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Stand-tending and Rehabilitation Treatment Options for 36-year-old, Height-repressed Lodgepole Pine

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Ministry of Forests Forest Science Program

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ABSTRACT

This trial is testing stand-tending and rehabilitation (replacement) treatments in a 36-year-old, height-repressed lodgepole pine stand to determine what regime might provide the most cost-effective means of increasing timber productivity. Key among the preliminary (3rd-year) findings for the stand-tending treatments is that fertilization, even in very dense unthinned stands, increased the average annual height growth significantly. Thinning alone produced a diameter-growth response but no height-growth response, and a combination of thinning and fertilization resulted in the largest height- and diameter-growth responses. Although longer-term performance results for the rehabilitation treatments are still to come, the trial findings to date show the potential for growth revitalization using stand-tending treatments in the large areas of height-repressed, wildfire-origin lodgepole pine in British Columbia's Interior.

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David Blevins (University of British Columbia doctoral candidate) assisted in developing the treatment options. Rob Brockley (B.C. Ministry of Forests, Kalamalka Research Station) provided valuable advice on nutrient analyses, prescribed the fertilizer based on the foliar analysis, and recommended procedures for post-treatment foliar sampling.

Claire Tretheway conducted the ecological classification and mapping of the trial area. Zimonick Silviculture laid out the rehabilitation treatment blocks, and planted and assessed the seedlings. Romar Contracting completed the thinning and slashing treatments, and Don Gesinger and Janet Zimonick hand-applied the fertilization treatments. Sonya Heilmeier and Craig Smith collected most of the post-treatment data, and Amanda Nemec conducted a majority of the statistical analysis. Foliar analysis was completed by Pacific Soil Analysis Laboratory in Richmond, B.C.

Noel Roddick Ltd. provided the fertilizer for the trial at cost and covered the delivery charges from Vancouver to Williams Lake.

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TABLE OF CONTENTS

TABLES

FIGURES

1 INTRODUCTION

1.1 Background

Forest fires facilitate natural regeneration in lodgepole pine (*Pinus contorta* var. *latifolia*). The heat from a fire causes the cones that are serotinous to open and release their seed. However, the pine stands that regenerate after wildfires are often very dense, which creates high competition among the stems for light, moisture, and nutrients. These high densities usually limit height growth in a stand and thus delay, or even prevent, the achievement of commercial operability. Such stands are said to be "height repressed."

Several studies of height-growth differences in wildfire-origin lodgepole pine growing at various densities have found that the rate of height growth decreases with increasing stand establishment density (Goudie 1980; Mitchell and Goudie 1980; Farnden and Herring 2002). Above threshold establishment densities of 10 000–50 000 stems/ha (Goudie 1980; Farnden and Herring 2002; Johnstone 2000[1]), rates of height growth decline dramatically with increasing numbers of trees. For example, Farnden and Herring (2002) estimated site index[2] reductions from 19 m to 9 m for stands established with 250 000 stems/ha. In controlled field experiments, threshold establishment densities as low as 20 000 stems/ha have been found to lead to repression (W. Johnstone, B.C. Ministry of Forests [now retired], pers. comm., 2003). J.S. Thrower and Associates (1993), using retrospective studies, found densities as low as 10 000 stems/ha in height-repressed 30- to 40-year-old stands, although establishment densities would probably have been higher.

1.1.1 Treatment options tested in the past for alleviating height-repressed stands Rehabilitation treatments, which remove existing stands of lodgepole pine and replace them with new ones, provide one option for restoring an area's productive capacity and therefore increasing its timber supply.

Another option is to use silviculture treatments to reduce or reverse height repression. In British Columbia and Alberta, the effectiveness of such treatments and regimes—primarily thinning and fertilization—have been tested.

Thinning treatments Thinning trials established in older dense pine stands have produced variable results. Smithers (1957) found a positive diameter response, but no height response, 15 years after stands were thinned at 41 and 75 years. Thinning at 5 years of age produced much better results, suggesting that a stand's ability to respond to treatment declines with age. Worrall (1996) found no growth response 10 years after thinning a 23-year-old pine stand with 75 000 stems/ha, a result that again suggested that stands can reach a point where thinning will not produce any gains. Similarly, a trial established in an 18-year-old height-repressed lodgepole pine stand at Fish Lake in the Prince George Forest Region showed a poor response 19 years after thinning (Farnden and Herring 2002).

Johnstone (1982) reported on a 77-year-old lodgepole pine stand that was thinned from 7200 stems/ha to 1710 stems/ha. After 21 years, a positive diameter response was found, but the height response—although also posi-

1 Johnstone, W.D. 2000. Lodgepole pine repression trial (EP 770.55). B.C. Ministry of Forests, Victoria, B.C. Unpublished file report.

2 All site index estimates are based on the height of trees at 50 years breast height age. Breast height age is determined by the number of rings in a tree at breast height (1.3 m).

tive—was minimal. As well, Johnstone (2002), reporting on growth 46 years after thinning 53-year-old, fire-origin pine, found positive diameter responses to thinning in older lodgepole pine, but few or no changes in height.

Taking a different approach, J.S. Thrower and Associates (1993) studied very dense but non–height-repressed lodgepole pine stands thinned at 16–18 years of age. Twelve to 15 years after treatment, trees in the unthinned control were showing signs of height repression, but the thinned trees were not. In another trial, located on the Alex Graham Fire site in the SBPSxc biogeoclimatic subzone (Steen and Coupé 1997) west of Williams Lake, lodgepole pine was thinned at two different ages.[3] Height repression was prevented where pine was thinned at less than 20 years of age. A remaining portion of the stand, later thinned at 30 years of age after the onset of height repression, experienced reduced height growth for at least 4 years after thinning. The results of both of these studies suggest that thinning can prevent the onset of height repression in very dense pine stands if the stands are thinned before height repression begins, but not after.

Fertilization treatments The effects of fertilization treatments in height-repressed lodgepole pine stands have also been reported in two published trials. Keane (1985) applied ammonium nitrate to 20-year-old lodgepole pine growing at three different densities: 5000, 50 000, and 150 000 stems/ha. Applying nitrogen alone induced a sulphur deficiency. Diameter growth resulting from the fertilization was not significant and interactions between fertilizer treatments and density levels for height-growth response prevented further analysis of these data. Farnden and Herring (2002) found a very positive response to thinning and fertilizing a very dense stand (over 200 000 stems/ha) of repressed pine. The 19-year results showed that the fertilized-plus-thinned trees had become largely released from repression and were growing at a site index of approximately 17 m—well above the untreated stand, which was growing at a site index of 9 m. The trees that were only thinned are now growing at a site index of approximately 11 m, indicating that the addition of nutrients was critical for relieving height repression.

1.2 Purpose of This Trial

Severely height-repressed lodgepole pine occupies large portions of the Cariboo-Chilcotin area in the Southern Interior Forest Region.[4] These stands are situated mostly in the SBPS biogeoclimatic zone and the MSxv subzone on the Fraser Plateau, west of the Fraser River. In 1996, a regional government–industry group, the Timber Investment Strategy Committee (TISC), examined the existing forest inventory database to determine the extent of these stands and suggest options for restoring their productive capacity.

According to the TISC, stands in height class 1 (under 10.4 m tall) and age class 2, 3, or 4 (21–80 years old) would be considered potentially suitable for rehabilitation. Over 130 000 ha of stands in the area formerly known as the Cariboo Forest Region were found to meet that definition. The TISC believed that if those stands could be successfully treated, then the productive land base for supplying timber might increase.[5]

3 Newsome, T. 1997. Treatment of repressed pine stands in the Cariboo Forest Region. Presentation to operational silviculture foresters in Williams Lake. Nov. 27, 1997.
4 The Southern Interior Forest Region includes what was previously known as the Cariboo Forest Region. Regional amalgamation went into effect on April 1, 2003.
5 Timber Investment Strategy Committee. 1996. Report on interim timber investment priorities. Cariboo Forest Region TISC. Oct. 16. Unpublished document.

The TISC's realization of how much area was occupied by height-repressed stands prompted further study. A forest-level silviculture analysis was conducted for the Williams Lake Timber Supply Area (TSA), using a forest estate computer model to project changes in timber supply resulting from a variety of silviculture treatments.[6] In the analysis, 50 000 ha of height-repressed pine stands growing at a site index of less than 7 m were rehabilitated. (These stands are not currently considered to be capable of producing a merchantable crop and have been deleted from the TSA's productive land base.) Rehabilitation assumes that the newly initiated stands will grow at the site potential, eventually contributing to the timber supply. Modelling resulted in a potential 48 700 m^3 increase in the projected annual timber supply—representing a rise of approximately 1.6% in the total harvestable volume.

The trial on which this technical report is based was established in 1997 to determine the best treatment options—in terms of increasing timber supply—for managing height-repressed lodgepole pine. The two principal regimes examined were (1) stand tending—treating an existing stand to increase the growth rate of trees, and (2) rehabilitation—removing an existing stand and replanting it with new trees. These different approaches are being compared over the long term to determine the most practical and cost-effective means of treating height-repressed pine. Presented here are early results obtained from the trial: 3rd-year results for stand tending and 1st-year results for rehabilitation.

1.2.1 Objectives The overall goal of this trial is to find cost-effective treatment regimes that can make older, height-repressed lodgepole pine stands merchantable within 80–120 years, which is within the range of rotation lengths for lodgepole pine stands on the western Fraser Plateau.

The trial's three main objectives are:

1. to compare the growth response of repressed lodgepole pine to three stand-tending treatments (thinning, fertilizing, and thinning plus fertilizing);
2. to compare lodgepole pine seedling performance in stand replacement treatments:
   - on six rehabilitation regimes, and
   - with and without fertilization at the time of planting; and
3. to compare stand performance between the stand-tending treatments and rehabilitation regimes over the long term.

The third objective is not addressed in this paper, since long-term trial data (over 10 years) are required.

The site is also planned for use in demonstrating various treatments.

6 Inland Timber Management Ltd. 2000. Type 2 forest level silviculture analysis report for the Williams Lake Timber Supply Area. May. Unpublished document.

2 METHODS

2.1 Study Area

The trial is located within the Rosita Fire area, approximately 96 km west of Williams Lake on the Mackin Creek (100) Forest Road, in the Central Cariboo Forest District, part of the Southern Interior Forest Region (Figure 1).[7] The site is located on mapsheet 93B045. The trial is registered with the B.C. Ministry of Forests as operational silviculture trial SX97403.

Most of the treatment plots are clustered around a road junction whose UTM coordinates are North 5811150 and East 489400 (latitude 52° 27' 09" and longitude 123° 09' 21"), at an elevation of approximately 1200 m. An additional group of treatment plots is located approximately 2 km southwest of the road junction, at an elevation of approximately 1230 m.

2.2 Site Description

The Rosita Fire was a natural wildfire that burned approximately 900 ha in the summer of 1961. Lodgepole pine stands regenerated after the fire and by 1997, 36 years later, stand densities ranged from 4000 to more than 30 000 stems/ha. This range of densities is associated with a large variation in observed pine growth. Some stands will achieve merchantable operability by the projected rotation age, whereas others areas are so dense that few or no stems will ever be large enough (and definitely not within a normal rotation of 80–120 years) to produce a commercial sawlog.

The experimental site is located in the SBPSdc (Sub-Boreal Pine Spruce–dry, cold) biogeoclimatic subzone and is mostly in the zonal 01 (Pine–Juniper–Feathermoss) site series, with some drier areas on sandier soils in the 03 (Pine–Kinnikinnick–Feathermoss) site series (Steen and Coupé 1997). The soils are predominantly Luvisols (Soil Classification Working Group 1998), their fine textures ranging from silt loams to clay loams.

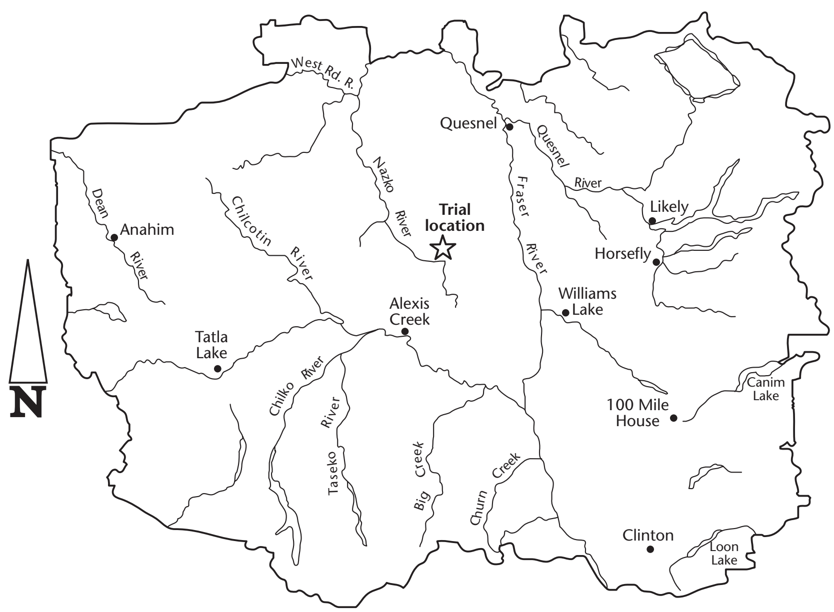

FIGURE 1 *Location of the trial at the Rosita Fire site.*

7 The Central Cariboo Forest District was established on April 1, 2003, and includes the former Williams Lake Forest District and the Horsefly Forest District.

The forest floors are only about 1–2 cm thick. Rooting depth varies from 20 to 35 cm. Coarse fragment content of the soil is high, varying from 40 to 80%, and large dispersed boulders are common at the surface. In a few treatment plots, soils are sandier and classified as Brunisols.

Up to 10% of the trial area is in small, wet depressions that collect and hold water in the early spring. Here, vegetation is sparse and dominated by palmate coltsfoot (*Petasites frigidus* var. *palmatus*). Dissolved soil nutrients seep into the depressions, making the soil richer than the rest of the site. Some of the soils in these areas are Gleysols. Because of the small, dispersed nature of these units, they have not been classified in the biogeoclimatic ecosystem classification system (R. Coupé, B.C. Ministry of Forests, pers. comm., 2003). Stand density is lower within and immediately surrounding these wetter areas and tree growth is higher than in the remainder of the stand.

For this trial, the Rosita Fire area was stratified into treatment units based on stand conditions and performance. Some portions of the area were determined to be marginal for thinning; others were identified for stand removal and replacement through planting. These two strata contained the smallest and most height-repressed trees. Average dominant and co-dominant tree height was approximately 4.6 m, and annual height growth was approximately 10 cm. Based on assessments at the time of trial establishment, the apparent 50-year site index of these stands ranged from a low of 7 m up to 15 m in the wet depressions. All of the trees in these two strata are growing below the expected normal site indices of 18 m for the 01 site series estimated by the Site Index–Biogeoclimatic Ecosystem Classification system (SIBEC) and 15 m for the 03 site series (B.C. Ministry of Forests 1997).

2.3 Treatment Descriptions

A total of four stand-tending and six rehabilitation options were tested within the defined treatment area.

The four stand-tending treatments included:

1. preserving an untreated, height-repressed control;
2. fertilizing an unthinned stand;
3. thinning to a target density of approximately 2000–3000 stems/ha, keeping only the largest and most dominant stems (inter-tree spacing was intentionally ignored in favour of crop tree quality selection); and
4. thinning to target density as above and then fertilizing the residual stand.

The stand rehabilitation treatments included planting lodgepole pine once the existing stand was removed by:

5. hand-slashing and leaving the felled stems;
6. hand-slashing, leaving the felled stems, aligning the slash with a V-blade, and disc-trenching;
7. hand-slashing, piling and burning the debris, and disc-trenching;
8. mechanically mulching with a Hydro-Axe;
9. mechanically mulching with a Hydro-Axe and disc-trenching; and
10. hand-slashing and piling and burning the debris.

Machine trafficability for the disc-trenching treatments was unacceptable on some hand-slashed treatment plots because of high soil moisture 1 year after tree removal. Consequently, not all treatments with disc-trenching were fully replicated. The 10th treatment was added when the disc-trenching could not be completed on some of the blocks (see section 2.7.2, "Implementation: rehabilitation treatments").

All of the six rehabilitation treatments included a split-plot factor—fertilized versus control (no fertilizer)—making a total of 12 treatment combinations.

2.4 Trial Layout

Aerial photographs of the Rosita Fire area were used to select the most homogeneous stands and sites exhibiting the smallest and most height-repressed pine. Experimental plot boundaries were drawn on the photos before being established on the ground, laid out to avoid the small, wetter areas where possible. A surrounding area of approximately 18 ha for operational treatment was also delineated.

A total of 27 main treatment plots, each measuring 70 × 70 m, were established (Figure 2). At the centre of each plot was a 30 × 30 m measurement plot surrounded by a 20-m buffer. The trial area boundaries and all the plot centres were located using Global Positioning System (GPS).

2.5 Pre-treatment Sampling and Analysis

Pre-treatment sampling was conducted to describe the existing stand and determine whether initial variation in stand conditions would require stratification to reduce statistical variability.

2.5.1 Tree measurements Four subplots (circular plots with a 1.78-m radius) were located 10.6 m from the centre of each main plot, measured along lines that were 45° to the plot sides. All pine trees within each subplot were assessed for height, diameter, vigour, disease and damage, crown size, and acceptability as a crop tree. A tree was considered to be "acceptable" if it was free of western gall rust (*Endocronartium harknessii*) on or within 10 cm of the main stem, displayed over 20% live crown, lacked any serious defects such as forking, and occupied a dominant or co-dominant canopy position.

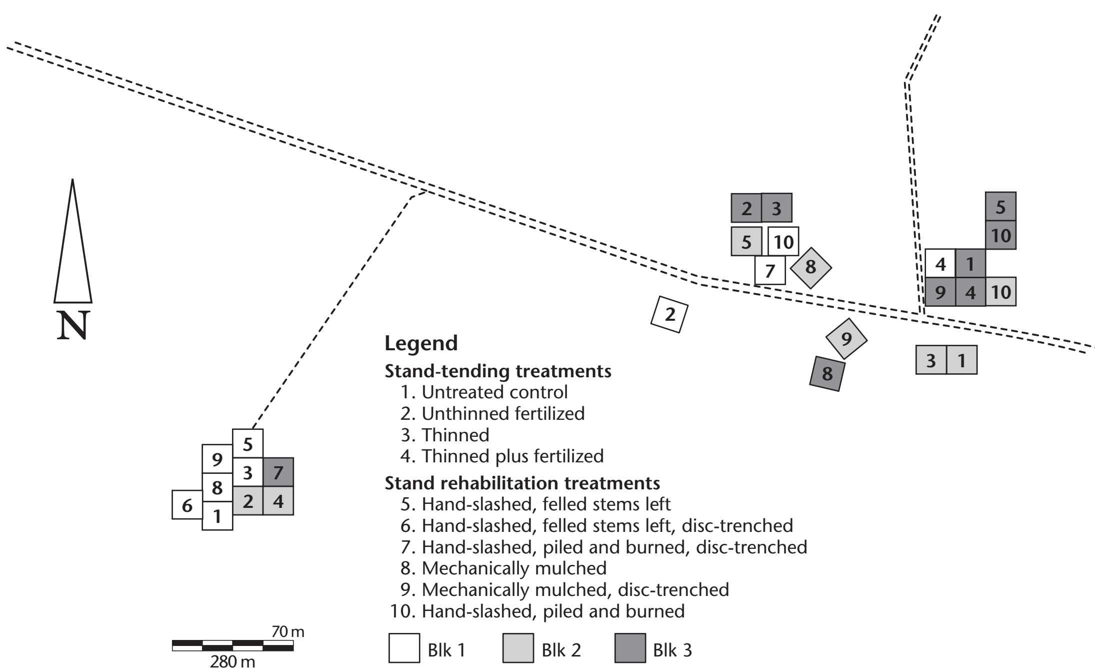

FIGURE 2 *Plot layout for each of the 10 treatment types.*

2.5.2 Foliar assessments Pre-treatment foliar samples were collected in October 1997, following the protocol of Ballard and Carter (1986). Five trees were selected within each of the main measurement plots, one from each subplot and one at the centre. All were the tallest trees with the best vigour within the given area. The five samples from each plot were composited, dried, and analyzed for nutrient concentration—nitrogen (N), total sulphur (S), sulphate sulphur (SO_4), phosphorus (P), calcium (Ca), magnesium (Mg), potassium (K), copper (Cu), zinc (Zn), iron (Fe), manganese (Mn), and boron (B). Three replicates of 100 needles of dried samples were counted and the average weight recorded. Results were used to develop the fertilizer prescription and are presented with the post-treatment data for foliar sampling in section 3.1.3, "Foliar nutrients."

2.5.3 Pre-treatment analysis Pre-treatment tree height data were analyzed to determine whether tree heights varied enough among the 27 main plots to warrant being stratified into blocks by height before treatment. Tree height is the principal variable of concern for the stand-tending portion of this trial because the goal is to increase the rate of height growth. In the untreated stand, height correlated well with density: the tallest trees were found in the plots with the lowest densities. Height variability among plots—assessed with a likelihood ratio test (Littell et al. 1996) based on a random-effects analysis of variance (ANOVA performed with PROC MIXED in SAS; see Table 1)—was found to be highly significant ($p < 0.0001$). Therefore, the main plots were grouped into three blocks according to average tree height, and treatments were randomly assigned within each of the blocks.

The rehabilitation treatments were grouped into blocks in a similar manner to ensure that sites of the same productive capacity were compared.

Diameter and total density also varied significantly among plots ($p < 0.0001$ in both cases), with lower densities and larger diameters tending to occur in those plots having taller trees. Table 2 summarizes the tree height, diameter, and other pre-treatment stand attributes for each block.

Several damaging agents were found in the stand before treatment. Table 3 shows the major ones. There were sufficient numbers of acceptable crop trees for the trial, despite the presence of some damaging agents in the stand. Scars ranged in incidence from approximately 15 to 19% but they were generally minor. A high level of pine needle cast (*Lophodermella concolor*)—infecting more than 75% of the trees—was present in 1997 but not in later years. While 56–74% of the foliage was affected by the disease, growth of the current needles was not. The incidence of western gall rust was relatively low for a lodgepole pine stand of its age and overall condition.

TABLE 1 *ANOVA table for pre-treatment pine data*

Source of Variation	Degrees of Freedom	Type of Effect
Plot, P	27 – 1 = 26	Random
Subplot, S(P)	(4 – 1) × 27 = 81	Random
Tree E(SP)*	(25 – 1) × 4 × 27 = 2592	Random
Total	(25 × 4 × 27) – 1 = 2699	Random

* Since the number of trees varied between subplots, an approximate number (i.e., 25 trees per subplot) was used for the purposes of this table.

TABLE 2 *Summary of pre-treatment data after stratification of blocks by tree height*

Block	Statistical Measure	Height (cm)	dbh (cm)	Percent Live Crown	Crown Radius (cm)	Density of Live Stems (sph)	Total Density of Live and Dead Stems (sph)	Percent Acceptable as Crop Trees
1	Mean	273.7	2.2	24.7	24.6	30 275	38 650	23.7
	Standard Deviation	76.0	0.9	12.5	10.1	8 794	11 877	
2	Mean	366.0	3.0	29.0	28.9	19 625	25 219	27.0
	Standard Deviation	111.0	1.2	13.1	12.2	6 344	8 787	
3	Mean	467.9	4.1	30.8	34.3	12 417	15 639	32.7
	Standard Deviation	131.5	1.5	13.9	13.6	4 825	5 728	

TABLE 3 *Major damaging agents recorded in pre-treatment assessments. The crown data refer to the percent infection of foliage within individual crowns.*

Block	Incidence of Scars (% of Trees)	Average Percent Infection			
		Pine Needle Cast		Western Gall Rust	
		Trees	Crowns	Main Stems	Branches
1	18.4	79.1	55.7	11.3	3.7
2	19.1	75.8	67.9	15.7	4.1
3	15.1	77.8	73.6	23.1	8.3

The nine treatments initially proposed were randomly assigned to plots, and the pre-treatment plot data were analyzed to determine whether significant differences existed between blocks prior to treatment. (The 10th treatment of hand-slash–pile–burn–plant was added later in response to operational constraints, as described in section 2.7.2, "Implementation: rehabilitation treatments.") Table 4 shows the ANOVA and Table 5 provides the results. No pre-treatment differences were found for any of the variables of interest. The three plots for the 10th treatment were later assigned to blocks according to the same stratification criterion.

2.6 Sampling Design

The trial employed different sampling designs (methods of tree selection) for the two types of treatments, stand tending and rehabilitation.

2.6.1 Stand-tending treatments This portion of the trial is a 2 × 2 factorial, randomized complete block design with three blocks and four treatments

TABLE 4 *ANOVA table for testing the pre-treatment data (assuming 25 trees per subplot)*

Source of Variation	Degrees of Freedom	Type of Effect
Block (B)	3 – 1 = 2	Random
Treatment (T)	9 – 1 = 8	Fixed
B*T	(3 – 1) (9 – 1) = 16	Random
Subplot S(BT)	3 × 9 × (4 – 1) = 81	Random
Tree E(SBT)	3 × 9 × 4 (25 – 1) = 2592	Random
Total	(3 × 9 × 4 × 25) – 1 = 2699	Random

TABLE 5 *Summary of the* ANOVA *of pre-treatment data: p-value for assessing statistical differences between treatments (Column 2), standard error of mean (which is the same for all treatment means) (Column 3), and pre-treatment means (Columns 4–12)*

			Stand Tending				**Rehabilitation**				
Variable	**p-value**	**SE**	**Control**	**Thinned**	**Unthinned Fertilized**	**Thinned plus Fertilized**	**Hand-slashed**	**Hand-slashed, Burned, and Disc-trenched**	**Mulched with Hydro-Axe**	**Mulched with Hydro-Axe and Disc-trenched**	**Hand-slashed and Burned**
Height (cm)	0.2208	60	355	342	361	388	413	347	394	377	414
Diameter (cm)	0.2025	0.6	2.9	3.0	3.1	3.1	3.5	3.0	3.4	3.2	3.4
Percent live crown	0.5120	3	26.0	33.6	29.1	29.8	28.1	25.2	27.8	27.6	29.6
Radial crown width (cm)	0.8018	3.9	30.4	28.0	32.0	29.3	30.5	28.5	31.2	31.6	26.7
Density of live stems (stems/ha)	0.4447	6 117	21 833	23 417	21 833	21 083	19 583	22 715	17 667	23 417	16 917
Total density of live and dead stems (stems/ha)	0.1609	8 015	28 583	29 500	29 083	27 500	25 417	32 340	20 500	29 167	20 750
Estimated number of acceptable stems (stems/ha)	0.6740	625	2 042	1 708	2 042	1 292	854	2 351	1 917	2 250	1 271

(2 levels of thinning × 2 levels of fertilization) per block. Blocks were based on tree height (as described in section 2.5.3, "Pre-treatment analysis").

Two sampling regimes have been established for this trial: one assesses the treatment response of crop trees; the other monitors tree response at the stand level (i.e., all trees).

Crop trees Crop trees were selected before treatment according to the following process. Thirty-six gridpoints were established, the first 2.5 m from the edge of the 30 × 30 m measurement plot, and the others at 5-m intervals (Figure 3). At each point, the nearest tree that would be acceptable to leave in a thinning project (as described in section 2.7.1, "Implementation: stand-tending treatments") was tagged and assessed. These were referred to as crop trees. They were numbered from 1 to 36, with each number shown on a metal tag nailed to the tree 1.3 m above the germination point.

Stand assessment Since crop tree assessments do not yield overall tree volume for a given area, another set of plots was required. These stand-level plots were established after treatment and have a fixed radius within which all trees were measured. One 12.64-m radius plot was established on the thinned treatments, with the plot centre in the middle of the 30 × 30 m measurement plot. Given the thinning guidelines of leaving 2000–3000 stem/ha, this plot size provided the prescribed minimum sample size of 100 trees/plot.

Since the unthinned treatments were very dense, establishing a 12.64-m radius plot in them was impractical. Furthermore, one small plot at the middle would not capture the on-site variability within the plots. Therefore, the four subplots used for the pre-treatment assessment were re-established. If

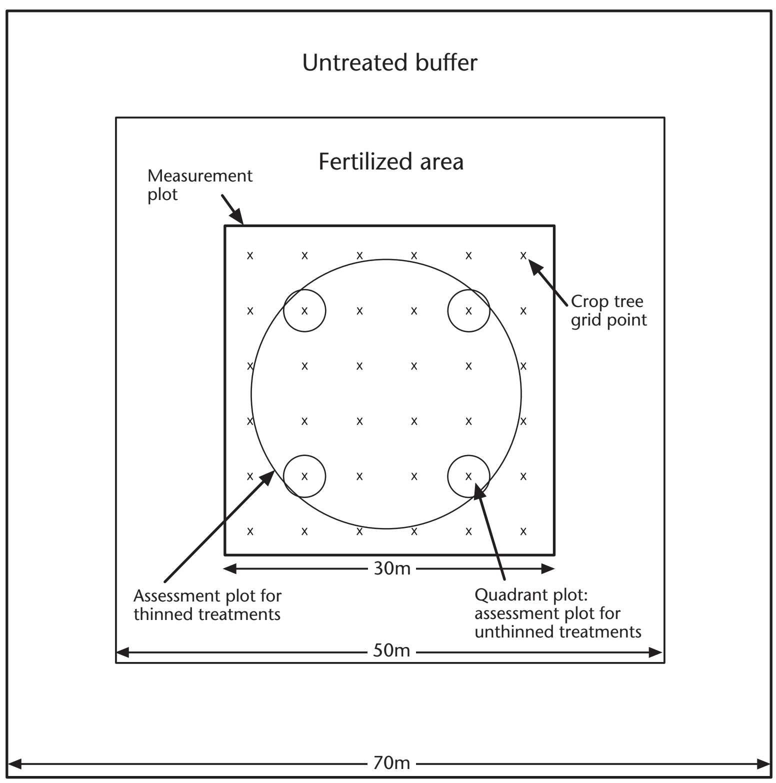

FIGURE 3 *Plot layout for the stand-tending treatments.*

the pre-treatment assessment did not include at least 100 trees, the subplot radius of 1.78 m was increased to 2.5 m, and then by successive increments of 0.5 m, until the minimum total sample size of 100 trees was achieved. Subplot size was always the same within a measurement plot. Plot sizes and resultant areas sampled are given in Table 6.

A tag was nailed to each sample tree or, if the tree was too small, the tag was attached with wire to a branch. The point where diameter was assessed (at the 1.3-m height) was marked with a paint pen.

2.6.2 Sampling design: rehabilitation treatments Rehabilitation treatments were grouped into blocks using the same methods as for the stand-tending treatments. The rehabilitation portion of the trial is a split-plot, completely randomized block design. The main plot factor is the type of rehabilitation treatment and the split-plot factor is the fertilization treatment. Each 30 × 30 m measurement plot was divided in half and a fertilizer or control (no fertilizer) treatment was randomly assigned to each half. Where the site preparation treatments allowed, five rows of 15 trees were planted. The 45 seedlings in the centre three rows were assessed.

On some of the disc-trenched areas, the number of rows dropped to four within half of the measurement plot. In such a case, the first trench was used for the first row of assessed seedlings. After treatment, each seedling location was flagged and tagged. The planting plot layout is shown in Figure 4.

2.7 Treatment Implementation

All treatments were implemented in 1997 and 1998. The exceptions were two plots for the slash-and-burn rehabilitation treatment, which were delayed until summer 1999 (described in section 2.7.2, "Implementation: rehabilitation treatments").

2.7.1 Implementation: stand-tending treatments Three stand-tending treatments were applied: thinning, fertilizing, and a combination of the two.

Thinning Thinning was completed in September and October 1997. A final target density of 2000–3000 stems/ha was prescribed, with a preference to

TABLE 6 *Sampling area used for each treatment*

Treatment Block	Treatment	Subplot Radius (m)	No. of Subplots	Sampling Area	
				m^2	ha
1	Untreated	1.78	4	39.80	0.004
	Thinned	12.64	1	501.68	0.050
	Unthinned fertilized	1.78	4	39.80	0.004
	Thinned plus fertilized	12.64	1	501.68	0.050
2	Untreated	2.5	4	78.50	0.008
	Thinned	12.64	1	501.68	0.050
	Unthinned fertilized	1.78	4	39.80	0.004
	Thinned plus fertilized	12.64	1	501.68	0.050
3	Untreated	2.5	4	78.50	0.008
	Thinned	12.64	1	501.68	0.050
	Unthinned fertilized	3.0	4	113.04	0.011
	Thinned plus fertilized	12.64	1	501.68	0.050

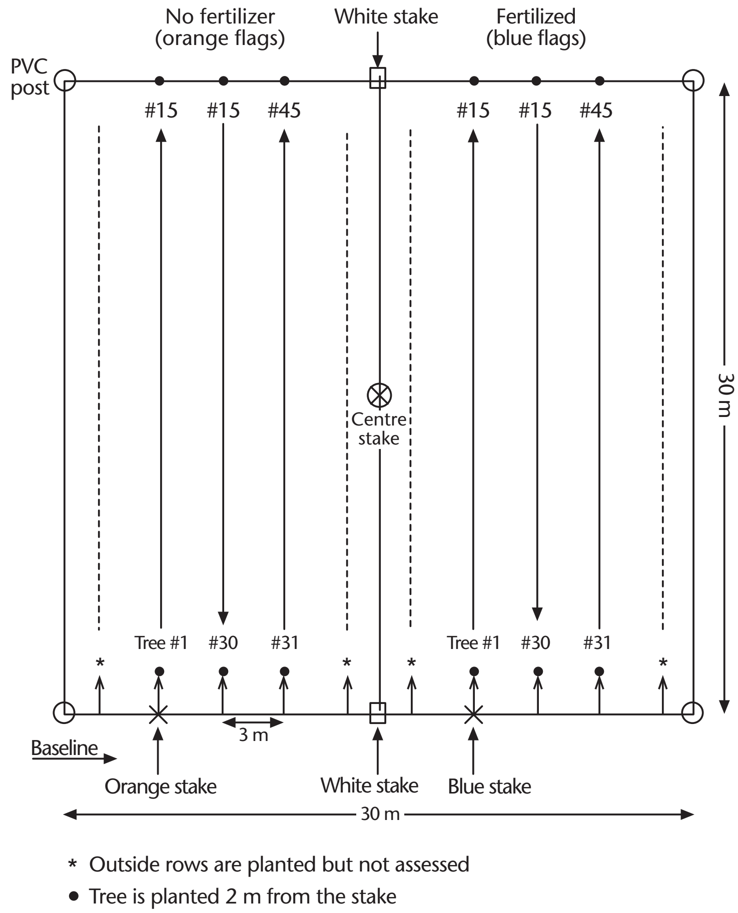

FIGURE 4 *Plot layout for the rehabilitation treatments.*

achieving closer to the maximum than the minimum. These treatments are considered thinning rather than juvenile spacing because the stand was thinned to a target residual density rather than to a prescribed inter-tree spacing.

The thinning crew was instructed to keep the better trees, to meet operational leave-tree criteria for form and vigour as described in the provincial stand-tending guidelines in effect in 1997 (B.C. Ministry of Forests 1995). There was no specified inter-tree spacing requirement. Experience from an adjacent pilot thinning project on the Rosita Fire site suggested that, because the majority of the trees were in such poor condition, keeping the most vigorous ones was critical.

Fertilization Fertilization was completed during October 13–17, 1998. On the last day, approximately 10 cm of snow covered the site when the fertilizer was applied to the thinned-plus-fertilized treatment plot in Block 1. Otherwise, all fertilizer was applied to bare ground. The total area fertilized was 50 × 50 m, which included the entire central measurement plot and 10 m into the buffer. The plot was sectioned with rope into 10-m squares and 12.27 kg of fertilizer was applied evenly by hand to each square at a rate of 306.75 kg/plot (equivalent to 1227 kg/ha).

The fertilizer prescription was a customized blend that delivered nutrients at the following rates (kg/ha): 200N, 100P, 100K, 75S, 36Mg, and 3B. The prescription (Tables 7 and 8) was developed to address the severe nutrient deficiencies shown by the pre-treatment foliar nutrient analysis.[8]

2.7.2 Implementation: rehabilitation treatments The six rehabilitation treatment regimes are presented in Table 9.

Each treatment regime involved one of more of the following treatments.

Hand-slashing Hand-slashing was completed with chainsaws at the same time as the thinning treatments were implemented in September and October 1997. All trees were felled and left on site.

Disc-trenching Disc-trenching began on October 22, 1998. The machine used was a TD20E CAT with a Donaren 180 disc-trencher. It also had a V-blade with three retractable teeth, which was useful when dealing with the slash loads that remained after both hand-slashing and mulching with the Hydro-Axe. The treatment produced a berm and an associated trench.

Disc-trenching in the area treated by the Hydro-Axe was completed successfully. However, three hand-slashed plots, one of which was also piled and burned, could not be trenched because of the excessively wet soils. With no trees growing on the site for one year and a thick layer of slash covering the ground, moisture accumulated in the soil, likely because of the absence of evaporation and tree transpiration. Adjacent plots, where trees were removed by the Hydro-Axe immediately before trenching, did not have the same problem. Those plots that could not be disc-trenched became the S-B treatment plots. That left two treatments, S-DT and S-B-DT, with only one and two replicates, respectively.

Piling and burning The hand-felled slash was piled with an excavator in early August 1998. Four piles were made in the applicable (70 m × 70 m) treatment plot in each block, near the corners of the interior (30 m × 30 m) measurement plot. Burning was completed over October 17–19, 1998. The piling arrangement distributed the ashes and burned material over a large area of the plot rather than concentrating it in the middle of the measurement plot. There was light snow cover on the ground and minimal wind at the time of burning. The piles all burned very well, leaving little slash.

Problems with disc-trenching in fall 1998 (just discussed) resulted in two plots assigned to this treatment having to be piled in summer 1999 and burned that October. This delayed planting and measurement of the trees by a year.

Mulching with a Hydro-Axe The Hydro-Axe is a rubber-tired, articulated machine with a hydraulically driven rotating front blade. It mechanically mows down and mulches trees into a range of sizes, from small chips to larger chunks of whole stems up to about 1 m long. It typically leaves sharp, pointed stems up to 50 cm in height, which can present problems for movement of wildlife or cattle.

8 The prescription was recommended by Rob Brockley, B.C. Ministry of Forests, Kalamalka Research Station.

TABLE 7 *Type and amount of blended fertilizers applied to the trial. The nutrient content of each fertilizer is presented as a percent of the total weight (kg).*

	Total Weight	**Ingredient Analysis (%)**						**Nutrient Content (kg)**					
Fertilizer Source	**(kg/ha)**	**N**	**P_2O_5**	**K_2O**	**Mg**	**S**	**B**	**N**	**P_2O_5**	**K_2O**	**Mg**	**S**	**B**
Urea	328.0	46						150.9					
Monoammonium phosphate	446.0	11	52					49.1	231.9				
Muriate of potash	75.0			60						45.0			
Sulphate potassium magnesia	357.0			21	10	21				75.0	35.7	75.0	
Borate granular	21.0						14.3						3.0
Total	1227.0							200.0	231.9	120.0	35.7	75.0	3.0

TABLE 8 *Fertilizer composition by type and amount (kg/t) of fertilizer. The nutrient content of each fertilizer is expressed as a percent of the total weight (kg).*

	Total Weight	**Ingredient Analysis (%)**						**Nutrient Content (kg)**					
Fertilizer Source	**(kg/ha)**	**N**	**P_2O_5**	**K_2O**	**Mg**	**S**	**B**	**N**	**P_2O_5**	**K_2O**	**Mg**	**S**	**B**
Urea	267.3	46						123.0					
Monoammonium phosphate	363.5	11	52					40.0	189.0				
Muriate of potash	61.1			60						36.7			
Sulphate potasssium magnesia	291.0			21	10	21				61.1	29.1	61.1	
Borate granular	17.1						14.3						2.4
Total	1000.0							163.0	189.0	97.8	29.1	61.1	2.4

TABLE 9 *Summary of rehabilitation treatment regimes, number of completed replications, and associated treatment code. The S-DT treatment is not presented on any results graphs because there was only one replication.*

Treatment No.	Rehabilitation Treatment Regime	No. of Replications	Code
5	Hand-slash and leave felled stems	3	S
6	Hand-slash, leave felled stems, align the slash with a V-blade, and disc-trench	1	S-DT
7	Hand-slash, pile and burn the debris, and disc-trench as site preparation	2	S-B-DT
8	Mechanically mulch using a Hydro-Axe	3	HA
9	Mechanically mulch using a Hydro-Axe and disc-trench	3	HA-DT
10	Hand slash and pile and burn the debris	3	S-B

The treatment was completed in October 1998. There was no snow on the ground and the temperature ranged between 5 and 15°C. The machine worked well on the site under these conditions.

Planting The planted seedlings had been sown earlier that year in PSB 410 styroblock containers (4 × 10 cm). They were grown at K&C Nursery from lodgepole pine seedlot 45527. After setting their first terminal buds, they were lifted for transport. The planting layout was completed in June 1999, and the trees in the 30 × 30 m plots were planted on June 22–25, 1999, by experienced research trial planters. The weather was wet and cool, and remained that way into July. In 2000, two S-B treatment plots were planted, 1 year after the other rehabilitation treatment regimes.

On the disc-trenched treatments, most of the seedlings were planted mid-slope on the berm unless the ground was sandy, in which case they were planted closer to the bottom of the trench. Where there was water in the trench, the seedlings were planted higher on the berm. Small screefs were used for planting with no trenching. Where there was heavy slash, inter-tree spacing was reduced to less than 2 m to maintain a straight line of seedlings. The planters found it difficult to manoeuvre through the slash where it was left on the site. As well, the jagged stumps left by the Hydro-Axe treatment reduced the rate of planting.

Fertilization of planted seedlings The fertilizer treatment was randomly assigned to one-half of each measurement plot (Figure 4). Seedlings were fertilized at the time of planting using a 10-g biodegradable planting packet ("tea bag" style) from Reforestation Technologies International. Each packet was composed of 16% N, 6% P_2O_5, 8% K_2O, 7.2% S, 0.7% Zn, 0.71% Fe, and 0.14% Mn. The nitrogen, phosphorus, and potassium were coated with polyurethane to slow the release of the nutrients. The fertilizer was buried in a separate hole 2.5 cm below the soil surface and 2.5 cm from the tree roots in an uphill location if possible. The planters found the fertilizer packets were easy to use and caused minimal reduction in planting rate compared to that with the unfertilized planting.

2.8 Plot Assessments

2.8.1 Plot assessments: stand-tending treatments Assessments of the stand-tending treatments were completed every fall from 1997 to 2001. All reported measurements are from the fall of the indicated year.

Tree measurements The crop trees and all trees in the stand-level fixed-radius plots were assessed for:

- total height
- diameter
- crown radius
- height to base of live crown
- tree vigour (see assessment codes in Appendix 1)
- damaging agents

Diameter was assessed at breast height (1.3 m above the germination point) directly above the nail. If the tree was less than 1.3 m in height, diameter was measured at ground level.

Crown radius was assessed by measuring the average radius at the point on the stem where the branches were largest.

For each crop tree, the length of the live crown was measured. The bottom of the live crown was measured from the ground up the stem to where the longest branches were attached. (Other live branches may have been farther down the stem, but they were smaller and totally shaded, and not considered to be functioning as well as the larger branches.)

The percent live crown was determined by calculating the height to the base of the live crown as a proportion of the tree's total height. On the stand-level plots, an ocular estimate of the percent live crown was made. This measurement was eliminated in 1998, then re-assessed in 1999 and in subsequent years in the same manner as for the crop trees.

Foliar sampling Foliage was sampled on all three stand-tending treatments and the control in late October 1999 (1 year after the fertilizer was applied) and again in 2000 and 2001. Ten trees were sampled on each measurement plot. The same trees were sampled as in 1997 (before treatment) and five more were added to increase the accuracy of the data (R. Brockley, B.C. Ministry of Forests, pers. comm., 1999). The trees sampled all had good vigour and most were in a dominant canopy position. By 2001, repeated sampling was found to be depleting foliage on some trees. They were replaced by trees having similar size and vigour. The same sampling protocol (Ballard and Carter 1986) was followed for both the pre-treatment and post-treatment measurements.

Ten foliar samples were taken in each measurement plot in 1999. These were dried and a 100-needle weight recorded for each sample. Two composites of five trees—with an equal weight from each sample—were then made for each measurement plot. One composite contained trees sampled in the pre-treatment analysis; the second consisted of trees sampled after treatment. Nutrients were analyzed for each composite. In 2001, different trees in the unfertilized treatments were sampled to avoid depleting the foliage and potentially affecting tree growth.

2.8.2 Plot assessments: rehabilitation treatments Assessments were completed on 45 seedlings in each split plot, for a total of 90 seedlings per main plot. The seedlings were measured at the time of planting (June 1999) and in the fall of 2000. Assessment on two plots in the S-B was delayed (as described in section 2.7.2, "Implementation: rehabilitation treatments"). Those seedlings will be assessed on the same schedule, but delayed by a year. All seedlings were assessed for:

- total height
- leader length
- ground-level diameter
- vigour (see assessment codes in Appendix 1)
- damaging agents
- vegetation competition (see assessment codes in Appendix 1)

2.9 Analysis

Analysis of variance (ANOVA) and analysis of co-variance (ANCOVA) using the mixed-model procedure (PROC MIXED) in SAS were used to evaluate the effects of the various treatments (Littell et al. 1996). The reported means are all least-squares means and the standard errors associated with each mean are from the same mixed-model procedure. Bonferroni's method was used to compare all pairs of individual treatment means and to identify means that were not significantly different (taking into account the multiple comparisons).

ANCOVA (where the pre-treatment measurement served as a co-variate) was used for crop tree analysis (Table 10) and for stand-level analysis (Table 11) to adjust for any significant pre-treatment difference in tree size within a block.

TABLE 10 *ANCOVA table for stand-tending treatments: crop tree analysis*

Source of Variation	Degrees of Freedom	Type of Effect
Block (B)	3 – 1 = 2	Random
Covariate (1997 height, diameter)	1	Fixed
Fertilizer (F)	2 – 1 = 1	Fixed
Thinning (T)	2 – 1 = 1	Fixed
T*F	(2 – 1) (2 – 1) = 1	Fixed
B*T*F, B*F, B*T (pooled error)	(3 – 1) (2 – 1) (2 – 1) + (3 – 1) (2 – 1) + (3 – 1) (2 – 1) = 6	Random
Trees E(BFT)	(36 – 1) 3 × 2 × 2 – 1 = 419	Random
Total	(3 × 2 × 2 × 36) – 1 = 431	

TABLE 11 *ANCOVA table for stand-tending treatments: stand-level analysis (assumes 100 trees/treatment plot, but actual sample sizes vary)*

Source of Variation	Degrees of Freedom	Type of Effect
Block (B)	3 – 1 = 2	Random
Covariate (1997 height, diameter)	1	Fixed
Thinning (T)	2 – 1 = 1	Fixed
Fertilizing (F)	2 – 1 = 1	Fixed
T*F	(2 – 1) × (2 – 1) = 1	Fixed
B*T*F, B*F, B*T (pooled error)	(3 – 1) (2 – 1) (2 – 1) + (3 – 1) (2 – 1) + (3 – 1) (2 – 1) = 6	Random
Trees E(BTF), Subplots S(BTF) (pooled error)	(100-1) × 3 × 4 – 1 = 1187	Random
Total	(3 x 4 × 100) – 1 = 1199	

ANOVA was used for the crop tree and stand-level foliar analysis (Table 12) and rehabilitation treatment (Table 13) comparisons. Rehabilitation treatments with only one replication were not included in the analysis.

TABLE 12 *ANOVA table for foliar assessments*

Source of Variation	Degrees of Freedom	Type of Effect
Block (B)	3 – 1 = 2	Random
Fertilizer (F)	2 – 1 = 1	Fixed
Thinning (T)	2 – 1 = 1	Fixed
T*F	(2 – 1) × (2 – 1) = 1	Fixed
Composites: C(BFT), B*F, B*T, B*T*F (pooled error)	(2 – 1) × 3 × 2 × 2 + (3 – 1) (2 – 1) (2 – 1) + (3 – 1) (2 – 1) + (3 – 1) (2 – 1) = 18	Random
Total	3 × 2 × 2 × 2 – 1 = 23	

TABLE 13 *ANOVA table for the rehabilitation treatments. Only treatments with more than one replication are included.*

Source of Variation	Degrees of Freedom	Type of Effect
Block (B)	3 – 1 = 2	Random
Site Preparation (S)	5 – 1 = 4	Fixed
B * S	(3 – 1) (5 –1) = 8	Random
Fertilizer (F)	2 – 1 = 1	Fixed
F * S	(2 – 1) (5 – 1) = 4	Fixed
F * B	(2 – 1) (3 – 1) = 2	Random
F * S * B	(2 – 1) (5 – 1) (3 – 1) = 8	Random
Tree, E(BSF)	(45 – 1) × 3 × 5 × 2 = 1320	Random
Total	(3 × 5 × 2 × 45) – 1 = 1349	

3 RESULTS

Results are described below according to the two main treatment types, stand tending and rehabilitation. Stand-tending results are based on data collected 4 years after thinning and 3 years after fertilization and include 3rd-year results for crop trees, fixed-radius plots (stand-level assessment), and foliar nutrient analysis. Rehabilitation results summarize data collected 1 year after planting.

The data tables presenting the results provide the mean, standard error, and mean separation (which is indicated by the lowercase letters following the means). If only one standard error is reported, this indicates that it was the same for all means. Also shown is the F-value and corresponding probability (p-value) associated with the "fixed effects" (thinning or fertilization) that produced the mean treatment differences and any interactions between them.

3.1 Results: Stand-tending Treatments

3.1.1 Crop trees Three years after fertilization, the 36-year-old repressed lodgepole pine showed a positive response in height growth. However, the combination of thinning and fertilization produced the greatest response. Responses from 1997 to 2001, by crop tree variable, are given in Tables 14–21 (3rd-year results for fertilization and 4th-year results for thinning).

Cumulative height and diameter growth All the stand-tending treatments produced different, but significant, increases in tree growth from 1998 to 2001 compared with the untreated control (Table 14). Cumulative height and diameter growth (reflecting 1st-year post-thinning treatment in 1998 and 3rd-year post-fertilization treatment from 1999 to 2001) were significantly better in the two treatments that included fertilization. The unthinned fertilized treatment produced the largest height growth, whereas the combination of thinning plus fertilization produced the largest diameter growth. A significant difference in cumulative 4-year diameter growth was found between the thinned and untreated trees, but not in height growth. Although thinning, the main fixed effect, produced a significant difference in height growth, this was only true for the combination of thinning and fertilizing and not for thinning alone. Conversely, diameter growth response was equal for thinning and fertilizing alone, and the greatest diameter response resulted from the combination of thinning plus fertilizing.

Annual height and diameter growth Trends in the annual height- and diameter-growth response did not always correspond to the cumulative growth response, as shown in Tables 15 and 16. The treatment blocks had been stratified by height before treatment, but despite random assignment of treatments within blocks, the trees in the thinned-plus-fertilized plots had slightly longer leaders before treatment and those in the thinned plots had the shortest leaders. This difference caused a pre-treatment interaction (Table 15). All subsequent analyses used ANCOVA to account for these pre-treatment differences, and any interactions between thinning and fertilization were found to be due to treatment differences. In 1998, no treatment interaction was found when the 1997 height was used as a co-variate.

Thinning, as a main fixed effect, initially reduced annual height growth in 1998. Then in 1999, the first growing season after fertilization, a positive height-growth response was observed on the unthinned fertilized treatment and not on the thinned-plus-fertilized treatment. Annual height growth remained significantly higher on the unthinned fertilized treatment than on the other treatments for the next 2 years. By 2001, the unthinned fertilized and the thinned-plus-fertilized treatments were responding similarly. At that point, the interaction observed in 1999 and 2000 between the two main fixed effects, thinning and fertilization, became non-significant, as both fertilizer treatments were causing a similar increase in annual height growth.

Unlike for annual height growth, thinning and fertilization each had a similar and positive effect on annual diameter growth (Table 16). A more consistent and eventually significant response was observed for each factor. Initially in 1999, the only treatment significantly different from the untreated plots was the combination of thinning and fertilization. By 2000, both thinned-only and fertilized-only plots showed increased diameter growth compared to the untreated plots, with the combined treatments producing the largest response. However, in 2001, diameter growth in the unthinned fertilized treatment was no longer significantly larger than in the control,

TABLE 14 *Mean crop tree height (cm) and diameter (cm) in 1997 and cumulative growth from 1998 to 2001, reflecting 1-year post-thinning and 3-year post-fertilization treatments. Within a row, means that were found to be significantly different by the Bonferroni method at p = 0.05 are followed by a different letter.*

Type and Year of Assessment	Means					Fixed Effects					
	Untreated	Thinned	Unthinned Fertilized	Thinned plus Fertilized	Standard Error	Thinned		Fertilized		Thinned * Fertilized	
						F-value	p-value	F-value	p-value	F-value	p-value
Height 1997	457	431	448	491	53	0.15	0.7103	1.4	0.2815	2.52	0.1632
Height growth 1998–2001	33.7a	30.8a	79.6b	58.3c	3.3	13.26	0.0067	120.56	<0.0001	7.56	0.0250
Diameter 1997	4.36	4.15	4.36	4.62	0.48	0.04	0.8514	3.36	0.1051	3.62	0.1057
Diameter growth 1998–2001	0.46a	1.0b	1.06b	1.65c	0.15	59.21	0.0003	72.01	0.0001	0.15	0.7089

TABLE 15 *Mean annual height growth (cm) for crop trees, 1997–2001. Within a row, means that were found to be significantly different by the Bonferroni method at p = 0.05 are followed by a different letter.*

Year of Assessment	Means					Fixed Effects					
	Untreated	Thinned	Unthinned Fertilized	Thinned plus Fertilized	Standard Error	Thinned		Fertilized		Thinned * Fertilized	
						F-value	p-value	F-value	p-value	F-value	p-value
1997	13.7	13.1	13.4	14.4	0.58	0.19	0.6606	1.74	0.1881	4.43	0.0359
1998	12.1a	10.1ab	10.7ab	8.9b	0.62	9.67	0.015	4.15	0.0768	0.05	0.8285
1999	9.9a	9.7a	17.3b	9.7a	0.75	26.89	0.0010	24.10	0.0013	24.03	0.0013
2000	9.3a	8.6a	28.6b	19.1c	1.46	12.22	0.0088	103.8	<0.0001	8.80	0.0185
2001	7.3a	7.7a	28.2b	25.2b	1.4	0.90	0.3715	201.22	<0.0001	7.56	0.2500

TABLE 16 *Mean annual diameter growth (cm) for crop trees, 1998–2001. Within a row, means that were found to be significantly different by the Bonferroni method at p = 0.05 are followed by a different letter.*

	Means					Fixed Effects					
						Thinned		Fertilized		Thinned * Fertilized	
Year of Assessment	Untreated	Thinned	Unthinned Fertilized	Thinned plus Fertilized	Standard Error	F-value	p-value	F-value	p-value	F-value	p-value
1998	0.10	0.12	0.13	0.13	0.019	0.31	0.5961	1.08	0.3376	0.39	0.5559
1999	0.15a	0.28ab	0.27ab	0.39b	0.049	21.54	0.0036	17.85	0.005	0.07	0.8044
2000	0.11a	0.27b	0.39b	0.60c	0.043	38.22	0.0008	100.01	<0.0001	0.47	0.5179
2001	0.10a	0.32b	0.27ab	0.54c	0.06	53.93	0.0003	33.36	0.0012	0.61	0.4651

suggesting that thinning would possibly be required to maintain the increase in growth initially provided by the fertilizer.

Height:diameter ratios Before treatment in 1997, height:diameter ratios were similar across all blocks (Table 17). Treatment effects were not apparent until 2000, when thinning as a main fixed effect was significant for the height:diameter ratio ($p = 0.0326$). Although this trend of decreasing height:diameter ratios was evident, individual treatment means were not found to be significantly different using Bonferroni's test. By the following year, the thinned-plus-fertilized treatment had a significantly smaller mean height:diameter ratio than did the untreated control.

Percent live crown The percent live crown in crop trees was over 25% in all treatments for all years (Table 18). It was slightly lower in 2001 on the untreated trees, but not significantly. Conversely, a weakly significant trend ($p < 0.10$) indicated that the treatments have produced an increase in the actual width of the crown. By 2001, fertilized trees were also showing the highest vigour (Table 19).

Damaging agents At the time of trial establishment, most of the lodgepole pine in all of the treatment blocks had a high level of pine needle cast, apparent in at least two-thirds of the crowns (Table 20). However, this pathogen affected only the older needles. The needle cast did not appear in subsequent years and, over time, has not had a serious effect on the more vigorous trees. Additionally, western gall rust was observed predominantly on pine branches, with only a very minor incidence on stems in the untreated blocks.

By 2001, red band needle blight (*Mycosphaerella pini*) had infected a number of trees in the trial area (Table 21). A higher incidence, with more of the crown affected, was found on the thinned-plus-fertilized trees compared to the other treatments. Wildlife damage (believed to be rabbit damage) was highest on the fertilized treatments but still low. The untreated and fertilized-only trees had some occurrence of chlorosis, 15% and 27%, respectively, while the thinned treatments had healthier-looking foliage.

3.1.2 Stand-level response

Cumulative and annual height and diameter growth The 1997 measurements indicated that thinning, through removal of the smaller trees, increased the mean stand height ($p = 0.009$), although the Bonferroni test did not find differences between individual treatments (Table 22). The 4-year height-growth response was very clear: fertilization increased the height growth whereas thinning did not. In 1999, the 1st year after fertilization, no differences were found in leader growth. In the subsequent 2 years, however, significantly longer leaders were found on the fertilized plots (Table 23).

In 1997, thinning also increased the mean diameter of the stand by removing all of the smaller trees (Table 22). As well, thinning increased the cumulative 4-year diameter growth, and the combination of thinning and fertilizing produced a significantly larger response than did either of the individual treatments. The unthinned fertilized treatment resulted in larger annual diameter growth compared to the untreated control, but only in 2000 was it significantly larger (Table 24).

TABLE 17 *Mean height:diameter ratio for crop trees. Within a row, means that were found to be significantly different by the Bonferroni method at p = 0.05 are followed by a different letter.*

	Means					Fixed Effects					
						Thinned		Fertilized		Thinned * Fertilized	
Year of Assessment	**Untreated**	**Thinned**	**Unthinned Fertilized**	**Thinned plus Fertilized**	**Standard Error**	**F-value**	**p-value**	**F-value**	**p-value**	**F-value**	**p-value**
1997	106	105	105	107a	2.85	0.1	0.7577	0.07	0.7936	0.34	0.5767
1998	106	104	104	106	2.86	0.00	0.9904	0.01	0.9321	0.60	0.4621
1999	104	99	101	99	3.27	1.3	0.2983	0.24	0.6425	0.15	0.7106
2000	104	95	99	91	3.17	7.76	0.0326	1.96	0.2119	0.03	0.8687
2001	103a	91ab	99ab	88b	3.4	21.45	0.0038	1.45	0.2743	0.01	0.9404

TABLE 18 *Mean radial crown width (RCW) and mean percent live crown (% LC) for crop trees*

	Means					Fixed Effects					
						Thinned		Fertilized		Thinned * Fertilized	
Type and Year of Assessment	**Untreated**	**Thinned**	**Unthinned Fertilized**	**Thinned plus Fertilized**	**Standard Error**	**F-value**	**p-value**	**F-value**	**p-value**	**F-value**	**p-value**
RCW 1997	47	47	52	53	3.41	0.12	0.7388	11.37	0.0150	0.33	0.5888
RCW 2001	55	61	61	67	3.0	4.68	0.0634	4.06	0.0794	0.01	0.9258
% LC 1997	52	54	52	52	2.62	0.15	0.7096	0.15	0.7103	0.02	0.8868
% LC 2001	54	58	59	59	2.1	1.05	0.3361	1.59	0.2421	0.95	0.3575

TABLE 19 *Tree vigour expressed as percent of crop trees rated as good or fair*

Treatment	1997	1998	1999	2000	2001
Untreated	47.3	64.9	55.6	45.3	50.9
Thinned	48.2	40.7	40.7	36.1	34.3
Unthinned fertilized	43.5	34.3	38.0	51.0	75.0
Thinned plus fertilized	59.3	42.6	42.6	44.5	76.8

TABLE 20 *Major damaging agents found in crop trees, recorded in 1997 by percent of affected trees and the percent infection of foliage in individual crowns*

	Pine Needle Cast		Western Gall Rust	
	Trees	Crown	Branch	Stem
Untreated	98.1	69.6	5.6	0.9
Thinned	97.2	65.4	8.3	0
Unthinned fertilized	94.4	63.6	12.0	0
Thinned plus fertilized	95.4	64.6	8.3	0

TABLE 21 *Major damaging agents found in crop trees, recorded in 2001 by percent of affected trees and the percent infection of foliage within individual crowns*

	Red Band Needle Blight		Western Gall Rust		Wildlife
	Trees	Crown	Branch	Stem	Trees
Untreated	3.7	15.0	13.0	1.9	0.0
Thinned	13.9	12.4	8.3	1.9	0.0
Unthinned fertilized	12.0	11.9	14.8	0	0.9
Thinned plus fertilized	24.1	31.7	12.0	0.9	3.7

Height:diameter ratios Mean height:diameter ratios are listed in Table 25. Stands in which trees have a high height:diameter ratio (i.e., higher than 100) are prone to stem damage from climatic conditions such as wind or accumulations of wet snow, especially after thinning. Thinning decreased the height:diameter ratios in 1997 by removing the smaller and spindlier stems. Clear treatment trends were not apparent until 2000, when the thinned-only stands had a significantly lower height:diameter ratio. In 2001, the height:diameter ratio of the thinned-plus-fertilized stand was also significantly lower. Compared to the untreated stands, the thinned treatments increased only in diameter, whereas the thinned-plus-fertilized treatment increased in diameter and height, producing a slower decline in height:diameter ratio. The height:diameter ratios of the fertilized-only treatment remained the same as those of the untreated control.

Radial crown and percent live crown The radial crown width increased on the thinned plots in 1997 after the smaller and poorer-quality trees were removed (Table 26). Radial crown width gradually increased on the fertilized-only treatment even though the smaller trees were not removed. By 2001, percent live crown had increased significantly on the thinned-only treatment and to a lesser degree on the fertilized treatment.

TABLE 22 *Mean height (cm) and diameter (cm) in 1997 after thinning and cumulative growth from 1998 to 2001, including 1-year post-thinning and 3 years post-fertilization, at the stand level. Within a row, means that were found to be significantly different by the Bonferroni method at p = 0.05 are followed by a different letter.*

	Means					Fixed Effects					
						Thinned		Fertilized		Thinned * Fertilized	
Type and Year of Assessment	Untreated	Thinned	Unthinned Fertilized	Thinned plus Fertilized	Standard Error	F-value	p-value	F-value	p-value	F-value	p-value
Height 1997	360	419	356	469	52.8	14.24	0.0091	1.02	0.3509	1.38	0.2846
Height growth 1998–2001	25.5a	30.8ab	54.4c	51.5bc	4.6	0.08	0.7863	32.78	0.013	0.88	0.3840
Diameter 1997	2.91a	4.07bc	3.05ab	4.33c	0.48	38.32	0.0008	1.03	0.3491	0.10	0.7577
Diameter growth 1998–2001	0.31a	0.95b	0.59ab	1.50c	0.13	82.17	<0.0001	24.41	0.0026	2.57	0.1604

TABLE 23 *Mean annual height growth (cm) at the stand level, 1998–2001. Within a row, means that were found to be significantly different by the Bonferroni method at p = 0.05 are followed by a different letter.*

	Means					Fixed Effects					
						Thinned		Fertilized		Thinned * Fertilized	
Year of Assessment	Untreated	Thinned	Unthinned Fertilized	Thinned plus Fertilized	Standard Error	F-value	p-value	F-value	p-value	F-value	p-value
1998	6.21	6.99	6.62	5.27	0.69	0.25	0.6338	1.37	0.2866	3.57	0.1078
1999	7.89	8.27	10.81	9.34	1.46	0.17	0.6927	2.30	0.1795	0.49	0.5086
2000	6.11a	7.49a	17.8b	15.6b	1.44	0.10	0.7569	61.42	0.0002	2.00	0.2078
2001	5.2a	7.6a	18.8b	21.4b	1.90	1.78	0.2188	53.77	<0.0001	0.00	0.9491

TABLE 24 *Mean annual diameter growth (cm) at the stand level, 1998–2001. Within a row, means that were found to be significantly different by the Bonferroni method at p = 0.05 are followed by a different letter.*

	Means					Fixed Effects					
Year of Assessment	Untreated	Thinned	Unthinned Fertilized	Thinned plus Fertilized	Standard Error	Thinned		Fertilized		Thinned * Fertilized	
						F-value	p-value	F-value	p-value	F-value	p-value
1998	0.06a	0.13b	0.09ab	0.11b	0.017	28.10	0.0009	0.03	0.8636	5.32	0.0607
1999	0.11a	0.28b	0.17ab	0.36c	0.034	31.88	0.0012	4.92	0.0686	0.06	0.8117
2000	0.07a	0.23b	0.17b	0.50c	0.043	272.13	<0.0001	165.09	<0.0001	34.05	0.0012
2001	0.06a	0.29b	0.15ab	0.51c	0.050	62.33	0.0002	16.64	0.0066	2.98	0.135

TABLE 25 *Mean height:diameter ratio at the stand level, 1997–2001. Within a row, means that were found to be significantly different by the Bonferroni method at p = 0.05 are followed by a different letter.*

	Means					Fixed Effects					
Year of Assessment	Untreated	Thinned	Unthinned Fertilized	Thinned plus Fertilized	Standard Error	Thinned		Fertilized		Thinned * Fertilized	
						F-value	p-value	F-value	p-value	F-value	p-value
1997	134a	105b	129ac	110bc	4.4	28.06	0.0007	0.00	0.9768	1.47	0.2595
1998	127	104	121	115	6.2	6.9	0.0386	0.15	0.7124	2.29	0.1807
1999	126	99	119	107	6.3	11.45	0.0145	0.01	0.9395	1.86	0.2213
2000	126a	95b	119ab	100ab	6.7	18.17	0.0052	0.04	0.8516	1.14	0.3259
2001	126a	91b	120ab	95b	6.9	27.26	0.0019	0.02	0.8823	0.83	0.3986

TABLE 26 *Mean radial crown width (RCW) and percent live crown (% LC) at the stand level. Within a row, means that were found to be significantly different by the Bonferroni method at p = 0.05 are followed by a different letter.*

	Means					Fixed Effects					
						Thinned		Fertilized		Thinned * Fertilized	
Type and Year of Assessment	Untreated	Thinned	Unthinned Fertilized	Thinned plus Fertilized	Standard Error	F-value	p-value	F-value	p-value	F-value	p-value
RCW 1997	33.5a	47.5b	35.2a	50.9b	3.5	148.37	<0.0001	4.44	0.0806	0.43	0.5365
RCW 1998	36.7	43.8	36.7	41.8	2.0	6.91	0.0298	0.00	0.9645	0.94	0.3611
RCW 1999 *	40.1±3.2	45.0±1.4	43.1±2.9	47.4±1.5	NA	4.01	0.0473	1.42	0.2352	0.02	0.9001
RCW 2000	41.4a	53.4b	44.8ab	53.6b	2.4	17.92	0.0029	0.54	0.4848	0.42	0.5358
RCW 2001	41.7a	59.7b	47.0ab	59.8b	3.4	20.45	0.0020	0.64	0.4481	0.56	0.4769
% LC 1997			No data collected					NA			
% LC 1998			No data collected					NA			
% LC 1999	42.9	53.2	45.5	49.4	2.7	7.02	0.0289	0.05	0.8333	1.46	0.2616
% LC 2000	42.8	53.8	48.2	51.6	2.4	8.97	0.0169	0.42	0.1501	2.53	<0.0001
% LC 2001	44.2a	55.8b	50.9ab	54.9ab	2.4	10.92	0.0105	1.52	0.2529	2.59	0.1463

* The standard error varied for each mean and is reported separately.

The post-treatment stand densities are provided in Table 27 and the proportion of trees rated as good or fair (trees that are expected to eventually become merchantable) is provided in Table 28. Thinning alone generally increased the vigour of the remaining trees. With fertilization only, the effect was not as great. On the thinned-plus-fertilized treatment, by 2001, the proportion of stems categorized as good or fair was over 60%. This suggests that, based on the average stand density of 2678 stems/ha for this treatment, there are 1676 stems/ha with acceptable vigour that can now be expected to grow to maturity with minimal competition.

Damage Mortality was minimal in the thinned treatments (Table 29), but continued in the unthinned treatments after 4 years.

At the stand level, thinning reduced the incidence of some types of physical damage and stem galls (Table 30). Pine needle cast was highly prevalent in 1997, affecting almost all trees, but by 1998 it was not observed, showing that all the control and treated trees had recovered well from the infestation. Western gall rust was removed as much as possible in the thinning treatments. Stem gall was reduced by approximately 20% in thinned compared with unthinned plots. Branch galls remained after thinning, but are not considered seriously detrimental to the trees' vigour.

In 2001, very little damage was recorded across all treatments (Table 31). Despite the high height:diameter ratio of the stems before treatment (resulting from high stand densities), there was a very low incidence of bent stems and damage from snow press in any of the treatments. Wildlife damage on

TABLE 27 *Post-treatment density (stems/ha) at the stand level*

	Block 1	Block 2	Block 3	Average
Untreated	32 148	17 825	18 462	22 812
Thinned	2 272	2 212	2 372	2 286
Unthinned fertilized	31 395	25 367	10 345	22 369
Thinned plus fertilized	2 771	2 472	2 790	2 678

TABLE 28 *Percent of trees at the stand level rated as good or fair*

	1997	1998	1999	2000	2001
Untreated	16.2	14.5	14.3	14.5	16.5
Thinned	14.3	16.3	31.1	37.0	36.7
Unthinned fertilized	16.3	13.4	16.1	20.5	26.4
Thinned plus fertilized	30.6	27.3	30.6	40.4	62.6

TABLE 29 *Percent tree mortality*

	1997	1998	1999	2000	2001
Untreated	0	1.5	2.7	4.6	5.3
Thinned	0	0.3	0.6	0.6	0.9
Unthinned fertilized	0	1.7	3.5	5.6	5.8
Thinned plus fertilized	0	0	0	0	0.2

TABLE 30 *Major damaging agents recorded in 1997 at the stand level shown by the percent of affected trees and the percent infection of foliage within individual crowns*

	Average Percent Incidence				Average Percent Infection			
	Dead		Bent or with		Pine Needle Cast		Western Gall Rust	
Treatment	Terminal	Forked	Basal Sweep	Scarred	Tree	Crown	Branch	Stem
Untreated	2.4	5.1	13.8	24.9	98.1	75.8	5.6	32.7
Thinned	0	0.3	5.2	5.8	99.7	74.8	9.3	8.1
Unthinned fertilized	2.3	6.1	12.8	28.9	99.1	62.6	8.2	26.8
Thinned plus fertilized	0	0.5	1.5	10.4	98.8	70.1	7.9	8.7

TABLE 31 *Incidence of damage recorded in 2001 at the stand level shown by the percent of affected trees and the percent infection of foliage within individual crowns*

			Red Band Needle Blight		
Treatment	Snow Press	Bent Stems	Trees	Crown	Wildlife Damage
Untreated	0.0	1.6	1.7	13.6	1.1
Thinned	0.1	1.6	4.3	12.7	0.1
Unthinned fertilized	0.3	0.1	7.0	14.1	1.1
Thinned plus fertilized	0.8	0.2	5.3	22.9	0.5

fertilized trees was found, but the incidence was low (maximum 1.1%) and predominantly in the unthinned stands.

3.1.3 Foliar nutrients Foliar nutrient concentrations are presented in Tables 32 and 33 for all the macronutrients and micronutrients, respectively, by treatment. The classification of nutrient concentration levels used below is from Brockley (2001).

Macronutrients Nitrogen and sulphur were found to be the only deficient macronutrients before treatment (Table 32). Pre-treatment assessments in 1997 indicated that nitrogen was severely deficient (< 1.0%) and sulphur was severely to moderately deficient (0.06–0.08%). There were no differences in nutrient concentrations between treatments before fertilization.

Both thinning and fertilizing increased concentrations of nitrogen in 1999, relative to the untreated control, although only fertilization increased the percent nitrogen from the severely deficient range to the slightly-to-moderately deficient category (1.15–1.35%). By 2000, the effect of thinning was no longer significant and the foliar nitrogen levels had slipped to the moderately-to-severely deficient level (1.00–1.15%). By 2001, there were no differences between any of the treatments and levels had all returned to the severely deficient category.

Fertilization increased the sulphur concentration from the moderately-to-severely deficient level (0.06–0.08%) to an adequate level (> 0.10%) in 1999. In 2000 and 2001, the fertilized treatments still had significantly higher concentrations of total sulphur, but they had dropped from adequate to slightly-to-moderately deficient (0.08–0.10%) in 2001. No effect of thinning was observed. Sulphate sulphur levels also indicated a severe sulphur deficiency (< 40 ppm) in 1997, and fertilization increased the concentrations to the adequate or slight-to-moderate deficiency (60–80 ppm) category.

TABLE 32 *Mean macronutrient concentrations before treatment (1997) and one, two, and three growing seasons after fertilization (1999–2001). Within a row, means that were found to be significantly different by the Bonferroni method at p = 0.05 are followed by a different letter.*

		Means					Fixed Effects					
							Thinned		Fertilized		Thinned * Fertilized	
Macronutrient (Adequate Value)	Year	Untreated	Thinned	Unthinned Fertilized	Thinned plus Fertilized	Standard Error	F-value	p-value	F-value	p-value	F-value	p-value
Nitrogen (%) (> 1.35%)	1997	0.98	0.92	0.89	0.9	0.046	0.34	0.58	1.52	0.25	0.64	0.45
	1999	0.81a	0.89a	1.22b	1.31b	0.032	8.43	0.0095	217.78	<0.0001	0.03	0.86
	2000	0.88a	0.94a	1.10b	1.15b	0.036	3.59	0.11	56.51	0.0003	0.02	0.88
	2001	0.88	0.92	0.97	0.92	0.028	0	0.95	2.87	0.14	2.65	0.15
Sulphur (total) (%) (> 0.10%)	1997	0.079	0.078	0.078	0.076	0.0035	0.23	0.65	0.14	0.71	0.01	0.93
	1999	0.066a	0.071a	0.105b	0.11b	0.0042	1.71	0.24	114.02	<0.0001	0.03	0.88
	2000	0.066a	0.068a	0.093b	0.091b	0.0024	0.01	0.94	152.77	<0.0001	0.81	0.40
	2001	0.072	0.069	0.081	0.084	0.0038	0.01	0.93	16.77	0.0064	0.79	0.41
Sulphate sulphur (ppm) (> 80 ppm)	1997	35	39	42	48	6.4	0.58	0.47	1.39	0.27	0.02	0.90
	1999	38	34	83a	70	18	0.37	0.57	8.78	0.025	0.12	0.12
	2000	38a	31a	95b	78b	9.0	3.34	0.12	61.13	0.0002	0.55	0.49
	2001	34ab	23a	71ab	101b	14	0.54	0.49	19.71	0.0044	2.42	0.17
Phosphorus (%) (> 0.12%)	1997	0.15	0.14	0.14	0.14	0.0060	0.08	0.79	1.92	0.20	0.08	0.79
	1999	0.13a	0.14ab	0.15b	0.14ab	0.0052	0.03	0.88	4.29	0.052	4.29	0.052
	2000	0.13a	0.15ab	0.16b	0.16b	0.0044	2.42	0.17	25.04	0.0024	1.21	0.31
	2001	0.12	0.13	0.14	0.14	0.0057	0.82	0.40	7.36	0.0035	0.82	0.40
Calcium (%) (> 0.10%)	1997	0.19	0.18	0.2	0.2	0.014	0.06	0.82	1.45	0.26	0	1.00
	1999	0.20a	0.18abc	0.18b	0.23c	0.0083	1.97	0.18	4.02	0.059	14.5	0.0011
	2000	0.17	0.19	0.19	0.22	0.017	1.89	0.22	3.56	0.11	0.19	0.68
	2001	0.16a	0.18a	0.14a	0.17a	0.0092	8.37	0.028	1.07	0.34	0.38	0.56
Magnesium (%) (> 0.08%)	1997	0.092	0.094	0.09	0.095	0.0034	0.84	0.39	0.06	0.82	0.19	0.68
	1999	0.085ab	0.087a	0.091a	0.078b	0.0034	6.89	0.017	0.48	0.50	12.06	0.0027
	2000	0.089	0.089	0.083	0.113	0.067	5.4	0.059	1.93	0.21	5.16	0.064
	2001	0.09	0.094	0.084	0.09	0.0038	2.21	0.19	1.68	0.24	0.06	0.82
Potassium (%) (> 0.40%)	1997	0.42	0.38	0.4	0.39	0.021	1.53	0.26	0.06	0.81	0.55	0.49
	1999	0.42a	0.43a	0.5b	0.51b	0.020	0.63	0.44	60.83	<0.0001	0.23	0.64
	2000	0.43a	0.45ab	0.46ab	0.50b	0.022	6.42	0.021	8.97	0.0078	0.76	0.40
	2001	0.41a	0.44ab	0.44ab	0.47b	0.016	5.43	0.032	4.23	0.055	0.02	0.89

Fertilization also increased the foliar concentrations of potassium and phosphorus, although neither was initially deficient. They both remained above the critical threshold for adequate tree nutrition.

Micronutrients Foliar micronutrient concentrations were adequate before treatment (Table 33), except for boron. The levels at which it occurred indicated a possible (6–12 ppm) to probable (3–6 ppm) deficiency. After fertilization, the concentrations increased to well above the adequate level and have remained there. By 2001, both fertilization treatments had lower boron concentrations compared to immediately after fertilizer application, and boron levels for the fertilized-only treatment had become significantly lower than for the thinned-plus-fertilized treatment.

The only other micronutrients that increased significantly after treatment were zinc and manganese. Zinc concentrations increased after thinning and manganese decreased in 2001 in fertilized plots, but there were no differences between individual treatments.

Nutrient ratios showed that the proportions of nutrients remained within an acceptable balance for all the treatments, except for the nitrogen:phosphorus ratio on the thinned-plus-fertilized treatment in 1999 (Table 34). This ratio did increase slightly but significantly beyond the acceptable range immediately after fertilization, but decreased the next year, indicating that a nitrogen-induced phosphorus deficiency lasted for only 1 year.

No differences between treatments in current-year 100-needle weights were detected in 1997 (Table 35). One year after treatment, needle weight increased on all treatments except the control, but on the trees in the thinned plots it was significantly less than in the thinned-plus-fertilized treatment. Initially, both fertilization treatments resulted in significantly larger needles than on the control. By the 3rd year after treatment, however, needles in the unthinned fertilized treatment decreased in size until their mean weight was not significantly different from those on the untreated trees. Needles on the thinned-plus-fertilized treatment also decreased in weight until 2001, but the needle weight was still significantly larger on this treatment compared to the other three treatments.

Of the three most limiting nutrients—nitrogen, sulphur, and boron—nitrogen was the only one for which foliar nutrient concentrations had declined and were no longer significantly different between treatments by 2001 (Table 32). However, needle weight was still significantly higher in the thinned-plus-fertilized treatment compared with the control, indicating that there was still more nitrogen per tree but it was simply diluted within larger needles. Changes in nutrient content per needle by treatment for nitrogen, sulphur, and boron are shown in Figures 5–7, respectively. Note that in 2001 the nitrogen concentration was 0.097% for the unthinned fertilized treatment and 0.092% for the thinned-plus-fertilized treatment, but the latter treatment resulted in more nitrogen per needle because the needles were larger.

3.2 Results: Rehabilitation Treatments

The rehabilitation results presented here are from assessments made after the first growing season. This was approximately 14 months after planting because the planted seedlings were summer stock and leader elongation did not occur until the following spring. Results for the treatment that consisted of hand-slashing, aligning the slash with a V-blade, disc-trenching, and planting (S-DT) are not reported because only one replication could be completed.

TABLE 33 *Mean micronutrient concentrations before treatment (1997) and one, two, and three growing seasons after fertilization (1999–2001). Within a row, means that were found to be significantly different by the Bonferroni method at p = 0.05 are followed by a different letter.*

		Means					Fixed Effects					
							Thinned		Fertilized		Thinned * Fertilized	
Macronutrient (Adequate Value)	**Year**	**Untreated**	**Thinned**	**Unthinned Fertilized**	**Thinned plus Fertilized**	**Standard Error**	**F-value**	**p-value**	**F-value**	**p-value**	**F-value**	**p-value**
Copper (ppm)	1997	3.3	3.3	3.3	3.3	0.33	0.00	1.0	0.00	1.0	0.00	1.0
(> 3 ppm)	1999	4.8	4.7	5.0	4.3	0.32	1.67	0.23	0.07	0.80	0.60	0.46
	2000	3.6	4.2	3.9	4.0	0.17	3.23	0.088	0.03	0.89	1.62	0.22
	2001	3.8	4.3	4.2	3.5	0.27	0.10	0.76	0.88	0.36	4.80	0.040
Zinc (ppm)	1997	34	39	38	40	2.4	1.68	0.23	0.79	0.40	0.38	0.56
(> 15 ppm)	1999	40a	52b	45a	48ab	1.5	28.92	0.0017	0.05	0.83	14.51	0.0089
	2000	36a	48b	43ab	46b	1.4	26.24	0.0022	3.22	0.12	12.01	0.013
	2001	35a	47b	41ab	46b	1.43	46.47	0.0005	4.54	0.077	8.07	0.030
Iron (ppm)	1997	29	21	24	26	3.4	0.88	0.38	0.00	0.96	2.34	0.16
(> 30 ppm)	1999	33	32	32	33	1.8	0.02	0.89	0.02	0.89	0.11	0.75
	2000	25	25	25	28	1.6	1.51	0.23	1.42	0.25	1.66	0.21
	2001	27	27	28	30	1.4	0.68	0.42	2.35	0.14	0.35	0.56
Manganese (ppm)	1997	296	272	304	280	37	0.42	0.54	0.04	0.84	0.00	0.99
(> 25 ppm)	1999	303	293	357	286	30	2.51	0.16	0.85	0.39	1.42	0.28
	2000	311	284	318	284	26	1.67	0.24	0.02	0.91	0.03	0.86
	2001	320	284	253	232	25	1.45	0.27	6.39	0.045	0.11	0.75
Boron (ppm)	1997	6.3	4.3	5.0	5.0	1.5	1.11	0.33	0.12	0.74	1.11	0.33
(> 15 ppm)	1999	7.8a	9.0a	30.8b	32.7b	2.8	0.38	0.56	92.3	<0.0001	0.02	0.90
	2000	8.7a	9.9a	26.0b	26.13b	2.1	0.31	0.6	199.8	<0.0001	0.17	0.69
	2001	7.2a	9.8a	20.3b	25.0c	1.4	23.84	0.0001	355.8	<0.0001	1.77	0.20

TABLE 34 *Mean nutrient ratios before treatment (1997) and one, two, and three growing seasons after fertilization (1999–2001). Within a row, means that were found to be significantly different by the Bonferroni method at p = 0.05 are followed by a different letter.*

		Means					**Fixed Effects**					
							Thinned		**Fertilized**		**Thinned * Fertilized**	
Ratio (Threshold Value)	**Year**	**Untreated**	**Thinned**	**Unthinned Fertilized**	**Thinned plus Fertilized**	**Standard Error**	**F-value**	**p-value**	**F-value**	**p-value**	**F-value**	**p-value**
N:P	1997	6.7	6.4	6.5	6.6	0.15	0.38	0.55	0	0.97	1.35	0.28
(< 9)	1999	6.5a	6.5a	8.2b	9.7c	0.34	4.89	0.04	53.6	<0.0001	4.33	0.05
	2000	6.6	6.5	6.9	7.1	0.15	0.16	0.70	9.04	0.02	1.54	0.26
	2001	7.5	7.2	7.0	6.7	0.27	1.24	0.28	3.97	0.06	0.00	0.98
N:K	1997	2.3	2.4	2.2	2.3	0.14	0.54	0.49	0.64	0.45	0.00	0.97
(< 2.5)	1999	2.0a	2.1a	2.4b	2.6b	0.073	5.76	0.03	73.56	<0.0001	0.11	0.74
	2000	2.1a	2.1ab	2.4b	2.3ab	0.087	0.18	0.69	19.19	0.0047	1.10	0.33
	2001	2.1	2.1	2.2	2.0	0.071	4.76	0.04	0.07	0.80	2.28	0.15
N:Mg	1997	10.6	9.8	9.86	9.49	0.39	2.41	0.16	1.67	1.67	0.36	0.56
(< 15)	1999	9.6a	10.3ab	13.53b	17.1c	0.86	10.84	0.02	66.76	0.0002	4.80	0.07
	2000	10.0	10.5	13.2	10.7	0.88	1.56	0.25	4.57	0.08	4.00	0.09
	2001	9.9	9.8	11.6	10.3	0.51	2.66	0.15	7.61	0.03	2.38	0.17
N:S	1997	12.3	11.8	11.3	11.8	0.29	0.05	0.82	3.12	0.12	2.96	0.12
	1999	12.4	12.5	11.4	12.0	0.51	0.39	0.54	2.24	0.15	0.02	0.90
	2000	13.5ab	14.0a	11.9b	12.7ab	0.36	4.21	0.09	21.59	0.0035	0.17	0.69
	2001	12.3ab	13.4a	12.1ab	11.1b	0.49	0.00	0.96	8.79	0.010	5.44	0.03

TABLE 35 *Mean 100-needle weight (g) before treatment (1997) and one, two, and three growing seasons after fertilization (1999–2001). Within a row, means that were found to be significantly different by the Bonferroni method at p = 0.05 are followed by a different letter.*

	Means					Fixed Effects					
						Thinned		Fertilized		Thinned * Fertilized	
Year	**Untreated**	**Thinned**	**Unthinned Fertilized**	**Thinned plus Fertilized**	**Standard Error**	**F-value**	**p-value**	**F-value**	**p-value**	**F-value**	**p-value**
1997	1.74	1.61	1.46	1.59	0.095	0	0.98	2.67	0.14	1.96	0.20
1999	1.19a	2.05b	2.55bc	3.23c	0.16	32.82	0.0012	88.74	<0.0001	0.4	0.55
2000	1.29a	1.59ab	1.78b	2.30c	0.078	33.09	0.0012	71.89	0.0001	2.46	0.17
2001	1.41a	1.57a	1.38a	2.09b	0.11	16.68	0.0035	5.18	0.050	6.73	0.03

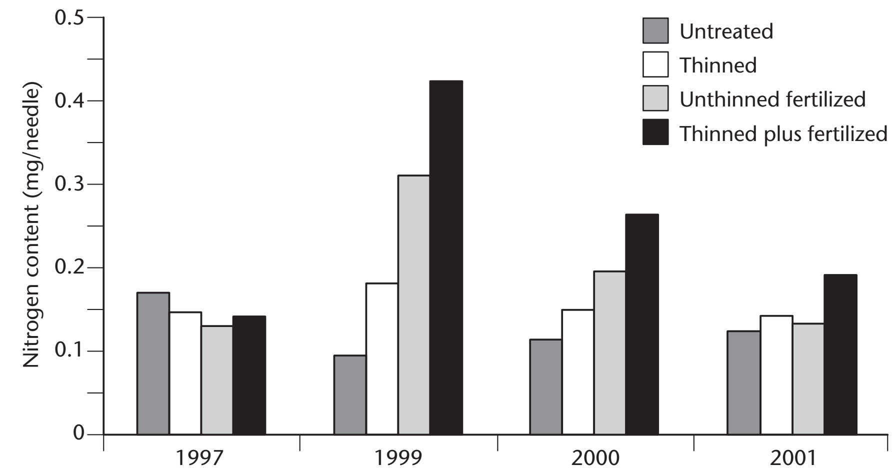

FIGURE 5 *Nitrogen content of foliage in each treatment and year (pre-treatment values given in 1997).*

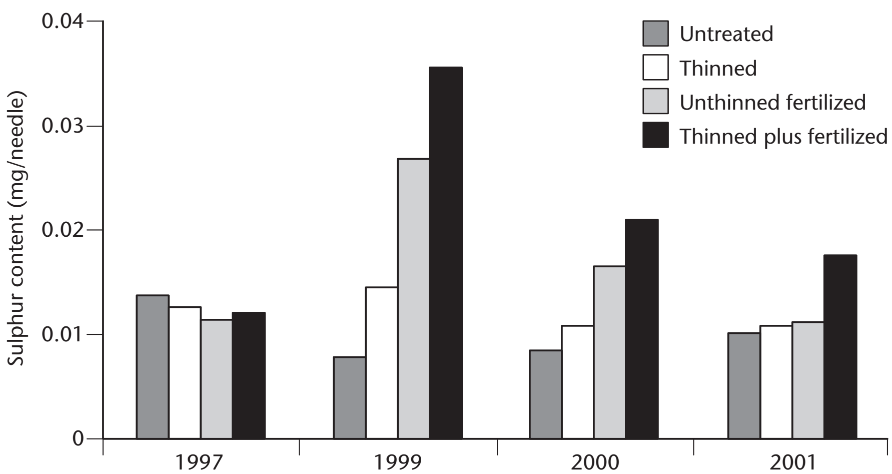

FIGURE 6 *Sulphur content of foliage in each treatment and year (pre-treatment values given in 1997).*

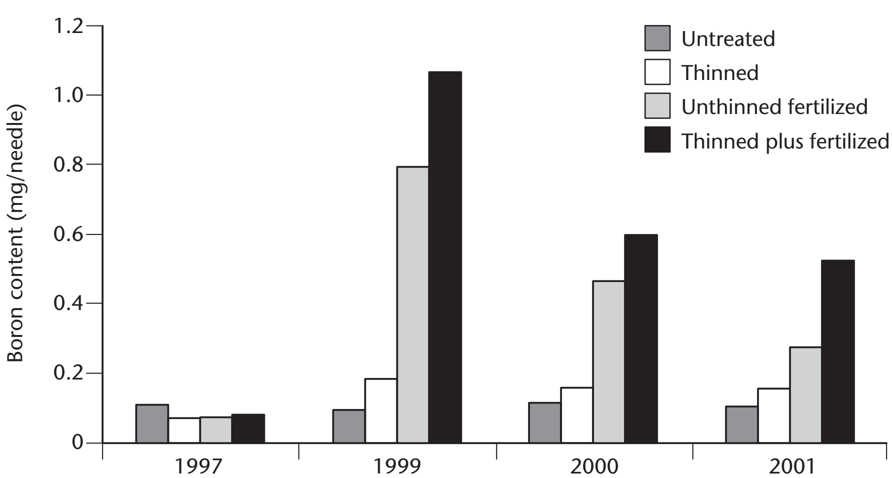

FIGURE 7 *Boron content of foliage in each treatment and year (pre-treatment values given in 1997).*

3.2.1 Seedling survival and vigour Seedling survival was high for all the treatments. The lowest recorded survival rate was 94%. Seedling condition, however, varied between treatments. The best seedlings were found on the fertilized sections of the mulch–disc-trench (with 90% of the seedlings rated as good [Appendix 1]) and the hand-slash–burn–disc-trench treatments (64% of the seedlings rated as good). On other treatments, the percentage of seedlings showing good vigour did not exceed 37%. The poorest seedlings were found on the hand-slash–burn treatment, where 52% were rated as poor on the unfertilized and 34% on the fertilized treatments. The two hand-slash–burn plots planted 1 year after the others produced the majority of the poor seedlings as a result of browsing damage, probably by rabbits. Most seedlings fell into the fair condition category and, although these are less vigorous than those rated as good, they are expected to become crop trees in the future.

3.2.2 Seedling damage Foliage was found to be generally healthy, with some needles showing discoloration and mottling. Scattered browsing, probably by rabbits, was evident on the leaders and stems. Total browse damage was less than 11% on most treatments except for those planted 1 year later. The unfertilized plots showed 19% browse damage and the fertilized plots showed 28%. The amount of browse damage seemed to be related more to plot location than to type of treatment.

On the individual treatment plots planted in 1999, up to 22% of the seedlings in any one plot were browsed. The same trend was apparent for the two plots planted a year later, but the percent damage was significantly higher in one of the plots, where 60% of browse damage affected the fertilized seedlings and 39% of browse damage affected the unfertilized seedlings. The higher level of damage in these two plots assessed 1 year later could have been the result of a number of factors: the plots being located next to the untreated stand; there being fewer seedlings fresh from the nursery; or the rabbit population undergoing a cyclical increase. However, there was no relationship between type of treatment—site preparation or fertilization—and the amount of browse damage.

3.2.3 Vegetation competition More fertilized seedlings were found to be overtopped by vegetation than were those seedlings not fertilized (Figure 8). The dominant vegetation on the trial site is grass, which, although not limiting light, can create competition for moisture.

3.2.4 Seedling growth First-year data, although not conclusive, suggest some future trends in seedling height (Figure 9) and diameter growth (Figure 10). A summary from the ANOVA is provided in Table 36.

Although very few significant differences appear between individual treatments, the ANOVA results indicate that both site preparation and fertilization had a significant effect on seedling height and diameter growth.

First-year trends are not well defined and further assessments will be required before any recommendations can be made.

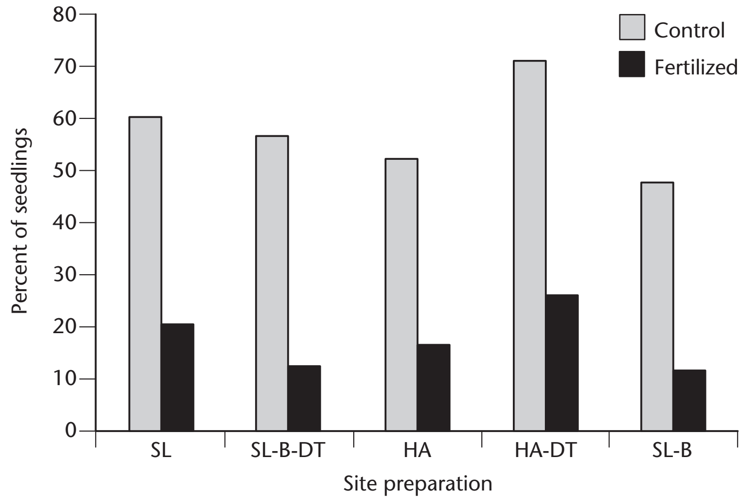

FIGURE 8 *Percent of seedlings taller than the surrounding vegetation after the first growing season.*

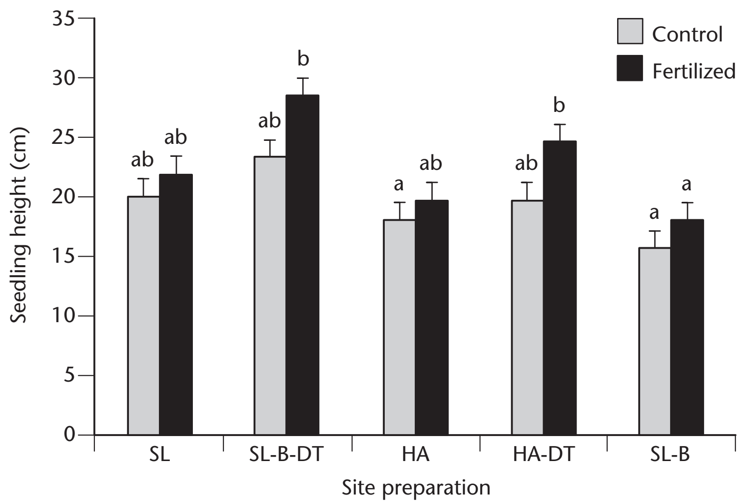

FIGURE 9 *Mean seedling height (and one standard error) after the first growing season. Significant differences are indicated by the letters above the bars.*

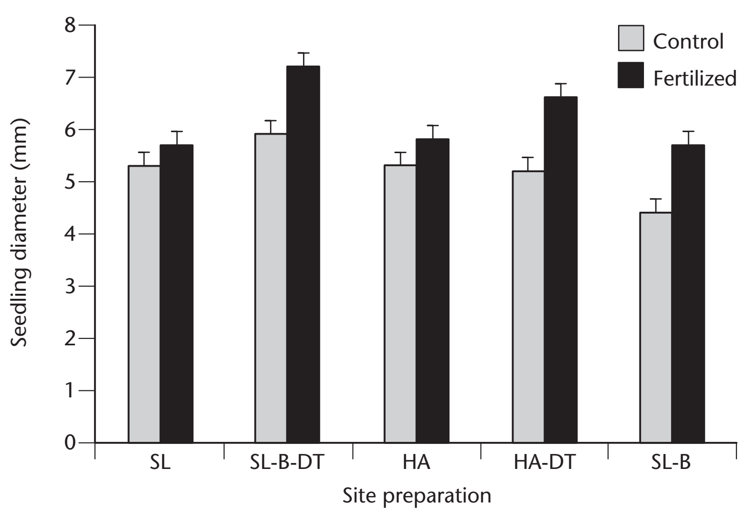

FIGURE 10 *Mean seedling diameter (and one standard error) after the first growing season. No significant differences were found between treatments.*

TABLE 36 *Results from the ANOVA on seedling height and diameter after the first growing season*

	Site Preparation		Fertilization		Site Preparation * Fertilization	
Variable	**F-value**	**p-value**	**F-value**	**p-value**	**F-value**	**p-value**
Height	6.65	0.009	20.15	0.0015	1.16	0.3894
Diameter	5.55	0.0176	35.44	0.0170	2.9	0.1085

4 DISCUSSION

The primary objective of this trial is to find cost-effective treatment regimes that will make older, height-repressed lodgepole pine stands merchantable within 80–120 years. Two options are being tested. One is to treat the existing stand to increase the growth rate of the trees now occupying the site. However, the response of height-repressed pine to treatment is less certain than the response of seedlings planted in a freshly initiated stand. On the other hand, treating the existing stand could result in a merchantable crop of trees sooner and more cost-effectively than would be possible to harvest by starting all over again with new stands.

The other option is to remove the existing trees and then plant. This presents higher initial risks and uncertainties than the first option, because small, fragile seedlings are more susceptible to animal browsing and adverse microclimate (such as frost and cold soils) than are established trees.

4.1 Growth Responses

After 3 years, some of the stand-tending treatments are showing a positive growth response. For the rehabilitation treatments, only the 1st-year results are available and therefore future projections for this option cannot yet be evaluated.

4.1.1 Growth response: thinning Thinning treatments commonly increase diameter growth even in older stands. Johnstone (2002), for example, found long-term increases in diameter increment after thinning a 53-year-old lodgepole pine stand, and Navratil (2002) reported similar results after thinning a 77-year-old pine stand.

The Rosita Fire trial also found diameter growth increases from thinning. These increases followed higher needle weights, recorded in 1999. Higher needle weight can precede an increase in stemwood production, as described in section 4.1.2, "Growth response: fertilization" (Brockley 2000), and may be a result of the added nutrients that leach from the slash into the soil after thinning. Relative to the effect of fertilization, however, the increases in needle weight and subsequent diameter growth response were small.

Increases in height growth after thinning, even in younger stands, are not common and are modest where they have been observed (Johnstone 1985). This trial found the same lack of height-growth increase attributable to thinning.

4.1.2 Growth response: fertilization In addition to having limited growing space, wildfire-origin lodgepole pine usually has nutrient deficiencies—particularly of nitrogen—as a result of volatilization during burning (Brockley 1996). Analysis of tree foliage at the Rosita Fire trial found nitrogen, as well as sulphur and boron, to be deficient. These nutrients are almost always found to be lacking in stands on the Fraser Plateau (G. Newsome, B.C. Ministry of Forests, pers. comm., 2003). Immediately after the fertilization treatment in this trial, the foliar concentration of the three deficient nutrients increased. In subsequent years, the concentrations decreased, with only boron remaining above an adequate concentration after 3 years. Nitrogen returned to severely deficient levels. Nevertheless, increases in annual height growth have continued in the 3 post-treatment years. This response suggests that nutritional status may have been the most limiting growth factor for the height-repressed pine. Despite the expected return of foliar nitrogen concentrations to their original low levels, height-growth increases continued after fertilization.

Studies (some with 14 years of results) on non-repressed pine have shown that fertilization commonly increases diameter but not height growth (Brockley 1996; Kishchuk et al. 2002). The height-growth potential of a site (its site index) is strongly influenced by site conditions such as climate and soils. Therefore, fertilization will not substantially change the rate of height growth in the trees if they are growing at or near the estimated site index. However—as shown by this trial and by Farnden and Herring (2002)—for stands that are height-repressed and growing below the estimated site index, it appears that fertilization can increase the rate of height growth. Forest managers need to know which combination of stand-tending treatments can be used successfully on height-repressed stands, and, if possible, which can restore height growth to that projected by SIBEC (B.C. Ministry of Forests 1997).

Given that nitrogen was a limiting factor, it is unclear why height growth continued to increase after the foliar concentrations declined. Was nutrition the limiting factor, or was the addition of nutrients the catalyst required to address other limitations to tree growth? Foliar biomass on these height-repressed trees had been diminished through excessive inter-tree competition and, in some cases, by foliar disease. Although no measurements were taken of total foliar biomass, both radial crown width and percent live crown are indicators of crown size. Radial crown width is an absolute measurement of actual tree size; percent live crown is a proportional measure indicating what percentage of the total stem is occupied by the crown. Thus, radial crown width can be used to compare differences in growth response between treatments, and percent live crown can be used to assess the ability of a tree to provide enough photosynthate to support a stem of its size.

Fertilization, especially in combination with thinning, increased the pine crown dimensions and needle size, producing more foliar biomass. Needle biomass was first to increase following fertilization. This response is commonly observed before stemwood production increases following fertilization and can be used as a screening technique to identify a stand's potential response to a fertilizer application (Brockley 2000). After the 1st-year needle response, longer branches were produced by the fertilized trees and needle size was larger compared to the untreated trees, although smaller than in the 1st-year response. Crowns increased in both length and width, especially in the fertilized treatments (Table 37). After 3 years, the thinned-plus-fertilized treatment had produced the largest crowns and the largest increase in overall height growth. The larger crown size means that the trees will have an increased ability to maintain their current growth rate.

TABLE 37 *Comparison of crop tree variables in 2001*

	Crop tree height 2001 (m)	Length of live crown (m)	Percent live crown	Radial crown width (cm)
Untreated	4.9	2.55	52	55
Thinned	4.6	2.48	54	61
Unthinned fertilized	5.3	3.13	59	61
Thinned plus fertilized	5.5	3.25	59	67

The addition of nutrients through fertilization appears to have promoted an increase in foliar biomass, the previous lack of which may have been a primary factor limiting tree growth. The increased foliar biomass may now be able to support a height-growth rate closer to that of the estimated site index. More time is required to determine if this response will continue. Operational trials on non-repressed stands have shown that a diameter-growth response lasts for only about 6–9 years after fertilizer is applied (Brockley 1996). According to Brockley, the continued growth of trees, even after nutrient concentrations have dropped, is an indirect response to fertilizer application: as the tree becomes bigger, its ability to sustain an increased growth rate is better. However, the growth response Brockley observed was in tree diameter and not height. Data reported by Farnden and Herring (2002) suggested that a combination of density reduction and a single fertilization treatment in a severely repressed pine stand near Prince George alleviated height repression. The stand is still growing well 19 years after treatment, indicating that this indirect response to fertilization has continued over a long period of time. Although the stand was younger when treated (18 years) than that in the Rosita Fire trial, and situated on a more productive site, its long-term results offer hopeful prospects for continued stand response at the Rosita Fire site.

4.2 Stand-tending Treatment Options

Increasing the rate of height growth in height-repressed trees is necessary to make these stands commercially valuable for timber production. Based on the results of this trial, it appears that the best stand-tending treatment for repressed pine is a combination of thinning plus fertilizing. Both height and diameter growth responded positively to this treatment.

Fertilization without thinning may not be as optimal a treatment, as suggested by the fact that the high densities in the unthinned fertilized treatment apparently limited diameter growth. However, where thinning cannot be carried out because stands are inaccessible by road, aerial application of fertilizer might at least boost the stands onto an improved height-growth trajectory. This would allow merchantable timber to be produced within a more reasonable time period than would result if no fertilization had taken place. In this trial, the unthinned fertilized treatment increased height growth, a response that—unlike any of the other treatments—was observed as early as the 1st year after fertilization. Comparable leader length was not achieved on the thinned-plus-fertilized treatment until 2001. However, diameter-growth response on the unthinned fertilized treatment was smaller than on the thinned-plus-fertilized treatment.

In addition, the trial results indicate that the larger crop trees increased proportionally more in height than did the smaller trees. Over time, these potential crop trees may dominate the stand. Brockley (1996) also found that larger trees responded better to fertilization (although the densities of the stands in that study were not as high as at the Rosita Fire site). Nevertheless, at some point, stand density will have to be reduced to increase diameter growth. Fertilization on its own may be enough to accelerate natural thinning by increasing the rate of mortality of the smaller, less competitive pine—but if it is not, then thinning at a later date would still be required.

4.3 Potential Treatment Gains

Some very approximate projections for the stand-tending and rehabilitation treatments might also be made.

If it is assumed that trees in the height-repressed control continue to grow at 10 cm/year, then their estimated height at 100 years would be about 11 m. The optimal treatment in this trial—thinned-plus-fertilized—produced an annual height-growth increase of 20 cm in 2000 and 25 cm in 2001, as well as substantial increases in tree diameter. Thus, if the annual height-growth rate could be maintained at 20 cm/year over the remainder of the rotation, a total 4-m height gain would be realized. Then, if that increase in height could be achieved, thinning plus fertilizing would greatly increase the potential merchantable value of this stand by 100 years of age. At the same time, the trees planted on the rehabilitation regimes would be 64 years old. If they could attain 1.3 m in height by age 14, they would (as defined by SIBEC, site index at 50 years) be expected to be 18 m tall by age 64.

These are only projected scenarios. More data must be collected over time before treatment costs, stand merchantability, and risk of treatment success between the stand-tending and rehabilitation treatment regimes can be accurately compared for height-repressed lodgepole pine.

4.4 Summary

Full evaluation of the differences between the stand-tending and rehabilitation treatments cannot be done for several more years. However, preliminary (3rd-year) results from the stand-tending treatments suggest that fertilization in a 36-year-old, height-repressed stand can increase annual height growth. Thinning alone, though, will not achieve the same results.

The following are three key findings of this trial to date:

1. Fertilization, in both thinned and unthinned stands, increased the annual height growth from 10 cm to approximately 25 cm in very dense, height-repressed 36-year-old lodgepole pine stands in the SBPSdc subzone.
2. Thinning alone produced a diameter-growth response but no height-growth response.
3. The combination of thinning and fertilization produced the largest height- and diameter-growth response on these stands.

Thus, for the vast area of height-repressed, wildfire-origin lodgepole pine in the British Columbia Interior, the potential for growth revitalization using stand-tending treatments seems promising. These treatments may improve the volume contribution of low-productivity stands to the timber supply—effectively increasing the value of stands not currently considered part of the productive land base.

The trial reported here involves a single 36-year-old stand in the SBPSdc biogeoclimatic zone and uses one fertilizer mix. Two other trials have been established to test related growth-response factors.

One trial is located in an older (approximately 70-year-old) height-repressed pine stand in the slightly drier SBPSxc subzone, where management of northern caribou habitat is a significant concern. The effects of stand-tending treatments on caribou habitat are already being assessed in combination with the tree response (Newsome and Heineman 2002). Although height-repressed lodgepole pine stands have biodiversity values and are used by a number of small animals, they do not provide desirable habitat for some species of wildlife, such as northern caribou (*Rangifer tarandus caribou*), as stated in the Cariboo-Chilcotin Land Use Plan (Province of British Columbia 1995). The very high tree densities prevent caribou from using these areas and accessing their main winter food source, terrestrial lichen, which is abundant in many dense pine stands in the SBPSxc and MSxv biogeoclimatic subzones. While thinning such stands is believed to improve access for caribou, the effects of thinning (and fertilization) on terrestrial lichen are unknown. Miège et al. (2001) found that clearcutting substantially reduced lichen abundance, so stand rehabilitation is not a preferred treatment in areas of caribou habitat. In 2000, the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) identified woodland caribou within the Southern Mountain National Ecological Area (which includes northern caribou on the Fraser Plateau) as nationally threatened. These animals are also blue-listed provincially, which means they are deemed to be vulnerable and in need of special management (Caribou Strategy Committee 2002).

The other trial is further testing fertilizer mixes in previously thinned stands near Anahim Lake to determine if fertilization will induce a height-growth response and, if so, which fertilizer mix is most effective. The complete-nutrition fertilizer blend used in the Rosita Fire trial and the subsequent trials is very expensive, and testing of more operationally feasible blends may help decrease the treatment costs.

Additional testing could also examine repeated fertilization of stands if the growth trends are not maintained over time. Such trials would also help identify methods that could be used to predict stand response to treatment, such as an increase in initial needle size. Historically, the potential of these height-repressed stands has been considered very poor. However, with the recognition of nutritional status as a possible primary limiting factor—as shown in early results from the Rosita Fire trial—it may be possible to develop treatments that will produce a merchantable stand.

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APPENDIX 1 Codes for Tree and Seedling Vigour and Vegetation Competition Assessments*

Overall Tree or Seedling Vigour Codes:

Code		
1	Good	Seedling shows no signs of stress, has a vigorous growth rate, and has 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	

Vegetation Competition Codes:

O	Overtopped	The leader of the crop tree is at present overtopped by surrounding vegetation; sunlight available to the crop tree 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.

* Source: B.C. Ministry of Forests, Cariboo Forest Region, Research Section Trial Protocol (unpublished).