrounding vegetation and is not likely to become threatened.

Seedling damage codes

Stem condition code
H – No visible effect (healthy)
P – Bark peeled or abraded
B – Stem bent
S – Stem smashed, crushed, trampled
C – Stem cut, clipped, broken
D – Tree dead, dying
M – Tree missing
F – Stem forked
G – Gall rust
Ø – Other symptoms (specify)

Foliage condition code
H – No visible effect (healthy)
Y – Chlorotic (yellow)
M – Mottled
N – Necrotic
A – Needles absent, defoliated
B – Browsed
D – Dead buds on lateral branches
G – Gall aphid
Ø – Other symptoms (specify)

Leader shoot condition code
H – No visible effect (healthy)
C – Curled
F – Forked
B – Browsed
T – Dead terminal bud
S – Snapped, broken
A – Absent, missing
P – Pissodes
Ø – Other symptoms (specify)
N – No or abnormal flush

Damage cause code
A – None
H – Herbicide
M – Mechanical equipment
T – Hand tools
S – Falling slash (human caused)
X – Falling or sliding debris
E – Climate-frost
N – Snowpress
V – Vegetation press
W – Climate-drought
R – Rodents, small animals
B – Big game
L – Livestock
F – Fire
I – Insects
D – Disease
Z – Destructively sampled
G – Winter-damage
P – Whipping damage
Ø – Other (specify)
U – Unknown