

Eighteen-year growth responses to thinning and fertilization of a height-repressed lodgepole pine stand in interior British Columbia

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ABSTRACT

Challenges to the mid-term timber supply in interior British Columbia resulting from losses to insect outbreaks and wild-fires have prompted interest in silvicultural interventions to hasten growth of regenerating forests, including high-density (overstocked), height-repressed stands of lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm.). A trial was established in a dense (4000 to 30 000 trees ha⁻¹) 36-year-old wildfire-origin pine stand in the Cariboo-Chilcotin region of interior BC to assess the efficacy of thinning, fertilization and a combination of the two treatments for improving tree growth and stand development. Height and diameter of the 36 crop trees in each plot was greater in fertilized plots than control plots for six years following fertilization, while the height and diameter responses to thinning and thinning + fertilization were sustained throughout the 18-year measurement period. Cumulative basal area and volume growth of crop trees and all stand trees over the 18-year period was significantly greater in thinned and thinned + fertilized treatments than control plots. Projections based on the TASS growth and yield model suggested that total stand volumes in thinned plots would surpass that of the control at age 74 and would surpass that of the fertilized treatment at 89 years. Unthinned stands (i.e., control and fertilized treatments), did not accumulate significant merchantable volume; in thinned stands (i.e., thinned and thinned + fertilized treatments), the minimum harvest criteria of 80 m³ ha⁻¹ for pine-leading stands in this region was reached at age 102 years. Repeated fertilization would be needed to further hasten stand development. The potential long-term benefits of these silvicultural interventions for timber supply must be weighed against treatment costs and risks of mortality related to wildfire, insects and disease. These results highlight the value of long-term research trials for informing silviculture decisions.

Keywords: *Pinus contorta*; height growth suppression; growth response; fertilization; thinning

RÉSUMÉ

Les défis entourant l'approvisionnement à moyen terme en bois pour l'intérieur de la Colombie-Britannique découlant des pertes occasionnées par les épidémies d'insectes et les feux de forêts ont suscité l'intérêt pour les interventions sylvicoles permettant d'accélérer la croissance des forêts de régénération, notamment dans le cas des peuplements à forte densité (densité excessive) et à dominance par la hauteur de pin lodgepole (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm.). Un site expérimental a été mis en place dans un peuplement dense (comprenant de 4 000 à 30 000 tiges à l'hectare), âgé de 36 ans issu d'un feu de forêt survenu dans la région de Cariboo-Chilcotin de l'Intérieur de la Colombie-Britannique, afin d'évaluer l'efficacité des traitements d'éclaircie, de fertilisation et d'une combinaison des deux traitements dans l'amélioration de la croissance des arbres et du développement du peuplement. La hauteur et le diamètre de 36 arbres retenus pour la récolte étaient plus importants dans les parcelles fertilisées que dans les parcelles témoins au cours des six années suivant la fertilisation, tandis que les réactions en hauteur et diamètre suite à une éclaircie suivie d'une fertilisation ont été constantes tout au long des 18 années de suivi. La surface terrière cumulative et la croissance en volume des arbres retenus pour la récolte ont été significativement plus importantes dans les parcelles éclaircies et fertilisées que dans les parcelles témoins. Les projections basées sur le modèle TASS de croissance et de rendement laissent entendre que le volume total des parcelles éclaircies seraient supérieurs à celui des parcelles témoins à l'âge de 74 ans et seraient supérieurs à celui des parcelles fertilisées à l'âge de 89 ans. Les parcelles non éclaircies (c'est-à-dire, les parcelles témoins et les parcelles fertilisées), n'ont pas atteint un volume marchand significatif; dans le cas des parcelles éclaircies (c'est-à-dire, éclaircies et éclaircies + fertilisées), le volume minimal fixé de 80 m³ par hectare pour les peuplements dominés par le pin dans cette région a été atteint à l'âge de 102 ans. Des fertilisations répétées seraient requises pour accélérer le développement du peuplement. Les bénéfices potentiels à long terme de ces interventions sylvicoles rattachées à la production de bois doivent être évalués relativement aux coûts des traitements et des risques de mortalité occasionnés par les feux de forêt, les insectes et les maladies. Ces résultats mettent en lumière l'importance des essais expérimentaux à long terme face à la prise de décisions en sylviculture.

Mots clés : *pinus contorta*, suppression de la croissance en hauteur, fertilisation, éclaircie, réaction de croissance

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Introduction

Lodgepole pine is an important commercial tree species in British Columbia (B.C.), constituting 39% of the total harvested volume of interior B.C. forests (Kishchuk *et al.* 2002) prior to the outbreak of mountain pine beetle (*Dendroctonus ponderosae* Hopk.; MPB). In the Williams Lake Timber Supply Area, in the Cariboo Forest Region of B.C., lodgepole pine is the leading species on 64% of the timber-harvesting land base (British Columbia Ministry of Forests, Lands and Natural Resource Operations 2015). In Alberta, lodgepole pine constitutes about 20% of the mature standing timber and accounted for approximately 40% of the annual harvest in the province prior to MPB (Huang *et al.* 2004). Standing stock of lodgepole pine in B.C. has been severely reduced by MPB – by the projected end of the outbreak in 2020, MPB will have killed an estimated 55% of B.C.'s mature merchantable pine, more than 730 million m³ (Government of British Columbia 2019). The resulting timber-supply challenge has been exacerbated by heightened wildfire damage in recent years. The 2017 wildfires alone burned more than 1.2 million ha of forested land in B.C.; over 1.0 million ha of this was within the Cariboo region in the interior of the province (British Columbia Ministry of Forests, Lands and Natural Resource Operations 2018.) These losses further impact the mid-term timber supply in this region (British Columbia Ministry of Forests, Lands and Natural Resource Operations 2015), reinforcing the need for research into silvicultural interventions which could stimulate the growth of existing and regenerating stands.

By virtue of serotinous cones, lodgepole pine naturally regenerates abundantly after fire, and in some situations, stocking rates in young stands can be in excess of 100 000 stems ha⁻¹. These extremely high stand densities are often associated with extremely slow growth, particularly in height—a phenomenon referred to as 'height repression or growth stagnation' (Keane and Weetman 1987). The slow growth rates can delay, or even prevent, repressed pine stands from reaching commercial operability (minimum dbh 12.5 cm); in fact many such stands are not included in estimates of the productive land base of B.C. (Newsome and Perry 2003).

Silvicultural solutions to lodgepole pine repression usually involve juvenile spacing or thinning to reduce densities, or in some cases, stand replacement (i.e., removal of the existing stand, followed by site preparation and planting of lodgepole pine seedlings). Spacing is recommended prior to onset of repression and has been found to be most effective in young

stands (Yang 1991; Johnstone and van Thienen 2004). In older, repressed stands, thinning has been demonstrated to increase diameter growth of the remaining trees, but height growth response has been inconsistent (Farnden and Herring 2002; Stewart *et al.* 2006).

Fertilization may be another silvicultural solution to lodgepole pine repression. Nutrient deficiencies are widespread throughout the

B.C. interior, and many studies have shown improved growth of young lodgepole pine forests following fertilization with nitrogen (N) and other nutrients (Weetman *et al.* 1988; Yang 1998; Brockley 2000, 2003, 2004; Kishchuk *et al.* 2002). Observations of foliar chlorosis and low concentrations of N and sulphur (S) in needles of height-repressed lodgepole pine trees (Farnden and Herring 2002), as well as the small amount of foliage, despite high stocking in repressed pine stands (Blevins *et al.* 2005), prompted investigations of the potential for fertilization to improve growth of height-repressed lodgepole pine. Farnden and Herring (2002) reported that N fertilization (150 kg N ha⁻¹ in the form of urea), combined with selective hand-thinning of a dense (> 200 000 stems ha⁻¹), height-repressed, 18-year-old stand increased top height by about 3 m, 19 years after treatment. In comparison, untreated trees were growing at a site index of 9 m, trees that were thinned only were growing at a site index of 11 m, and trees that were fertilized and thinned were growing at a site index of 17 m.

To assess the potential for thinning, fertilization or a combination of both to stimulate growth and stand development of overstocked, height-repressed lodgepole pine stands, the B.C. Ministry of Forests established a trial in a dense stand of pine that originated following a 1961 wildfire in the Cariboo-Chilcotin region of interior BC. Thirty-six years after the fire (in 1997), the area was covered with dense, even-aged lodgepole pine forests. Plots were thinned from the original density of 22 558 stems ha⁻¹ to 2472 stems ha⁻¹, and/or fertilized with a mix of N, P, K, S, B and Mg. During the 3rd year after fertilization (4th year after thinning), volume growth of the entire stand was greatest in the fertilized plots, but volume growth of crop trees (largest 400 trees ha⁻¹) in plots that received fertilization + thinning was twice that in plots that were either fertilized or thinned, and seven times that in control plots (Blevins *et al.* 2005). Trees have been periodically re-measured, and here we present the 18-year responses of crop trees and the stand to fertilization and thinning treatments.

Methods

Study site

The trial is located approximately 96 km west of Williams Lake, B.C. (latitude 52° 27' 09" and longitude 123° 09' 21; North 5811150 and East 489400) in the SBPSdc (Sub-Boreal Pine Spruce–dry, cold) biogeoclimatic subzone, at an elevation of about 1200 m a.s.l. (Newsome and Perry 2003). Mean annual and summer precipitation are 508 mm and 275 mm,

respectively, and mean annual and warmest month temperatures are 1.9 °C and 13.9 °C, respectively. The soils are predominantly Luvisols (Soil Classification Working Group 1998), with textures ranging from silt loams to clay loams. Forest floors were 1–2 cm thick and rooting depth ranged from 20 to 35 cm. Coarse fragment content of the soil was 40 to 80%, and large dispersed boulders were common at the surface (Newsome and Perry 2003).

The stand regenerated naturally after the Rosita Wildfire burned approximately 900 ha in the summer of 1961 (Newsome and Perry 2003). In 1997, (36 years later), stand densities ranged from 4000 to more than 30 000 stems ha⁻¹. 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 7 m up to 15 m in wet depressions. Expected normal site indices estimated by the Site Index–Biogeoclimatic Ecosystem Classification system are 18 m for the 01 site series and 15 m for the 03 site series (British Columbia Ministry of Forests 1997).

Experimental design

The trial is a 2 × 2 factorial (2 levels of thinning × 2 levels of fertilization), randomized complete block design with three blocks and four treatments. Twelve plots, each measuring 70 × 70 m, were established and randomly assigned to one of four treatments: 1) untreated control; 2) fertilized and unthinned; 3) thinned to 2000–3000 stems ha⁻¹, keeping the largest and most dominant stems; and 4) thinned as above and then fertilized (thinned + fertilized). At the center of each plot was a 30 × 30 m measurement plot surrounded by a 20-m buffer (Newsome and Perry 2003).

Prior to treatment, 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 serious defects such as forking, and occupied a dominant or co-dominant canopy position (Newsome and Perry 2003).

Pre-treatment tree height data were analyzed to determine whether tree heights varied enough among the plots to warrant being stratified into blocks by height prior to treatment. Height variability among plots—assessed with a likelihood ratio test (Littell *et al.* 1996) based on a random-effects analysis of variance—was 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 (Newsome and Perry 2003).

Pre-treatment 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. Height also correlated with density: the tallest trees were found in the plots with the lowest densities. Pine needle cast (*Lophodermella concolor*) infected more than

75% of the trees in 1997 but not in later years. The incidence of western gall rust was relatively low for a lodgepole pine stand of its age and overall condition. There were sufficient numbers of acceptable crop trees for the trial, despite the presence of some damaging agents in the stand.

The pre-treatment plot data were analyzed to determine whether significant differences existed within blocks prior to treatment. No pre-treatment differences were found for any of the variables of interest (Newsome and Perry 2003).

Treatment responses were assessed in: 1) crop trees, and 2) all trees in each plot. Crop trees were selected before treatment by establishing 36 grid points in each measurement plot (400 stems ha⁻¹) and selecting at each point the nearest tree that would meet operational leave-tree criteria for form and vigour as described in the provincial stand-tending guidelines in effect in 1997 (British Columbia Ministry of Forests 1995). Stand-level assessment plots were established after treatment and have a fixed-radius within which all trees were measured. In thinned plots, one 12.64-m radius plot was established in the middle of the 30 × 30 m measurement plot. This plot size provided the prescribed minimum sample size of 100 trees/plot after thinning. In the un-thinned treatments, four small subplots were established, each of which contained at least 100 trees. The radius of these subplots ranged from 1.78 m to 3.0 m.

Treatments

Appropriate plots were thinned in September and October 1997 to a final target density of 2000–3000 stems ha⁻¹, keeping the better trees, as many of the trees were in poor condition. As no inter-tree spacing requirement was specified, this treatment is considered thinning rather than juvenile spacing.

One year after the thinning treatment, appropriate plots were fertilized by hand on October 13–17, 1998. The total area fertilized was 50 × 50 m, which included the entire central measurement plot and 10 m into the buffer. The fertilizer prescription was a customized blend to address the severe nutrient deficiencies indicated by pre-treatment foliar nutrient analysis. The fertilizer delivered nutrients at the following rates (kg ha⁻¹): 200 N, 100 P, 100 K, 75 S, 36 Mg, and 3 B.

Tree measurements

Responses to treatments were assessed at the end of each growing season from 1997 to 2001, and in 2003, 2006, 2008 and 2016. All reported measurements are from the fall of the indicated year. 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 and damaging agents.

Diameter was assessed at breast height (1.3 m above the germination point). Crown radius was estimated by measuring the average radius at the point on the stem where the branches were longest. Height of each crop tree was measured, and height to live crown was measured from the ground up the stem to where the longest live branches were attached. The percent live crown was calculated as a proportion of the tree's total height. Ocular estimates of percent live crown were made in the stand-level plots.

Data analysis

A repeated measures 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 analyses used all live trees in plots. Plot estimates for the control and fertilized treatments were based on the four subplots combined. 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 test 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 and for stand-level analysis to adjust for any significant pre-treatment difference in tree size within a block. A $\log_{10}$ transformation was used for gross volume and basal area analyses in order to satisfy assumptions of variance homogeneity.

The repeated-measures ANOVA model for trees in fixed plots and for crop trees is as follows:

$$y_{ijkt} = a_{it} + b_j + p_{ij} + e_{ijkt}$$

where:

y_{ijkt} = measured height or dbh of tree k , treatment i , block j , year t ;

a_{it} = (fixed) mean height or mean dbh for treatment i and year t ; b_j = random block effect; p_{ij} = random (treatment $\times$ block) plot effect; $\{e_{ijkt}\}$ = random (tree) errors for 1997, 1998, ..., 2016;

$b_j \sim \text{Normal}(0, \sigma_B^2)$; $p_{ij} \sim N(0, \sigma_P^2)$; $\{e_{ijk1997}, e_{ijk1998}, \dots, e_{ijk2016}\} \sim N(\{0, 0, \dots, 0\}, V)$, where V = unstructured 9×9 variance-covariance matrix.

The repeated-measures ANOVA model for plot (per ha) totals for each year are as follows (plot estimates for control and fertilized plots are based on four subplots combined):

$$yijt = ait + bj + pijt$$

where:

$yijt$ = $\log_{10}$ -transformed basal area or gross volume for treatment i , block j , and year t ;

ait = (fixed) mean basal area or gross volume for treatment i and year t ;

bj = random block effect; $bj \sim \text{Normal}(0, \sigma_B^2)$;

and $pijt$ = random (plot) errors for 1997, 1998, ..., 2016; $pijt \sim N(0, \sigma_{Pi2})$ (i.e., plot variances vary across treatments).

Growth and yield modelling

Growth simulations to predict the long-term effects of the four treatments were explored using Tree and Stand Simulator (TASS) (multi-canopy version, TASS v3.01.19W) (British Columbia Ministry of Forests and Range 2010). TASS plot-

level simulations were customized to follow individual-plot data summaries for stand density and height (ages 37 to 55). Customization of TASS input parameters has previously been used to simulate observed stand-level trajectories based on longer-term growth and yield research information (Goudie *et al.* 2005; Harper *et al.* 2008; Boateng *et al.* 2009). Custom height-over-age curves were created for each treatment based on site index (SI) curves of 9.2 m from Nigh (2016) modified to follow treatment mean height growth. For the fertilization treatment, the accelerated height growth response was added incrementally over a 6-year period. TASS simulations also involved calibrating initial start densities to ensure alignment with pre- and post-treatment plot densities including thinning outcomes.

Results

Mean values for each attribute in each treatment at each measurement time are presented in Tables S1 and S2. The two treatments were not simultaneously applied (plots were thinned in 1997 and fertilized in 1998); we report results in terms of years after fertilization. In 2016, (18 years after fertilization and 19 years after thinning), mean stand densities (ha^{-1}) in the four treatments (alive + dead, respectively) were: control 14 469 + 8343; fertilized 13 566 + 8803; thinned 2192 + 93; and thinned + fertilized 2617 + 60 (Fig. 1). Among crop trees (36 trees/plot), cumulative mortality during the 18 years after treatment was 6-7% in control and fertilized plots and less than 5% in the thinned plots (Fig. 2). At the stand level, cumulative mortality was also < 5% in the thinned plots, but 35% in unthinned (control and fertilized) plots (Fig. 2).

Crown growth responded differently to thinning and fertilizing over the 18-year period (Fig. 3). For crop trees, mean crown-radius growth was greater than the control in the two thinned treatments (Fig. 3; Table 1), but for all stand trees all treatments differed from the control (Fig. 3; Table 2). Fertilization-alone elevated annual crown-radius growth rates for two years, after which crown-radius growth tracked those of control trees. Thinning (with and without fertilization) also increased crown-radius growth for two years before leveling off, but increased again between 2006 and 2016 in all thinned treatments. For crop trees, crown-radius growth responses were significantly higher from controls in the fertilizer treatment in years 1 to 2 (1998–2000), in the thinned treatment in years 2 to 3 (1999 to 2000) and 10 to 18 (2008 to 2016), and in the thinned + fertilized treatment in years 2 to 18 (1999 through to 2016) (Table 1). For all stand trees (fixed plots), annual crown-radius growth rates in the fertilizer treatment were greater than in the control in the 2000–2001 period only; in the thinned treatment from 1999 to 2003 and again from 2008 to 2016; and in the thinned + fertilized treatment through the entire 1999 to 2016 period (Table 2). Mean height to live crown of crop trees over the 18-year period increased in fertilized-alone treatment, decreased in the thinned-alone treatment, and was similar to controls in the thinned + fertilized treatment (Fig. 4; Table 1).

After 18 years, height growth of crop trees was greatest in the thinned + fertilized plots (Table 1); height increased in fertilized plots initially but slowed after five years (2003), while height of trees in thinned plots increased relative to controls over the 18-year period (Fig. 5). Crop-tree annual height-growth rates increased in the fertilized treatment for

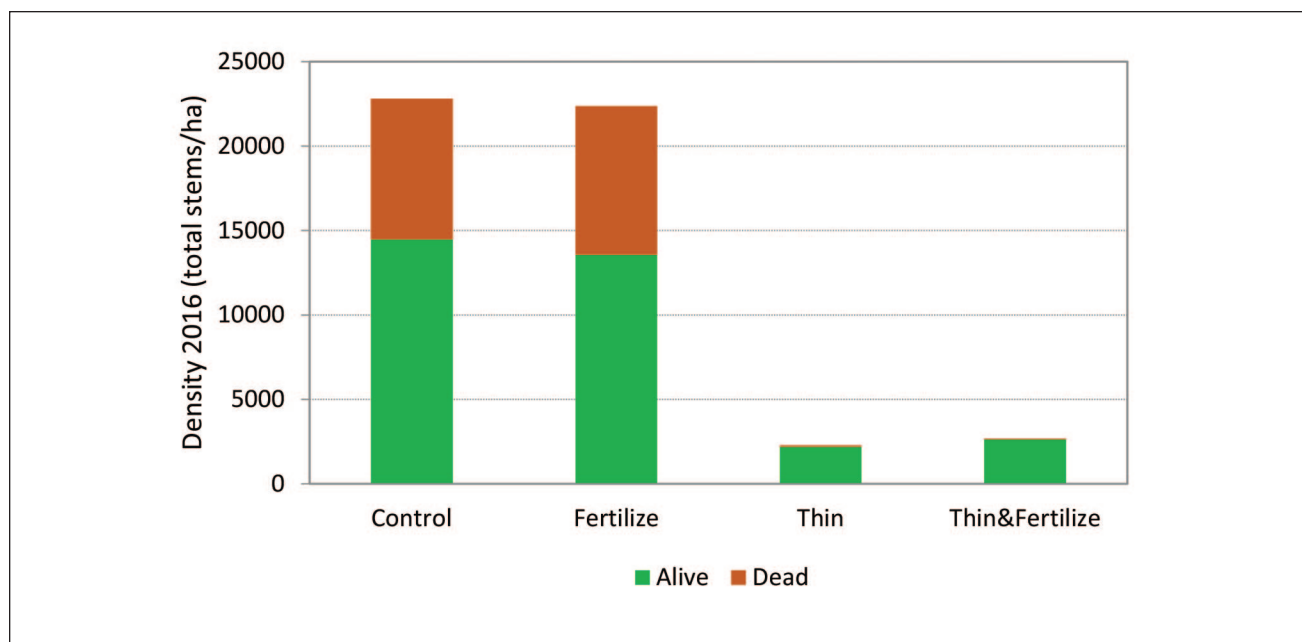


Fig. 1 Density of trees (stems/ha) in plots of the four treatments in 2016 – 18 years after treatment

the first five years (1998 to 2003), in the thinned treatment after eight years (2006 through 2016); and in the thinned + fertilized treatment for the entire 18-year period (1999 through 2016) (Table 1). Annual height growth of all stand trees was greater than the controls in the fertilized treatment for the first 10 years (1998 to 2008), in the thinned treatment after three years (2001 through 2016); and thinned + fertilized treatment throughout the measurement period (1998 to 2016; Table 2).

Diameters at breast height of thinned crop trees increased relative to controls throughout the study period, and the greatest response was in the combined thinned + fertilized treatment (Fig. 6; Table 1). A similar pattern occurred for all stand trees (Fig. 6; Table 2). Crop-tree annual dbh growth was greater than controls in the fertilized treatment for the first five years (1998 to 2003) and in the thinned and thinned + fertilized treatments throughout the study period (1998 to 2016; Table 1). Annual dbh growth of all stand trees was greater than the control in the fertilized treatment for the first eight years (1998 to 2006), and in the thinned and thinned + fertilized treatments throughout the study period (1998 to 2016; Table 2).

For crop trees, basal area and volume growth over the 18-year period was greatest in the thinned + fertilized plots (Figs. 7 and 8). For all stand trees (fixed plots), basal area and volume were greatest in the fertilized plots, but rates of growth were higher in the thinned and thinned + fertilized plots (Figs. 7 and 8). Annual growth rates for basal area and volume of crop trees and all stand trees over the 18-year period were significantly higher in the thinned and thinned + fertilized treatments (Tables 1 and 2).

Stand density and mean heights predicted by TASS simulations closely matched measured treatment mean values except in the thinned + fertilized treatment where the height

difference was approximately 0.8 m by year 55. TASS underestimated stand diameter by approximately 1.2 cm over the 18-year measurement period. Although TASS diameter estimates were smaller than the treatment means, the relative differences between control and thinned treatments, and between thinned and thinned + fertilized treatments was in keeping with the measured changes over time.

Although at the time of treatment, the unthinned stands (i.e., control and fertilized treatments) had 71 to 81% more volume than the thinned stands, their total volume growth over time decreased relative to the thinned treatments. TASS projections suggested that total stand volumes in the thinned and the thinned + fertilized treatments would surpass that of the control at age 74 and 57 years respectively, and would surpass that of the fertilized treatment at 89 and 79 years, respectively (Fig. 9).

Merchantable volume (minimum dbh 12.5 cm) predictions (Fig. 10) indicated that the unthinned stands, (i.e., control and fertilized treatments), did not accumulate significant merchantable volume, whereas the thinned stands (i.e., thinned and thinned + fertilized treatments) did. The minimum harvest criteria of 80 m³ ha⁻¹ for pine-leading stands set for the Williams Lake Timber Supply Area (British Columbia Ministry of Forests, Lands and Natural Resource Operations 2015) was reached at age 102 for stands in both the thinned and the thinned + fertilized treatments.

Discussion

The findings of this study confirm that growth of dense, height-repressed lodgepole pine stands are responsive to silvicultural interventions. Thinning alone resulted in increased crown radius and diameter growth of the stand in the first four years after treatment. Height growth increased after four years, and the greater diam-

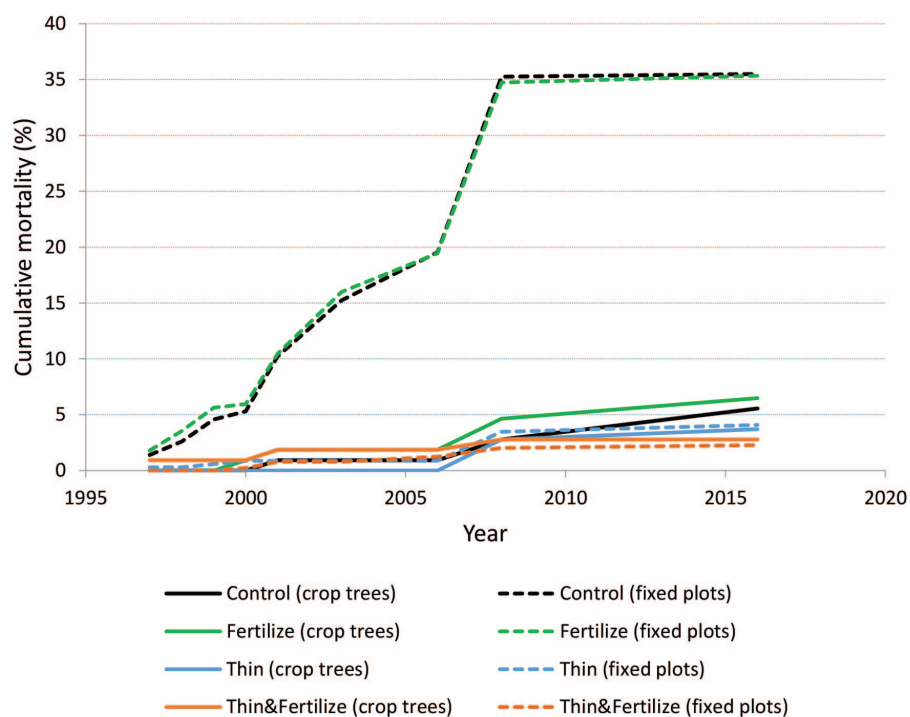


Fig. 2 Cumulative mortality (% of total trees) of crop trees and all stand trees (fixed plots) during the 18 years after treatments

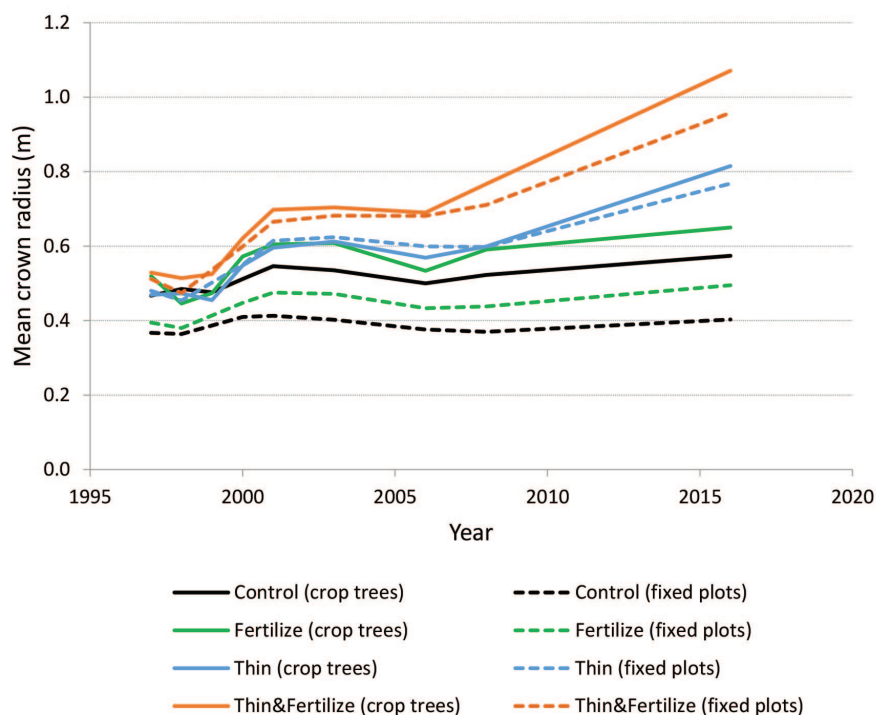


Fig. 3 Mean crown radius growth (m) of crop trees and all stand trees (fixed plots) in the four treatments during the 18 years following treatment

Table 1. Analysis of variance results for differences from control values in annual growth rates of crop trees in each treatment during each measurement interval, and cumulative growth over the 18-year measurement period

Attribute	Treatment	1998–1999			1999–2000			2000–2001			2001–2003			2003–2006			2006–2008			2008–2016			1997–2016 ^a		
		Mean	SE	Adj. p	Mean	SE	Adj. p	Mean	SE	Adj. p	Mean	SE	Adj. p	Mean	SE	Adj. p	Mean	SE	Adj. p	Mean	SE	Adj. p	Mean	SE	Adj. p
Crown radius (m/year)	FERTILIZE	0.038	0.011	0.01	0.061	0.013	<0.01	0.000	0.012	1.00	0.007	0.007	1.00	-0.010	0.004	0.04	0.017	0.006	0.08	0.001	0.002	1.00	0.03	0.03	1.00
	THIN	-0.010	0.011	1.00	0.057	0.012	<0.01	0.015	0.012	1.00	0.013	0.007	1.00	0.000	0.004	1.00	0.003	0.006	1.00	0.021	0.002	<0.01	0.24	0.03	<0.01
	THINFERT	0.021	0.011	1.00	0.060	0.012	<0.01	0.044	0.012	<0.01	0.008	0.007	1.00	0.007	0.004	1.00	0.027	0.006	<0.01	0.032	0.002	<0.01	0.44	0.03	<0.01
Height to live crown (m/year)	FERTILIZE	0.12	0.02	<0.01	0.02	0.03	1.00	0.05	0.02	0.36	0.00	0.02	1.00	0.08	0.02	<0.01	0.01	0.04	1.00	0.06	0.01	<0.01	0.65	0.11	<0.01
	THIN	0.12	0.02	<0.01	-0.07	0.03	0.21	0.01	0.02	1.00	-0.13	0.02	<0.01	-0.01	0.02	1.00	-0.07	0.04	0.94	-0.03	0.01	0.41	-0.77	0.11	<0.01
	THINFERT	0.07	0.02	0.08	-0.04	0.03	1.00	0.00	0.02	1.00	-0.10	0.02	<0.01	-0.01	0.02	1.00	0.05	0.04	1.00	0.00	0.01	1.00	-0.26	0.11	0.23
Height (m/year)	FERTILIZE	0.10	0.01	<0.01	0.19	0.01	<0.01	0.21	0.01	<0.01	0.14	0.01	<0.01	0.02	0.01	1.00	0.08	0.02	<0.01	0.01	0.01	1.00	1.06	0.19	<0.01
	THIN	0.02	0.01	0.61	-0.02	0.01	1.00	0.01	0.01	1.00	0.02	0.01	0.61	0.03	0.01	0.22	0.07	0.02	0.03	0.09	0.01	<0.01	0.98	0.19	<0.01
	THINFERT	0.02	0.01	0.61	0.09	0.01	<0.01	0.18	0.01	<0.01	0.14	0.01	<0.01	0.08	0.01	<0.01	0.16	0.02	<0.01	0.14	0.01	<0.01	2.19	0.19	<0.01
DBH (cm/year)	FERTILIZE	0.13	0.02	<0.01	0.28	0.02	<0.01	0.17	0.02	<0.01	0.13	0.02	<0.01	0.03	0.01	0.13	0.00	0.01	1.00	-0.01	0.01	1.00	0.92	0.20	<0.01
	THIN	0.13	0.02	<0.01	0.15	0.02	<0.01	0.21	0.02	<0.01	0.17	0.02	<0.01	0.14	0.01	<0.01	0.12	0.01	<0.01	0.11	0.01	<0.01	2.38	0.20	<0.01
	THINFERT	0.25	0.02	<0.01	0.49	0.02	<0.01	0.45	0.02	<0.01	0.30	0.02	<0.01	0.17	0.01	<0.01	0.13	0.01	<0.01	0.13	0.01	<0.01	3.63	0.20	<0.01
Basal area Log ₁₀ (m ² /ha/year)	FERTILIZE	0.02	0.04	1.00	0.07	0.04	1.00	0.02	0.04	1.00	0.02	0.02	1.00	0.00	0.01	1.00	-0.01	0.02	1.00	0.01	0.01	1.00	0.10	0.04	0.53
	THIN	0.03	0.04	1.00	0.04	0.04	1.00	0.04	0.04	1.00	0.03	0.02	1.00	0.01	0.01	1.00	0.01	0.02	1.00	0.01	0.01	1.00	0.28	0.04	<0.01
	THINFERT	0.04	0.04	1.00	0.09	0.04	1.00	0.06	0.04	1.00	0.04	0.02	1.00	0.01	0.01	1.00	0.01	0.02	1.00	0.01	0.01	1.00	0.37	0.04	<0.01
Gross volume Log ₁₀ (m ³ /ha/year)	FERTILIZE	0.03	0.05	1.00	0.08	0.05	1.00	0.04	0.05	1.00	0.03	0.03	1.00	-0.01	0.02	1.00	-0.01	0.03	1.00	0.01	0.01	1.00	0.16	0.05	0.14
	THIN	0.04	0.05	1.00	0.04	0.05	1.00	0.04	0.05	1.00	0.03	0.03	1.00	0.02	0.02	1.00	0.02	0.03	1.00	0.01	0.01	1.00	0.36	0.05	<0.01
	THINFERT	0.05	0.05	1.00	0.09	0.05	1.00	0.07	0.05	1.00	0.05	0.03	1.00	0.01	0.02	1.00	0.02	0.03	1.00	0.01	0.01	1.00	0.50	0.05	<0.01

^aGrowth response over 19 growing seasons

Table 2. Analysis of variance results for differences from control values in annual growth rates of all stand trees in each treatment during each measurement interval, and cumulative growth over the 18-year measurement period

Attribute	Treatment	1998–1999			1999–2000			2000–2001			2001–2003			2003–2006			2006–2008			2008–2016			1997–2016 ^a		
		Mean	SE	Adj. p	Mean	SE	Adj. p	Mean	SE	Adj. p	Mean	SE	Adj. p	Mean	SE	Adj. p	Mean	SE	Adj. p	Mean	SE	Adj. p	Mean	SE	Adj. p
Crown radius (m/year)	FERTILIZE	-0.01 ^b	0.008	1.0	0.011 ^c	0.004	0.16	0.025	0.008	0.02	0.004	0.004	1.00	0.000	0.003	0.89	0.006	0.004	1.00	0.003	0.002	0.89	0.06	0.02	<0.01
	THIN	-0.02 ^b	0.008	0.05	0.024 ^c	0.004	<0.01	0.062	0.007	<0.01	0.011	0.004	0.05	0.000	0.002	1.00	0.003	0.004	1.00	0.017	0.001	<0.01	0.25	0.02	<0.01
	THINFERT	-0.04 ^b	0.007	<0.01	0.039 ^c	0.004	<0.01	0.064	0.007	<0.01	0.014	0.003	<0.01	0.008	0.002	<0.01	0.018	0.003	<0.01	0.027	0.001	<0.01	0.41	0.02	<0.01
Height (m/year)	FERTILIZE	0.04	0.01	<0.01	0.15	0.01	<0.01	0.17	0.01	<0.01	0.13	0.01	<0.01	0.05	0.01	<0.01	0.05	0.01	<0.01	0.02	0.01	<0.01	0.99	0.13	<0.01
	THIN	0.01	0.01	1.00	0.01	0.01	1.00	0.02	0.01	0.06	0.03	0.01	<0.01	0.05	0.01	<0.01	0.09	0.01	<0.01	0.09	0.01	<0.01	1.14	0.11	<0.01
	THINFERT	0.03	0.01	<0.01	0.10	0.01	<0.01	0.18	0.01	<0.01	0.14	0.01	<0.01	0.08	0.01	<0.01	0.17	0.01	<0.01	0.12	0.01	<0.01	2.16	0.11	<0.01
DBH (cm/year)	FERTILIZE	0.08	0.01	<0.01	0.15	0.02	<0.01	0.13	0.01	<0.01	0.09	0.01	<0.01	0.02	0.01	0.03	0.01	0.01	0.94	0.00	0.01	1.00	0.68	0.13	<0.01
	THIN	0.19	0.01	<0.01	0.20	0.01	<0.01	0.26	0.01	<0.01	0.18	0.01	<0.01	0.20	0.01	<0.01	0.16	0.01	<0.01	0.14	0.01	<0.01	3.07	0.12	<0.01
	THINFERT	0.27	0.01	<0.01	0.49	0.01	<0.01	0.49	0.01	<0.01	0.30	0.01	<0.01	0.20	0.01	<0.01	0.17	0.01	<0.01	0.13	0.01	<0.01	3.87	0.11	<0.01
Basal area Log ₁₀ (m ² /ha/year)	FERTILIZE	0.01	0.04	1.00	0.03	0.04	1.00	0.03	0.04	1.00	0.01	0.02	1.00	0.00	0.01	1.00	0.01	0.02	1.00	0.00	0.01	1.00	0.10	0.04	0.39
	THIN	0.04	0.04	1.00	0.03	0.04	1.00	0.05	0.04	1.00	0.03	0.02	1.00	0.03	0.01	1.00	0.04	0.02	1.00	0.01	0.01	1.00	0.41	0.04	<0.01
	THINFERT	0.04	0.04	1.00	0.08	0.04	1.00	0.07	0.04	1.00	0.04	0.02	1.00	0.02	0.01	1.00	0.04	0.02	1.00	0.00	0.01	1.00	0.44	0.04	<0.01
Gross volume Log ₁₀ (m ³ /ha/year)	FERTILIZE	0.02	0.05	1.00	0.04	0.05	1.00	0.04	0.05	1.00	0.02	0.03	1.00	0.01	0.02	1.00	0.01	0.03	1.00	0.00	0.01	1.00	0.16	0.05	0.08
	THIN	0.03	0.05	1.00	0.03	0.05	1.00	0.04	0.05	1.00	0.03	0.03	1.00	0.03	0.02	1.00	0.04	0.03	1.00	0.01	0.01	1.00	0.45	0.05	<0.01
	THINFERT	0.04	0.05	1.00	0.08	0.05	1.00	0.08	0.05	1.00	0.05	0.03	1.00	0.02	0.02	1.00	0.04	0.03	1.00	0.01	0.01	1.00	0.50	0.05	<0.01

^aGrowth response over 19 growing seasons ^b 1997–1998 growth period since crown radius not collected in 1999 for stand trees c 1998–2000 growth period since crown radius not collected in 1999 for stand trees

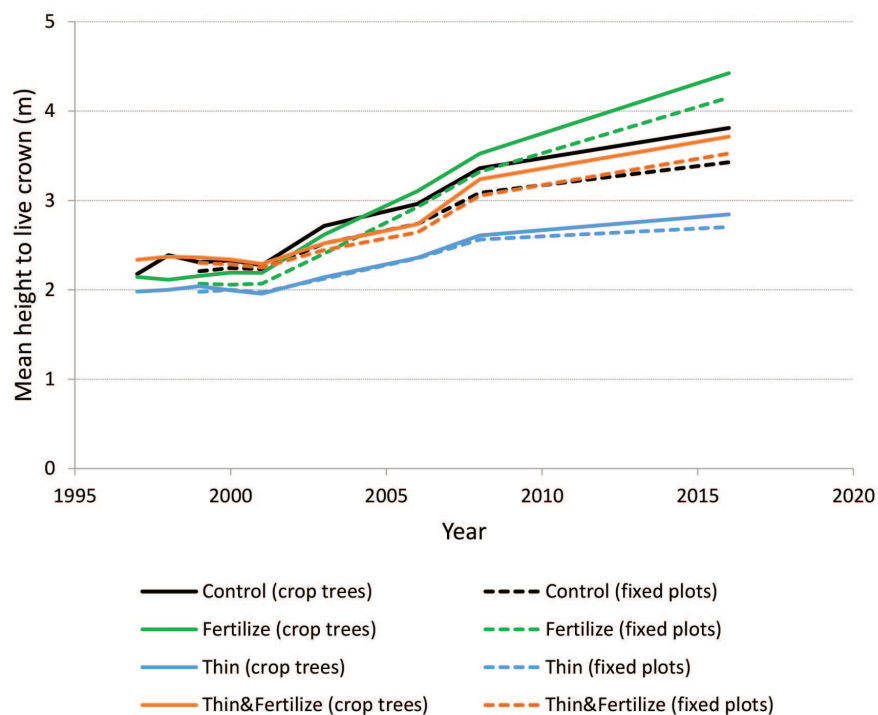


Fig. 4 Mean height to live crown in crop trees and all stand trees (fixed plots) in the four treatments during the 18 years following treatment

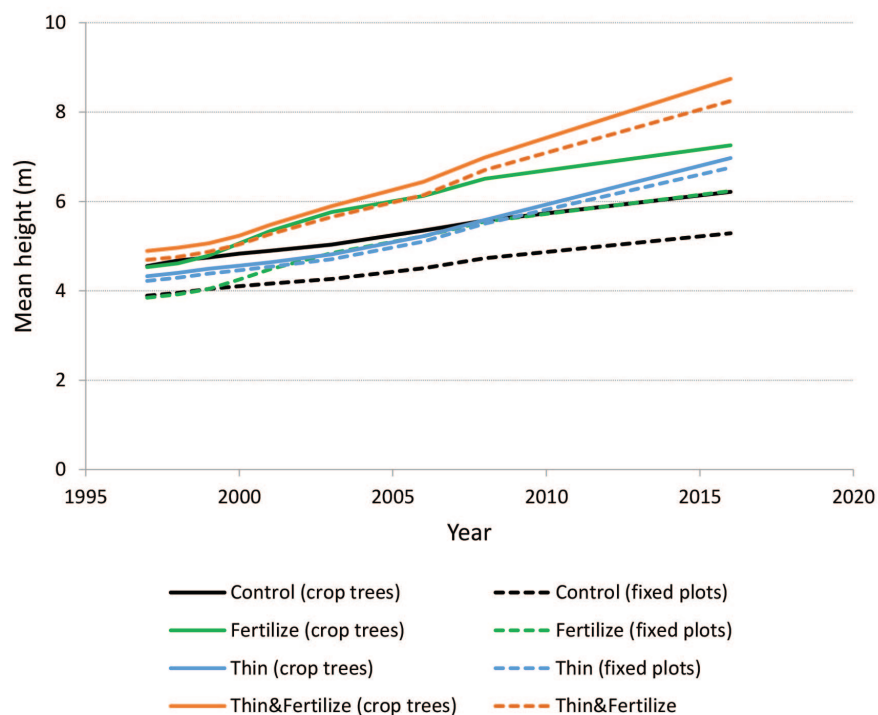


Fig. 5 Mean height of crop trees and all stand trees (fixed plots) in the four treatments during the 18 years following treatment

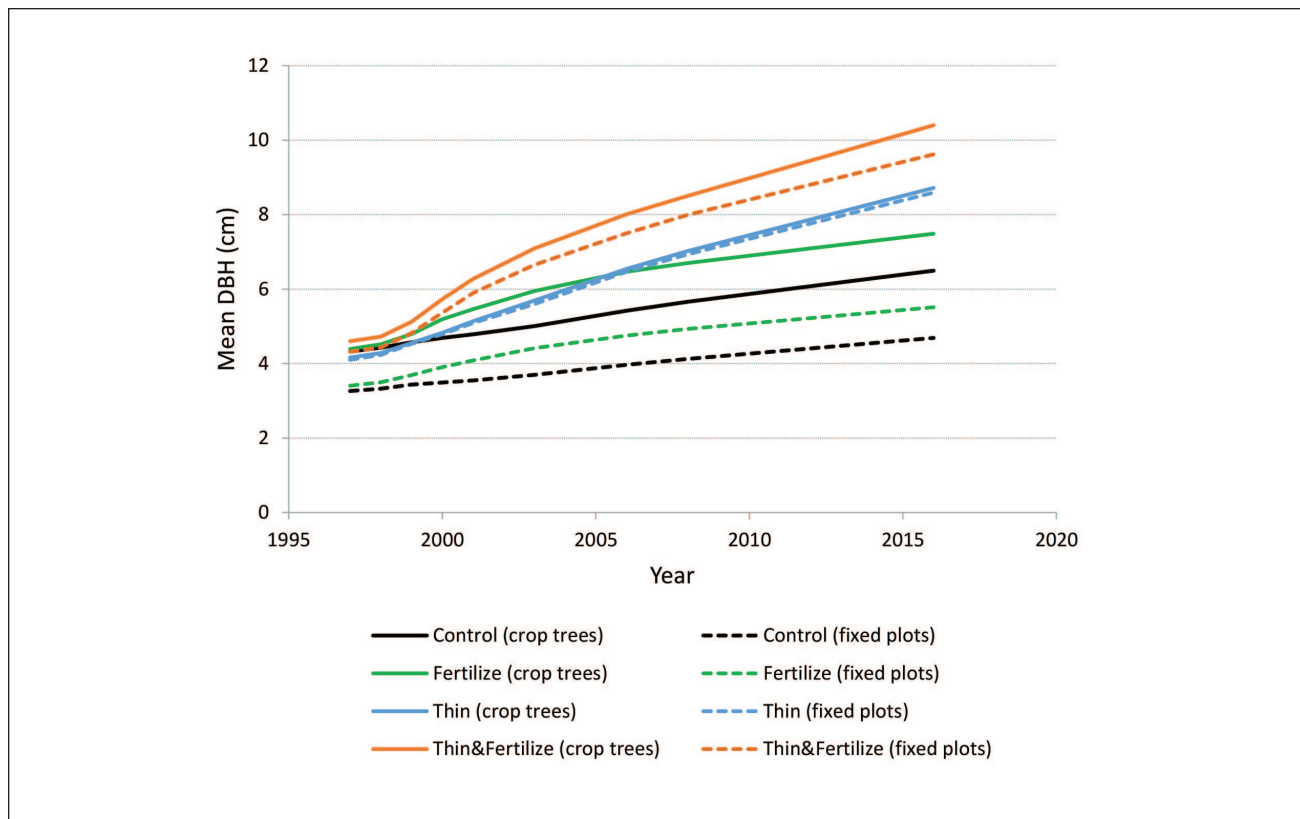


Fig. 6 Mean diameter at breast height of crop trees and all stand trees (fixed plots) in the four treatments during the 18 years following treatment

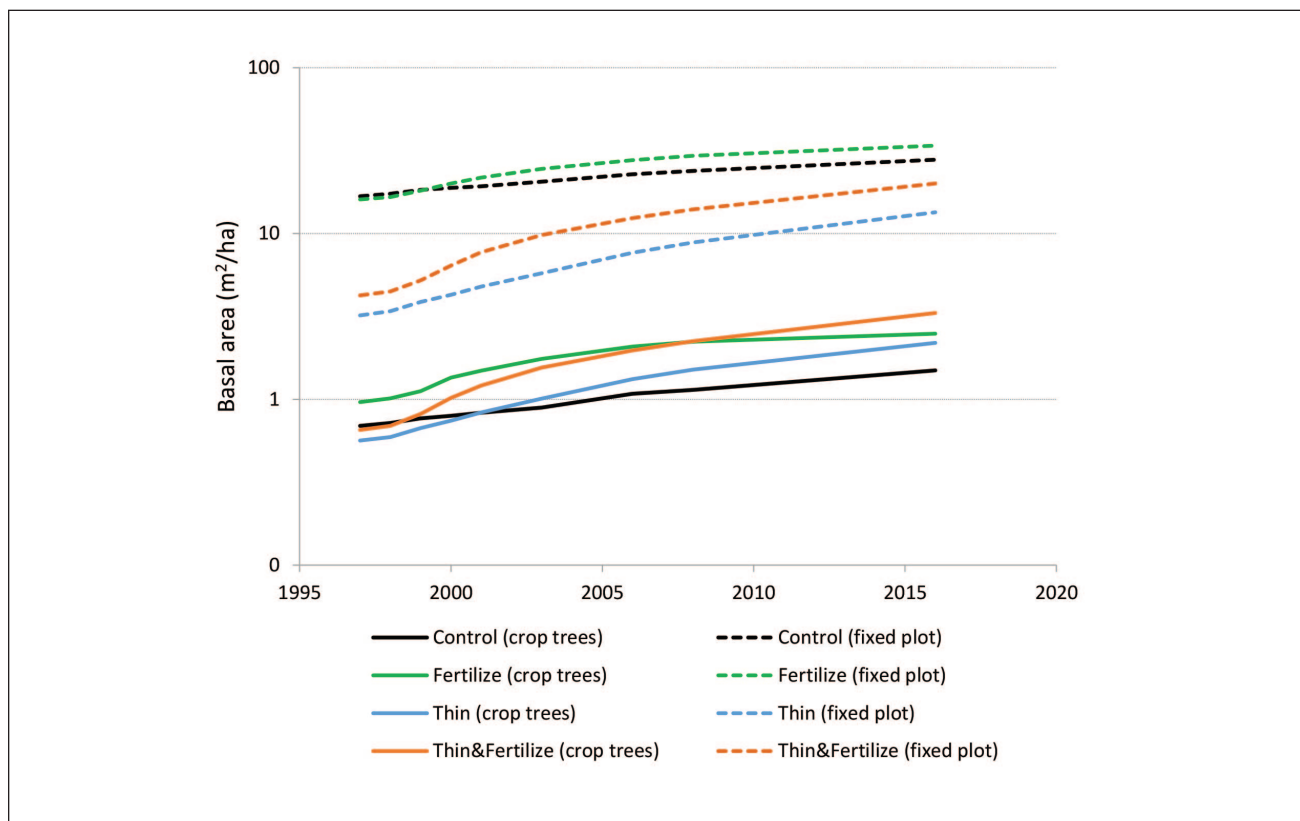


Fig. 7 Mean basal area of crop trees and all stand trees (fixed plots) in the four treatments during the 18 years following treatment

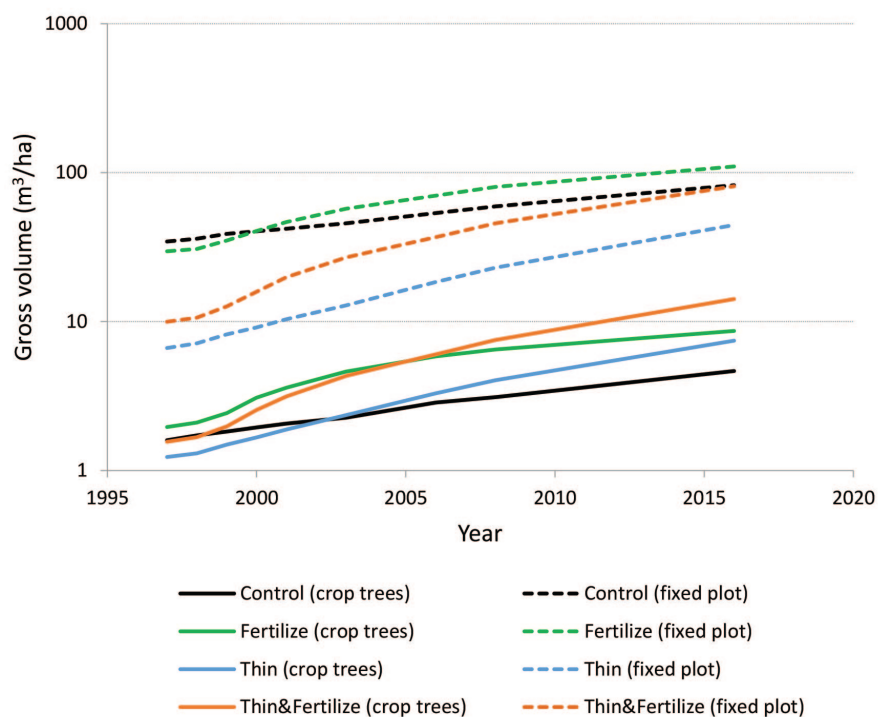


Fig. 8 Mean gross volume of crop trees and all stand trees (fixed plots) in the four treatments during the 18 years following treatments

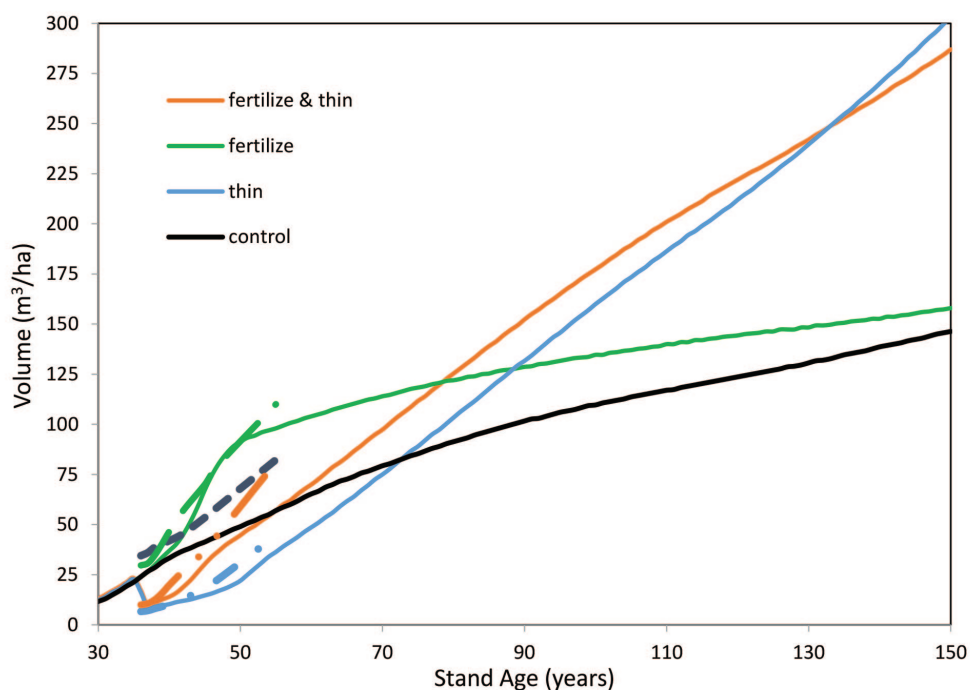


Fig. 9 Measured volumes (dashed lines) and TASS-projected volumes as a function of stand age in plots of each treatment

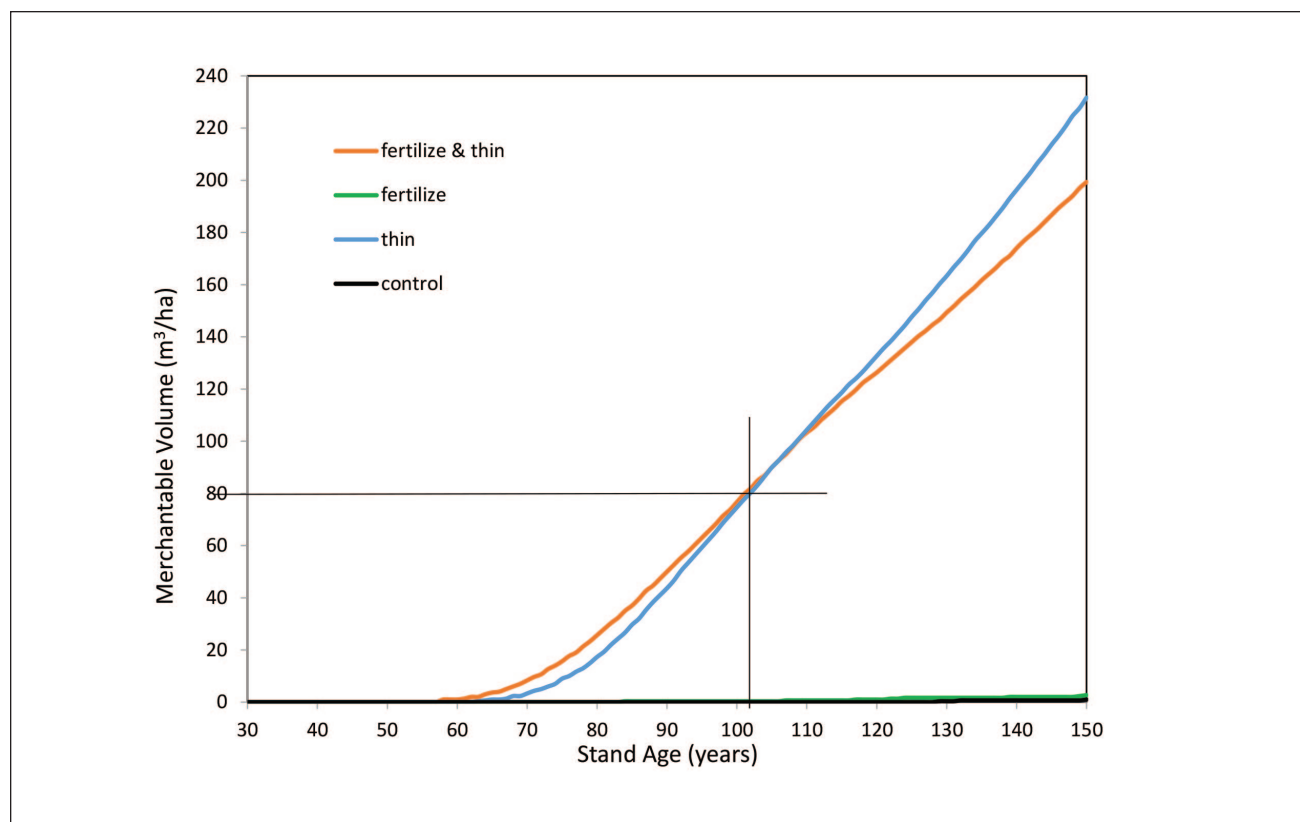


Fig. 10 TASS projections for merchantable volume as a function of stand age in plots of each treatment. The minimum harvest criteria of 80 m³/ha for pine-leading stands in the Williams Lake Timber Supply Area is shown. Merchantable volume was calculated using minimum DBH 12.50 cm, top diameter 10.0 cm and stump height 0.3 m.

eter and height growth of trees in thinned plots were sustained through the study period. This is consistent with the suggestion that reducing the number of trees in these stands allows for crown expansion of the dominant trees, thereby facilitating their growth (Reid 2003, 2004). Thinning would also reduce belowground competition for water and nutrients, which may be more critical than light on this site, where mean summer precipitation is 275 mm and soil coarse fragment content is 40 to 80%. At the time of trial establishment, Newsome and Perry (2003) noted that up to 10% of the trial area was in small, wet depressions that held water in early spring and had gleysolic soil. The vegetation in these depressions was dominated by palmate coltsfoot (*Petasites frigidus* var. *palmatus*), which is common on moist-to-wet sites (Klinkenberg 2017). Stand density was lower within and around these wetter areas and tree growth was higher than in the remainder of the stand. The apparent 50-year site index at the time of trial establishment was 15 m in the wet depressions of these stands—more than double that in the remainder of the stand (7 m). This observation, and the known sensitivity of lodgepole pine top-height to site productivity (Stewart and Salvail 2017) indicates a principal role of water availability in limiting height growth of pine on such sites. Slow height growth would in turn impede stand self-thin-

ning, thereby prolonging the period of high stand density.

The slow growth of trees in these stands was at least partly the result of nutrient deficiencies, as crown radius, height and diameter growth were stimulated by the addition of a fertilizer blend. Based on the early growth responses to fertilization in this trial, Newsome and Perry (2003) speculated that fertilization, by hastening stand development, could obviate the need for thinning. Blevins *et al.* (2005) recommended both thinning and fertilization, and suggested that the growth responses might endure because of the large increase in foliage biomass and continuing elevated levels of sulphur and boron in the needles of fertilized trees observed three years after fertilization. However, measurements taken over the 18-year post-treatment period revealed that the growth response to the single fertilizer application was short-lived. Annual stand growth after fertilization was greater than the control only in the second year for crown radial growth, the first six years for diameter growth, and the first 10 years for height growth. Fertilization of the unthinned stands resulted in much smaller crown-radius growth increments (significant only in the 3 to 4-year period) than observed in the thinned + fertilized plots where radial crown growth was significant throughout the study period. Although diameter growth was significantly greater in thinned than in unthinned plots during the first eight years after treatment, the incremental increase was not as large and did not persist as in the thinned

+ fertilized stands. Similarly, annual height growth increased immediately after fertilization but the growth difference was no longer significant after 10 years. Therefore, the 18-year results of this trial indicate that this site would need to be fertilized at least every 10 years in order to sustain the increase in tree and stand growth.

The greatest growth response at both crop-tree and stand levels was achieved with the combined treatment of thinning plus a single application of blended fertilizer. This treatment combined the pulse of growth during the few years (3–10) after fertilization with the sustained growth improvement following thinning. This is consistent with earlier findings of Farnden and Herring (2002) and Blevins *et al.* (2005). Optimum nutrition trials in B.C. have demonstrated large basal area and volume responses of thinned lodgepole pine to repeated additions of blended fertilizers, but not N alone (Kishchuk *et al.* 2002; Brockley 2007). Using 12-year response data of lodgepole pine to two applications of fertilizer containing N, S and B, Brockley (2007) estimated that a total of four applications of NSB fertilizer would produce 30–35 m³ ha⁻¹ of “extra” wood over the following 12 years, and would reduce the technical rotation length (minimum merchantable harvest or target dbh) by six or seven years compared with the unfertilized stand. Therefore, decisions regarding the use of fertilization to improve operability of height-repressed lodgepole pine stands should assume that four applications of blended fertilizer would be required to sustain the growth responses observed during the first few years of this trial.

Despite the lower standing gross volume resulting from the thinning treatment, gross volume in the thinned + fertilized plots recovered to that in the control plots by the end of the 18-year measurement period. According to the TASS model simulations, total stand volume in both thinned treatments would surpass those of the unthinned treatments by 90 years. Thinning was the only treatment that reached the minimum harvest criteria for merchantable volume, as a consequence of the larger diameters of trees in thinned plots. Thinning dense stands has the added benefit of reducing wildfire severity by reducing the likelihood of crown fires (Graham *et al.* 1999; Pollet and Omi 2002). With only one density treatment in our experiment, it is not possible to determine the optimal post-thinning density for maximizing the positive effect on tree growth while minimizing losses in volume. In long-term studies in Alberta, Stewart and Salvail (2017) concluded that the optimal post-thinning density was 2000–3000 stems ha⁻¹, and our densities were 2200–2900 stems ha⁻¹.

The TASS growth-model simulations were reasonable given the low productivity of the site and the challenges of modelling high-density repressed pine (Harper *et al.* 2018). The TASS model provided relatively accurate simulations of density and height but was weak in the simulation of diameter response (although diameters were within 1.2 cm of treatment values). The apparent underestimation of diameter response by TASS may have resulted from differences between small-tree distribution between field data and TASS modelling. Some trees may have been missed during the field assessments, given the high densities and small size of many trees. In contrast, the TASS model creates a tree list that covers the entire tree distribution, even at high repression densities, resulting in smaller mean diameters estimates in the

model. TASS projections of stand volume growth were close to the observed growth responses to the silvicultural treatments measured during the 18 years following treatments.

Although fertilizer was applied only once in this trial, results from studies of repeated fertilization trials in B.C. (Kishchuk *et al.* 2002; Brockley 2007) indicate that stand volume growth could be considerably hastened by repeated fertilization of thinned stands. Increased productivity of N-fertilized forests has additional benefits in terms of carbon sequestration (Chen *et al.* 2011; Dou *et al.* 2015). Additions of N to forests consistently increase stocks of carbon in soil and forest floor (Johnson and Curtis 2001; Nave *et al.* 2009). Heavy thinning of lodgepole pine stands (to 1000 stems ha⁻¹) coupled with repeated fertilization has been demonstrated to increase the value for biodiversity by hastening the development of old-growth structural attributes (Sullivan *et al.* 2006; Sullivan and Sullivan 2017) and increasing the abundance of grasses, forbs and herbs, which benefit cattle grazing (Lindgren *et al.* 2017). These potential benefits for timber supply, carbon sequestration and biodiversity must be weighed against the costs of the treatment and the risk of stand loss to wildfire, disease or insects (Heineman *et al.* 2010; Woods *et al.* 2010).

In conclusion, the 18-year results from this installation confirm earlier indications that silvicultural interventions can improve the productivity of dense, height-repressed lodgepole pine stands by increasing crop-tree dbh and height growth and shortening the time to reach a merchantable size, allowing them to contribute to the timber supply for the interior of BC. Growth projections indicated that thinning was necessary for this stand to reach the minimum harvest criteria for merchantable volume. Fertilization has the potential to further improve productivity of height-repressed lodgepole pine stands, especially in combination with thinning, but repeated fertilizer applications would be necessary to sustain the growth response.

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