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Early Effects of Manipulating Aspen Density on Lodgepole Pine Performance, Aspen Sucker Production, and Stand Development in the IDFxm Subzone near Williams Lake, B.C.

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British Columbia

Ministry of Forests Forest Science Program

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ABSTRACT

An experiment was established at Meldrum Creek in the IDFxm subzone of the Cariboo-Chilcotin region in 1998 to study the effects of reducing aspen density to 0, 1000, 2500, or 4000 stems ha^{-1} on lodgepole pine performance. After 4 years, when the stand was 10 years old, the treatments had resulted in no significant differences in mean lodgepole pine stem diameter, diameter increment, height, leader length, crown width, or height:diameter ratio (HDR). Survival was at least 92% in all treatments, including the untreated control. One of the objectives of the study was to test and refine competition thresholds for aspen retention on dry-belt IDF sites that had been defined in an earlier study in the Cariboo-Chilcotin (Newsome et al. 2003).

Regression analysis showed that aspen within a 1 m radius of target pine were more important competitors with the pine than aspen farther away. However, aspen competition was relatively unimportant when the stand was 10 years old. The density of aspen that was as tall as, or taller than, target pine predicted, at best, 14.6% of the variation in pine stem diameter increment. At the stand level, reducing aspen density immediately changed the diameter distribution of aspen and reduced its basal area (BA); and, after 4 years, aspen continued to have less basal area than pine in the 0 and 1000 stems ha^{-1} treatments. Two years after cutting, aspen sucker density ranged from 16 623 stems ha^{-1} in the 4000 stems ha^{-1} treatment to 33 599 stems ha^{-1} in the 0 stems ha^{-1} treatment. Because of substantial variability in the numbers of suckers counted, however, these differences between treatments were not statistically significant. Sucker densities naturally declined by one-third to one-half between years 2 and 4 after cutting, but still exceeded 8500 stems ha^{-1}.

ACKNOWLEDGEMENTS

This study was initiated to continue investigation of an issue identified as a regional priority in 1991 by Guy Newsome, who was the current stand-tending forester in the former Cariboo Forest Region. Kim Peel helped to find the site. Field assessments were completed by a variety of summer students (notably Lanny Englund) and contractors, including Zimonick Silviculture and Industrial Forestry Services Limited. Valuable advice was provided by Craig Sutherland, Phil Comeau, and Lorne Bedford. Ongoing support from Ken Soneff is greatly appreciated. Valuable review comments regarding this report were provided by Craig Delong, Richard Kabzems, Chris Hawkins, Jacob Boateng, and Gordon Nigh.

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1 INTRODUCTION

Trembling aspen (*Populus tremuloides* Michx.) is a common component of forests throughout interior British Columbia, particularly in north and central parts of the province. In the Cariboo-Chilcotin area of the Southern Interior Forest Region,[1] aspen commonly regenerates along with planted and natural lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.) in the Interior Douglas-fir (IDF), Sub-Boreal Spruce (SBS), Sub-Boreal Pine–Spruce (SBPS), and Interior Cedar–Hemlock (ICH) biogeoclimatic zones (Meidinger and Pojar 1991).

Although aspen can be a strong competitor with shade-intolerant pine, maintaining a low-density aspen component within stands offers many benefits to both individual conifers and the site as a whole:

- Young aspen take up large amounts of nutrients, especially calcium, and retain them within the ecosystem (Pastor 1990).
- Aspen is 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).
- Mature aspen canopies offer young conifer seedlings more protection from frost damage than do 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).
- Because of its communal root system, sucker-origin aspen is mechanically stable (Strong and La Roi 1983), which can reduce windthrow among neighbouring conifers (Frivold 1985; Yang 1989).

At high densities, however, aspen can reduce 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 of particular importance to lodgepole pine because of its low shade tolerance (Klinka and Scagel 1984; Wright et al. 1998), and studies have shown that in low-light environments, pine stem diameter growth decreases, height:diameter ratio increases, and crown width decreases (e.g., Simard et al. 2001). Where light availability is restricted, lodgepole pine allocates more growth to terminal than lateral shoots and reduces branch number (Chen et al. 1996). In addition to these concerns, mechanical "whipping" damage to pine by aspen branches is common where aspen are growing near pine (Lees 1966).

Until recently, managing aspen included reducing its presence among young pine as much as possible by applying aggressive site preparation and brushing treatments. While strategies for managing mixed broadleaf–conifer stands are now changing throughout British Columbia, forest practitioners still require information about threshold levels of broadleaves that can be retained without seriously affecting conifer performance. A retrospective study to investigate the effects of aspen competition on lodgepole pine in the Cariboo region was established in 1992 and, by 1997, results were suggesting that dry-belt (IDFdk) thresholds for aspen as tall or taller than target pine were in the range of 2000–5000 stems ha^{-1} (Newsome et al. 2003).

1 Formerly the Cariboo Forest Region.

To investigate pine–aspen interactions further and to more clearly define thresholds for aspen retention in the Cariboo-Chilcotin dry-belt, a variable density study was established in 1998 at a site near Meldrum Creek in the IDFxm subzone. This technical report presents 4th-year results of that study.

2 OBJECTIVES

The objectives of the study were:

1. to compare vigour, survival, and growth of target lodgepole pine growing in control neighbourhoods where no aspen was removed with that of target pine growing in neighbourhoods where aspen density was reduced to 0, 1000, 2500, and 4000 stems ha^{-1}.
2. to study the effects of these density treatments on aspen sucker production.
3. to test the aspen density thresholds for lodgepole pine growth that were previously defined in a retrospective study of naturally regenerated pine–aspen stands in the IDFdk subzone.
4. to compare untreated pine–aspen stand structure with that of treated stands where aspen density has been reduced to 0, 1000, 2500, and 4000 aspen stems ha^{-1}.
5. to examine the size of the competitive neighbourhood in which aspen and lodgepole pine affect the target pine.
6. to provide a demonstration site for variable density aspen thinning treatments in a pine–aspen complex in the IDFxm subzone.

3 METHODS

3.1 Study Areas and Site Selection

The Meldrum Creek site was selected for the study because it had (when the study was begun in 1998) a relatively homogeneous stand of approximately 6-year-old aspen with minimum average density of 4000 stems ha^{-1}. At least 4000 aspen stems ha^{-1} were necessary so that treatments could be randomly allocated to plots (the highest treatment density was 4000 stems ha^{-1}).

The Meldrum Creek site, located approximately 30 km southwest of Williams Lake at an elevation of 900 m, is generally flat (0–5% slope), with occasional small areas of variable slope. It has a submesic to subhygric moisture regime and a medium nutrient regime, and is zonal (site series 01) in the IDFxm subzone (Interior Douglas-Fir Very Dry Mild subzone). The IDFxm subzone has mean annual precipitation of 392 mm, a mean annual temperature of 4°C, an average frost-free period of 163 days per year, and luvisolic zonal soils (Steen and Coupé 1997). The site (mapsheet 92O 099, opening 5) was clearcut logged in 1980, brushed in 1989, ripped in 1992, and planted with lodgepole pine in 1993. By 1998, when this study was established, aspen regeneration was again abundant.

The location of the Meldrum Creek site is shown in Figure 1.

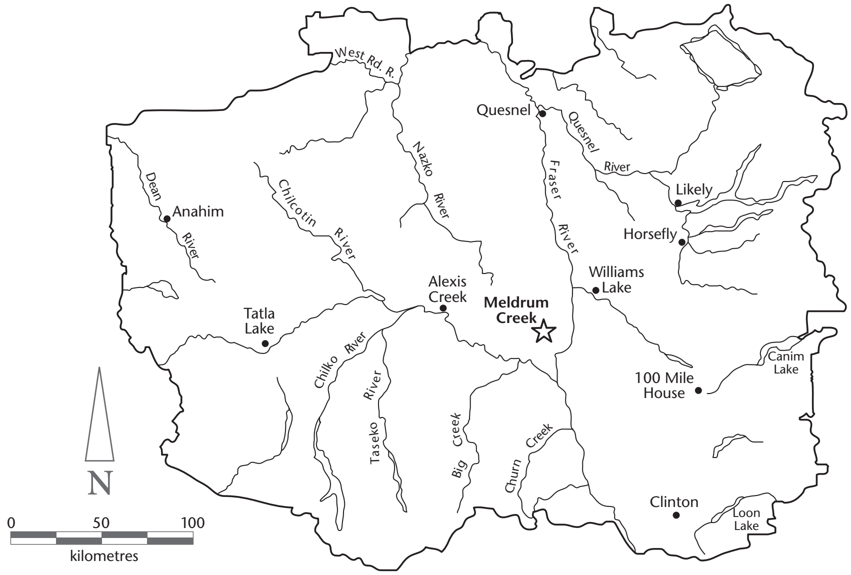

FIGURE 1 *Location of the Meldrum Creek variable density study.*

3.2 Sampling Design and Treatment

The study used a randomized complete block design (RCBD) with three blocks and five treatments. Blocking was based on analysis of pre-treatment data (see Section 3.4.1), which showed that a significant gradient in aspen height ($p=0.0010$) and density ($p<0.0001$) existed across the study area. Because aspen size reflects variation in localized site productivity, and also because density was to be manipulated within the treatments, height was selected as a basis for stratification. Plots were ranked according to mean aspen height to minimize within-block variability. The five plots with the shortest aspen were assigned to block 1, the five with medium-height aspen to block 2, and the five with the tallest aspen to block 3.

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

- control (no aspen removal)
- 0 aspen stems ha^{-1} (all aspen removed)
- 1000 aspen stems ha^{-1}
- 2500 aspen stems ha^{-1}
- 4000 aspen stems ha^{-1}

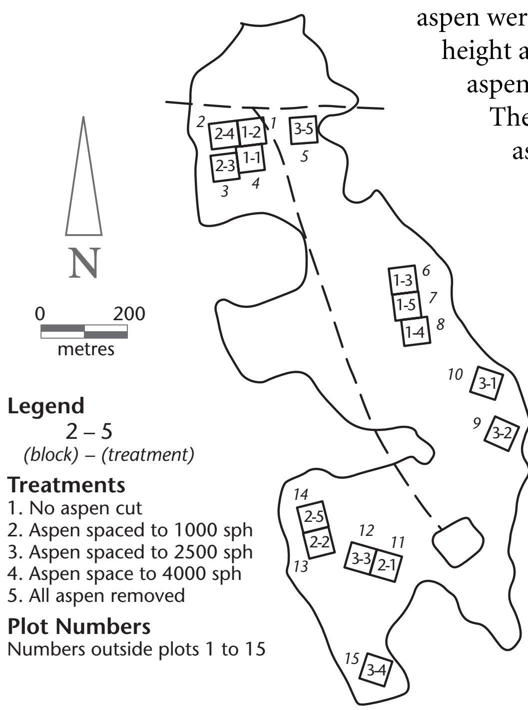

FIGURE 2 *Plot layout at the Meldrum Creek study site.*

Each treatment plot was 60 × 60 m in area and contained a 40 × 40 m measurement area surrounded by a 10-m buffer. Within the measurement area, a 7.5 × 7.5 m grid of 25 points was established, starting 5 m inside one of the corners. Of the 25 grid points, numbers 7 and 19 were selected for the establishment of permanent vegetation plots where no other data would be collected. This was to avoid trampling damage to the vegetation. Plots 9 and 17 were designated as alternative vegetation plots if 7 or 19 was unsuitable. Vegetation plots had a 3.99-m radius (50 m^2), with the grid point as plot centre. At the remaining 21 grid points, the closest healthy, undamaged lodgepole pine was chosen as a potential target pine, and tall aspen (i.e., aspen as tall or taller than the target pine) were counted within a 3.0-m radius (28.3 m^2) of the pine. The first 16 of those potential target pine growing in neighbourhoods with at least 4000 tall aspen stems ha^{-1} (i.e., with at least 12 tall aspen within a 3.0-m radius) were selected as *the* target pines. They then became the centres for the sixteen 3.0-m radius subplots included in the experiment.

From July 8 to 17, 1998, brush saws were used to reduce aspen density to the appropriate treatment levels (0, 1000, 2500, and 4000 stems ha^{-1}) on a broadcast basis. Crews were instructed to retain the tallest and most vigorous aspen stems, keeping in mind the target density for each plot. Within the subplots, "leave" aspen were marked to ensure accurate densities. Any natural lodgepole pine older than the planted stock were also removed to avoid additional competition.

3.3 Measurements

3.3.1 Pre-treatment Before the stands were thinned, pre-treatment measurements were carried out in the spring of 1998. The purpose of taking these measurements was to characterize each plot and determine whether there was sufficient variation in neighbourhood aspen or pine size to warrant the use of blocks in the experimental design. So that a representative sample could be obtained, a random bearing was established through the centre of each subplot and the closest 10 stems each of aspen and lodgepole pine within the subplot (except the target pine) were measured for height and ground-level stem diameter. This meant that virtually 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 also recorded in the vegetation plots (results for individual species are not included in this report). Height and diameter of target pine were measured to determine whether differences existed between treatment plots.

3.3.2 Post-treatment Full assessments were carried out in 1998, 2000, and 2002. Target and neighbourhood pine were also measured in 1999 to assess the extent of moose browse damage that had occurred in early spring of that year. No broadleaf measurements were taken in 1999.

Target lodgepole pine The following target lodgepole pine variables were assessed in 1998, 1999 (results not reported), 2000, and 2002:

- 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 during specific time periods were also calculated. As well, pine survival, vigour, damage, damage cause, and degree of overtopping were assessed according to standard Cariboo Region Research protocol (Appendix 1).

Stand and neighbourhood measurements In 1998, stand structure (the relative abundance and stature of all pine and aspen, including the target pine) and competition effects from neighbouring trees (the effects of surrounding pine and aspen on the target pine) were assessed in the 3.0 m radius subplots around each target lodgepole pine seedling. The height and ground-level stem diameter of all original broadleaf and conifer trees were also measured (i.e., not including aspen suckers that had emerged following the 1998 thinning treatment). These stems were painted for future identification and then remeasured in 2000 and 2002. Basal area (using ground-level diameter) and density of both aspen and pine were calculated for each subplot. Quadratic mean diameter (based on ground-level diameter) was also calculated for aspen (Equation 1).

$$QMD = ((\sum DBH_i^2)/n)^{-1/2} \quad (1)$$

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

In 1998 and 2000, stem-to-stem distance (distance from the outside edge of the neighbourhood tree stem to the stem centre of the target pine) and crown-to-stem distance (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 in the 3.0 m radius subplots (not including suckers). These measurements were made so that plot size could be varied and the size of the competitive neighbourhood investigated. In 2002, stem-to-stem distances were measured for original aspen and pine, but crown-to-stem distances were not recorded.

In 2000 and 2002, suckers that had originated following the 1998 thinning treatments were counted within the subplots. Starting from due north and travelling in a clockwise direction around the subplot, height of the first 15 suckers was measured. In 2002, ground-level stem diameter was also measured for three representative (small, medium, large) suckers of the 15 measured for height.

3.4 Analysis

SAS statistical software (SAS Institute Inc. 1996, 1999) was used for all data analyses. Before analysis, data were checked for outliers and normality using PROC UNIVARIATE. Summary statistics were compiled using PROC TABULATE, and regression models were fitted with the SAS macro NLINMIX (Wolfinger 2000). A square-root transformation was applied to some variables to stabilize variance and improve normality. Analysis of variance (ANOVA) was done with PROC MIXED. The statistical significance of differences between all pairs of treatment means was assessed by the Bonferroni method of multiple comparisons.

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 of neighbourhood aspen and pine varied significantly among treatment plots before treatments were applied. The analysis revealed a significant between-plot variability in neighbourhood aspen heights and densities. To reduce the amount of unexplained variability (and thereby increase the power of the design), plots were ranked according to the pre-treatment mean aspen height and then assigned to one of three blocks, after which treatments were randomly assigned to plots within each block (see Section 3.2).

3.4.2 Post-treatment data Lodgepole pine responses to aspen density treatments were analyzed using a mixed-model ANOVA applied to three different, but overlapping, sets of data. Treatment effects were analyzed using the data sets that included: 1) live target lodgepole pine only; 2) neighbourhood lodgepole pine (all pine within a 3.0 m radius of live target pine, but not including the target pine); and 3) pine at the stand level (all live pine in all 3.0 m radius subplots, including both target and neighbourhood pine). The target pine variables analyzed included height, leader length, stem diameter, HDR, and crown width. The neighbourhood and stand-level pine variables that were analyzed were height, stem diameter, quadratic mean diameter, basal area, and density.

The effects of aspen density on aspen height and stem diameter were also analyzed at the neighbourhood and stand levels using a mixed-model ANOVA. At both levels, only aspen that were present before the cutting treatment (not new suckers) were included. At the neighbourhood level, analysis was also carried out for "tall aspen" (meaning aspen as tall as, or taller than, the target pine). Aspen sucker density and height were analyzed separately using a mixed-model ANOVA.

The pine analysis (Table 1) has more degrees of freedom than the aspen analysis (Table 2) because only four of the five treatments included aspen (i.e., there were no aspen in the 0 stems ha^{-1} treatment).

TABLE 1 *ANOVA table for examining the effects of aspen density on lodgepole pine growth*

Source of variation	Degrees of freedom	Type of effect
Block (B)	2	Random
Treatment (T)	4	Fixed
B × T	8	Random
Error (tree)	n–15	Random

TABLE 2 *ANOVA table for examining the effects of aspen density on aspen growth*

Source of variation	Degrees of freedom	Type of effect
Block (B)	2	Random
Treatment (T)	3	Fixed
B × T	6	Random
Subplot	180	Random
Error (tree)	n–192	Random

Starting in 2002, regression analysis was used to examine the relationship between aspen density or aspen basal area, and pine size. A non-linear model (Equation 2) was fitted for pine diameter, diameter increment, height, and leader length.

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

where y is one of the pine growth variables, x is the density of all broadleaf and conifer trees as tall or taller than the target pine, and γ_{block}, $\delta_{treatment\ plot\ (block)}$, and ε are, respectively, the random errors associated with blocks, treatment plots within blocks, and the residual (tree) error.

To assess the size of the competitive neighbourhood, the above regression analysis was done using data sets that included all aspen and tall aspen within the following radii of target pine: 0.5 m, 1.0 m, 1.78 m, 2.5 m, and 3.0 m.

4 RESULTS

4.1 Target Lodgepole Pine

At the time cutting treatments were applied at the Meldrum Creek site, target pine were considered to have the potential to grow through the rotation to a harvestable size. They differed from neighbourhood and stand-level pine in that they were necessarily free of damage at the start of the experiment due to the criteria by which they were selected.

4.1.1 Target pine survival and vigour Only one target pine on the study site, located in the 0 stems ha^{-1} treatment, was killed during the cutting treatments. In the winter of 1998/1999, however, the pine were heavily browsed by moose because of a late snowmelt. The heaviest damage occurred in the control, 4000 stems ha^{-1}, and 2500 stems ha^{-1} treatments, probably because they provided greater cover and food for moose than the lower-density treatments. In 1999, heavily damaged stems were noted for possible exclusion from the experiment, but by 2002 most had recovered to average form and vigour. Lodgepole pine survival in 2002 was at least 92% in all treatments (Table 3).

Vigour of target lodgepole pine decreased between 1998 and 2002 (Table 3, Figure 3). The proportion of "good" seedlings decreased and that of "fair" seedlings increased. The proportion of "poor" seedlings also rose slightly, but the increase was similar in all treatments. Moose browse of lateral branches was the most common reason for the vigour reduction, affecting 34% of pine, with slightly more damage occurring in the 2500 stems ha^{-1} treatment than in others. Damage occurred approximately equally across all blocks.

In 2002, an average 7% of target pine were affected by pine needle cast (*Lophodermella concolor*). Although no damage of this type was recorded in the untreated control, neither did the incidence of this disease appear to be decreasing as aspen density increased. Also in 2002, an average of 12% of target pine were affected by western gall rust (*Endocronartium harknessi* [J.P. Moore] Y. Hirat), but again there were no identifiable trends with regard to aspen density.

TABLE 3 *Mean survival[a] and vigour of target lodgepole pine[b] in aspen density treatments, 1998–2002*

Pine variable		Aspen density treatment (aspen stems ha^{-1})				
		0	**1000**	**2500**	**4000**	**Control**
Survival (%)						
	1998	100	100	100	100	100
	2000	96	98	98	96	100
	2002	92	98	98	94	92
Good vigour (%)						
	1998	79	65	81	88	81
	2000	44	54	42	50	54
	2002	38	42	19	44	35
Fair vigour (%)						
	1998	19	29	17	13	19
	2000	48	44	54	46	40
	2002	44	46	71	40	44
Poor vigour (%)						
	1998	0	4	0	0	0
	2000	4	0	2	0	6
	2002	10	10	8	10	13

a Moribund and missing seedlings are classified as dead.
b The data set includes all target pine.

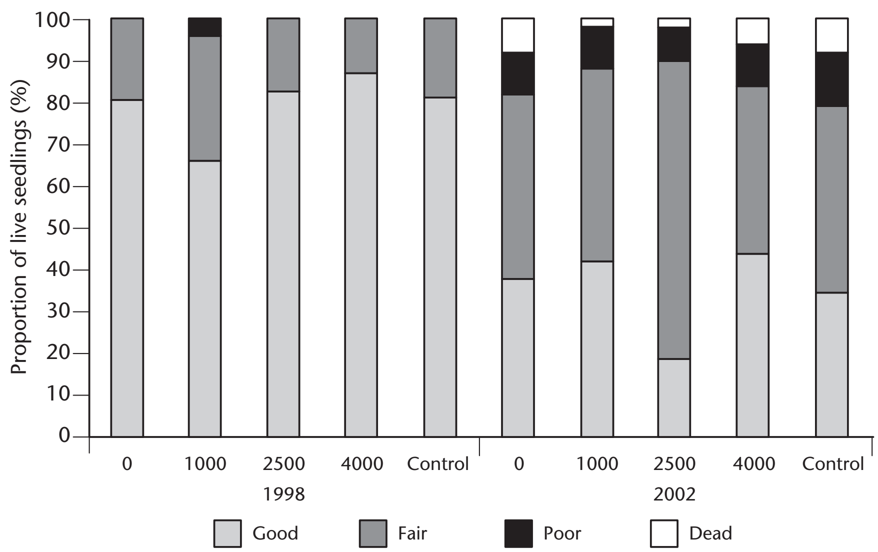

FIGURE 3 *Comparison of target lodgepole pine vigour in aspen density treatments in 1998 and 2002. Moribund and missing seedlings were considered to be dead.*

4.1.2 Target pine growth No significant differences in the height, stem diameter, crown width, or HDR of target lodgepole pine were found between aspen density treatments in 1998, 2000, or 2002 (Table 4). In 2000, pine leader length varied significantly among treatments according to ANOVA ($p=0.0476$), but the Bonferroni test was unable to detect differences between means and, by 2002, the difference was no longer significant. Also by 2002, although HDR did not vary significantly among treatments, there was a slight upward trend with increasing aspen density. Target pine height and stem diameter increments for the period 1998–2002 averaged 87 and 1.7 cm, respectively, but there were no significant between-treatment differences in the rates of growth (Table 5).

TABLE 4 *Mean[a] size of target lodgepole pine[b] in aspen density treatments in 1998 and 2000*

		Aspen density treatment (aspen stems ha^{-1})					
		0	**1000**	**2500**	**4000**	**Control**	**p-value[c]**
Height (cm)							
	1998	115 ± 5	115 ± 5	112 ± 5	115 ± 5	113 ± 5	0.9796
	2000	145 ± 6	145 ± 6	140 ± 6	150 ± 6	143 ± 6	0.8365
	2002	199 ± 11	200 ± 11	189 ± 11	215 ± 11	204 ± 11	0.5833
Leader length (cm)							
	1998	26 ± 1	25 ± 1	25 ± 1	24 ± 1	25 ± 1	0.9211
	2000	19 ± 2	23 ± 2	20 ± 2	25 ± 2	27 ± 2	**0.0476**[d]
	2002	30 ± 4	31 ± 3	29 ± 3	37 ± 4	33 ± 4	0.5085
Diameter (cm)							
	1998	1.54 ± 0.07	1.51 ± 0.07	1.47 ± 0.07	1.58 ± 0.07	1.51 ± 0.07	0.8450
	2000	2.29 ± 0.16	2.31 ± 0.16	2.09 ± 0.16	2.31 ± 0.16	2.01 ± 0.15	0.5387
	2002	3.41 ± 0.27	3.41 ± 0.27	2.98 ± 0.27	3.37 ± 0.27	2.96 ± 0.27	0.5788
Height:diameter ratio							
	1998	76 ± 4	77 ± 4	78 ± 4	74 ± 4	78 ± 4	0.9581
	2000	64 ± 4	65 ± 3	68 ± 3	66 ± 4	71 ± 3	0.5144
	2002	59 ± 3	60 ± 3	64 ± 3	65 ± 3	69 ± 3	0.1498
Crown width (cm)							
	1998	38 ± 2	36 ± 2	36 ± 2	39 ± 2	38 ± 2	0.8923
	2000	53 ± 6	51 ± 6	48 ± 6	58 ± 6	47 ± 6	0.6792
	2002	81 ± 7	78 ± 7	74 ± 7	84 ± 7	68 ± 7	0.5537

a Values are presented in the form of "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 are in **bold** if they are significant at p≤0.05 according to analysis of variance.
d The Bonferroni test was unable to distinguish differences between means, in spite of the significant p-value (p≤0.05).

TABLE 5 *Mean[a] height and diameter increments among target lodgepole pine[b] in aspen density treatments, 1998–2002*

	Aspen density treatment (aspen stems ha^{-1})					
	0	**1000**	**2500**	**4000**	**Control**	**p-value**
Height increment (cm)	83 ± 12	85 ± 12	76 ± 12	99 ± 12	90 ± 12	0.6921
Diameter increment (cm)	1.9 ± 0.2	1.9 ± 0.2	1.5 ± 0.2	1.8 ± 0.2	1.4 ± 0.2	0.4460

a Values are presented in the form of "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 all live target pine.

4.1.3 Neighbourhood vegetation responses To investigate competitive interactions between aspen and pine, neighbourhood vegetation was assessed in the 3.0 m radius subplots around target pine .

Neighbourhood tall aspen The density of tall aspen (i.e., aspen as tall as, or taller than, the target pine) was reduced to near the nominal treatment densities as a result of manual cutting in 1998. Actual average densities of tall aspen in the 1000, 2500, and 4000 stems ha^{-1} treatments were, respectively, 1260, 2594, and 4495 stems ha^{-1} (no tall aspen were retained in the 0 stems ha^{-1} treatment), compared with 13 521 stems ha^{-1} in the untreated control (Table 6). Tall aspen densities decreased as a result of self-thinning in all treatments between 1998 and 2002, with the largest decrease occurring in the untreated control (a 45% decrease in the control versus 22–27% decreases in the 1000, 2500, and 4000 stems ha^{-1} treatments).

There were no differences between treatments in the height of tall aspen in any of the measurement years, but ground-level stem diameter of tall aspen differed significantly in all years. In 1998 and 2000, tall aspen diameter was significantly larger in all density treatments than in the untreated control ($p<0.0001$), but by 2002 there was no longer a significant difference between the control and the 4000 stems ha^{-1} treatment. In 1998 and 2000, the basal area of tall aspen was significantly lower in all aspen density treatments than in the untreated control, and the 1000 and 2500 stems ha^{-1} treatments also had a significantly lower basal area than the 4000 stems ha^{-1} treatment. However, by 2002, again there was no longer a significant difference in basal area between the untreated control and the 4000 stems ha^{-1} treatment (Table 6).

TABLE 6 *Mean[a] tall aspen[b] density, size, and basal area in aspen density treatments, 1998–2002*

		Aspen density treatment (aspen stems ha^{-1})				
Aspen variable		**1000**	**2500**	**4000**	**Control**	**p-value[c]**
Density (stems ha^{-1})						
	1998	1260 ± 799 b	2594 ± 799 b	4495 ± 799 b	13,521 ± 799 a	**0.0001**
	2000	1111 ± 907 b	2372 ± 907 b	3972 ± 910 b	10,868 ± 904 a	**0.0008**
	2002	924 ± 711 b	2016 ± 711 b	3338 ± 714 b	7494 ± 716 a	**0.0011**
Height (cm)						
	1998	187 ± 11	192 ± 11	183 ± 11	174 ± 10	0.2826
	2000	229 ± 14	236 ± 14	238 ± 14	219 ± 14	0.1860
	2002	293 ± 19	312 ± 19	325 ± 18	297 ± 18	0.5148
Diameter (cm)						
	1998	2.05 ± 0.07 a	2.01 ± 0.07 a	2.07 ± 0.06 a	1.81 ± 0.06 b	<**0.0001**
	2000	2.79 ± 0.10 a	2.72 ± 0.10 a	2.7 ± 0.09 a	2.31 ± 0.09 b	<**0.0001**
	2002	3.60 ± 0.11 a	3.6 ± 0.10 a	3.46 ± 0.09 ab	3.02 ± 0.09 b	**0.0101**
Basal area (m^2 ha^{-1})						
	1998	0.4 ± 0.2 c	0.9 ± 0.2 bc	1.6 ± 0.2 b	3.6 ± 0.2 a	<**0.0001**
	2000	0.7 ± 0.4 c	1.5 ± 0.4 bc	2.4 ± 0.4 b	4.6 ± 0.4 a	**0.0005**
	2002	1.0 ± 0.6 c	2.2 ± 0.6 bc	3.3 ± 0.6 ab	5.6 ± 0.6 a	**0.0013**

a Values are presented in the form of "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 Values are in **bold** if they are significant at p≤0.05 according to analysis of variance. Means are assigned different letters if they are significantly different within the given year according to the Bonferroni test.

Neighbourhood lodgepole pine In 1998, there was an average of 1461 lodgepole pine stems ha^{-1} in the neighbourhoods of the target lodgepole pine, with a basal area of 0.31 m^2 ha^{-1}. By 2002, neighbourhood pine density had decreased to 1422 stems ha^{-1} and basal area had increased to 1.30 m^2 ha^{-1}. Because the original selection criteria for target lodgepole pine excluded damaged stems, neighbourhood pine were, on average, slightly shorter than target pine (Figure 4) and had slightly smaller stem diameter. No significant differences in the density, height, stem diameter, or basal area of neighbourhood lodgepole pine were found in 1998, 2000, or 2002 ($p<0.05$, Table 7). Pine density was slightly lower at the neighbourhood than the stand level because target pine were not included in the neighbourhood data set.

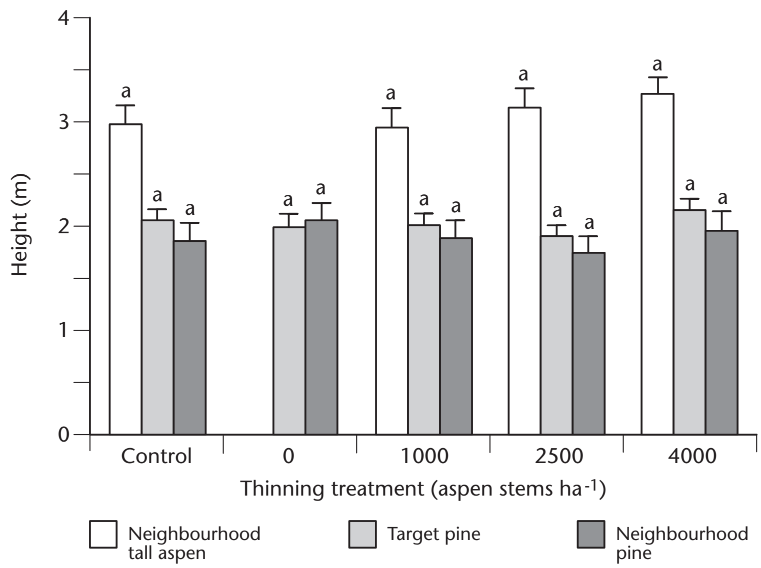

FIGURE 4 *Comparison of mean height of target lodgepole pine, neighbourhood tall aspen, and neighbourhood pine between aspen density treatments in 2002. Error bars represent 1 standard error. Means having the same letter within a single tree category (i.e., bars that have the same shading) are not significantly different from one another according to the Bonferroni test (adjusted p>0.05).*

4.1.4 Aspen abundance as a predictor of lodgepole pine growth In 2002, tall aspen density was a better predictor of 10-year-old pine size than tall aspen basal area, total aspen density, or total aspen basal area (Table 8). However, the relationship was relatively weak. The best correlation was between 1998–2002 stem diameter increment and tall aspen density, where the latter was able to explain 14.6% of the variation in diameter growth. Tall aspen basal area was the second best predictor, explaining 11.2% of the variation in 1998–2002 diameter increment. Both tall aspen density and basal area had a stronger relationship with diameter increment and diameter than with height or leader length.

4.1.5 Size of the competitive neighbourhood Coefficients of determination (R^2) values for the relationships between tall aspen density or tall aspen basal area and pine diameter, diameter increment, and height were consistently maximized (and root mean square error [RMSE] values were minimized)

TABLE 7 *Mean[a] neighbourhood lodgepole pine[b] density, size, and basal area in aspen density treatments, 1998–2002*

Pine variable		Aspen density treatment (aspen stems ha^{-1})					
		0	1000	2500	4000	Control	p-value
Density (stems ha^{-1})							
	1998	1465 ± 169	1304 ± 168	1348 ± 168	1525 ± 168	1665 ± 168	0.5900
	2000	1424 ± 164	1314 ± 164	1335 ± 164	1573 ± 164	1636 ± 164	0.5714
	2002	1387 ± 168	1322 ± 166	1306 ± 166	1530 ± 167	1563 ± 168	0.7342
Height (cm)							
	1998	112 ± 5	104 ± 6	96 ± 6	97 ± 5	99 ± 5	0.1270
	2000	151 ± 10	134 ± 10	123 ± 10	132 ± 10	131 ± 10	0.3732
	2002	204 ± 17	187 ± 17	172 ± 17	195 ± 17	185 ± 17	0.7652
Diameter (cm)							
	1998	1.64 ± 0.07	1.51 ± 0.07	1.47 ± 0.07	1.53 ± 0.07	1.49 ± 0.07	0.5487
	2000	2.44 ± 0.18	2.22 ± 0.18	2.00 ± 0.18	2.16 ± 0.18	1.94 ± 0.18	0.3748
	2002	3.58 ± 0.30	3.29 ± 0.30	2.91 ± 0.30	3.17 ± 0.30	2.73 ± 0.30	0.3530
Basal area (m^2 ha^{-1})							
	1998	0.35 ± 0.05	0.27 ± 0.05	0.27 ± 0.05	0.33 ± 0.05	0.34 ± 0.05	0.7286
	2000	0.78 ± 0.15	0.61 ± 0.15	0.51 ± 0.15	0.69 ± 0.15	0.58 ± 0.15	0.7494
	2002	1.57 ±0.33	1.35 ± 0.33	1.03 ± 0.33	1.45 ± 0.33	1.08 ± 0.33	0.7465

a Values are presented in the form of "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).

TABLE 8 *Regression equation parameters,[a] coefficients of determination (R^2),[b] and root mean square error (RMSE) values for predicting lodgepole pine growth from (a) tall aspen density and (b) tall aspen basal area in 2002[c]*

Lodgepole pine growth response variable		n	a	b	R^2	RMSE
a) Tall aspen density						
Stem diameter	2002	183	3.48	-0.281	0.114	0.94
Stem diameter increment	1998–2002	182	1.90	-0.446	0.146	0.68
Stem diameter increment	2000–2002	183	1.11	-0.430	0.139	0.39
Height	2002	183	220.00	-0.262	0.057	55.90
Leader length	2002	180	34.60	-0.213	0.009	12.00
b) Tall aspen basal area						
Stem diameter	2002	183	3.41	-0.026	0.077	0.96
Stem diameter increment	1998–2002	182	1.85	-0.042	0.112	0.70
Stem diameter increment	2000–2002	183	1.09	-0.043	0.111	0.40
Height	2002	183	213.10	-0.020	0.037	56.50
Leader length	2002	180	33.90	-0.0173	0.008	12.00

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

b $R^2 = 1 - \sum(y - ae^{bx})^2 / \sum - (y - \bar{y})^2$, where $\bar{y}$ is the overall mean.

c Regression analysis included aspen within a 1.0-m radius around target lodgepole pine.

when tall aspen within a 1.0 m radius of target pine were included in the regression model (Table 9). Including tall aspen within smaller (0.5 m) or larger (1.78, 2.5, and 3.0 m) radius subplots reduced the predictive ability of tall aspen density and tall aspen basal area. Lodgepole pine leader length was best predicted by including tall aspen within only a 0.5-m radius of the pine, but the relationship was extremely weak (R^2 values were less than 0.02).

4.1.6 Understorey vegetation Removal of aspen to desired treatment densities reduced broadleaf cover in the thinning treatments relative to the control, but there were no obvious effects on total vegetation cover, or on the cover of conifers, shrubs, or herbs across the treatments (Table 10). Shrub cover increased and herb cover decreased between 1998 and 2002, but the changes were consistent across treatments and might be partly explained by differences in the subjective estimates made by assessors.

TABLE 9 *Coefficients of determination (R^2) and root mean square error (RMSE) for regression models[a,b] that predict target lodgepole pine size from (a) tall aspen density and (b) tall aspen basal area in different-sized neighbourhoods around the target pine*

			Neighbourhood radius									
			0.5 m		**1.0 m**		**1.78 m**		**2.5 m**		**3.0 m**	
		n	**R^2**	**RMSE**	**R^2**	**RMSE**	**R^2**	**RMSE**	**R^2**	**RMSE**	**R^2**	**RMSE**
a) Tall aspen density												
Stem diameter	2002	183	0.052	0.97	**0.114**	**0.94**	0.073	0.96	0.070	0.96	0.051	0.97
Diameter increment	1998–2002	182	0.060	0.72	**0.146**	**0.68**	0.115	0.70	0.119	0.69	0.115	0.70
Diameter increment	2000–2002	183	0.052	0.41	**0.139**	**0.39**	0.100	0.40	0.096	0.40	0.086	0.40
Height	2002	183	0.032	56.70	**0.057**	**55.90**	-0.046	58.90	-0.090	60.10	-0.174	62.40
Leader length	2002	180	**0.014**	**12.00**	0.009	12.00	-0.041	12.30	-0.057	12.40	-0.078	12.50
b) Tall aspen basal area												
Stem diameter	2002	183	0.039	0.98	**0.077**	**0.96**	0.041	0.98	0.036	0.98	0.039	0.98
Diameter increment	1998–2002	182	0.047	0.72	**0.112**	**0.70**	0.080	0.71	0.079	0.71	0.076	0.71
Diameter increment	2000–2002	183	0.047	0.41	**0.111**	**0.40**	0.076	0.40	0.066	0.41	0.068	0.41
Height	2002	183	0.019	57.00	**0.037**	**56.50**	0.002	57.50	-0.001	57.60	-0.001	57.60
Leader length	2002	180	**0.018**	**12.00**	0.008	12.00	-0.010	12.10	-0.008	12.10	-0.010	12.10

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

b The highest R^2 and lowest RMSE values are shown in bold.

TABLE 10 *Mean percent cover of understorey vegetation in 1998 (before manual cutting of aspen to treatment densities) and in 2000 and 2002*

		Aspen density treatment (aspen stems ha^{-1})				
		0	1000	2500	4000	Control
All vegetation (%)						
Pre-treatment	1998	97 ± 1	98 ± 1	96 ± 2	97 ± 1	97 ± 1
	2000	90 ± 1	97 ± 0	96 ± 1	97 ± 1	96 ± 1
	2002	84 ± 2	86 ± 2	85 ± 1	87 ± 2	90 ± 1
Conifers (%)						
Pre-treatment	1998	5 ± 1	7 ± 1	7 ± 3	9 ± 2	6 ± 1
	2000	8 ± 1	9 ± 1	5 ± 1	8 ± 1	7 ± 1
	2002	7 ± 1	8 ± 1	4 ± 1	7 ± 1	4 ± 0
Broadleaves (%)						
Pre-treatment	1998	31 ± 3	42 ± 5	44 ± 1	46 ± 5	28 ± 3
	2000	15 ± 3	19 ± 2	28 ± 3	28 ± 4	37 ± 4
	2002	21 ± 5	20 ± 2	25 ± 5	28 ± 3	43 ± 4
Shrubs (%)						
Pre-treatment	1998	12 ± 5	9 ± 2	7 ± 2	9 ± 3	6 ± 1
	2000	20 ± 3	18 ± 4	21 ± 4	25 ± 9	19 ± 3
	2000	23 ± 5	18 ± 5	31 ± 4	30 ± 9	28 ± 7
Herbs (%)						
Pre-treatment	1998	91 ± 4	94 ± 1	94 ± 2	95 ± 1	96 ± 1
	2000	78 ± 3	78 ± 4	75 ± 3	75 ± 6	77 ± 6
	2002	67 ± 4	68 ± 5	67 ± 4	68 ± 2	69 ± 2

4.2 Stand-level Treatment Responses

Treatment effects on stand structure were assessed by considering all live aspen and pine stems in the subplots.

4.2.1 Stand-level aspen

Density Manual cutting treatments applied in 1998 reduced total aspen density from the control value of 23 483 stems ha^{-1} to 1371, 2807, and 4937 stems ha^{-1} in the 1000, 2500, and 4000 stems ha^{-1} retention treatments, respectively (Table 11). Between 1998 and 2002, total aspen density in the untreated control decreased by approximately 6000 stems ha^{-1} as a result of self-thinning—a rate of approximately 6% per year. Total aspen density increased slightly between 1998 and 2000 in the retention treatments because stems that were previously shorter than 30 cm grew tall enough to be included in the data set. By 2002, it was no longer possible to differentiate consistently between suckers that had emerged following the cutting treatment and small stems that had been present before cutting, so only previously measured painted stems were included in the density calculations. Total aspen density declined slightly between 2000 and 2002 because there had been a small amount of mortality in the treatments, but continued to remain above the nominal values in all the treatments.

Height and diameter During the cutting treatments that were applied to reduce aspen densities to the nominal treatment values, short aspen were removed and the tallest, most vigorous stems were retained. As a result, mean aspen height became significantly larger in the 1000, 2500, and 4000 stems ha^{-1} treatments than in the untreated control immediately after cutting in 1998 (p=0.0061, Table 11). As shown by the diameter distributions in Figure 5, aspen in the cutting treatments moved into larger diameter classes at a faster rate (by proportion, not absolute numbers) than aspen in the uncut control. In all measurement years, quadratic mean diameter, which gives greater weight to larger stems, was significantly larger in all density treatments than in the control. Figure 6 portrays stand characteristics before application of the 2500 stems ha^{-1} retention treatment and during the 4 years after treatment.

Basal area In 1998, aspen basal area was significantly reduced from the control level by all thinning treatments (p<0.0001). Aspen basal area was also larger in the 4000 than in the 2500 or 1000 stems ha^{-1} treatments. This trend (Figure 7) continued through 2002, although the significant difference between the 2500 and 4000 stems ha^{-1} treatments eventually disappeared. Between 1998 and 2002, aspen basal area increased by 72% in the untreated control compared with 140%, 178%, and 141% in the 1000, 2500, and 4000 stems ha^{-1} treatments, respectively.

TABLE 11 *Mean[a] stand-level aspen[b] density, height, stem diameter, quadratic mean diameter, and basal area in the control and 1000, 2500, and 4000 stems ha^{-1} density treatments, 1998–2002*

		Aspen density treatment (aspen stems ha^{-1})				
Aspen variable		**1000**	**2500**	**4000**	**Control[b]**	**p-value[c]**
Density (stems ha^{-1})	1998	1371 ± 683 c	2807 ± 683 bc	4937 ± 683 b	23,483 ± 683 a	<**0.0001**
	2000	1518 ± 625 c	3294 ± 625 bc	5932 ± 625 b	20,506 ± 625 a	<**0.0001**
	2002	1459 ± 457 c	2984± 457 c	5541 ± 457 b	17,522 ± 457 a	<**0.0001**
Height (cm)						
	1998	179 ± 11 a	185 ± 11 a	178 ± 10 a	134 ± 10 b	**0.0061**
	2000	198 ± 16	199 ± 16	195 ± 16	159 ± 16	0.0877
	2002	244 ± 26	255 ± 25	256 ± 25	202 ± 25	0.2047
Diameter (cm)						
	1998	1.99 ± 0.08 a	1.96 ± 0.07 a	2.03 ± 0.07 a	1.47 ± 0.06 b	<**0.0001**
	2000	2.47 ± 0.13 a	2.36 ± 0.13 a	2.32 ± 0.12 ab	1.77 ± 0. 12 b	**0.0071**
	2002	3.15 ± 0.18 a	3.07 ±0.18 a	2.91 ± 0.17 ab	2.17 ± 0.17 b	**0.0113**
Quadratic mean diameter (cm)	1998	1.42 ± 0.02 a	1.42 ± 0.02 a	1.44 ± 0.02 a	1.25 ± 0.02 b	<**0.0001**
	2000	2.61 ± 0.12 a	2.52 ± 0.11 a	2.47 ± 0.11 a	1.92 ± 0.11 b	**0.0012**
	2002	3.32 ± 0.16 a	3.26 ±0.16 a	3.08 ± 0.16 a	2.37 ± 0.16 b	**0.0056**
Basal area (m^2 ha^{-1})	1998	0.5 ± 0.2 c	0.9 ± 0.2 c	1.7 ± 0. 2 b	4.6 ± 0.2 a	<**0.0001**
	2000	0.8 ± 0.3 c	1.6 ± 0.3 bc	2.8 ± 0.3 b	6.0 ± 0.3 a	<**0.0001**
	2002	1.2 ± 0.5 c	2.5 ± 0.5 bc	4.1 ± 0.5 b	7.9 ± 0.5 a	<**0.0001**

a Values are presented in the form of "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 before cutting, but does not include new suckers.
c Values are in **bold** if they are significant at p≤0.05 according to analysis of variance. Means are assigned different letters if they are significantly different within the given year according to the Bonferroni test.

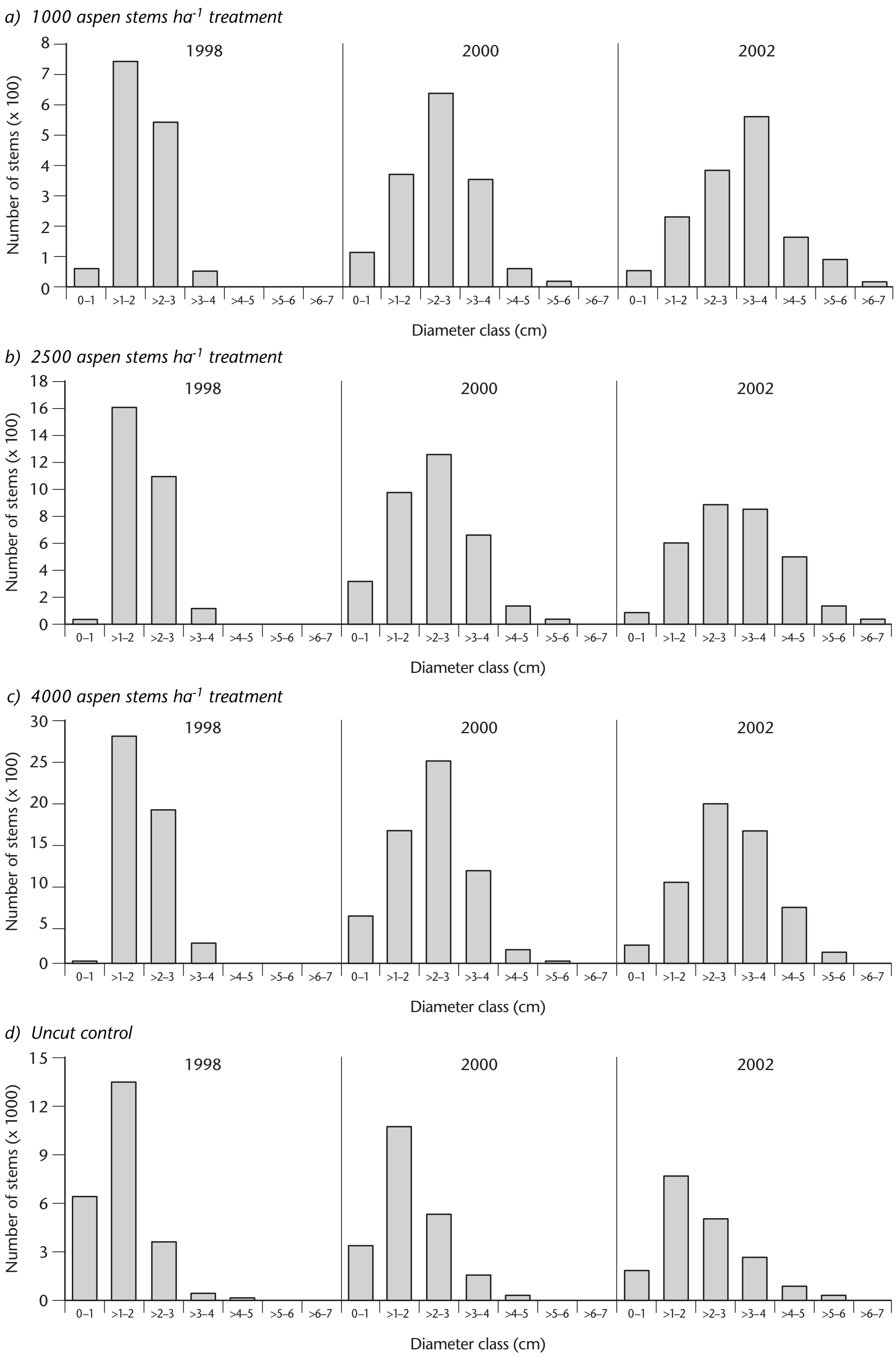

FIGURE 5 *Aspen diameter distributions in 1998, 2000, and 2002, by aspen density treatment.*

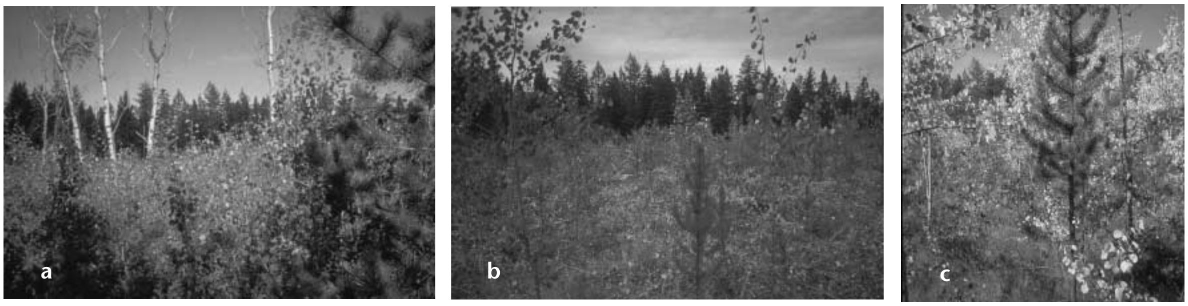

FIGURE 6 *Aspen and lodgepole pine in the 2500 aspen stems ha^{-1} retention treatment (a) before cutting, (b) immediately after cutting, and (c) 4 years after cutting.*

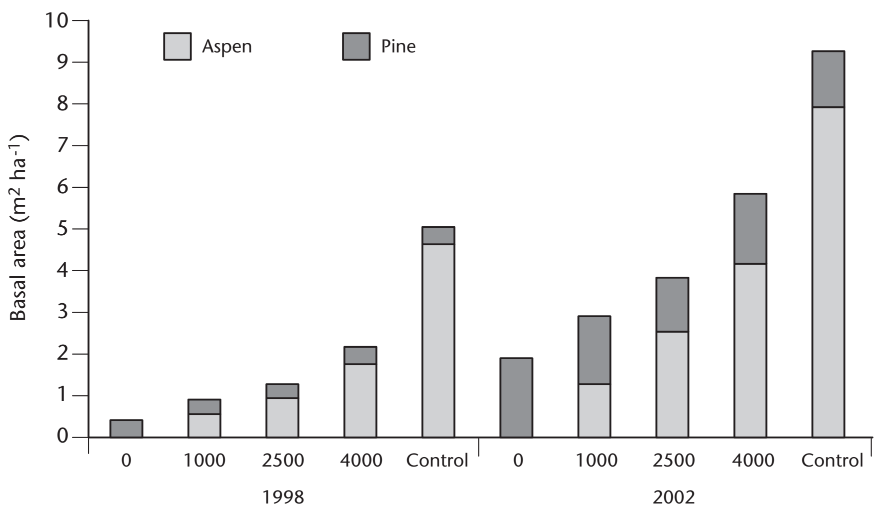

FIGURE 7 *Comparison of aspen and pine basal area in 1998 and 2002 (not including new suckers).*

Suckering No differences were found in the average number of suckers produced in the four density treatments in 2000 or 2002, nor any differences in sucker height (Table 12). In both years, however, the magnitude of the differences between treatments was large and there was a clear downward trend with increasing aspen density, despite the substantial variability within treatments and consequent lack of statistical significance. For example, by 2002, there were 2.5 times as many suckers in the 0 stems ha^{-1} treatment as in the 4000 stems ha^{-1} treatment.

Sucker densities also declined rapidly between assessment years. In 2000, the density averaged 24 510 suckers ha^{-1} across the 0, 1000, 2500, and 4000 stems ha^{-1} treatments, and sucker height averaged 46.2 cm. By 2002, the density averaged 14 854 suckers ha^{-1} across all treatments, with an average height of 75.3 cm (Figure 8). Figure 9 shows aspen sucker development in the 0 stems ha^{-1} treatment.

TABLE 12 *Mean[a] density and height of aspen suckers in aspen density treatments in 2000 and 2002*

		Aspen density treatment (aspen stems ha^{-1})				
		0	**1000**	**2500**	**4000**	**p-value**
Number of suckers per plot[b]						
(number of suckers per hectare)[c]	2000	95 ± 13	74 ± 13	61 ± 13	47 ± 13	0.1505
		(33 599)	(26 208)	(21 610)	(16 623)	
	2002	64 ± 10	42 ± 10	37 ± 10	25 ± 10	0.1156
		(22 635)	(14 854)	(13 086)	(8842)	
Average sucker height (cm)						
	2000	47 ± 4	48 ±4	45 ± 4	45 ± 4	0.2554
	2002	83 ± 7	72 ± 7	74 ± 7	72 ± 7	0.7073

a Values are presented in the form of "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 Means and standard errors refer to number of suckers per 28.3 m^2 plot (r=3.0 m). Values in brackets are numbers of suckers per hectare.
c Values in brackets are suckers per hectare.

4.2.2 Stand-level lodgepole pine No significant differences were found in the density of planted lodgepole pine in any measurement year. Average densities across treatments were 1805 stems ha^{-1} in 1998, 1793 stems ha^{-1} in 2000, and 1745 stems ha^{-1} in 2002.

There were also no significant between-treatment differences in lodgepole pine height, stem diameter, or basal area, in 1998, 2000, or 2002 (p>0.05, Table 13). In 1998, pine averaged a height of 102 cm and a ground-level stem diameter of 1.50 cm. By 2002, its average height was 191 cm and average diameter was 3.15 cm.

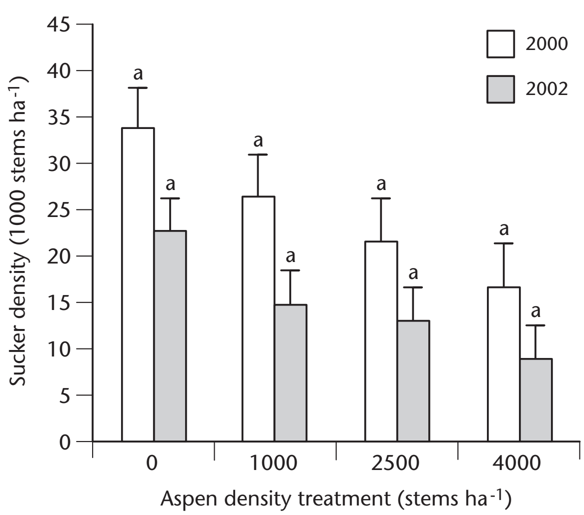

FIGURE 8 *Aspen sucker densities in aspen density treatments in 2000 and 2002. Error bars represent 1 standard error. Means having the same letter within a single year are not significantly different from one another according to the Bonferroni test (adjusted p>0.05).*

TABLE 13 *Mean[a] stand-level lodgepole pine[b] density, size, and basal area in aspen density treatments in 1998, 2000, and 2002*

		Aspen density treatment (aspen stems ha^{-1})					
Pine variable		**0**	**1000**	**2500**	**4000**	**Control**	**p-value**
Density (stems ha^{-1})							
	1998	1783 ± 169	1651 ± 169	1695 ± 169	1879 ± 169	2019 ± 169	0.5706
	2000	1739 ± 167	1658 ± 167	1687 ± 167	1894 ± 167	1989 ± 167	0.5940
	2002	1695 ± 162	1665 ± 162	1658 ± 162	1849 ± 162	1857 ± 162	0.8170
Height (cm)							
	1998	113 ± 5	106 ± 5	100 ± 5	97 ± 5	102 ± 5	0.1022
	2000	149 ± 8	137 ± 8	127 ± 8	135 ± 8	133 ± 8	0.4340
	2002	200 ± 15	191 ± 15	176 ± 15	198 ± 15	190 ± 15	0.8047
Diameter (cm)							
	1998	1.62 ± 0.07	1.51 ± 0.07	1.47 ± 0.07	1.54 ± 0.06	1.50 ± 0.06	0.5742
	2000	2.38 ± 0.17	2.24 ± 0.17	2.02 ± 0.17	2.18 ± 0.17	1.95 ± 0.17	0.4186
	2002	3.50 ± 0.27	3.32 ± 0.27	2.92 ± 0.27	3.20 ± 0.27	2.79 ± 0.27	0.3873
Basal area (m^2 ha^{-1})							
	1998	0.40 ± 0.06	0.34 ± 0.06	0.33 ± 0.06	0.40 ± 0.06	0.41 ± 0.06	0.7523
	2000	0.90 ± 0.16	0.77 ± 0.16	0.65 ± 0.16	0.83 ± 0.16	0.70 ± 0.16	0.8276
	2002	1.83 ±0.37	1.69 ± 0.37	1.30 ± 0.37	1.74 ± 0.37	1.31 ± 0.37	0.7647

a Values are presented in the form of "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.

Average pine basal area increased from 0.38 to 1.57 m^2 ha^{-1} between 1998 and 2002. In 1998, aspen basal area in the uncut control was approximately 11 times greater than pine basal area. In comparison, aspen basal area in the 1000 stems ha^{-1} treatment was approximately the same as that of pine, and was 2.7 and 4.3 times greater in the 2500 and 4000 stems ha^{-1} treatments, respectively (Figure 7). By 2002, aspen basal area in the untreated control was only 6 times greater than that of pine, compared with 1.9 and 2.4 times greater in the 2500 and 4000 stems ha^{-1} treatments, respectively.

In contrast, pine basal area in 2002 was 1.4 times greater than aspen basal area in the 1000 stems ha^{-1} treatment.

FIGURE 9 *Aspen sucker development in the 0 stems ha^{-1} treatment, 4 years after cutting.*

The Meldrum Creek variable density study is investigating the effects of five levels of aspen retention—an untreated control, a complete removal treatment, and 1000, 2500, and 4000 stems ha^{-1}—on lodgepole pine survival and growth in the IDFxm subzone. Stand development and neighbourhood interactions between pine and aspen under the different treatment regimes are also being studied.

5.1 Target Pine Responses

Four years after aspen density was manipulated, survival of the 10-year-old target lodgepole pine was at least 92% in all treatments, including the control, and there were no significant improvements in any growth parameters. Height:diameter ratio tended to decrease in the treatments relative to the control, but the differences were not statistically significant. The lack of response thus far is attributed to the young stand age, the fact that growth rates for both pine and aspen are relatively slow in the IDFxm, and the substantial natural variability among blocks. By 2002, aspen basal area was still less than 8 m^2 ha^{-1}, which indicates that at least 60% full light is available beneath the aspen canopy (Comeau 2002). In addition, moose browse damage to both pine and aspen has been ongoing at the Meldrum Creek site and has likely contributed to the slow stand development and the variability in treatment response. However, moose damage is common in pine–aspen stands in the IDFxm subzone and its occurrence is considered to be a normal factor.

Results from the retrospective study conducted by Newsome et al. (2003) in naturally regenerated pine–aspen stands in the IDFdk subzone of the Cariboo-Chilcotin area also showed no significant differentiation in lodgepole pine height with increasing tall aspen density when stands were 8–12 years old. At that age, pine stem diameter was significantly reduced by competition only when tall aspen densities exceeded 10 000 stems ha^{-1}. By the time the IDFdk retrospective sites were 13–17 years old, significant differences in stem diameter and height were emerging between pine with no neighbouring tall aspen and pine with neighbouring tall aspen at a density of more than 2000 stems ha^{-1}. Differences were more pronounced by the time stands were 15–19 years old, and the effects of competition may increase further as the stands age. 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), and significant differences in lodgepole pine size—particularly in stem diameter—are expected to appear in future assessments at Meldrum Creek.

Pine vigour at Meldrum Creek declined between 1998 and 2002, mainly because of ongoing moose browse. Although the frequency of moose-browsed trees was slightly higher in the 2500 stems ha^{-1} treatment than other treatments, the reason is not apparent. Likewise, pine western gall rust and pine needle cast were common in the stand, but there were no obvious trends of occurrence that could be linked to the density of aspen retention. Finck et al. (1989) report that western gall rust mainly attacks vigorously growing trees in open stands. Contrary to this, the disease at Meldrum Creek was approximately as common in the uncut control as in the treatment where all aspen had been removed. At another study site in the SBSdw2, western gall rust occurred somewhat more frequently in areas of dense aspen than where pine were open-grown (Newsome et al. 2004).

5.2 Competition Thresholds

Aspen can provide short- and long-term benefits to sites by maintaining productivity (e.g., Pearson and Lawrence 1958; Pastor 1990; Prescott et al. 2000), slowing the spread of root disease (Morrison et al. 1991; Peterson and Peterson 1995), improving microclimate for conifer growth (DeLong 2000), and increasing resistance to windthrow (Frivold 1985; Yang 1989). However, aspen is also a strong competitor for light, and at high densities it can hinder pine performance (Newsome et al. 2003). Since current management objectives in the Cariboo-Chilcotin area of the Southern Interior Forest Region focus on softwood timber production, silviculturists need to know how much aspen can be retained without leading to unacceptable conifer growth losses.

One of the objectives of the Meldrum Creek variable density study was to test and refine competition thresholds that had been suggested by early results of the retrospective study (Newsome et al. 2003). When the Meldrum Creek study was established in 1998, the retrospective study results were indicating that competition thresholds for lodgepole pine stem diameter growth were below 5000 tall aspen stems ha^{-1}. Therefore, densities of 1000, 2500, and 4000 stems ha^{-1} were applied at the Meldrum Creek site. The most recent data from the retrospective study were collected when IDFdk stands were 15–19 years old and led to recommendations that no more than 2000 tall aspen stems (i.e., stems taller than target pine) should be present to ensure good pine growth in stands of that age. Simard et al. (2001) identified an aspen density threshold of 3180 stems ha^{-1} for stem diameter growth of 2- to 10-year-old lodgepole pine in the MS and IDF zones of southern interior British Columbia., but all aspen stems—not only those taller than the target pine—were included in that threshold value.

Results from the retrospective study also suggested that thresholds were decreasing with stand age. Future assessments may thus cause the current recommendations to change. The competitive effects of aspen on lodgepole pine have not yet become significant at the Meldrum Creek site, but the study will continue to contribute information about thresholds for aspen retention on dry IDF sites as the stand ages. A variable density study to investigate the effects of manipulating aspen density on pine performance is also under way in the SBSdw2 variant of the Cariboo Forest Region, but results are not yet available (Wang and Letchford 2000). Comeau et al. found height growth of underplanted white spruce was slightly better in thinned than unthinned boreal aspen stands.[2]

5.3 Size of the Competitive Neighbourhood

Regression analysis of data collected in 2002 suggests that aspen within a 1.0 m radius of target lodgepole pine are the main competitors at Meldrum Creek. The highest R^2 values for relationships between tall aspen density and pine diameter variables were consistently found using a measurement plot radius of 1.0 m rather than smaller (0.5 m) or larger (1.78, 2.5, or 3.0 m) radii. Tall aspen density explained a maximum of 14.6% of the variation in stem diameter increment in the 10-year-old stand, and this correlation is expected to improve if competition for light becomes a more important factor as the stand ages. Retrospective study results suggested that competition was taking place within a 1.78 m radius of target pine at age

2 P.G. Comeau, C.N. Filipescu, R. Kabzems, and C. DeLong. [2004.] Early growth of white spruce underplanted beneath spaced and unspaced aspen stands in northeastern B.C. (Submitted to Can. J. For. Res.)

15–19 years (Newsome et al. 2003), and the distance over which aspen compete with target pine may also increase with age at Meldrum Creek.

Lieffers et al. (2002) found that plots less than 2 m in radius did not provide a good representation of light competition between aspen and white spruce in boreal stands. In that study, understorey light was minimized when aspen were 10–12 m tall, and the authors suggest that plots of 10-m radius would be required to assess understorey light conditions at that stage of stand development. Simard and Sachs (2004) also found that the size of the competitive neighbourhood in 11-year-old Douglas-fir and paper birch stands in the ICHmw subzone of the Kamloops area of the Southern Interior Forest Region was larger than has been found for aspen and pine in either the present Meldrum Creek study or in the retrospective study. In the Simard and Sachs study, broadleaves up to 3–4 m from the target conifers were found to be contributing to competition.

The apparently smaller neighbourhood size in the Cariboo-Chilcotin studies compared to that in the Lieffers et al. (2002) and Simard and Sachs (2004) studies could be due to a lesser height differential between conifers and broadleaves. Greater height differentials in the aspen–spruce and birch–Douglas-fir stands would have allowed broadleaves to shade conifers from a greater distance. Pine is more shade-intolerant than Douglas-fir or white spruce and is therefore less likely to survive over the long term, when it is severely overtopped. In our Cariboo-Chilcotin pine–aspen stands, pine tend to be growing within the aspen canopy rather than below it (i.e., it is co-dominant), which is important because light levels within aspen stands increase rapidly from the base to the top of the canopy. Conifers that have achieved 40% of the canopy height in aspen stands receive approximately 80% full sunlight (Comeau 2002). In 9- to 15-year-old IDF stands in the retrospective study, height differentials between aspen and pine were in the range of 0.3 –3.0 m. In the 10-year-old Meldrum Creek stand, they were in the range of 0.9–1.25 m.

5.4 Stand Characteristics

Interest in mixedwood management is increasing in British Columbia, particularly with regard to white spruce–aspen stands in boreal regions. Models for those stands suggest that biomass yield will be greater in mixed than pure conifer stands (Wang et al. 1995), especially where a two-pass harvesting strategy is adopted (Welham et al. 2002). Management objectives for Cariboo-Chilcotin stands currently focus on softwood timber production, with the interest in aspen retention being centred around issues of forest health, biodiversity, and sucker reduction. Nonetheless, aspen fibre is now being utilized by some local forest companies, and stand development data are likely to be useful for future analyses and modelling projects that will guide mixedwood management.

In 1998, when the thinning treatments were applied at Meldrum Creek, aspen density in the control was 23 483 stems ha^{-1}, of which 13 521 stems ha^{-1} were taller than the target lodgepole pine. Cutting treatments immediately reduced tall aspen densities to approximately the nominal treatment values of 0, 1000, 2500, and 4000 stems ha^{-1} and reduced total aspen basal area by 63–100%. Diameter distributions changed in the cutting treatments relative to the control because the largest, most vigorous aspen stems were retained and smaller stems were removed. As a result, increases in aspen basal area between 1998 and 2002 were proportionally larger in the cutting treatments (140–178%) than in the control (72%). Lodgepole pine basal area averaged

0.38 m^2 ha^{-1} in 1998, and, by 2002, had increased to 1.57 m^2 ha^{-1}. In 2002, aspen basal area exceeded that of pine in the 2500 and 4000 stems ha^{-1} treatments and the uncut control, whereas the opposite was true in the 0 and 1000 stems ha^{-1} treatments. Peterson and Peterson (1995) suggest that, although aspen self-thin efficiently, thinning treatments enhance aspen sawlog production.

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 produced. This phenomenon has been subjectively observed in the Cariboo Forest Region, and is currently being studied in the SBSdw1 variant (Wang and Letchford 2000). A clear downward trend in sucker production with increasing aspen density was likewise found at Meldrum Creek. However, although differences in sucker counts between the different cutting treatments were large, they were not statistically significant because of the large variability between subplots. Two years after cutting, sucker densities ranged from 33 599 in the 0 stems ha^{-1} treatment to 16 623 in the 4000 stems ha^{-1} treatment. Sucker densities decreased by one-third to one-half within 4 years of cutting, but were still above 8000 stems ha^{-1} in all treatments. Prévost and Pothier (2003) found that removing 35 or 50% basal area in a 60- to 65-year-old aspen–conifer stand in Quebec limited sucker production to less than 1000 stems ha^{-1} 5 years after cutting, whereas removing 65 or 100% basal area resulted in at least 8000 new stems ha^{-1}.

5.6 Future Work related to Management and Operational Recommendations

The Meldrum Creek study is one of a series of experiments currently underway 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 on site if partial brushing treatments are considered. 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 years (Newsome et al. 2003). The Meldrum Creek study will eventually provide information to corroborate or refine this recommendation, but longer-term measurements are required before this objective can be achieved.

Further data collection is also required before recommendations can be made regarding the effects of cutting treatments on sucker production, survival, and growth. In 2000 and 2002, sucker density was determined, and representative heights and diameters were measured. Densities are changing rapidly, however, and ongoing assessments are required to assess their development. In future assessments, all aspen suckers will be measured so that their contribution to stand development can be taken into account.

The effects of manipulating aspen density on stand development will be further investigated. Growth and yield plots will be established at the Meldrum Creek study site at the time of the next assessment. Data collected from these plots over the long term will be helpful in the calibration of a variety of models capable of predicting the long-term effects of variable density treatments on growth and yield and stand development. Much more in-depth analysis of the spatial aspects of competition between pine and aspen is also planned. Data have already been collected on the distance of aspen from target pine within the 3.0 m radius subplots, but they require further assessment and analysis before they can be used to model the competitive relationship between aspen and pine.

Finally, additional data collection is required to clarify issues related to free-growing guidelines. At the next assessment, when the stand is 12 years old, surveys will be carried out to determine which treatments have allowed the stand to meet current free-growing requirements (B.C. Ministry of Forests 2002). It is also necessary to determine whether the current guidelines are biologically appropriate for the IDFxm subzone. The collection of data beyond the latest free-growing age (15 years old for lodgepole pine in the IDFxm) will provide policy-makers with a basis for refining the current guidelines. The results, it is hoped, will allow aspen retention to be set at the maximum levels that will still allow pine to perform well through the rotation. The issue of refining allowable density guidelines is extremely important because of the long-term contribution that aspen make to stand health and site quality, and because of the potential for reducing stand-tending costs.

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, 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 has a poor growth rate.
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)

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 – Snow press
V – Vegetation press
W – Climate – drought
R – Rodents, small animals

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

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