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Effects of Variable Aspen Retention on Stand Development, Aspen Sucker Production, and Growth of Lodgepole Pine in the SBSdw1 Variant of South-central British Columbia

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Ministry of Forests and Range
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ABSTRACT

In 1999, an experiment was established to examine the effects of reducing aspen density on stand-level lodgepole pine and aspen growth in the SBSdw1 biogeoclimatic variant of the Cariboo–Chilcotin. Aspen retention treatments of 0, 500–800, 1000–1500, and 2000–2800 stems ha^{-1} were applied in an 11-year-old mixed-species stand of aspen and lodgepole pine. One year after cutting, aspen basal area in these retention treatments was 0, 1.25, 3.05, and 2.89 m^2 ha^{-1}, respectively, compared with 5.36 m^2 ha^{-1} in the control. Four years after treatment, based on stand-level measurements taken in permanent measurement plots, pine vigour tended to be better in treatments where <1000 aspen stems ha^{-1} had been retained but there were no significant differences in mean stand-level lodgepole pine height, stem diameter, quadratic mean diameter, or basal area as a result of the aspen retention treatments.

Aspen suckering was assessed 2 and 4 years after cutting. Sucker densities differed significantly between aspen retention treatments after 2 years, ranging from 28 187 stems ha^{-1} in the complete aspen removal treatment to 344 stems ha^{-1} in the 2000–2800 stems ha^{-1} treatment. Sucker densities appear to have declined naturally by approximately 35% between years 2 and 4 after cutting; however, this apparent decline may be partly due to a change in the sampling method. There were no significant differences between treatments in sucker height in either year 2 or 4 after cutting.

In addition to stand-level measurements, the ongoing performance of target lodgepole pine that had, or had not, met existing British Columbia Ministry of Forests free-growing requirements at a stand age of 12 years was assessed. By 2003, pine in the free-growing group were larger than those in the not free-growing group according to all measurement criteria. Regression analysis showed that tall aspen (i.e., aspen at least as tall as the target pine) within a 1.78-m radius were more important competitors with the target pine than aspen that were further away. When the stand was 13 years old, tall broadleaf basal area explained 25.7% of the variation in 2000–2003 lodgepole pine stem diameter increment.

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1 INTRODUCTION

Mixtures of trembling aspen (*Populus tremuloides* Michx.) and naturally regenerated or planted lodgepole pine (*Pinus contorta* var. *latifolia* Engelm. ex S. Wats.) occur throughout interior British Columbia. In the Cariboo–Chilcotin, they are especially common in the Sub-Boreal Spruce (SBS), Interior Douglas-fir (IDF), Sub-Boreal Pine–Spruce (SBPS), and Interior Cedar–Hemlock (ICH) biogeoclimatic zones (Meidinger and Pojar 1991). Juvenile pine–aspen stands may require management because fast-growing aspen often compete with shade-intolerant lodgepole pine for many years (Newsome et al. 2003). At low densities, however, aspen confers advantages to both individual conifers and the site as a whole.

Aspen benefits overall site quality by retaining nutrients, especially calcium, within the ecosystem (Pastor 1990). Aspen presence also slows the spread of Armillaria and Phellinus root rots on infected sites because it is more resistant to these diseases than most conifers (Morrison et al. 1991; Peterson and Peterson 1995; Gerlach et al. 1997). The communal, sucker-derived root system of aspen (Strong and La Roi 1983) may also reduce windthrow among neighbouring conifers (Frivold 1985; Yang 1989). Mature aspen canopies provide protection from frost damage to understorey conifer seedlings by decreasing nighttime radiative heat loss (Stathers 1989; DeLong 2000), although this is a more important consideration for white spruce than for lodgepole pine because of differences in frost tolerance (Farnden 1994).

Despite the beneficial role of aspen, at high densities it can reduce both light and soil water to levels that are limiting to conifer growth for at least part of the growing season (DeLong and Tanner 1996). Light availability is particularly important in pine–aspen stands because both species are very shade-intolerant (Klinka and Scagel 1984a, 1984b). In low-light environments, lodgepole pine will allocate more growth to terminal than lateral shoots, and reduce its branch production (Chen et al. 1996). Studies in young stands have shown that lodgepole pine growth is negatively affected by the presence of abundant broadleaves (e.g., Simard et al. 2001). Mechanical "whipping" damage to conifer leaders is also common in aspen stands (Lees 1966).

To develop effective management stategies for mixed stands where softwood timber production is the primary objective, silviculturists need information about levels of broadleaves that can be retained without seriously reducing conifer performance. They also require practical guidance on using this information to develop cost-effective treatment prescriptions. To address this topic in the Cariboo–Chilcotin, a pine–aspen competition project that includes studies in a variety of ecosystems is currently under way. The retrospective portion of the study, which was conducted in naturally regenerated pine–aspen stands from 1992 to 1999, suggested that 1000 tall aspen stems ha^{-1} (i.e., 1000 aspen stems at least as tall as the target pine) is an appropriate threshold for ensuring acceptable pine growth in 17- to 18-year-old stands in the SBSdw subzone. Above that density, diameter growth tended to decrease (Newsome et al. 2003). Longer-term information is currently being gathered because the study also indicated that the apparent threshold decreases with stand age.

Managers also require guidance regarding the degree of aspen suckering that can be anticipated under various aspen retention regimes. This is important for the management of juvenile pine–aspen stands because of the potential need for additional stand entries following abundant suckering.

Sucker production increases with the level of aspen that is removed (e.g., Huffman et al. 1999), a phenomenon that is currently being assessed as part of the Cariboo–Chilcotin pine–aspen competition project (Newsome et al. 2004a, 2006). The mechanisms governing aspen sucker production are not completely understood, but contributing factors appear to include: (a) changes to hormonal balances following cutting treatments (suckering is stimulated by the loss of apical dominance); (b) soil temperature, moisture, and nutrient conditions; (c) aspen basal area prior to harvesting (presumably because aspen root density increases with basal area); (d) genetic characteristics of individual aspen clones; (e) site disturbance; and (f) season of cutting (Frey et al. 2003).

In 1999, an operational trial to study the effects of variable aspen retention on stand-level lodgepole pine performance and aspen sucker production was established near McKinley Lake in the SBSdw1 variant of the Central Cariboo Forest District. The study, which was also intended to test the appropriateness of free-growing guidelines that were current at the time (B.C. Ministry of Forests 2002) was a co-operative undertaking by the B.C. Ministry of Forests and Weldwood of Canada, Ltd. In 2002, the study was adopted by the Silvicultural Systems Research Group of the Southern Interior Forest Region as part of the pine–aspen competition project, and objectives and methods were subsequently adapted to include the collection of long-term growth and yield and stand development data. This report summarizes fourth-year pine and aspen responses to aspen retention treatments, and provides baseline stand development information.

2 OBJECTIVES

The objectives of the study are:

1. To examine the effects of different aspen retention levels on the growth of residual lodgepole pine and aspen.
2. To examine the effects of different aspen retention levels on aspen suckering.
3. To test the effectiveness of the free-growing criterion which specifies that the target conifer must be free of overtopping vegetation in three of four quadrants within a 1-m cylinder (B.C. Ministry of Forests 2002) by comparing ongoing growth of lodgepole pine that did and did not meet that specific criterion immediately following treatment.
4. To study the effects of aspen density treatments on growth and yield and stand development.

3 METHODS

3.1 Study Area

The McKinley Lake study site is located approximately 37 km southeast of Horsefly, B.C. (52° 13' N, 120° 56' W), at an elevation of 1000 m (Figure 1). The site, which has a southwesterly aspect and a slope of 10–40%, is in the SBSdw1 variant (Sub-Boreal Spruce dry warm subzone, Horsefly variant), site series 01/04. The SBSdw1 has mean annual precipitation of 585 mm, a

mean annual temperature of 3.7°C, an average of 152 frost-free days per year, and brunisolic zonal soils (Steen and Coupé 1997). The study area is located on an 84-ha cutblock (mapsheet-opening 93A 026–20) that was clearcut in 1988 and left to naturally regenerate. After 10 years, aspen ingress resulted in a patchy stand that did not meet free-growing requirements. The site, including the study area, was fill-planted with lodgepole pine in 2000. The developing stand was dominated by aspen and lodgepole pine, but black cottonwood (*Populus balsamifera* ssp. *trichocarpa* [T. & G.] Brayshaw), paper birch (*Betula papyrifera* Marsh.), subalpine fir (*Abies lasiocarpa* [Hook.] Nutt.), interior spruce (*Picea glauca* × *engelmannii*), and Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) were also present.

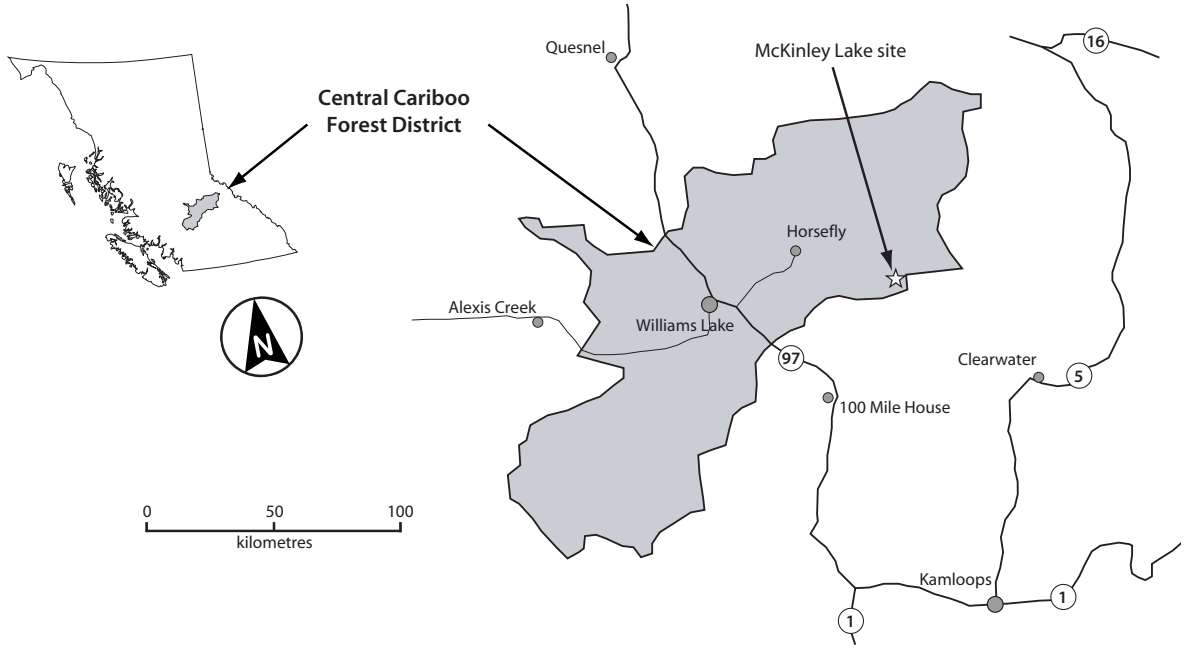

FIGURE 1 *Location of the McKinley Lake study site.*

3.2 Sampling Design and Treatments

The McKinley Lake study originally used a completely randomized design (CRD) with each of six density treatments replicated three times. Target densities for the treatments were 0, 600, 1200, 2500, and 5000 stems ha^{-1} plus the untreated control. These treatments were randomly assigned to eighteen 50 × 50-m treatment plots prior to cutting. Chainsaws were used to apply the treatments in July 1999, at the same time that the rest of the cutblock was operationally brushed to reduce aspen density to 600–1000 stems ha^{-1}. Crews were instructed regarding the appropriate spacing of aspen within individual treatment plots, but were hindered in their ability to achieve target densities by the patchy distribution of aspen and the fact that leave aspen were not marked. As a result, the densities achieved in most plots differed from the target densities, and the highest target density of 5000 stems ha^{-1} was not attained in any of the plots. After baseline data were further reviewed, the following aspen retention treatments were defined:

1. 0 stems ha^{-1} (three replicates)
2. 500–800 stems ha^{-1} (four replicates)
3. 1000–1500 stems ha^{-1} (four replicates)
4. 2000–2800 stems ha^{-1} (four replicates)
5. Untreated control (three replicates)

In 2000, one circular 5.64-m radius (0.01 ha) permanent measurement plot (PMP) was established in the aspen patch nearest to the centre of each treatment plot. Ten aspen and 10 pine stems were randomly selected in each PMP and were tagged for periodic measurement. The original intention had been to install 17.84-m radius PMPs, but it became apparent during installation of the first PMP in plot 1 that aspen densities were too high for this size to be practical. Consequently, in 2000, data were collected in a larger-radius PMP in plot 1 than in other plots. In 2003, the size of the PMP in plot 1 was reduced to 5.64 m. Also in 2003, PMPs were adapted for the periodic collection of growth and yield and stand development data by tagging all conifer and broadleaf stems ≥ 1.3 m tall. An exception was made for two of the three plots that had received the complete aspen removal (0 stems ha^{-1}) treatment because, by 2003, they included high densities of sucker-origin aspen that had grown taller than 1.3 m. In those two plots (15 and 17), broadleaves ≥ 1.3 m tall were tagged only within the four 1.78-m radius (0.001 ha) "small tree plots" (STPs—described below) that were established in 2003.

Different methods were used to assess aspen suckering in 2001 and 2003. In 2001, suckers were counted and measured within 10 randomly located 1 × 1-m quadrats within each treatment plot. In 2003, to facilitate repeated measures at the same location, four permanent 1.78-m radius (0.001 ha) small tree plots (STPs) were established in each PMP to assess sucker densities and growth, and to quantify trees of all species that were shorter than 1.3 m. The STPs were located 3 m from each PMP centre in the four cardinal directions.

A set of 60 target lodgepole pine was selected following treatment in 2000 to examine the ongoing performance of pine that, at age 12, had or had not met the free-growing criterion for overtopping (i.e., the target pine was taller than surrounding vegetation in three of four quadrants within a 1-m cylinder). Thirty pairs of target pine were selected: one that met the free-growing criterion, and one that did not. These pine were tagged and permanently assigned to either the free-growing or the not free-growing class for the duration of the study, regardless of whether their actual free-growing status

changed. Pairs were selected so that the two stems were growing in close proximity and were of similar height. Efforts were made to select two pine pairs in each aspen density treatment (except in the complete aspen removal treatment), but this proved impossible because free-growing pine were rare in some treatment plots.

3.3 Measurements

Assessments were done in either May or September. For the May assessments, total height was measured to the base of the previous year's growth because current year leader elongation was incomplete. For the September assessments, the current year leader was included in total height.

3.3.1 Stand development In May 2000, dbh of all trees within the 5.64-m PMPs was measured, and height was measured for the 10 pine and 10 aspen sample trees. In September 2003, all tagged trees (broadleaves and conifers) within each PMP were assessed for:

- Species
- dbh
- Total height
- Crown length
- Crown width (average of E–W and N–S)
- Vigour
- Damage and damage cause
- Height:diameter ratio (HDR) calculated from total height and dbh

Lodgepole pine survival, vigour, damage, and damage cause were assessed according to a standard research protocol (Appendix 1).

Quadratic mean diameter (QMD) was calculated from dbh for aspen and pine using Equation 1.

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

where QMD is quadratic mean diameter, dbh_i is diameter at 1.3 m of an individual aspen or pine tree, and n is the number of aspen or pine trees in the PMP.

3.3.2 Suckering In July 2001, aspen suckers were counted within each of ten 1 × 1-m quadrats that were randomly located in each PMP. Height and ground-level diameter were measured for the 10 tallest suckers in each quadrat. In 2003, aspen suckers were counted in the four 0.001-ha STPs that had been newly established in each PMP. The few black cottonwood or birch sprouts that were present were also counted in the 2003 assessment, and were treated as aspen for purposes of analysis (the presence of these species was so minor that it was judged unnecessary to distinguish them from aspen). Starting from due north from the centre to the edge of each STP, and travelling clockwise, height was measured for the first 15 suckers. Of these, ground-level diameter was measured for three representative (small, medium, large) suckers. Conifers between 0.3 and 1.3 m tall in the STPs were also counted.

3.3.3 Free-growing and not free-growing target lodgepole pine and their neighbourhoods In May 2000 and September 2001, target lodgepole pine in the free-growing and not free-growing classes were measured for:

- dbh
- Total height
- HDR (calculated)

In September 2003, the target pine were assessed for:

- dbh
- Total height
- Crown length
- Crown width (average of E–W and N–S)
- Vigour
- Damage and damage cause
- Free-growing status
- HDR (calculated)

Target pine survival, vigour, damage, and damage cause were assessed according to a standard research protocol (Appendix 1).

Also in May 2000, free-growing and not free-growing target pine neighbourhoods were assessed by measuring dbh of all neighbouring trees within a 3.99-m radius of each target pine. In 2003, to more closely investigate neighbourhood size and compare results with other studies, neighbourhood trees were assessed within 1.78-m and 3.99-m radii around each target lodgepole pine. Diameter (dbh) was measured for all stems at least 1.3 m tall, and height was measured for stems at least as tall as the target pine. Basal area and the change in basal area from 2000 to 2003 were calculated for all neighbourhood species. Densities were calculated on a per-hectare basis for all trees and for broadleaves. Additional information about 1999–2003 establishment and measurement activities at the McKinley Lake site is presented in Newsome and Heineman[1] (2006, unpublished report).

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. One-way analysis of variance (ANOVA) models (Tables 1, 2, 3) were fitted, and an *F*-test, with the error degrees of freedom calculated using Satterthwaite's method, was used to test the treatment effect on pine and aspen. All models include a fixed treatment effect and a random plot effect, which represents the variation among the experimental units to which treatments were randomly assigned. Where plots were subsampled there is an extra random factor to account for variation among the sampling units (i.e., trees or subplots) within plots (Tables 1, 3). The statistical significance of differences between all pairs of treatment means was assessed with the Bonferroni multiple comparison test (α=0.05). In some cases (i.e., aspen and pine basal area

1 Newsome, T.A. and J.L. Heineman. 2006. Effects of variable aspen retention on stand development, aspen sucker production, and growth of lodgepole pine in the SBSdw1 variant of south-central British Columbia (EP1269.02). Updated working plan/establishment report. B.C. Min. For. Range, Victoria, B.C. Unpublished report.

TABLE 1 *Sources of variation for examining the effects of aspen retention treatments on lodgepole pine and aspen height and diameter growth in PMPs*

Source of variation	Degrees of freedom[a,b]	Type of effect
Treatment	t–1=4	Fixed
Plots	n–t=13	Random
Trees	N–17–1	Random

a The associated degrees of freedom are the maximum values assuming no mortality or missing data.
b t=number of treatments; n=number of plots; N=total number of (live) trees.

TABLE 2 *Sources of variation for analyzing the effects of aspen retention treatments on lodgepole pine and aspen quadratic mean diameter and basal area per hectare*

Source of variation	Degrees of freedom[a,b,c]	Type of effect
Treatment	t–1=4	Fixed
Plots	n–t=13	Random

a The associated degrees of freedom are the maximum values assuming no mortality or missing data.
b For analyses that do not include the 0 stems ha^{-1} treatment, degrees of freedom for treatment decrease by 1 and degrees of freedom for the other terms decrease accordingly.
c t=number of treatments; n=number of plots.

TABLE 3 *Sources of variation for examining the effects of aspen retention treatments on aspen sucker density*

Source of variation	Degrees of freedom[a,b]	Type of effect
Treatment	t–1=4	Fixed
Plots	n–t=13	Random
Subplots	n(k–1)=54	Random

a The associated degrees of freedom are the maximum values assuming no mortality or missing data.
b t=number of treatments; n=number of plots (PMPs); k=number of quadrats (2001) or small tree plots (2003) per PMP.

per hectare and sucker density), a square-root transformation was applied to stabilize the variance and improve 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. Neighbourhood effects on free-growing and not free-growing pine were also investigated by fitting a non-linear model (Equation 2) relating pine growth to the abundance of remaining broadleaves (e.g., density or basal area increment). Boxplots and probability plots were used to examine the ANOVA and regression residuals for outliers and other departures from normality. Data analyses used the following SAS statistical software (SAS Institute Inc. 1996, 1999) procedures: PROC UNIVARIATE, PROC TABULATE, NLINMIX macro (Wolfinger 2000), and PROC MIXED (REML method of estimation).

3.4.1 Stand- and tree-level responses based on data collected in PMPs and STPs Summary statistics for all continuous PMP variables measured in 2001 or 2003 (the set of variables varied between the 2 years) were calculated by aspen retention treatment and year. Summary statistics for categorical PMP variables were calculated by aspen retention treatment for the 2003 assessment.

Tree-level responses of lodgepole pine and aspen to the aspen retention treatments (i.e., height, dbh, HDR) were analyzed using the ANOVA model shown in Table 1, based on data collected in 2003 for individual trees in PMPs. Stand-level 2003 responses of pine and aspen (i.e., quadratic mean diameter and square root–transformed basal area per hectare), based on data collected in PMPs, were analyzed using the model shown in Table 2. Sucker densities (square root–transformed) were analyzed using the model shown in Table 3. When sucker height was analyzed, Table 3 was modified to include individual stems within subplots or quadrats as an additional source of variation.

3.4.2 Free-growing and not free-growing target pine responses Summary statistics for continuous measurements of free-growing and not free-growing lodgepole pine were calculated for 2000, 2001, and 2003. Summary statistics for categorical variables were calculated by free-growing class for 2003. A paired *t*-test was used to compare means of pine growth variables for the free-growing and not free-growing groups by year.

3.4.3 Free-growing and not free-growing pine neighbourhood responses The following variables were calculated on the basis of 3.99-m radius neighbourhoods (50 m^2) around each of the 60 target pine:

- Total tree density[2] 2000
- Total tree density[2] 2003
- Broadleaf tree density[3] 2000
- Broadleaf tree density[3] 2003
- Total tree basal area[4] 2003
- Individual tree species basal area 2003[5]
- Change in individual tree species basal area[5] 2000–2003
- Change in total tree basal area[6] 2000–2003

The following variables were calculated on the basis of 1.78-m radius neighbourhoods (10 m^2) around each of the 60 target pine:

- Total tree density[2] 2003
- Broadleaf tree density[3] 2003
- Broadleaf tree basal area[3]
- Tall broadleaf tree density[7]
- Tall broadleaf tree basal area[7]

2 Includes all trees (broadleaves and conifers) ≥1.3m tall.
3 Includes aspen, black cottonwood, and paper birch ≥1.3m tall.
4 Includes broadleaves and conifers ≥1.3 m tall.
5 Includes stems ≥1.3m tall and calculated individually for each tree species.
6 Includes all tree species.
7 Includes aspen, black cottonwood, and paper birch taller than target pine.

Spearman's rank correlation coefficient was used to assess the degree of association between the above neighbourhood competition variables and the height, diameter, and 2000–2003 increments of the target lodgepole pine. Correlations were calculated separately for the free-growing and not free-growing pine, and for both groups combined. Relationships were further examined using scatter plots of pine size and growth versus the competition variables. Based on initial screenings, the neighbourhood abundance variables that showed the strongest relationships with pine height and diameter growth were (a) 2003 tall broadleaf basal area, (b) 2000–2003 tall aspen basal area increment, and (c) total 2003 tall broadleaf density based on a 1.78-m radius neighbourhood. These relationships were described by fitting regression models. Scatter plots indicated that the relationships were not linear, so the following exponential model (Equation 2) was selected to allow comparison of McKinley results with previously reported results for pine–aspen stands in other Cariboo–Chilcotin ecosystems (Newsome et al. 2003, 2004a, 2004b, 2006):

$$y = ae^{bx} + \delta_{\text{pair}} + \varepsilon_{\text{tree}} \tag{2}$$

where: y is pine height or diameter increment, x is the neighbourhood competition variable, δ_{pair} is the error due to random variation among pairs of pine, $\varepsilon_{\text{tree}}$ is the error due to variation between trees in individual pairs (and error due to lack of fit), 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….. Both error terms were assumed to be mutually independent and normally distributed with constant variances.

4 RESULTS

4.1 Stand Development

Stand development results are based on data collected in both PMPs and STPs (see Section 3.3.1), and include information about stems retained at the time of treatment and new suckers.

4.1.1 Stand composition In 2003, 4 years after broadleaf cutting treatments were applied at McKinley Lake, lodgepole pine and aspen were the dominant species in all treatments, but black cottonwood, paper birch, subalpine fir, interior spruce, and Douglas-fir also contributed 1–2% each to overall stand density (Table 4, Figure 2). In 2003, aspen density was greatest in the untreated control and least in the 500–800 stems ha^{-1} treatment. Pine density was highest in the 0 stems ha^{-1} treatment and lowest in the control. The high aspen density in the 0 stems ha^{-1} treatment was due to the presence of rapidly growing aspen suckers that had attained a height of 1.3 m by 2003. In other treatments, suckers had not grown as rapidly and densities reflect the presence of residual aspen only.

TABLE 4 *2003 stand composition (by stem density) in aspen retention treatments[a,b] at the McKinley Lake site*

	Aspen retention treament				
	0 stems ha^{-1}	**500–800 stems ha^{-1}**	**1000–1500 stems ha^{-1}**	**2000–2800 stems ha^{-1}**	**Control**
Aspen	2930 ± 1551	776 ± 193	1251 ± 119	1951 ± 65	4737 ± 884
Black cottonwood	0 ± 0	350 ± 350	50 ± 29	25 ± 25	0 ± 0
Paper birch	33 ± 33	75 ± 75	100 ± 100	0 ± 0	0 ± 0
Lodgepole pine	2902 ± 265	2202 ± 963	2502 ± 1519	1601 ± 329	1334 ± 883
Interior spruce	100 ± 100	150 ± 119	175 ± 175	50 ± 29	33 ± 33
Subalpine fir	100 ± 58	75 ± 48	0 ± 0	200 ± 142	0 ± 0
Douglas-fir	133 ± 133	50 ± 29	0 ± 0	25 ± 25	133 ± 67

a Presented as "mean ± 1 standard error."
b Densities are based on stems ≥1.3 m tall. Broadleaf stems in the 0 stems ha^{-1} treatment were mainly of sucker or sprout origin, and were relatively small compared with those in other treatments.

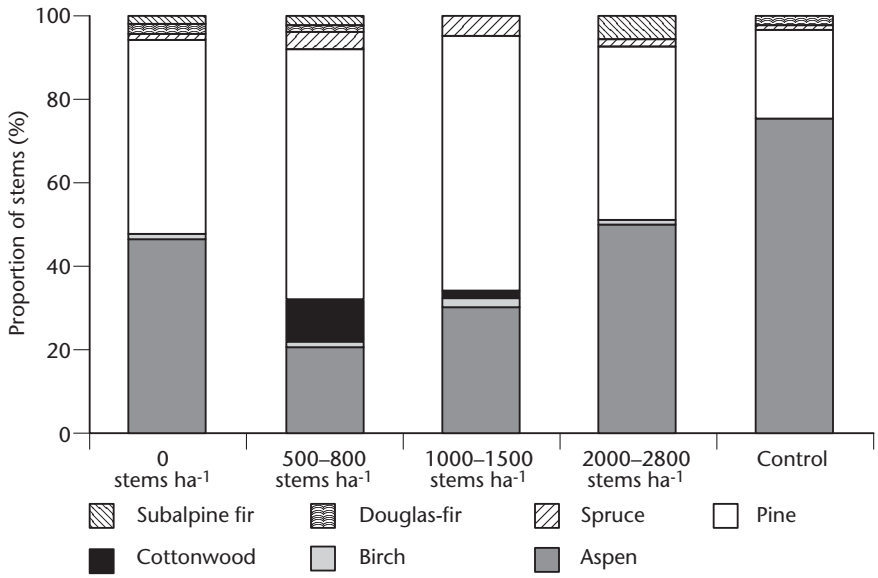

FIGURE 2 *2003 stand composition (by density of stems ≥1.3 m tall) in aspen retention treatments at the McKinley Lake site.*

4.1.2 Tree vigour The overall condition of conifer stems was poorer than that of broadleaves in 2003. Among lodgepole pine, which made up 90% of overall conifer density, 46–79% of stems had good or fair vigour across the five treatments, 21–47% had poor vigour, and 0–16% were moribund (Table 5, Figure 3). The largest proportion of poor and moribund seedlings occurred in the three highest-density aspen retention treatments (i.e., treatments where at least 1000 aspen stems ha^{-1} had been retained). The few interior spruce, Douglas-fir, and subalpine fir stems in poor condition were also found in the densest aspen retention treatments.

Western gall rust (*Endocronartium harknessii* Hirats.) was identified on branches of 3–12% of lodgepole pine and on 3–5% of stems, with a trend of higher occurrence in lower-density aspen retention treatments. Cooley gall aphid (*Adelges cooleyi* Gill.) was present on the branches of 67–100% of the interior spruce trees across the five treatments, but there were too few spruce

TABLE 5 *Mean 2003 vigour (% per class) of trees taller than 1.3 m in aspen removal treatments*

	Aspen retention treament				
	0 stems ha^{-1}	**500–800 stems ha^{-1}**	**1000–1500 stems ha^{-1}**	**2000–2800 stems ha^{-1}**	**Control**
Broadleaves					
Aspen					
Good	40	71	80	81	73
Fair	60	19	8	8	11
Poor	0	10	12	11	16
Moribund	0	0	0	0	0
Cottonwood					
Good	n/a[a]	0	50	0	n/a
Fair	n/a	100	50	100	n/a
Poor	n/a	0	0	0	n/a
Moribund	n/a	0	0	0	n/a
Birch					
Good	100	0	0	75	n/a
Fair	0	100	100	25	n/a
Poor	0	0	0	0	n/a
Moribund	0	0	0	0	n/a
Conifers					
Lodgepole pine					
Good	37	34	11	23	15
Fair	42	38	35	30	48
Poor	21	28	38	47	37
Moribund	0	0	16	0	0
Interior spruce					
Good	67	66	100	0	100
Fair	33	17	0	0	0
Poor	0	17	0	100	0
Moribund	0	0	0	0	0
Douglas-fir					
Good	75	50	100	25	n/a
Fair	25	50	0	75	n/a
Poor	0	0	0	0	n/a
Moribund	0	0	0	0	n/a
Subalpine fir					
Good	33	33	0	n/a	n/a
Fair	0	67	25	n/a	n/a
Poor	67	0	50	n/a	n/a
Moribund	0	0	25	n/a	n/a

a n/a indicates that the species did not occur in that particular treatment.

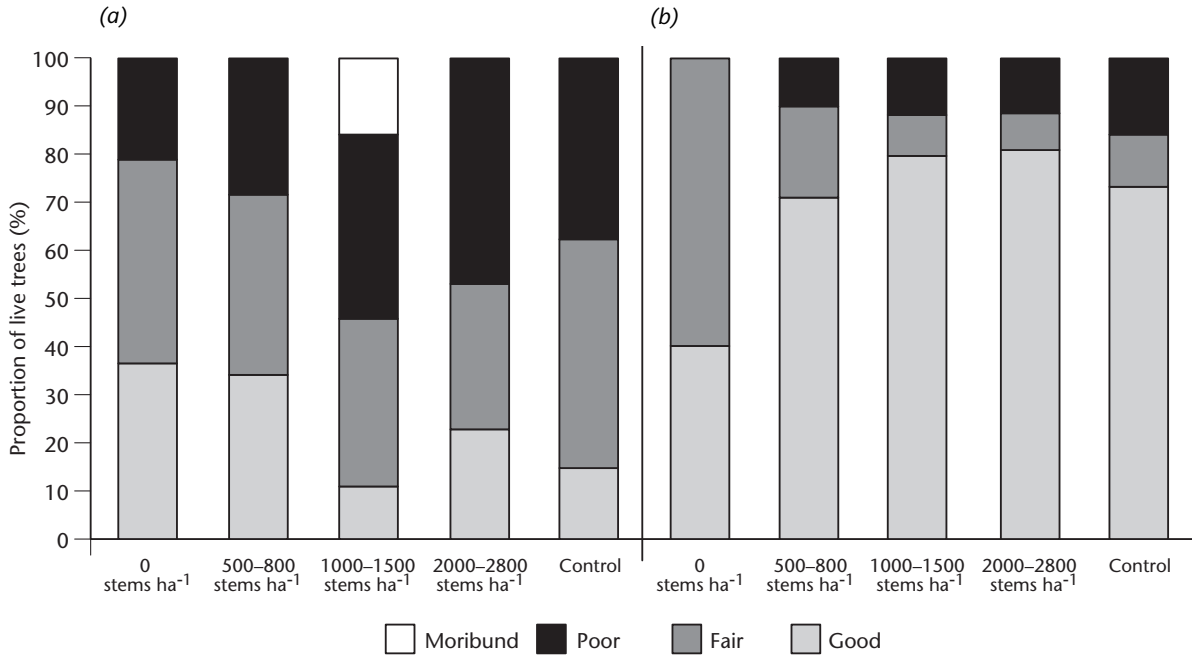

FIGURE 3 *Comparison of (a) lodgepole pine and (b) aspen vigour in aspen retention treatments in 2003.*

stems, overall, to identify trends associated with aspen density. Of all the conifer species, only subalpine fir sustained forking and lateral branch damage as a result of big-game browsing.

In 2003, the majority of broadleaves were in good or fair condition. Among aspen, which made up 94% of total broadleaf density, 84–100% of stems had good or fair vigour across the five treatments, 0–16% had poor vigour (Table 5, Figure 3), and none were moribund. There were no poor vigour aspen stems in the 0 stems ha^{-1} treatment, probably because all stems ≥1.3 m tall were vigorous new suckers. All cottonwood and birch stems present in 2003 were in good or fair condition. Very little damage to broadleaf foliage, leaders, or stems was recorded in 2003. Big game had browsed 7% of aspen leaders, but did not damage leaders of the few birch or cottonwood stems that were present. An average 6% of aspen stems across the various treatments also sustained physical damage (smashing and peeling). This occurred exclusively in the three highest-density treatments (≥1000 stems ha^{-1}) and is thought to have occurred during application of the cutting treatments.

4.1.3 Tree growth In 2000, immediately after cutting treatments were applied, the difference in aspen basal area between the four treatments that retained some aspen was marginally non-significant ($p=0.0517$, Table 6). The 0 stems ha^{-1} treatment was not included in the analysis in 2000 because all aspen had been cut to below a height of 1.3 m. Aspen basal area in 2000 ranged from 1.25 m^2 ha^{-1} in the 500–800 stems ha^{-1} treatment to 5.36 m^2 ha^{-1} in the uncut control. By 2003, some aspen suckers in the 0 stems ha^{-1} treatment had grown taller than 1.3 m, and contributed to basal area, but the mean was significantly lower than that of the other four treatments ($p<0.0001$). There were no significant differences in aspen basal area between any of the treatments where ≥500 stems ha^{-1} aspen were retained. There were no differences between treatments in lodgepole pine basal area in either 2000

or 2003 ($p>0.05$, Table 6). Average pine basal area was 1.1 m^2 ha^{-1} in 2000 and 2.7 m^2 ha^{-1} in 2003. In both 2000 and 2003, aspen had greater basal area than pine in the treatments where ≥1000 aspen stems ha^{-1} were retained, whereas proportions of the two species were approximately equal in the 500–800 stems ha^{-1} treatment (Figure 4).

TABLE 6 *Means and 95% confidence limits[a,b] for basal area of lodgepole pine and aspen[c] in 2000 and 2003*

	Aspen retention treatment					
Basal area (m^2 ha^{-1})	**0 stems ha^{-1}**	**500–800 stems ha^{-1}**	**1000–1500 stems ha^{-1}**	**2000–2800 stems ha^{-1}**	**Control**	**p-value[d]**
Lodgepole pine						
2000						
Mean	1.96	1.11	0.79	0.83	0.64	0.5865
Lower confidence limit	*0.63*	*0.28*	*0.13*	*0.15*	*0.04*	
Upper confidence limit	*4.03*	*2.49*	*2.00*	*2.06*	*1.98*	
2003						
Mean	5.24	2.86	1.62	2.48	1.46	0.5910
Lower confidence limit	*1.36*	*0.52*	*0.09*	*0.36*	*0.01*	
Upper confidence limit	*11.65*	*7.10*	*5.05*	*6.49*	*5.43*	
Aspen						
2000						
Mean	n/a[e]	1.25	3.05	2.89	5.36	0.0517
Lower confidence limit		*0.34*	*1.47*	*1.36*	*2.89*	
Upper confidence limit		*2.73*	*5.20*	*4.99*	*8.60*	
2003						
Mean	0.03 a	2.65 b	3.90 b	6.49 b	5.88 b	**<0.0001**
Lower confidence limit	*0.00*	*1.37*	*2.30*	*4.38*	*3.61*	
Upper confidence limit	*0.48*	*4.34*	*5.90*	*9.02*	*8.72*	

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 In 2000, data for plot 1, which contributed to the 500–800 stems ha^{-1} treatment mean, was collected within a 17.84-m radius plot rather than a 5.64-m radius plot. (See Section 3.2.)

c The stand includes minor amounts of black cottonwood and paper birch, which have been included in the above analysis as aspen.

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.

e There were no aspen ≥1.3 m tall in the 0 stems ha^{-1} treatment in 2000.

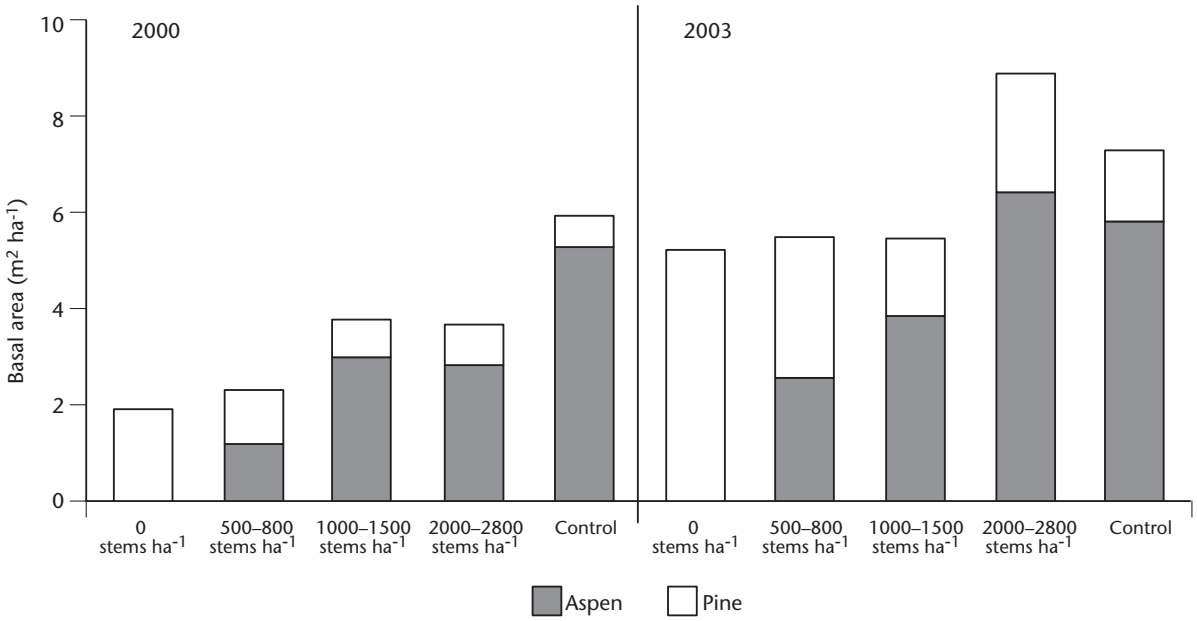

FIGURE 4 *Comparison of 2000 and 2003 stand-level lodgepole pine and aspen basal area in aspen retention treatments.*

In 2003, 4 years after cutting treatments were applied to adjust aspen density, there were no significant differences in lodgepole pine height, dbh, QMD, or HDR between the five treatments at McKinley Lake (Table 7). The size of aspen differed significantly between treatments, however, because stems in the 0 stems ha^{-1} treatment were suckers that had emerged since treatment, while stems in the other treatments were larger residuals that had been retained during cutting. Aspen were significantly taller in the 2000–2800 stems ha^{-1} treatment than in the complete removal treatment (0 stems ha^{-1}), and those in the 1000–1500 and 2000–2800 stems ha^{-1} treatments also had significantly larger dbh than those in the complete removal treatment ($p<0.05$, Table 7). Aspen quadratic mean diameter was smaller in the 0 stems ha^{-1} than in the 500–800, 1000–1500, and 2000–2800 stems ha^{-1} treatments. There were no differences in aspen height, dbh, or QMD between the three partial retention treatments and the control.

TABLE 7 *2003 mean[a] height, stem diameter (dbh), height:diameter ratio (HDR), and quadratic mean diameter (QMD) of lodgepole pine and aspen[b] in aspen retention treatments*

	Aspen retention treatment					
	0 stems ha^{-1}	**500–800 stems ha^{-1}**	**1000–1500 stems ha^{-1}**	**2000–2800 stems ha^{-1}**	**Untreated control**	**p-value[c]**
Lodgepole pine						
Height (cm)	389 ± 26	449 ± 27	373 ± 28	396 ± 26	424 ± 36	0.3831
dbh (cm)	4.4 ± 0.4	4.3 ± 0.4	3.4 ± 0.4	3.9 ± 0.4	4.2 ± 0.6	0.4791
HDR	107 ± 9	127 ± 9	138 ± 9	115 ± 9	116 ± 12	0.2011
QMD (cm)	4.9 ± 0.5	4.8 ± 0.5	3.7 ± 0.5	4.6 ± 0.4	5.0 ± 0.6	0.3948
Aspen[b]						
Height (cm)	180 ± 115 a	561 ± 92 ab	627 ± 90 ab	721 ± 88 b	460 ± 99 ab	**0.0290**
dbh (cm)	0.4 ± 1.0 a	4.4 ± 0.8 ab	5.4 ± 0.8 b	5.8 ± 0.8 b	3.6 ± 0.9 ab	**0.0117**
QMD (cm)	0.5 ± 0.8 a	5.9 ± 0.7 b	6.0 ± 0.7 b	6.4 ± 0.7 b	4.0 ± 0.8 ab	**0.0007**

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

b The stand includes minor amounts of black cottonwood and paper birch, which have been treated in the above analysis as aspen.

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.

4.1.4 Suckering In 2001, 2 years after cutting treatments were applied, mean aspen sucker densities ranged from 28 187 stems ha^{-1} in the complete aspen removal treatment (0 stems ha^{-1}) to 344 stems ha^{-1} in the 2000–2800 stems ha^{-1} treatment. Sucker presence in the uncut control was not assessed in 2001. By 2003, 4 years after cutting, there were 7–times as many aspen suckers in the 0 stems ha^{-1} treatment as in the average of the other retention treatments (Table 8, Figures 5, 6). Between 2001 and 2003, aspen sucker densities decreased by 36% in the complete aspen removal treatment, by 57% in the 500–800 stems ha^{-1} treatment, and by 33% in the 1000–1500 stems ha^{-1} treatment. In contrast, aspen sucker density apparently increased by 566% in the 2000–2800 stems ha^{-1} treatment during the same period (from 344 to 1948 suckers ha^{-1}). Different methods were used for assessing sucker densities in 2001 and 2003, which may account for some of the differences between years, especially in the 2000–2800 stems ha^{-1} treatment. Despite large differences in means, it was difficult to identify statistically significant differences between treatments because of the high variability between plots. ANOVA identified a significant between-treatment difference in 2001 sucker densities ($p=0.0496$), but only the 0 stems ha^{-1} treatment (28 187 suckers ha^{-1}) and the 2000–2800 stems ha^{-1} (344 suckers ha^{-1}) treatments differed from each other according to the Bonferroni test. There were no significant differences in aspen sucker height as a result of the aspen retention treatments in either 2001 or 2003 (Table 9). Four years after aspen retention treatments were applied, suckers were 89 cm tall, on average.

TABLE 8 *Means and 95% confidence limits[a] for sucker[b,c] density responses to aspen retention treatments in 2001 and 2003*

	Aspen retention treatment					
Density (suckers ha^{-1})	**0 stems ha^{-1}**	**500–800 stems ha^{-1}**	**1000–1500 stems ha^{-1}**	**2000–2800 stems ha^{-1}**	**Control**	**p-value[d]**
Aspen 2001						
Mean	28 187 a	5 981 ab	4 084 ab	344 b	n/a[e]	**0.0496**
Lower confidence limit	*8 352*	*123*	*6*	*2 277*		
Upper confidence limit	*59 726*	*20 617*	*16 941*	*7 189*		
Aspen 2003						
Mean	18 063	3 039	3 039	1 948	264	0.1820
Lower confidence limit	*4 071*	*36*	*36*	*289*	*0*	
Upper confidence limit	*42 023*	*13 517*	*13 517*	*11 082*	*7 539*	

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 Sucker data collection methods differed between 2001 and 2003. (See Section 3.3.2.)
c In 2001, only aspen suckers (or sprouts) were counted. The 2003 dataset includes minor amounts of black cottonwood and paper birch, which have been included in the above analysis as aspen.
d Values in **bold** are significant at $p \leq 0.05$, according 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.
e Suckers were not assessed in the control in 2001. The ANOVA for that year includes only the other four treatments.

FIGURE 5 *An illustration of sucker density and height in the complete aspen removal treatment (0 stems ha^{-1}), 4 years after cutting (2003). The area in the background is a control plot.*

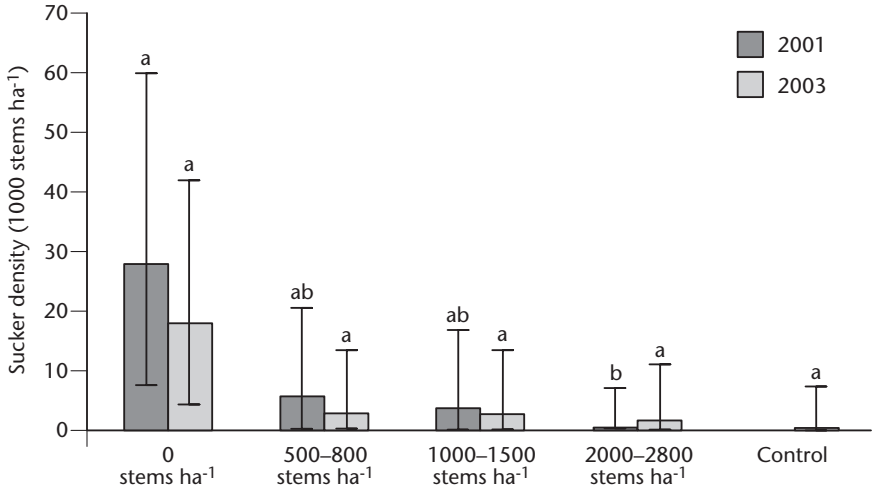

FIGURE 6 *2001 and 2003 aspen sucker densities in aspen retention treatments. Error bars represent 95% confidence limits. Means with the same letter (within a single year) are not significantly different from one another according to the Bonferroni test applied to square root–transformed data (p>0.05).*

TABLE 9 *2003 mean[a] sucker[b,c] height responses to aspen retention treatments*

	Aspen retention treatment					
	0 stems ha^{-1}	500–800 stems ha^{-1}	1000–1500 stems ha^{-1}	2000–2800 stems ha^{-1}	Control	p-value
Height 2001 (cm)	62 ± 3	59 ± 4	46 ± 4	47 ± 8	n/a[d]	0.0830
Height 2003 (cm)	102 ± 7	81 ± 6	80 ± 7	74 ± 7	107 ± 13	0.0923

a Presented as "mean ± 1 standard error," based on the ANOVA model (i.e., variances are assumed to be homogeneous for all treatments, blocks, and subplots).
b Sucker data collection methods differed between 2001 and 2003. (See Section 3.3.2.)
c In 2001, only aspen suckers (or sprouts) were counted. The 2003 dataset includes minor amounts of black cottonwood and paper birch, which have been included in the above analysis as aspen.
d Suckers were not assessed in the control in 2001. The ANOVA for that year includes only the other four treatments.

4.2 Free-growing and Not Free-growing Target Pine

In this section, "free-growing" and "not free-growing" designations refer to target pine status at the time of the free-growing assessment in 2000.

4.2.1 Target pine vigour and growth In 2003, target lodgepole pine in the free-growing group had better vigour than those in the not free-growing group (Table 10). Two-thirds of pine in the free-growing group had good vigour, and the remainder were fair. Most target pine in the not free-growing group had fair vigour. Of the free-growing target pine, 97% had healthy foliage, 83% had healthy leaders, and 93% had healthy stems. The small amount of recorded damage was attributed to unknown causes. In the not free-growing group, 76% of target pine had healthy foliage, 76% had healthy leaders, and 90% had healthy stems. Foliar damage was due to physical abrasion from adjacent aspen branches, which also caused about one-third of the recorded leader damage. About 7% of pine stems in the not free-growing group were described as "spindly due to high aspen density," but this condition did not exist in the free-growing group.

TABLE 10 *2003 vigour (% per class) of free-growing and not free-growing target lodgepole pine*

	Free-growing	Not free-growing
Good	66	14
Fair	34	79
Poor	0	7
Moribund	0	0

At the time of the free-growing assessment in 2000, target lodgepole pine in the free-growing group had significantly larger dbh, were significantly taller, and had significantly lower HDR than those in the not free-growing group ($p \leq 0.05$, Table 11). Differences continued to be significant through 2003, when target pine in the free-growing group were still significantly larger according to all assessed growth attributes, including crown length and width and leader length, which were not assessed previously ($p \leq 0.05$, Table 11).

TABLE 11 *Mean[a] size of free-growing and not free-growing target lodgepole pine from 2000 to 2003*

	Free-growing		Not free-growing		
	n	Mean ± SE	n	Mean ± SE	p-value[b]
2000					
Height (cm)	29	364 ± 12	29	333 ± 13	**0.0162**
dbh (cm)	29	3.7 ± 0.2	29	3.0 ± 0.2	**0.0002**
HDR	29	102 ± 3	29	117 ± 3	**0.0003**
2001					
Height (cm)	29	428 ± 13	29	390 ± 15	**0.0122**
dbh (cm)	29	5.2 ± 0.2	29	4.1 ± 0.2	**<0.0001**
2000–2001 height increment (cm)	29	65 ± 3	29	57 ± 3	0.0873
2000–2001 diameter increment (cm)	29	1.5 ± 0.1	29	1.1 ± 0.1	**<0.0001**
HDR	29	84 ± 2	29	97 ± 2	**<0.0001**
2003					
Height (cm)	28	523 ± 16	29	464 ± 16	**0.0028**
Leader length (cm)	28	49 ± 2	29	39 ± 2	**0.0035**
2000–2003 height increment (cm)	28	156 ± 7	29	130 ± 7	**0.0082**
dbh (cm)	29	6.7 ± 0.2	29	5.2 ± 0.2	**<0.0001**
2000–2003 diameter increment (cm)	29	3.0 ± 0.1	29	2.2 ± 0.1	**<0.0001**
Crown length (cm)	28	415 ± 15	29	324 ± 15	**<0.0001**
Crown width (cm)	29	209 ± 8	29	169 ± 8	**0.0003**
HDR	28	79 ± 3	29	91 ± 3	**0.0007**

a Presented as "mean ± 1 standard error," assuming equal variances for free-growing and not free-growing pine.
b Values in **bold** are significant at $p \leq 0.05$.

4.2.2 Target pine neighbourhoods In 2003, when the McKinley Lake stand was approximately 15 years old, free-growing target lodgepole pine were growing in neighbourhoods where lodgepole pine and aspen basal area were approximately equal, and where total neighbourhood basal area averaged 6.8 $m^2 ha^{-1}$, based on measurements within a 3.99-m radius around pine. In

contrast, not free-growing pine were growing in neighbourhoods where total basal area averaged 9.0 $m^2 ha^{-1}$, to which aspen contributed about 2.5 times as much as pine (Figure 7). The basal area contributed by other broadleaf species was minimal (0.05 $m^2 ha^{-1}$). Total tree densities in neighbourhoods surrounding free-growing and not free-growing lodgepole pine were 3668 and 4909 stems ha^{-1}, respectively. In free-growing target pine neighbourhoods, 49% of all stems were broadleaves, compared with 68% in not free-growing pine neighbourhoods. Based on measurements within a 1.78-m radius of target trees, free-growing pine grew among an average of 139 tall broadleaf stems ha^{-1} (i.e., broadleaf stems that were at least as tall as the target pine), compared with an average of 1836 tall broadleaf stems ha^{-1} for not free-growing pine.

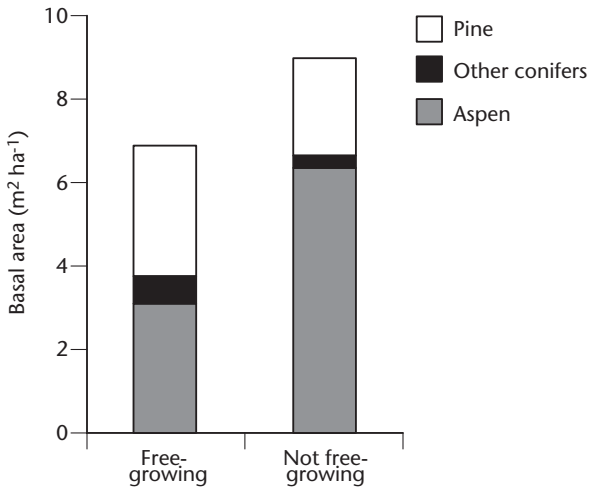

FIGURE 7 *A comparison of 2003 basal area in free-growing and not free-growing lodgepole pine neighbourhoods (based on 3.99-m radius plots).*

The aspen and broadleaf abundance variables that were most highly correlated with lodgepole pine height and diameter growth were: (a) tall broadleaf density within a 1.78-m radius of target pine; (b) 2003 aspen basal area within a 3.99-m radius; and (c) 2000–2003 aspen basal area increment within a 3.99-m radius. Correlations were higher for dbh increment than for height increment (Table 12). Correlations were highest when the dataset included both free-growing and not free-growing pine because of the wider spread of data points. Scatter plots including both groups revealed that free-growing pine tended to be larger than not free-growing pine, and associated with lower tall aspen density or basal area.

TABLE 12 *Spearman's rank correlation coefficients (R) for pairings of lodgepole pine height and diameter growth with aspen basal area and broadleaf density*

	2000–2003 pine height increment		2000–2003 pine dbh increment	
	R[a]	p≥|R|[b]	R	p≥|R|
2003 aspen basal area[c]				
Free-growing pine	-0.3577	0.0616	-0.2717	0.1539
Not free-growing pine	-0.1203	0.5343	-0.2426	0.2048
All pine[d]	-0.3647	**0.0053**	-0.4352	**0.0006**
2000–2003 aspen basal area increment[c]				
Free-growing pine	-0.3216	0.0952	-0.2490	0.1927
Not free-growing pine	-0.0616	0.7508	-0.2497	0.1914
All pine[d]	-0.3574	**0.0063**	-0.4334	**0.0007**
2000 broadleaf density in 50 m² neighbourhoods[e]				
Free-growing pine	-0.1529	0.4372	0.0363	0.8517
Not free-growing pine	0.0229	0.9060	-0.1417	0.4635
All pine[d]	-0.1360	0.3131	-0.1701	0.2018
2003 broadleaf density in 50 m² neighbourhoods[e]				
Free-growing pine	-0.3317	0.0846	-0.0156	0.9359
Not free-growing pine	0.0043	0.9822	-0.2835	0.1361
All pine[d]	-0.2374	0.0754	-0.2858	**0.0296**
2003 broadleaf density in 10 m² neighbourhoods[f]				
Free-growing pine	-0.2040	0.2978	-0.1114	0.5652
Not free-growing pine	-0.0407	0.8342	-0.0977	0.6143
All pine[d]	-0.2751	**0.0383**	-0.3708	**0.0042**
2003 tall[g] ***broadleaf density in 10 m² neighbourhoods***[f]				
Free-growing pine	-0.2845	0.1423	0.0239	0.9019
Not free-growing pine	-0.0402	0.8359	-0.2233	0.2443
All pine[d]	-0.3788	**0.0037**	-0.4780	**0.0001**

a Negative correlations improve as R decreases from 0 to -1; positive correlations improve as R increases from 0 to +1.
b Values in **bold** indicate significant differences from 0 (α=0.05).
c Based on broadleaves growing within a 3.99-m radius of the target lodgepole pine.
d Includes both free-growing and not free-growing lodgepole pine.
e Based on broadleaf counts within a 3.99-m radius of the target lodgepole pine.
f Based on broadleaf counts within a 1.78-m radius of the target lodgepole pine.
g Tall broadleaves are at least as tall as the target pine.

The most highly correlated aspen abundance variables were further explored using regression analysis (Table 13). In 2003, aspen basal area was a better predictor of lodgepole pine height and dbh increments than was broadleaf density. Pine dbh increment was more successfully predicted than pine height increment. Nonetheless, the relationships were relatively weak, with 2003 aspen basal area, 2000–2003 aspen basal area increment, and 2003 tall broadleaf basal area predicting 23.6%, 24.4%, and 25.7% of the variation in 2000–2003 lodgepole pine dbh increment, respectively. Relationships

between 2000–2003 pine diameter increment and tall broadleaf density or basal area in 2003 are illustrated in Figure 8.

TABLE 13 *Regression equation parameters[a] and coefficients of determination (R^2)[b] values for predicting lodgepole pine growth from: 2003 aspen basal area, 2000–2003 aspen basal area increment, 2000–2003 tall broadleaf basal area, 2003 total broadleaf density, and 2003 tall broadleaf density*

	n	*a*	*b*	R^2	RMSE[c]	p-value
2003 aspen basal area (m^2 ha^{-1})[d]						
2000–2003 pine height increment (m)	57	3.19	-0.0250	0.088	0.36	0.0260
2000–2003 pine dbh increment (cm)	58	6.42	-0.0470	0.236	0.66	0.0004
2000 - 2003 aspen basal area increment (m^2 ha^{-1})[d]						
2000–2003 pine height increment	57	3.24	-0.0560	0.112	0.35	0.0139
2000–2003 pine dbh increment	58	6.42	-0.0940	0.244	0.65	0.0002
2003 tall broadleaf basal area (m^2 ha^{-1})[d]						
2000–2003 pine height increment	57	3.14	-0.0268	0.151	0.35	0.0051
2000–2003 pine dbh increment	58	5.94	-0.0386	0.257	0.65	0.0001
2003 total broadleaf density (× 1000 stems ha^{-1})[e]						
2000–2003 pine height increment	57	2.94	-0.0132	0.031	0.37	0.2135
2000–2003 pine dbh increment	58	5.72	-0.0454	0.122	0.70	0.0054
2003 tall[f] broadleaf density (× 1000 stems ha^{-1})[e]						
2000–2003 pine height increment	57	3.09	-0.0835	0.151	0.35	0.0160
2000–2003 pine dbh increment	58	5.95	-0.1452	0.240	0.65	0.0001

a General form of the regression model for all variables is: $y = ae^{bx} + \delta_{pair} + \varepsilon_{tree}$, where *y* is a pine response variable, *x* is a neighbourhood competition variable, and δ_{pair} and ε_{tree} are error terms.
b $R^2 = 1 - \sum (y - ae^{bx})^2 / \sum (y - \bar{y})^2$, where $\bar{y}$ is the overall mean.
c Root mean square error.
d Includes stems (all aspen or tall broadleaves) within a 3.99-m radius around target lodgepole pine.
e Includes broadleaves of all species within a 1.78-m radius around target lodgepole pine.
f Tall broadleaves are as tall or taller than the target pine.

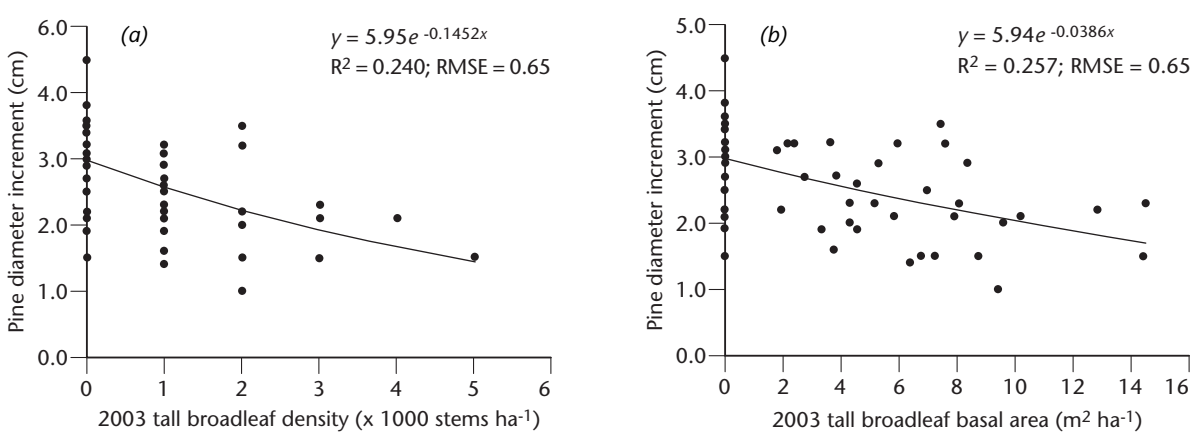

FIGURE 8 *Scatter plots with fitted non-linear regression lines showing the relationship between 2000–2003 lodgepole pine stem diameter increment (based on a 1.78-m radius plot around all target pine) and (a) 2003 tall broadleaf density or (b) 2003 tall broadleaf basal area.*

The McKinley Lake study was co-operatively established in 1999 by the B.C. Ministry of Forests and Weldwood of Canada, Ltd. to investigate the effects of variable aspen retention on lodgepole pine and aspen growth and on aspen suckering. In 2002, it was incorporated into a larger project that is currently under way to study pine–aspen interactions across a range of ecosystems in the Cariboo–Chilcotin. In 2003, PMPs at McKinley Lake were modified for the collection of growth and yield data, and the original methodologies were revised to more closely resemble those in the related studies. Consequently, there are some differences in the methodologies applied before and after 2003. For some variables, the 2003 dataset will serve as the baseline for future measurements. The focus of the McKinley Lake study also differs somewhat from that of other studies in the pine–aspen competition project because it does not measure the responses of individual target lodgepole pine to the aspen retention treatments.

5.1 Stand Development

The McKinley Lake stand (based on stand-level data collected in PMPs) was dominated by aspen and lodgepole pine, but black cottonwood, paper birch, subalpine fir, interior spruce, and Douglas-fir also contributed 1–2% each to overall density. The minor presence of other mixed species in juvenile stands dominated by pine and aspen is typical of the SBSdw1 variant (Steen and Coupé 1997).

5.1.1 Lodgepole pine In 2003, lodgepole pine vigour tended to be higher in treatments where aspen density was ≤ 800 stems ha^{-1} than in treatments with greater aspen retention. This agrees with retrospective study results for the SBSdw, where 17- to 18-year-old lodgepole pine vigour declined steeply in neighbourhoods where the density of tall aspen (i.e., aspen as tall as or taller than the target pine) exceeded 1000 stems ha^{-1} (Newsome et al. 2003). In that study, declining vigour in neighbourhoods with high aspen density became more apparent as stands aged. At McKinley Lake, vigour data were collected for the first time in 2003, so it is not possible to comment on changes that may have occurred since treatments were applied. Summary statistics regarding the presence of various damaging agents at the McKinley Lake site suggested that western gall rust was most common in treatments that retained the fewest aspen. This is consistent with information presented by Finck et al. (1989) that vigorously growing trees are more vulnerable to gall rust infection than those that are growing poorly. In general, mixed-species stands are reported to have lower incidence of disease than single-species stands (e.g., Comeau et al. 2005). These issues will be investigated more fully in subsequent assessments.

Four years after aspen retention treatments were applied at the McKinley Lake site, there were no significant differences in stand-level lodgepole pine height, dbh, QMD, or basal area among the five 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 no trends were apparent at McKinley Lake to suggest that pine dbh or QMD were responding to the treatments. Pine basal area tended to be larger in the treatment where all aspen were removed, but the differ-

ence was not significant in either 2000 or 2003. Four years after treatment, pine had higher basal area than aspen only in those treatments where aspen density was ≤800 stems ha^{-1}.

Early lodgepole pine responses to aspen retention treatments have varied in Cariboo–Chilcotin studies. In a study in the SBSdw2, growth of planted lodgepole pine did not increase significantly during a 9-year period where aspen were removed annually from within 0.5 or 1.0 m of the target pine (Newsome et al. 2004b). In the IDFxm subzone, target planted lodgepole pine growth also failed to improve within 4 years of aspen removal treatments that reduced aspen density from the control level of 23 483 stems ha^{-1} to 0–4000 stems ha^{-1} (Newsome et al. 2004a). Contrary to these findings, diameter growth of naturally regenerated lodgepole pine in the SBPSxc increased significantly within 2 years of treatments that reduced aspen density from control levels of 14 185 stems ha^{-1} to 0–2500 stems ha^{-1} (Newsome et al. 2006).

Significant treatment responses are more difficult to discern for pine at the stand level, where means include all stems regardless of size or condition, than for individual target pine that were initially selected according to specific health and vigour criteria. For example, in the above-mentioned SBPSxc study (Newsome et al. 2006), overall diameter increases for lodgepole pine at the stand level were not statistically significant after 2 years ($p>0.05$), despite the significant response of target pine. At McKinley Lake, the difficulty of detecting significant growth responses at the stand level is compounded by the inclusion of a range of densities in each treatment grouping.

Lodgepole pine in the 15-year-old stand at McKinley Lake may not have significantly responded to treatments that reduced aspen density because, in comparison, pine in the untreated control had not yet been substantially affected by competition. Retrospective study results for the SBSdw (Newsome et al. 2003) showed that competition effects between aspen and pine were not pronounced until stands were 17–18 years old. When those stands were younger (age 10–11), significant differences in diameter were found only between those pine growing in neighbourhoods with no aspen and those growing in neighbourhoods with over 5000 tall aspen stems ha^{-1} (i.e., aspen at least as tall as the target pine). At McKinley Lake, total aspen density in the untreated control averaged only 4737 stems ha^{-1} in 2003.

The relatively small height differential between aspen and pine at McKinley Lake also suggests that pine were not experiencing strong competition for light. Light availability increases rapidly from the base to the top of aspen canopies (Comeau 2002; Comeau et al. 2006). In 2003, lodgepole pine in the untreated control at McKinley Lake were approximately three-quarters as tall as aspen. Based on the Comeau et al. (2006) models, light availability beneath the canopy was approximately 52% of full sunlight. However, pine growing among these aspen were receiving 65–80% full sunlight by virtue of their canopy positions. Lodgepole pine is very shade-intolerant, and its diameter growth may be reduced by 50% at 60% light availability (Wright et al. 1998).

5.1.2 Aspen In 2003, 4 years after aspen retention treatments were applied, aspen basal area and quadratic mean diameter were larger in treatments that retained aspen than in the complete removal treatment. However, there were no differences among the treatments that retained aspen (including the untreated control). In related studies in the IDFxm and SBPSxc subzones, reducing aspen density to 1000–4000 stems ha^{-1} immediately reduced basal area of (at least) the lowest-density treatments in comparison with the untreated control (Newsome et al. 2004a, 2006). At McKinley Lake, the difference in aspen density between treatments was marginally non-significant ($p=0.0517$) immediately after cutting, mainly because of the range of densities within each treatment class.

By 2003, nearly 3000 aspen suckers ha^{-1} in the complete removal treatment had grown tall enough (≥1.3 m) to be included in basal area calculations, but this was not yet the case in any of the treatments that retained residual aspen. Although these young suckers contributed only minor basal area to the stand in 2003, they are expected to account for a larger component as the stand ages.

Other studies associated with the Cariboo–Chilcotin pine–aspen competition project have shown that aspen diameter distributions immediately changed following aspen removal treatments because the largest and most vigorous aspen stems were selectively retained. Stems in the low-density treatments tended to move into larger diameter classes more quickly than those in the untreated control (Newsome et al. 2004a). Although enhancing softwood timber production is currently the main objective when managing juvenile pine–aspen stands, Peterson and Peterson (1995) note that aspen sawlog production may also be enhanced by such treatments.

5.1.3 Suckering One of the anticipated benefits of retaining residual aspen stems during manual cutting treatments is a reduction in the abundance and vigour of aspen suckers. 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 on Cariboo–Chilcotin sites. Sucker abundance and growth at varying levels of aspen retention are currently being studied for a range of Cariboo–Chilcotin ecosystems.

At McKinley Lake, there was a clear downward trend in sucker production with increasing density of retained aspen, which supports the findings of Huffman et al. (1999). Although differences in sucker counts between the retention treatments were large at McKinley Lake, it was difficult to identify significant differences due to the high variability between subplots. Significant differences in sucker densities were found only in 2001, and only between the complete removal and 2000–2800 aspen stems ha^{-1} treatments (28 187 versus 344 suckers ha^{-1}). A similar lack of significance, in spite of definite trends, was also observed in the IDFxm subzone of the Cariboo–Chilcotin (Newsome et al. 2004a). In contrast, a study in the SBPSxc subzone found the first year post-treatment sucker density of approximately 100 000 suckers ha^{-1} in the complete removal treatment was significantly higher than that of any treatment where aspen was retained (Newsome et al. 2006).

The density of suckers that appeared within 2 years of complete aspen removal (0 stems ha^{-1}) at McKinley Lake was similar to the density that developed at the above-mentioned IDFxm site (Newsome et al. 2004a), but less than one-third of the density that developed at the SBPSxc site (Newsome et al. 2006). A combination of factors may contribute to differences in

sucker production at different sites. The literature, summarized by Frey et al. (2003), suggests that sucker initiation is governed mainly by growth regulators (e.g., hormones and carbohydrates) that affect the expression of apical dominance, and is further influenced by soil temperature, moisture, and nutrient conditions. Genetic differences between aspen clones also play a role. Hence, retaining residual aspen stems discourages sucker initiation through the expression of apical dominance, and through the creation of shade that restricts soil warming.

Following the initiation of aspen suckers, their survival and growth are influenced by the availability of light, nutrients, and warm soil conditions. The presence of residual aspen lessens the availability of these resources. At McKinley Lake, aspen suckers increased in height at an average rate of approximately 20 cm year^{-1}. Sucker height did not differ significantly between the various aspen retention treatments applied at McKinley Lake, which agrees with other Cariboo–Chilcotin studies (Newsome et al. 2004a, 2006), but contrasts with studies in the boreal where sucker height was more responsive than sucker density to variation in the level of aspen retention (P. Comeau, pers. comm., Jan. 2006). Despite the lack of significant differences in sucker height between aspen retention treatments at McKinley Lake, at least some suckers in the complete removal treatment had grown to ≥1.3 m within 4 years of cutting (i.e., tall enough to be included in PMP measurements). The presence of even moderate densities of faster-growing suckers could influence the need for additional vegetation management treatments following complete aspen removal.

The literature also suggests that sucker initiation, survival, and growth can be influenced to some extent by treatment timing and soil disturbance. Removing aspen early in the growing season will stimulate earlier initiation of suckers, increasing their exposure to warm soil conditions during the growing season (Frey et al. 2003). Cutting treatments at McKinley Lake and related Cariboo–Chilcotin studies (Newsome et al. 2004a, 2006) were applied during early summer (usually July), which is optimal for minimizing suckering (Hart and Comeau 1992). Fraser et al. (2004) also found that wounding aspen roots during harvesting or site preparation increases sucker initiation and growth rates. No site preparation treatments were applied at McKinley Lake, which helps account for the relatively low densities of aspen in the 15-year-old stand.

5.2 Free-growing and Not Free-growing Target Pine

Target lodgepole pine were selected at the McKinley Lake site to allow periodic monitoring of the performance of pine that had been determined, at age 12, to be either "free-growing" or "not free-growing" with regard to the presence of overtopping vegetation. The free-growing assessment was made according to newly revised guidelines that allowed tall vegetation to be present within one quadrant of a 1-m cylinder (B.C. Ministry of Forests 2002). Although efforts were made to select pairs of free-growing and not free-growing pine that were of similar height, baseline data revealed that free-growing pine were significantly taller than not free-growing pine, and also had larger dbh and smaller HDR. This reflects that, prior to treatment, at least some of the free-growing pine had already been growing in less competitive neighbourhoods, and had benefitted from greater resource availability.

By 2003, lodgepole pine in the free-growing group had better vigour than those in the not free-growing group, and were significantly larger according to all measures of growth. These results contrast with stand-level responses in this study, where there were no significant differences in lodgepole pine size as a result of the different levels of aspen retention, even between the complete aspen removal treatment and the untreated control. In the retrospective study (Newsome et al. 2003), stem diameter of 10- to 11-year-old lodgepole pine was significantly reduced by tall aspen densities over 5000 stems ha^{-1}, and the effects of competition became even more pronounced as stands aged. According to those results, the competitive effects of aspen on pine tended to manifest when SBSdw stands were about 10 years old. However, there was variation among stands within the same ecosystem, probably because of local differences in aspen clone characteristics, conifer and aspen health, and the impacts of wildlife.

The size of the neighbourhood within which surrounding trees affected growth of the free-growing and not free-growing pine at McKinley Lake was examined using Spearman's rank correlation analysis. Overall, the correlations between broadleaf density and lodgepole pine size were weak, but they were slightly better when broadleaves were considered within a 1.78-m rather than a 3.99-m radius of the target pine. Correlations were also stronger for pine diameter than for height. The 1.78-m radius neighbourhood size in 15-year-old SBSdw pine–aspen stands is consistent with retrospective study results, where correlations also weakened using larger (or smaller) neighbourhood sizes (Newsome et al. 2003). In contrast, a smaller neighbourhood radius of 1.0 m was identified for lodgepole pine in the IDFxm subzone (Newsome et al. 2004a), and a neighbourhood radius of 2.56 m or greater was identified in the SBPSxc (Newsome et al. 2006). Differences in the size of competitive neighbourhoods may be related to the height differentials between broadleaves and pine. In the above-mentioned studies, for example, aspen at the IDFxm site were 1.5–1.7 times as tall as pine, whereas they were 2.2–3.2 times as tall at the SBPSxc site. Tall individuals capture more light than shorter individuals (Keddy 1990), and they also cast shade over a greater distance.

The effectiveness of broadleaf abundance variables as competition indices to predict the competitive effects of aspen on lodgepole pine has been investigated throughout the Cariboo–Chilcotin pine–aspen competition project. Tall aspen density has consistently been the best predictor of lodgepole pine stem diameter growth, and tall aspen basal area has been second best (Newsome et al. 2003, 2004a, 2004b, 2006). In contrast, at McKinley Lake, tall broadleaf basal area was a slightly better predictor of 3-year lodgepole pine diameter growth (R^2=0.257) than tall broadleaf density (R^2=0.240). Comeau (2002) found that aspen basal area was a better predictor than aspen density of light availability in the understorey of 10- to 30-year-old boreal aspen stands. Comeau also notes that basal area, which accounts for both density and size of aspen, may 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. Density, on the other hand, often only works well as a site- and age-specific competition index (P. Comeau, pers. comm., Jan. 2006).

At McKinley Lake, the best relationship was obtained when the regression model included both free-growing and not free-growing pine, rather than

just one group. This is probably because a wider range of values was included. Relationships examined in the above-mentioned Cariboo–Chilcotin studies were relatively weak in young stands, but strengthened as the stands aged. For example, by the time retrospective study stands were 15–years old, tall aspen density explained 48–68% of the variation in pine stem diameter in the SBSdw and 50–63% in the IDFdk (Newsome et al. 2003).

5.3 Future Work Related to Management and Operational Recommendations

The McKinley Lake study is one of a series of experiments currently under way to provide information about thresholds for aspen retention in mixed pine–aspen stands in the Cariboo–Chilcotin. 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 will provide guidance regarding the appropriate density of aspen to leave if partial brushing treatments are considered. The Cariboo–Chilcotin retrospective study suggested that aspen density should be reduced to a maximum of 1000 tall aspen stems ha^{-1} to achieve acceptable lodgepole pine performance in 15- to 19-year-old pine–aspen stands in the SBSdw (Newsome et al. 2003). The McKinley Lake study will eventually provide information to corroborate or refine this recommendation. Longer-term measurements will also provide information regarding the incidence and effects of pine-damaging agents at various levels of aspen retention.

Aspen suckering is being studied at the McKinley Lake site, and 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 various levels of aspen retention on sucker initiation, survival, and growth. Initial trends suggest that sucker densities decrease with increasing density of retained aspen, but results also consistently show large within-site variability.

Growth and yield plots have now been established at the McKinley Lake site to further investigate the effects of manipulating aspen density on stand development. Data collected from these plots will aid in calibrating models that predict the long-term effects of variable density treatments on growth and yield and stand development.

As the McKinley Lake stand ages, continuing assessment of the vigour and growth of pine that were either free-growing or not free-growing at age 12 will test the long-term biological appropriateness of the free-growing standards (B.C. Ministry of Forests 2002). The periodic collection of neighbourhood data will provide information about the size of the pine–aspen competitive neighbourhood in the SBSdw1 and the maximum levels of aspen retention that will allow pine to perform well through the rotation. These results will permit informed decisions to be made regarding standards for management of pine–aspen stands. Refining allowable broadleaf density guidelines is extremely important because of the long-term contribution that aspen makes to stand health and site quality, and also to potentially reduce 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 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 target tree is at present overtopped by surrounding vegetation; target tree available sunlight is greatly reduced.
T Threatened	The leader of the target 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 target 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 – Snow press
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