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Evaluation of Precommercial Thinning of Lodgepole Pine from Long-term Research Installations in Alberta

J. D. Stewart and J. C. Salvail

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J. D. Stewart¹ and J. C. Salvail²

Information Report FI-X-16

Natural Resources Canada
Canadian Forest Service
Canadian Wood Fibre Centre
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Cover photos: Lodgepole pine thinning trial near MacKay, Alberta. Top left: aerial photo of treated stand; bottom left: oblique view of canopy in a thinned plot; bottom center: bird's eye view of a thinned plot; right: ground-level view of a thinned plot.

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Abstract

As the forestry landbase shrinks and demand for wood increases, improving productivity of commercial forest stands becomes more important. Because of its commercial value and common occurrence, lodgepole pine is a candidate for productivity improvement. Regenerating lodgepole pine forests are often characterized by very high density and slow growth, limiting their value. Therefore, a variety of precommercial thinning treatments have been tried at long-term installations, which provide valuable data to evaluate projections from existing growth and yield models. In this report, we evaluate the stand growth and yield from different thinning treatments in long-term silviculture installations in the Upper Foothills (Gregg Burn and Teepee Pole Creek) and Lower Foothills (MacKay) subregions of Alberta. The MacKay installation was established in 1954 with the objective of determining whether precommercial thinning of lodgepole pine could improve merchantable volume and quality at

a young age, and in turn shorten rotation and increase annual allowable cuts. The Gregg Burn and Teepee Pole Creek installations were established in the 1960s to assess the response of tree and stand growth to different juvenile spacing treatments, with densities ranging from 500 to 8 000 stems per hectare. Tree growth and survival in these installations are measured periodically to evaluate the effect of different intensities of thinning on the growth and yield of the lodgepole pine crop trees. To provide a decadal update to previous measurements and evaluation, published in 2006, we examined total and merchantable volumes in these installations using the most recent data (2011–2014). Our analysis found that thinning is unlikely to increase yields; however, if thinning is carried out for other reasons, judicious choice of a thinning regime can avoid a yield loss. Thinning to 2 000–3 000 stems per hectare appears to be optimal, maximizing the positive effect on tree growth without major losses in volume.

Résumé

Comme les territoires forestiers diminuent et que la demande en bois augmente, l'accroissement de la productivité des peuplements commerciaux devient crucial. En raison de sa valeur commerciale et de sa présence commune, le pin tordu latifolié est un bon candidat pour accroître la productivité. La régénération des forêts de pins tordus latifoliés est souvent caractérisée par une très forte densité et un faible taux de croissance, ce qui a pour conséquence d'en limiter la valeur. C'est pourquoi une variété de coupes d'éclaircie précommerciales a été testée dans des installations à long terme, ce qui procure d'excellentes données pour évaluer les projections des modèles de croissance et de production actuels. Dans ce rapport, nous évaluons la croissance et la production d'un peuplement, à la suite de l'utilisation des différentes sortes de coupes d'éclaircie pour des installations à long terme de sylviculture situées dans les sous-régions du Upper Foothills (Gregg Burn et Teepee Pole Creek) et du Lower Foothills (Mackay) de l'Alberta. L'installation Mackay a été mise en place en 1954 dans le but de déterminer si les coupes d'éclaircie précommerciales du pin tordu latifolié pouvaient augmenter le volume et la qualité marchande, à un jeune âge, ce qui, en retour, permettrait de raccourcir la

période de rotation et d'augmenter la quantité de coupes annuellement possibles. Les installations Gregg Burn et Teepee Pole Creek furent établies dans les années 1960 afin d'évaluer la réponse des arbres et la croissance du peuplement à des coupes d'éclaircie hâtives, avec des densités variant de 500 à 8 000 tiges par hectare. La croissance et la survie des arbres sont mesurées périodiquement afin d'évaluer l'effet des différentes intensités des coupes d'éclaircie sur la croissance et la production des arbres exploitables de l'espèce du pin tordu latifolié. Pour amener une mise à jour décennale aux mesures et aux évaluations précédentes, publiées en 2006, nous avons examiné le volume total et le volume marchand de ces installations, à l'aide des plus récentes données (2011 à 2014). Notre analyse a déterminé que les coupes d'éclaircie ne sont pas susceptibles d'augmenter la production; cependant, si la coupe d'éclaircie est effectuée pour d'autres raisons, un choix judicieux de système d'éclaircie peut éviter une perte de production. Une coupe d'éclaircie qui vise à conserver de 2 000 à 3 000 tiges par hectare semble optimale, maximisant ainsi l'effet positif sur la croissance des arbres, sans causer de perte majeure de volume.

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Introduction

Development of the forest industry in Canada faces two constraints: a shrinking land base and increasing demand for many natural resources including wood products, energy, and minerals. These constraints mean that an increasing demand for forest fibre products will have to be met from development in a smaller area. Climate change is increasing forest disturbance from fire and insects, especially mountain pine beetle (*Dendroctonus ponderosae* Hopk.), which aggravates this situation. It is challenging for Canadian producers to be competitive in the global commodity market for wood fibre products, because of relatively low growth rates of tree stands as well as high transportation and labour costs. One strategy for addressing these challenges is more intensive management of forests to increase productivity and to improve the quality and value of the wood.

Lodgepole pine (*Pinus contorta* L.) is a candidate for intensive management because of its broad ecological amplitude (Lotan and Critchfield 1990), common occurrence, and high commercial value (Kennedy 1985; Koch 1996). In addition, post-fire regeneration often results in slow-growing stands of lodgepole pine with very high densities (Smithers 1961). Although there may be size differentiation in many of these stands, self-thinning often does not occur to an appreciable degree and the resulting stands would not meet current forest management objectives (Goudie 1980). Such excessive densities reduce average stand diameter, height, and merchantable volume while increasing mortality, length of rotations, and harvesting costs. As a result, much of the landbase of lodgepole pine is growing at well below its site-productivity potential. Early management of stand density through precommercial thinning has been shown to

mitigate many of the negative effects of excessive density in natural lodgepole pine stands (Johnstone 1985; Johnstone and Cole 1988; Johnstone and van Thienen 2011b). Therefore, natural lodgepole pine stands are good candidates for stand density management to improve timber production.

Forest management in Canadian lodgepole pine forests is based on projections from models such as Tree and Stand Simulator (TASS, Mitchell 1969), Growth and Yield Projection System (GYPSY, Huang et al. 2001), and Mixedwood Growth Model (MGM, Bokalo et al. 2013). Validation of these models, specifically to forecast yield of density-managed lodgepole pine, has been limited. It is essential to review actual case studies of stand development in response to site conditions and stand manipulations from long-term field installations as a check on the function of the models. A network of long-term lodgepole pine installations in Alberta, with a range of precommercial thinning prescriptions differing in timing and intensity, is available for this purpose. Several earlier reports are available for these installations (Smithers 1957; Johnstone 1981a, b; Johnstone 1982; Yang 1986, 1991; Stewart et al. 2006).

In this report, our objectives are (1) to provide an introduction to the long-term installations and their associated datasets for potential use in growth and yield models, (2) to test principles of thinning response reported in the literature, and (3) to evaluate responses to precommercial thinning that support or challenge conventional wisdom on early stand-density management of lodgepole pine. In this report, only growth and yield effects will be evaluated. The effect of thinning on products and their market values, as well as on wood quality, will be addressed elsewhere.

Methods

Site Description

Precommercial thinning treatments have been established in nine field installations in west-central Alberta. All stands regenerated naturally following wildfire. The Gregg Burn (two sites begun in 1963 [Gregg63] and 1984 [Gregg84]) and Teepee Pole Creek sites are located in the Upper Foothills ecological subregion, and the MacKay site in the Lower Foothills subregion (Beckingham et al. 1996). Plant community types were lodgepole pine–black spruce/Labrador tea/feather moss for the Gregg63 low-productivity site, Gregg84 low-productivity site,

Gregg84 medium-productivity site, and MacKay trial sites; lodgepole pine/Labrador tea/feather moss for the Gregg63 medium-productivity site, Gregg84 medium-productivity site, and Gregg84 high-productivity trial sites; and lodgepole pine/green alder/feather moss for the Gregg63 high-productivity and Teepee Pole Creek trial sites. Other site characteristics are summarized in Table 1. Geographic locations are shown in Figure 1. Further information on and results for stand development over time are found in Table 1 and Stewart et al. (2006).

Table 1. Stand treatment and site description for the four study sites

Name	Establishment (year)	Age (years)	Treatments density (stems/ha)	Nutrient regime	Moisture regime
Teepee Pole	1967	25	7 907 3 954 1 977 988 494	Flat: medium North: medium poor–medium rich	Flat: mesic North: submesic–subhygric
MacKay	1954	22	747 1 680 2 986 4 328 11 000 ^a	Poor	Mesic
Gregg63	1963	7	7 907 3 954 1 977 988 494	Low: very poor–poor Medium: poor High: medium poor–medium rich	Low: submesic Medium: mesic High: mesic to subhygric
Gregg84	1984	28	3 954 2 965 1 977 988	Low: poor Medium: poor–medium High: medium	Low: mesic Medium: mesic High: mesic

^aControl stands.

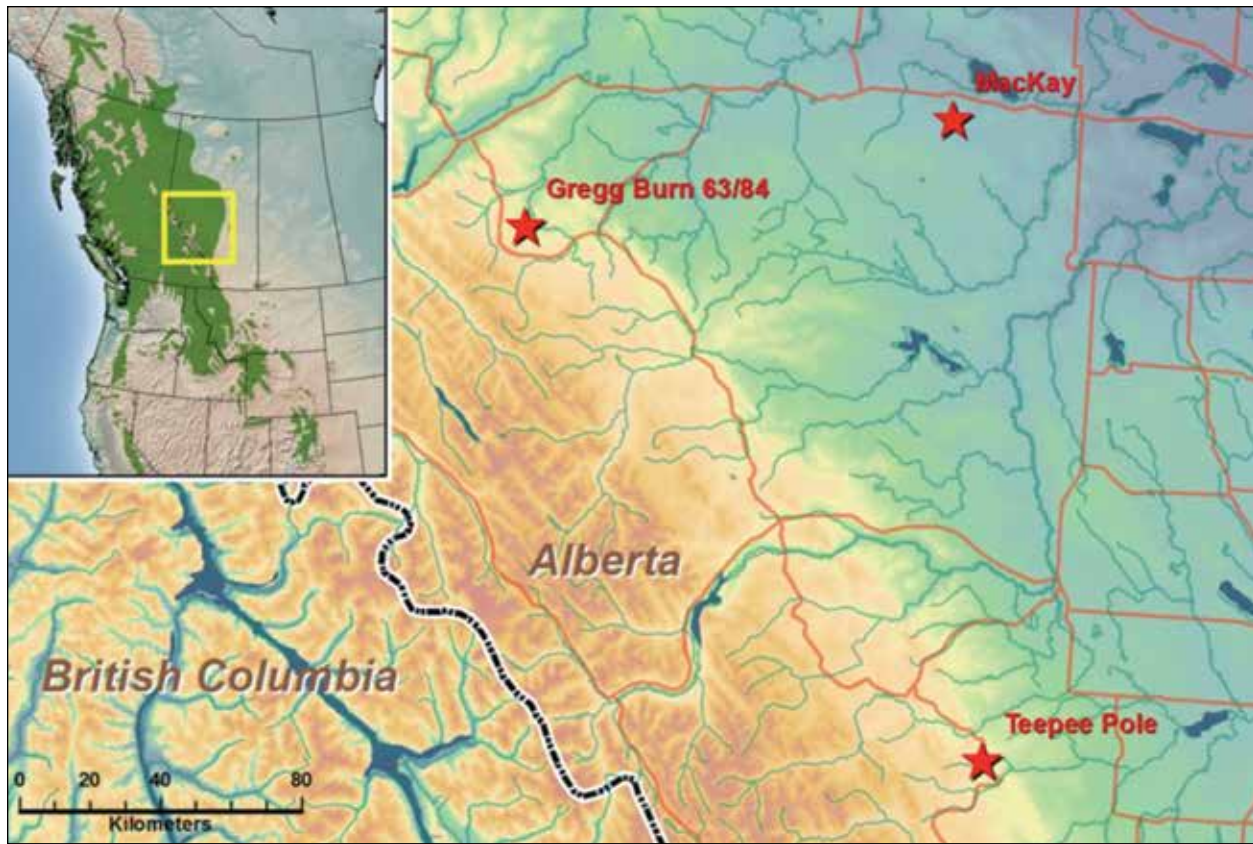


Figure 1. Location of the four study sites.

Experimental Design and Site Layout

The MacKay trial was established in 1954, at stand age 22 years, with three randomized complete blocks of similar productivity. Each block consisted of six treatment plots: an unthinned control and five thinned plots. Thinning treatment prescriptions were 1 680, 2 986 (replicated twice), and 4 328 stems per hectare. The fifth treatment regime involved a second thinning; however, this treatment is not included in this analysis. Spacing was done by hand, with a spacing grid set up as a guideline. An effort was made to retain the most vigorous trees rather than to rigidly adhere to the spacing prescriptions. An unreplicated treatment of 747 stems per hectare was also established adjacent to one of the complete blocks.

The Gregg Burn 1963 trial was established in 1963, at stand age seven years, in three sites of differing productivity (low, medium, and high), based on

pre-fire stand characteristics. Two semi-randomized complete blocks were established on each site. Each block contained five treatment plots, which were sized to contain exactly 100 trees on a uniform square grid. Spacing was done by hand in 1963–1964, following a string grid template, with residual trees located no farther than 46 cm from grid intersections. The treatments were 200, 400, 800, 1 600, and 3 200 stems per acre, or approximately 500, 1 000, 2 000, 4 000, and 8 000 stems per hectare.

The Teepee Pole Creek experiment has the same experimental design and establishment procedures as the earlier Gregg Burn 1963 trial: a semi-randomized complete-block design, with two replicate blocks of treatment plots in each site. In this case, the sites were of similar productivity but differed in slope aspect: flat, north, and south aspect slopes. The south aspect site was dropped

from analysis because of layout problems and later damage to the site. Spacing was done by hand in summer 1967 at the stand age of 25 years.

An extension to the Gregg63 trial was established in 1984, also in the Gregg Burn. The experimental design was identical to that of the Gregg63 trial, except that the 200 stems per acre treatment was replaced by a 1 200 stems per acre treatment, and the 3 200 stems per acre treatment was dropped, so that the resulting thinning levels were approximately 1 000, 2 000, 3 000, and 4 000 stems per hectare. The high- and low-productivity sites were located on different sites from those of the Gregg63 trial; however, the medium sites for both trials were co-located.

Measurements

The following data were collected after the growing season during each year of mensuration: diameter at breast height (DBH; 1.3 m from the estimated point of germination), height to the tallest live portion of the crown (Ht), height from the ground level to the base of the continuous live crown (HLC; i.e., the lowest contiguous whorl with at least three branches), and crown social class (dominant, co-dominant, intermediate, and suppressed). Tree condition and pathology were also noted. Measurements were taken on the following dates (Table 2):

- Gregg63 were taken in 1964, 1966, 1971, 1976, 1981, 1986, 1991, 1996, 2001, 2006, and 2011.
- Gregg84 were taken in 1984, 1989, 1996, 2004, 2009, and 2014 (medium-productivity site only).
- MacKay were taken in 1954, 1960, 1969, 1979, 1989, 1996, 2003, 2008, and 2013.
- Teepee Pole Creek were taken in 1967, 1972, 1977, 1982, 1987, 1992, 1996, 2003, 2009, and 2014 (medium-productivity site only).

Because of the large size of the MacKay trial, heights were measured only for a sample of the trees in each plot, and height was estimated for

Table 2. Dates measurements were taken at the study sites

Gregg63	Gregg84	MacKay	Teepee Pole Creek
1964	1984	1954	1967
1966	1989	1960	1972
1971	1996	1979	1977
1981	2009	1996	1987
1986	2014 ^a	2003	1992
1991		2008	1996
1996		2013	2003
2001			2009
2006			2014 ^a
2011			

^aOnly the medium-productivity site was measured.

all other trees. Data from the 1996 measurements at Teepee Pole Creek have been excluded because of suspected errors and lack of information about quality control during the collection of data. Crop trees tagged at establishment were included in the dataset for this analysis, along with ingress trees that were considered to interact with the crop trees (i.e., those that attained 90% of the height of the shortest unbroken crop tree).

When tree heights had not been measured, they were estimated from provincial height–diameter equations, using coefficients estimated for individual treatments in each trial for lodgepole pine and coefficients estimated for the Lower Foothills subregion for other species (Huang 1999). Before compilation for analysis, the data were screened for obvious errors (e.g., decreasing height or diameter measurements) and, when possible, such errors were corrected.

Total and merchantable volumes were calculated for each tree at each measurement time, using equations developed for lodgepole pine in Alberta (Huang 1994). Total volume was calculated as total residual live-stem volume inside bark (1.25 cm top diameter and 30 cm stump height). Merchantable volumes were calculated according to two utilization standards commonly used in Alberta:

13/7 and 15/10. In these standards, the first number refers to the diameter in centimeters outside the bark at stump height (30 cm) and the second number refers to the diameter in centimeters inside the bark at the top, with a minimum merchantable length of 2.44 m (Huang et al. 2001). Piece size was calculated as the merchantable volume (13/7 standard) per tree. Data for surviving trees were aggregated by plot and treatment and were converted to a per-hectare basis.

We calculated the relative rate of mortality as the lambda parameter from the exponential decay function for the number of live trees per hectare over time. Top height (TopHt) was calculated as the mean height of the 100 largest diameter trees per hectare, prorated to the actual plot size, with the minimum number of three trees used to calculate top height in the smallest plots. Quadratic mean diameter was calculated as follows:

$$[1] Dq = 100 \sqrt{\frac{4BAsum}{\pi Ntrees}}$$

where Dq = quadratic mean diameter, BAsum = the sum of basal area of all trees in the plot, and Ntrees = the number of trees in the plot.

Competition within the density treatments was calculated in two ways, as spacing factor (SF, Wilson 1946) and stand density index (SDI, Reineke 1933), as follows:

$$[2] SF = 100 / \left(\sqrt{\frac{\text{stems}}{\text{ha}}} \text{TopHt} \right)$$

where SF = spacing factor and TopHt = top height, and

$$[3] SDI = \frac{\text{stems}}{\text{ha}} \left(\frac{Dq}{25} \right)^{1.6}$$

where SDI = stand density index (standardized to a Dq of 25 cm) and Dq = quadratic mean diameter.

Statistical Analysis

Stand conditions changed over time; representing the density treatments by the target stand density when they were established fails to take into account the dynamic nature of the treated plots. Although the initial stand density is controlled to a particular level, subsequent stand development is subject to a number of other factors that affect growth and mortality. Therefore, the trajectories of post-thinning

stands may differ although they start at the same density. Because a stand is a dynamic system, there is no one measure (such as initial density) that adequately captures the conditions of the stand during the entire course of its development. A given stand density has different implications, depending on the age of the stand and the size of the trees. Therefore, we grouped initial treatments into density treatment categories to emphasize that initial conditions are an approximation of the treatment conditions and that treatments may converge during stand development. Results are presented as density class treatments A through G, corresponding to the establishment densities as follows: A (494 stems/ha), B (747 and 988 stems/ha), C (1 977 stems/ha), D (2 965 and 2 986 stems/ha), E (3 954 stems/ha), F (7 907 stems/ha), G (11 000 stems/ha unthinned).

Results of a particular treatment in different trials are not directly comparable because they were established and measured at different times and different ages. We chose not to project data to a common rotation age using existing growth and yield models. Therefore, no formal statistical comparisons among trials were made in this analysis, and statistical analysis was carried out on each of the four trials separately.

Statistical analysis of differences between treatments used only the latest mensuration data from each site. We used the square transformation of tree height and the log10 transformation of piece size, live crown ratio, and height diameter ratio in the analysis to meet assumptions of normality and homoscedasticity. Other variables did not require transformation. The significance of site and treatment factors was tested using analysis of variance (ANOVA, Proc GLM [SAS Institute]). The ANOVA models used were a linear combination of the main factors and their interactions, as follows:

$$\text{Var} \sim S + B(S) + D + S \times D + B \times D(S) + S \times B \times D(S) + \epsilon \text{ (for the Gregg Burn and Teepee Pole Creek sites)}$$

$$\text{Var} \sim B + D + B \times D + \epsilon \text{ (for the MacKay site)}$$

where Var represents the dependent variable being tested, S is site, B is block, D is the density class treatment, and ϵ is the error.

The Type III sums of squares were used because of uneven cell sizes in the analysis. For the Gregg Burn and Teepee Pole Creek trials, site effects were tested against the block(site) term, and the density effect and site × density interaction were tested against density × site × block(site) term. For the

MacKay trial, the density effect was tested against density × block term. The Tukey–Kramer test (also known as Tukey’s honestly significant difference [HSD] test; Tukey 1949) was used to test for differences among treatments.

Results

In this report, we evaluate the stand growth and yield from different thinning treatments in long-term silviculture installations in the Upper Foothills (Gregg Burn and Teepee Pole Creek) and Lower Foothills (MacKay) subregions of Alberta. The MacKay installation was established to determine whether precommercial thinning of lodgepole pine could improve merchantable volume and quality at a young age, and in turn shorten rotation and increase annual allowable cuts. In the Gregg Burn and Teepee Pole Creek installations we assess the response of tree and stand growth to different juvenile spacing treatments, with densities ranging from 500 to 8 000 stems per hectare. Tree and stand outcomes in these installations are measured periodically to evaluate the effect of thinning level on the growth and yield of the lodgepole pine crop trees. To provide a decadal update to previous measurements and evaluation, we examined total and merchantable volumes at these sites using the most recent data (2011–2014). Results are presented in Figures 2–16. Tree-level properties are presented as notched box-and-whisker plots to show the distribution of the data (Figures 6 to 10). Dot-plots of stand-level variables represent the plot means of the treatment for each block (Figures 2 to 5, 11 to 16).

Stand Development

Stand Density

In all trials, the latest stand densities were, as expected, related to the initial density (Figure 2,

Tables 3 and A1). However, stand densities have converged over time, as a result of mortality of the original trees. Stand densities still span a range from more than 5 000 stems per hectare in the Gregg63 low-productivity site to between 300 and 450 stems per hectare in the A treatments of the Gregg63 and Teepee Pole Creek trials, but only to 642 in the MacKay A treatment.

Stand density at the last measurement of the Gregg63 trial was affected by the interaction of the thinning treatment and site conditions; although stand density was decreased with the intensity of the thinning treatment, the differences among treatments were least in the high site and greater in the medium and low sites, suggesting that self-thinning was greater in the high site. There were no significant interactions between site and density treatment in the Gregg84 and Teepee Pole Creek trials (Figure 2, Tables 3 and A1). Therefore, the self-thinning trajectories for each treatment were approximately the same across the different sites. Stand density in the low site of the Gregg84 trial was slightly, but significantly, higher than in the medium and high sites. Site differences in stand density were not significant in the Teepee Pole Creek trial.

Mortality

Mean relative mortality rates over the course of the trial measurement period did not differ among sites, except in the Gregg64 trial, where the rates were higher in the high-productivity site than in

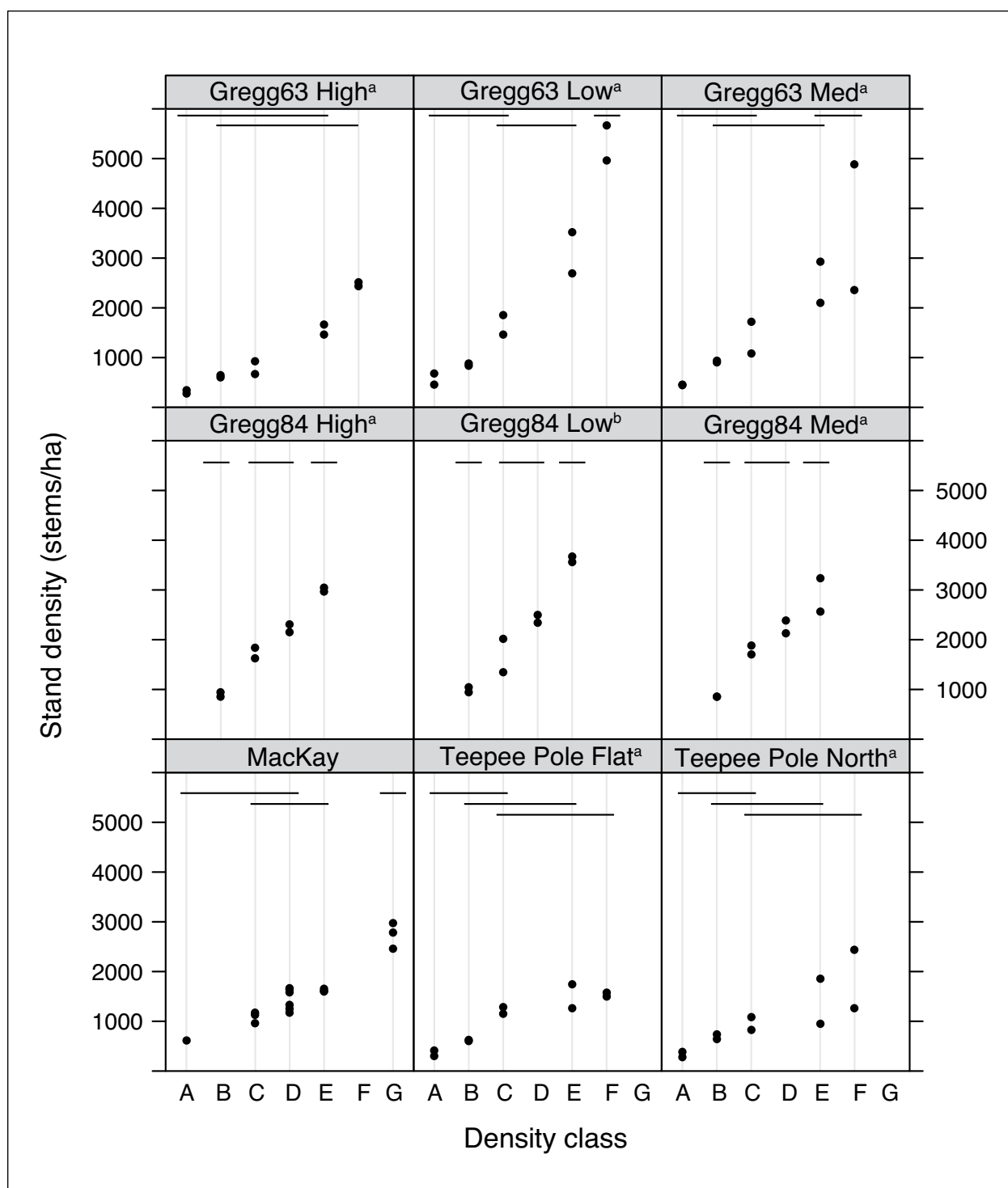


Figure 2. Stand density at latest measurement for four lodgepole pine precommercial thinning trials. See text for explanation of treatment design. Treatment plot means under the same horizontal line are not significantly different at the 0.05 probability level, based on the Tukey–Kramer tests. Where the results are too complex to indicate significant differences with lines, lower-case letters are used; those treatments that share the same letter are not significantly different from each other at the 0.05 probability level. Density class is described in the Stand Development and Tree-level Properties sections of the paper.

Table 3. Results of analysis of variance of the effect of site and density treatments on stand density at the latest measurement in four lodgepole pine precommercial thinning trials

Trial	Source	DF	Type III sum of squares	Mean squares	F value	Pr > F
Gregg63	Site	2	7 008 498	3 504 249	6.62	0.0794
	Block(site)	3	1 588 148	529 382	2.49	0.1102
	Density	4	45 154 424	11 288 606	53.07	<0.0001
	Site × density	8	6 091 757	761 469	3.58	0.0234
Gregg84	Site	2	3 158 051	1 579 025	17.11	0.0229
	Block(site)	3	276 849	92 283	0.60	0.6314
	Density	3	22 376 955	7 458 985	48.44	<0.0001
	Site × density	6	1 575 892	262 648	1.71	0.2262
Teepee Pole	Site	1	52.4135	52.4135	0.00	0.9884
	Block(site)	2	389 165	194 582	1.65	0.2510
	Density	4	4 814 235	1 203 558	10.21	0.0031
	Site × density	4	209 490	52 372	0.44	0.7740
MacKay	Block	2	133 690	66 845	1.59	0.2560
	Density	4	4 313 809	1 078 452	25.68	<0.0001

DF = degrees of freedom; Pr > F = the probability of getting by chance an F-value greater than the estimated value.

Table 4. Results of analysis of variance of the effect of site and density treatments on mortality rate at the latest measurement in four lodgepole pine precommercial thinning trials

Trial	Source	DF	Type III sum of squares	Mean squares	F value	Pr > F
Gregg63	Site	2	8.7436	4.3718	12.46	0.0352
	Block(site)	3	1.0527	0.3509	2.99	0.0734
	Density	4	6.6160	1.6540	14.09	0.0002
	Site × density	8	0.9642	0.1205	1.03	0.4666
Gregg84	Site	2	7.7788	3.8894	7.51	0.0680
	Block(site)	3	1.5545	0.5182	3.65	0.0337
	Density	3	1.5216	0.5072	3.58	0.0360
	Site × density	6	0.8743	0.1457	1.03	0.4414
Teepee Pole	Site	1	0.0764	0.0764	0.25	0.6696
	Block(site)	2	0.6237	0.3118	1.13	0.3692
	Density	4	18.4754	4.6188	16.76	0.0006
	Site × density	4	0.5145	0.1286	0.47	0.7592
MacKay	Block	2	0.1036	0.0518	1.53	0.2687
	Density	4	6.2736	1.5684	46.21	<0.0001

DF = degrees of freedom; Pr > F = the probability of getting by chance an F-value greater than the estimated value.

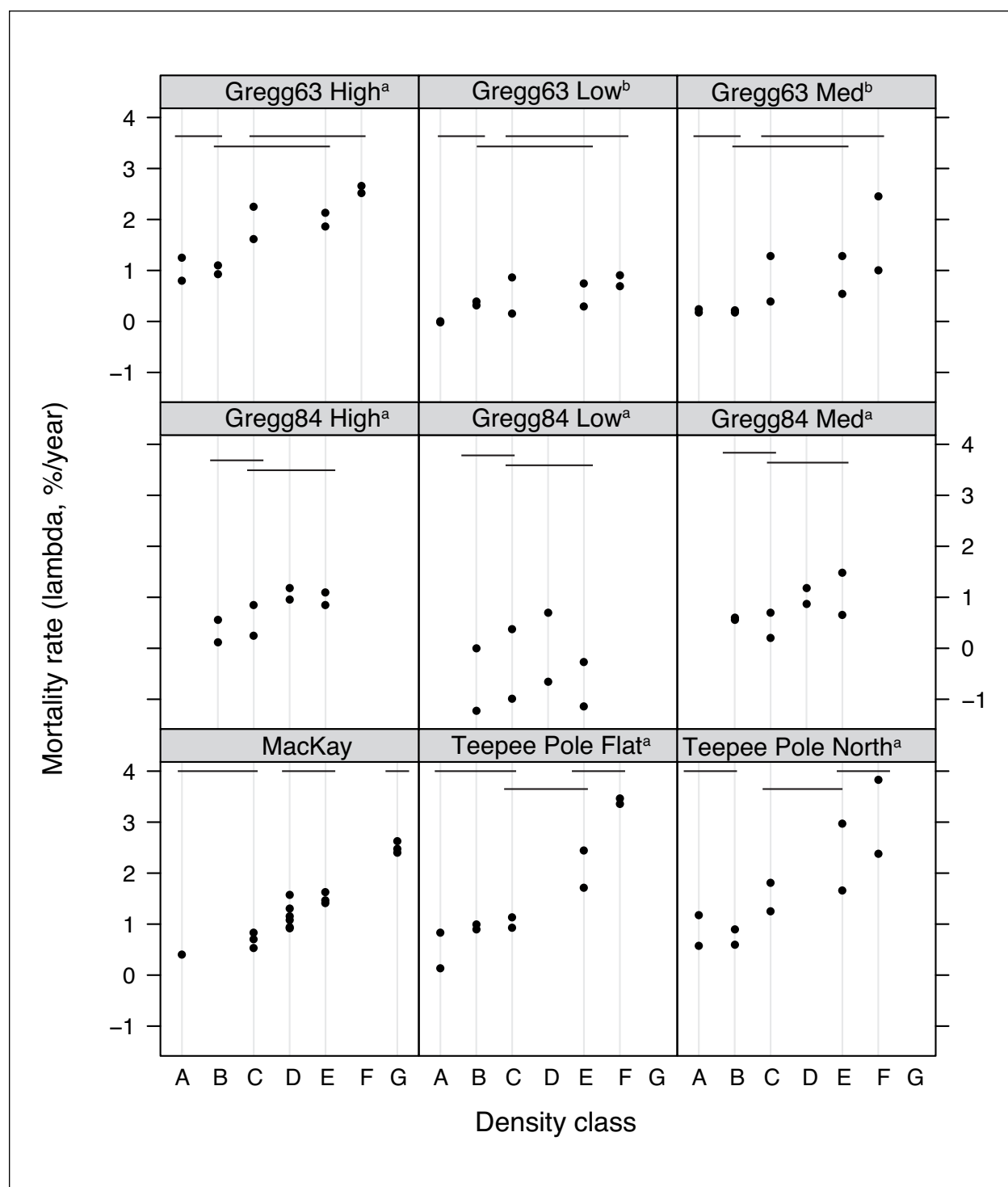


Figure 3. Relative annual mortality rate since establishment for four lodgepole pine precommercial thinning trials. See caption for Figure 2 for explanation of treatment design.

the medium- and low-productivity sites (Figure 3, Tables 4 and A2). In all sites, there is a significant effect of density treatment on relative mortality rate, although the mortality rates differed little between adjacent density treatments within a trial. Mortality was in the range of 2–4% per year in the highest density treatments, and less than 1% per year in the lowest density treatments. Although mensuration data in the past three cycles have included recording of tree condition, the causes of mortality are not clear. There is no indication that density has an effect on insect and disease occurrence; in fact, there is evidence of some level of attack in 100% of trees in most plots, and in at least 85% of the trees even in the healthiest stands.

Spacing Factor

Since the spacing factor (SF) is closely related to stand density, as well as to height, the results mirror those of stand density to some degree (Figure 4, Tables 5 and A3). In the Gregg84 trial, SF was higher in the low-productivity site, ranging up to almost 0.35, than in the medium- or high-productivity sites. The medium- and high-productivity sites had a similar range of SF (from

about 0.12 to 0.25; Figure 2). There was no significant difference among sites in the other trials.

Spacing factor decreased with increasing density treatment. Although SF differed among density treatments at establishment (not shown), after several decades of growth and mortality SF values have become similar among some of the adjacent density treatments. However, the SF values in the lowest-density treatments still differ from those in all other treatments in almost all cases. The lowest values of SF were in the MacKay trial, where they ranged from about 0.17 in the most open (A) treatment to less than 0.10 in the unthinned control (G treatment) plots.

Stand Density Index

Stand density index (SDI) shows a pattern of differences similar to that of SF, although the values of SDI increase, rather than decrease, with increasing density treatment (Figure 5, Tables 6 and A4). The values ranged from less than 300 to more than 1 200 stems per hectare. The low-productivity site in the Gregg84 trial had significantly lower SDI values than the medium- and high-productivity

Table 5. Results of analysis of variance of the effect of site and density treatments on spacing factor at the latest measurement in four lodgepole pine precommercial thinning trials

Trial	Source	DF	Type III sum of squares	Mean squares	F value	Pr > F
Gregg63	Site	2	0.0037	0.0019	3.23	0.1786
	Block(site)	3	0.0017	0.0006	1.06	0.4006
	Density	4	0.1527	0.0382	70.47	<0.0001
	Site × density	8	0.0041	0.0005	0.94	0.5193
Gregg84	Site	2	0.0131	0.0066	23.08	0.0151
	Block(site)	3	0.0009	0.0003	1.96	0.1906
	Density	3	0.0562	0.0187	128.95	<0.0001
	Site × density	6	0.0016	0.0003	1.85	0.1960
Teepee Pole	Site	1	0.0006	0.0006	0.96	0.4310
	Block(site)	2	0.0012	0.0006	0.70	0.5242
	Density	4	0.0747	0.0187	22.22	0.0002
	Site × density	4	0.0009	0.0002	0.28	0.8841
MacKay	Block	2	0.0000	0.0000	0.57	0.5825
	Density	4	0.0057	0.0014	58.63	<0.0001

DF = degrees of freedom; Pr > F = the probability of getting by chance an F-value greater than the estimated value.

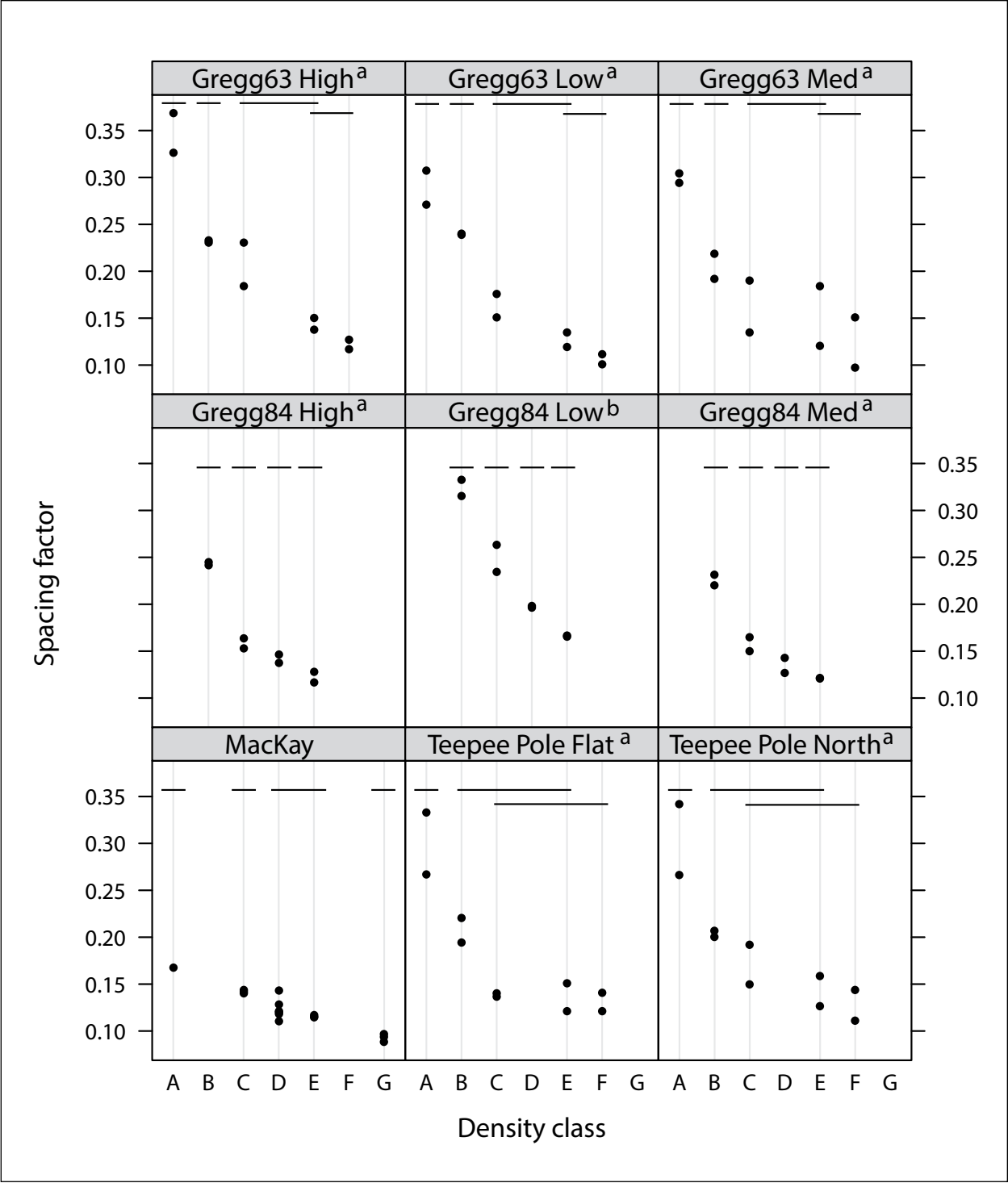


Figure 4. Spacing factor at latest measurement for four lodgepole pine precommercial thinning trials. See caption for Figure 2 for explanation of treatment design.

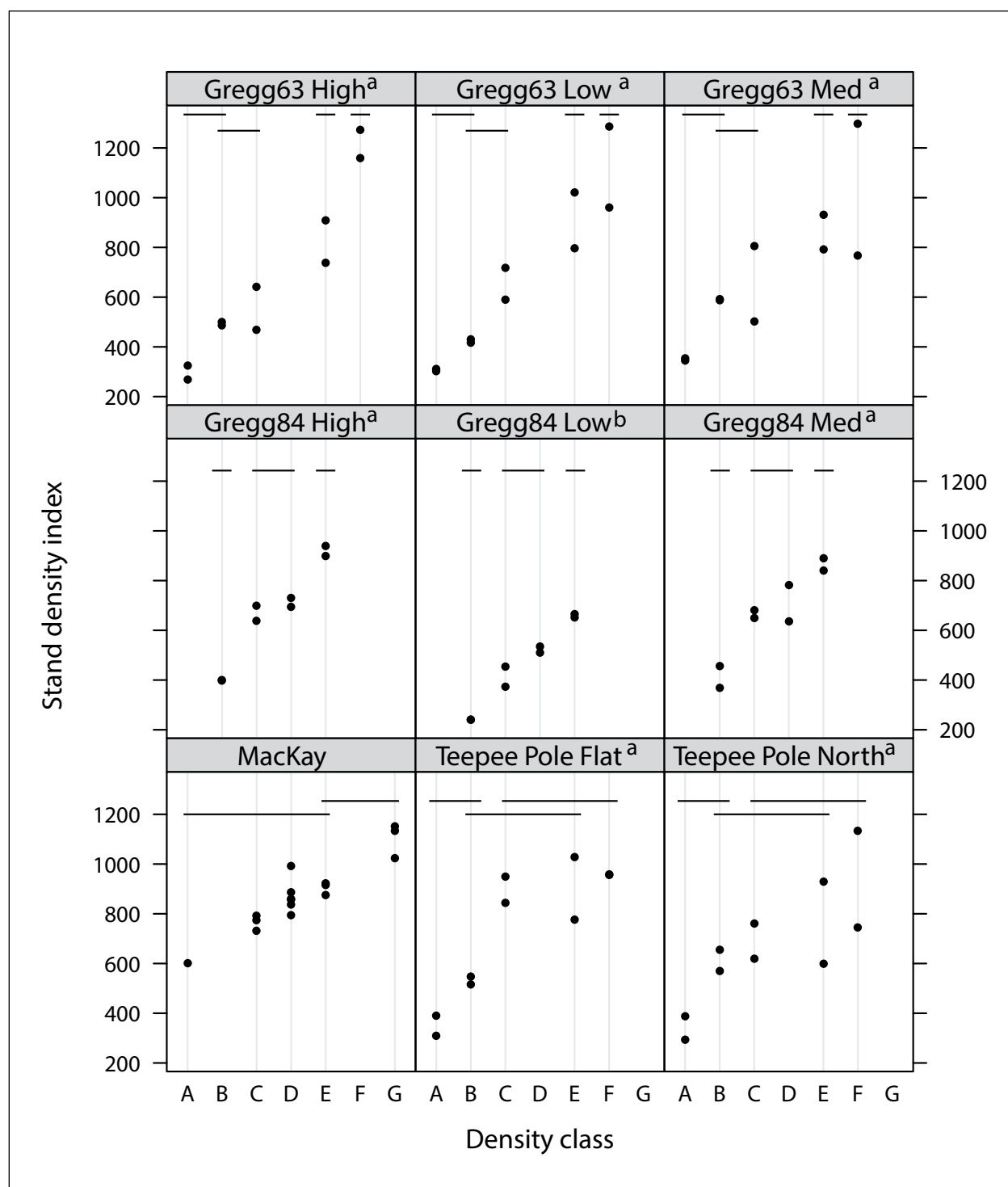


Figure 5. Stand density index at latest measurement for four lodgepole pine precommercial thinning trials. See caption for Figure 2 for explanation of treatment design.

Table 6. Results of analysis of variance of the effect of site and density treatments on stand density index at the latest measurement in four lodgepole pine precommercial thinning trials

Trial	Source	DF	Type III sum of squares	Mean squares	F value	Pr > F
Gregg63	Site	2	6 761	3 380	0.11	0.9009
	Block(site)	3	93 819	31 273	1.84	0.1933
	Density	4	2 345 009	586 252	34.52	<0.0001
	Site × density	8	60 447	7 555	0.44	0.8716
Gregg84	Site	2	157 516	78 758	43.01	0.0062
	Block(site)	3	5 492	1 830	0.99	0.4403
	Density	3	764 520	254 840	137.80	<0.0001
	Site × density	6	3 496	582	0.32	0.9133
Teepee Pole	Site	1	19 134	19 134	0.76	0.4746
	Block(site)	2	50 185	25 092	1.44	0.2924
	Density	4	891 474	222 868	12.79	0.0015
	Site × density	4	47 265	11 816	0.68	0.6262
MacKay	Block	2	29 443	14 721	3.53	0.0739
	Density	4	209 383	52 345	12.54	0.0010

DF = degrees of freedom; Pr > F = the probability of getting by chance an F-value greater than the estimated value.

sites, otherwise, the range of SDI values across the density treatments was not significantly different between the sites within a trial. The range of SDI values across the range of density treatments within a site was narrower in the MacKay and Gregg84 trials (415–537) compared with the Gregg63 and Teepee Pole Creek trials (588–859). As with the other stand-development variables examined, there were often no significant differences in SDI between adjacent density treatments with a site.

Tree-Level Properties

Tree Diameter

Precommercial thinning had a consistent significant effect on DBH (Figure 6, Tables 7 and A5). In general, DBH decreased with increasing stand density and increased with site productivity. Slope aspect had no effect on DBH in the Teepee Pole Creek trial. The range in DBH in the Gregg84 trial was less than in any of the other trials, for similar density treatments (about 10–18 cm in Gregg84 vs 10–24 cm in other trials).

Tree Height

In the Mackay trial, tree height increased with the severity of the thinning treatments (Figure 7, Tables 8 and A6). Although height differences among treatments were not as great as in the MacKay site, heights in the Gregg63 and Teepee Pole Creek trials also increased with the severity of the thinning treatments, except for the most severe thinning where it decreased. Maximum heights occurred in the B and C treatments. There were no significant differences in height among thinning treatments in the Gregg84 trial. Height responded to site productivity, being lower in the low-productivity sites than in the medium- or high-productivity sites in the Gregg Burn trials, although it was unaffected by site differences in the Teepee Pole Creek trial. Heights ranged from 10 m to 20 m or more in the trials, except for the Gregg84 low-productivity site, where heights were less than 10 m.

Height–Diameter Ratio

Tree slenderness, or height–diameter ratio (HDR), consistently increased with increasing density treatment in all trials and sites, as diameter

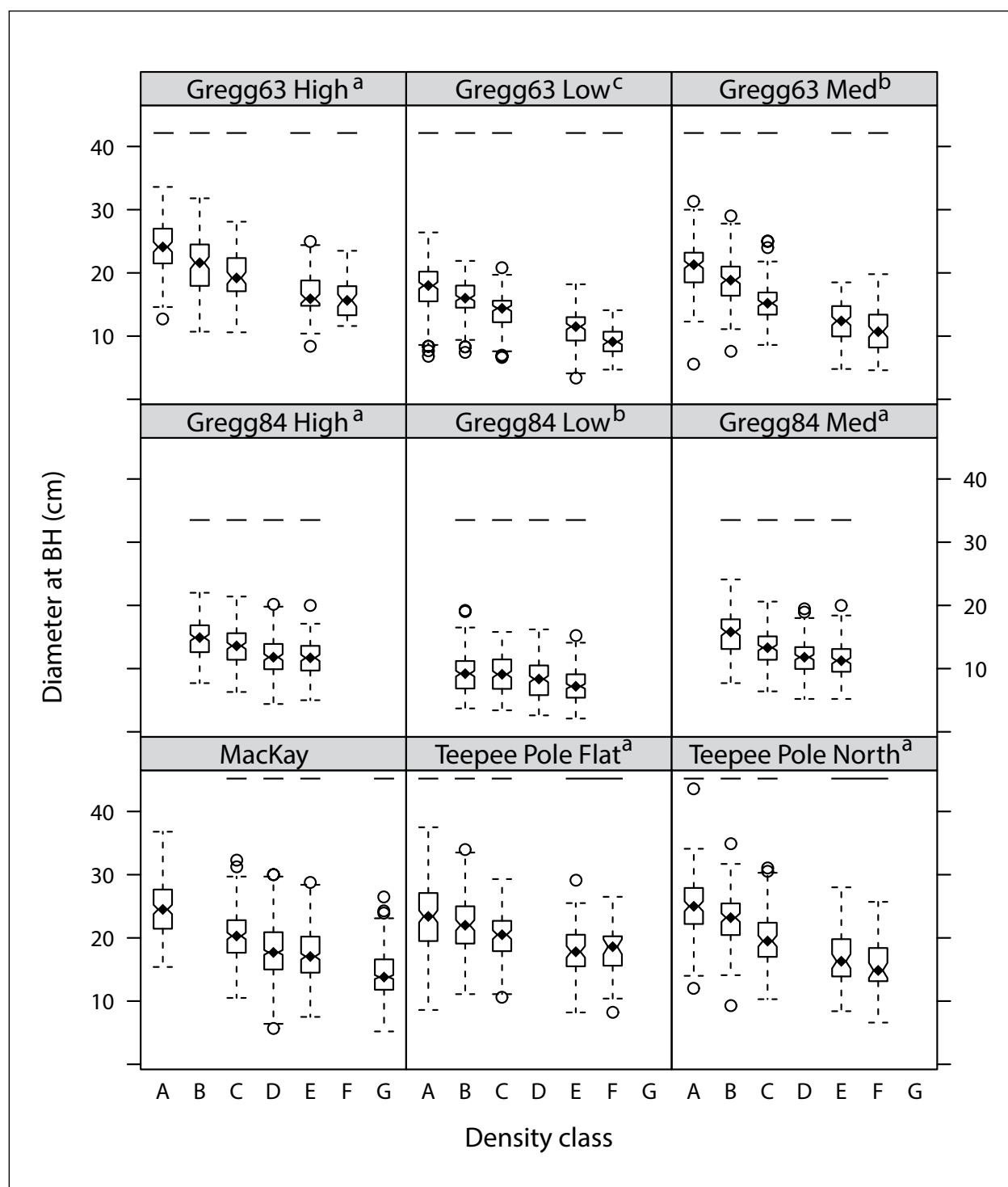


Figure 6. Diameter at breast height (BH) at latest measurement for four lodgepole pine precommercial thinning trials. Note that where notches overlap the means are not significantly different. Horizontal bars that overlap more than one treatment indicate that these treatments are not significantly different from each other at the 0.05 probability level, based on the Tukey-Kramer tests.

Table 7. Results of analysis of variance of the effect of site and density treatments on tree diameter at the latest measurement in four lodgepole pine precommercial thinning trials

Trial	Source	DF	Type III sum of squares	Mean squares	F value	Pr > F
Gregg63	Site	2	9 576.67	4 788.34	123.31	0.0013
	Block(site)	3	116.50	38.83	3.42	0.0167
	Density	4	19 098.54	4 774.64	219.65	<0.0001
	Site × density	8	448.39	56.05	2.58	0.0677
	Site × block × density(site)	12	260.85	21.74	1.91	0.0288
Gregg84	Site	2	10 387.43	5 193.71	648.49	<0.0001
	Block(site)	3	210.07	70.02	8.74	<0.0001
	Density	3	3 320.73	1 106.91	12.28	0.0016
	Site × density	6	522.71	87.12	0.97	0.4977
	Site × block × density(site)	9	811.56	90.17	11.26	<0.0001
Teepee Pole	Site	1	7.15	7.15	0.35	0.5547
	Block(site)	2	75.37	37.68	1.84	0.1593
	Density	4	6 435.53	1 608.88	67.76	<0.0001
	Site × density	4	343.03	85.76	3.61	0.0577
	Site × block × density(site)	8	189.94	23.74	1.16	0.3207
MacKay	Block	2	93.80	46.90	3.03	0.0486
	Density	4	15 076.79	3 769.20	85.37	<0.0001
	Block × density	6	264.90	44.15	2.85	0.0091

DF = degrees of freedom; Pr > F = the probability of getting by chance an F-value greater than the estimated value.

Table 8. Results of analysis of variance of the effect of site and density treatments on tree height at the latest measurement in four lodgepole pine precommercial thinning trials

Trial	Source	DF	Type III sum of squares	Mean squares	F value	Pr > F
Gregg63	Site	2	2 612 701	1 306 350	735.17	<0.0001
	Block(site)	3	5 330	1 776	0.80	0.4942
	Density	4	463 960	115 990	5.94	0.0071
	Site × density	8	225 488	28 186	1.44	0.2730
	Site × block × density(site)	12	234 237	19 519	8.78	<0.0001
Gregg84	Site	2	6 656 640	3 328 320	181.95	<0.0007
	Block(site)	3	54 877	18 292	13.69	<0.0001
	Density	3	109 949	36 649	1.03	0.4262
	Site × density	6	40 948	6 824	0.19	0.9716
	Site × block × density(site)	9	321 601	35 733	26.73	<0.0001
Teepee Pole	Site	1	63 108	63 108	11.43	0.0008
	Block(site)	2	85 620	42 810	7.75	0.0005
	Density	4	438 305	109 576	4.03	0.0445
	Site × density	4	297 217	74 304	2.73	0.1057
	Site × block × density(site)	8	217 688	27 211	4.93	<0.0001
MacKay	Block	2	411 994	205 997	29.04	<0.0001
	Density	4	5 560 142	1 390 035	9.61	0.0089
	Block × density	6	868 103	144 683	20.40	<0.0001

DF = degrees of freedom; Pr > F = the probability of getting by chance an F-value greater than the estimated value.

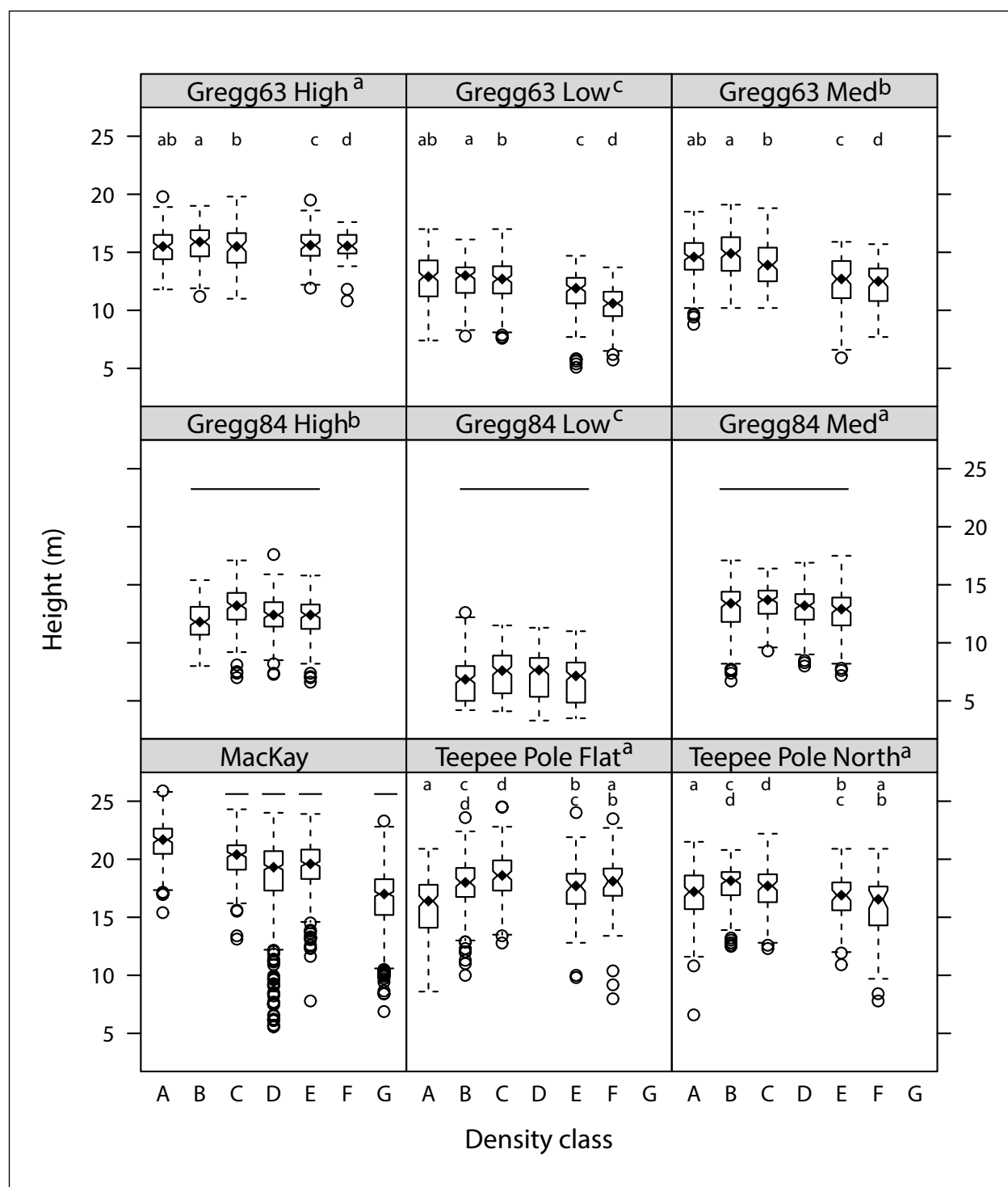


Figure 7. Height at latest measurement for four lodgepole pine precommercial thinning trials. See caption for Figure 6 for explanation of treatment design.

responded more strongly than height to changes in stand density (Figure 8, Tables 9 and A7). Trees with more growing space in the more open density treatments (A, B, and C) had HDR values mainly between 0.5 and 1.0, while those with more competition in the high density treatments (D, E, F, and G) had HDR values of about 1.0 and above.

Significant site effects were seen only in the Gregg84 trial, where there were small but significant increases in HDR from the low- to medium- to high-productivity sites.

Live Crown Ratio

Live crown ratio (LCR) generally decreased with increasing density, and with increasing site productivity, in the Gregg Burn and Teepee Pole Creek trials (Figure 9, Tables 10 and A8). Live crown ratios did not differ with slope aspect in the Teepee Pole Creek trial. Live crown ratios were lowest in the MacKay trial (mainly between 0.2 and 0.4) and were little affected by density treatments. Elsewhere, LCR values ranged from 0.3 to 0.6 or 0.7. In Gregg84, there was a significant interaction between the density treatment and site. In the low-productivity

site, the value of LCR in the C treatment did not differ from that in the B treatment, whereas the C treatment value was the same as that for the D treatment in the high-productivity site, and was intermediate between, and significantly different from, both B and D treatments in the medium-productivity site.

Piece Size

Piece size (i.e., merchantable volume per tree at the 13/7 standard) decreased significantly with increasing density in the Gregg63, MacKay, and Teepee Pole Creek trials (Figure 10, Tables 11 and A9). Density treatment had no significant effect on piece size in the Gregg84 trial, probably due to the small size of the trees this early in stand development, resulting in little merchantable volume in any of the treatments. In the D, E, and F density treatments, representing initial stand densities from about 3 000 to 8 000 stems per hectare, piece size did not differ in any of the trials. Significant differences in piece size were seen only among the A, B, and C treatments, representing initial densities from about 500 to 2 000 stems per hectare.

Table 9. Results of analysis of variance of the effect of site and density treatments on height–diameter ratio at the latest measurement in four lodgepole pine precommercial thinning trials

Trial	Source	DF	Type III sum of squares	Mean squares	F value	Pr > F
Gregg63	Site	2	0.1453	0.0727	76.80	<0.0001
	Block(site)	3	0.0285	0.0095	10.04	<0.0001
	Density	4	2.0032	0.5008	152.22	<0.0001
	Site × density	8	0.0292	0.0037	1.11	0.4202
	Site × block × density(site)	12	0.0395	0.0033	3.48	<0.0001
Gregg84	Site	2	0.6835	0.3418	360.30	<0.0001
	Block(site)	3	0.0022	0.0007	0.79	0.5009
	Density	3	1.1424	0.3808	110.52	<0.0001
	Site × density	6	0.0581	0.0097	2.81	0.0795
	Site × block × density(site)	9	0.0310	0.0034	3.63	0.0002
Teepee Pole	Site	1	0.0002	0.0002	0.16	0.6873
	Block(site)	2	0.0016	0.0008	0.69	0.5015
	Density	4	0.7628	0.1907	22.37	0.0002
	Site × density	4	0.0093	0.0023	0.27	0.8884
	Site × block × density(site)	8	0.0682	0.0085	7.49	<0.0001
MacKay	Block	2	0.0626	0.0313	21.71	<0.0001
	Density	4	0.2479	0.0620	5.77	0.0297
	Block × density	6	0.0645	0.0107	7.45	<0.0001

DF = degrees of freedom; Pr > F = the probability of getting by chance an F-value greater than the estimated value.

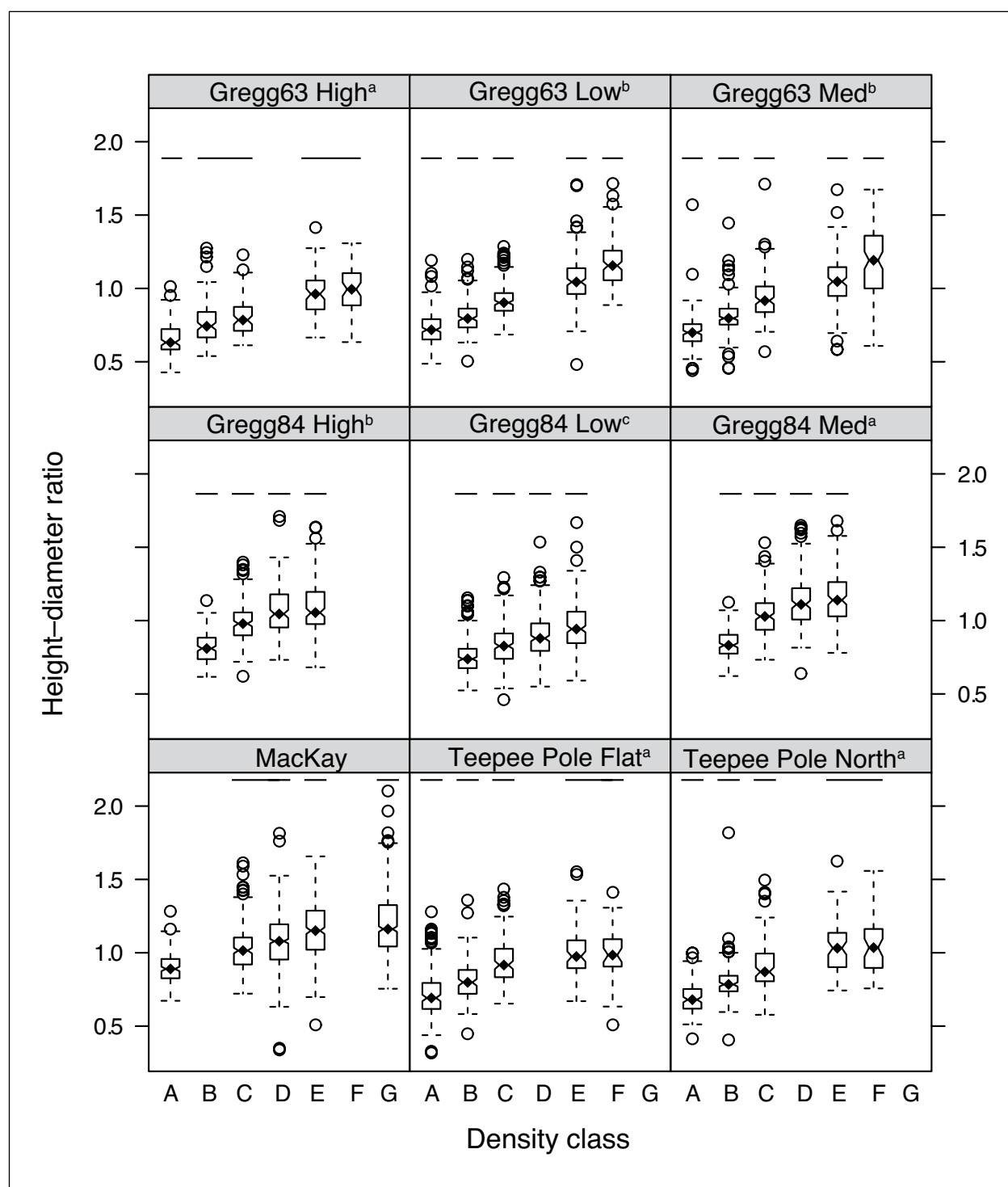


Figure 8. Height-diameter ratio at latest measurement for four lodgepole pine precommercial thinning trials. See caption for Figure 6 for explanation of treatment design.

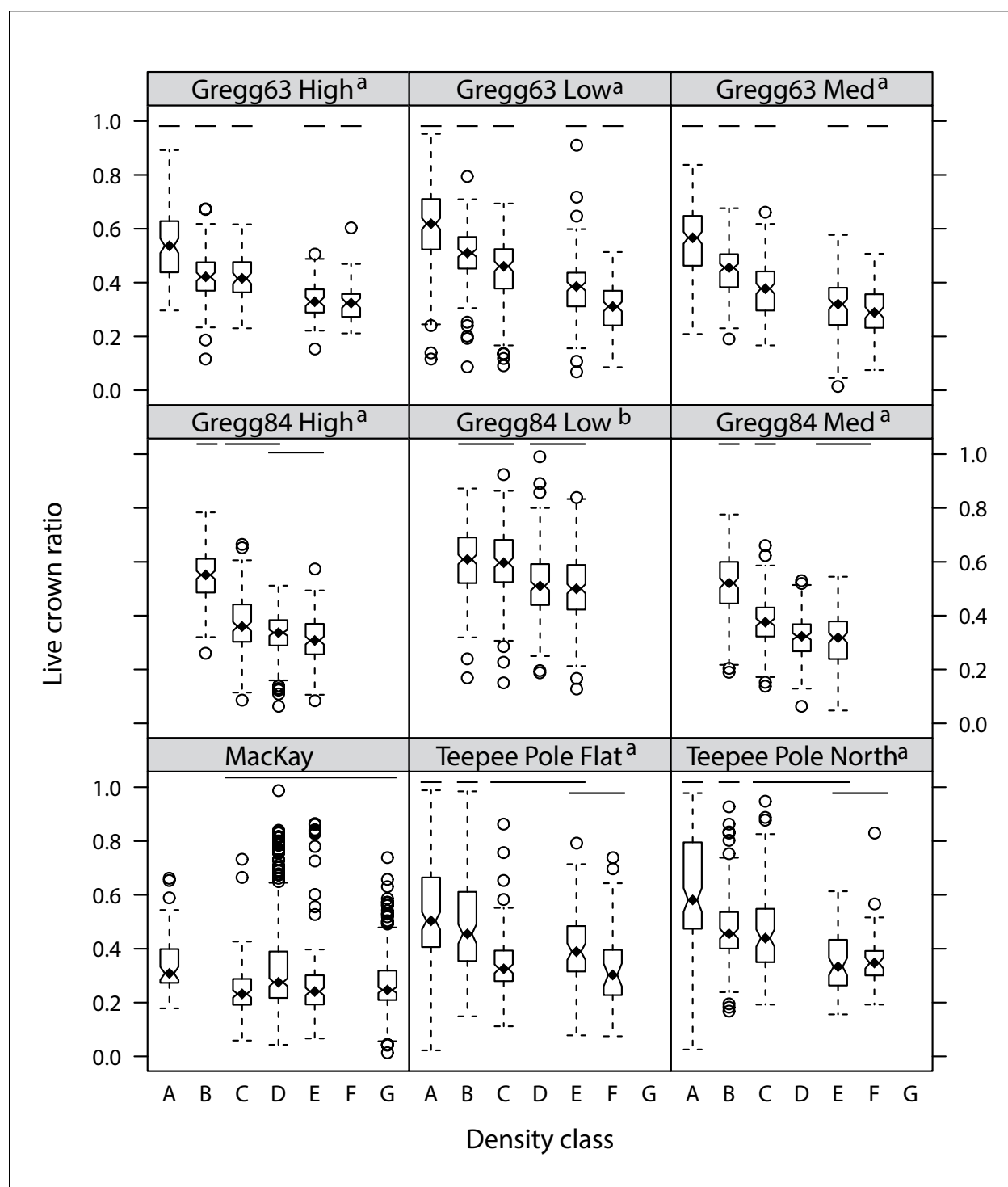


Figure 9. Live crown ratio at latest measurement for four lodgepole pine precommercial thinning trials. See caption for Figure 6 for explanation of treatment design.

Table 10. Results of analysis of variance of the effect of site and density treatments on live crown ratio at the latest measurement in four lodgepole pine precommercial thinning trials

Trial	Source	DF	Type III sum of squares	Mean squares	F value	Pr > F
Gregg63	Site	2	0.0961	0.0481	47.85	<0.0001
	Block(site)	3	0.0530	0.0177	17.60	<0.0001
	Density	4	1.3903	0.3476	36.36	<0.0001
	Site × density	8	0.0449	0.0056	0.59	0.7708
	Site × block × density(site)	12	0.1147	0.0096	9.52	<0.0001
Gregg84	Site	2	1.3643	0.6821	660.51	<0.0001
	Block(site)	3	0.0553	0.0184	17.86	<0.0001
	Density	3	1.0033	0.3344	80.41	<0.0001
	Site × density	6	0.1919	0.0320	7.69	0.0039
	Site × block × density(site)	9	0.0374	0.0042	4.03	<0.0001
Teepee Pole	Site	1	0.0248	0.0248	13.09	0.0003
	Block(site)	2	0.1120	0.0560	29.55	<0.0001
	Density	4	0.5948	0.1487	12.85	0.0015
	Site × density	4	0.1110	0.0278	2.40	0.1360
	Site × block × density(site)	8	0.0926	0.0116	6.11	<0.0001
MacKay	Block	2	0.1265	0.0633	40.85	<0.0001
	Density	4	0.1198	0.0300	0.88	0.5282
	Block × density	6	0.2043	0.0341	21.99	<0.0001

DF = degrees of freedom; Pr > F = the probability of getting by chance an F-value greater than the estimated value.

Table 11. Results of analysis of variance of the effect of site and density treatments on piece size at the latest measurement in four lodgepole pine precommercial thinning trials

Trial	Source	DF	Type III sum of squares	Mean squares	F value	Pr > F
Gregg63	Site	2	4.9431	2.4716	102.32	0.0017
	Block(site)	3	0.0106	0.0035	4.53	0.0036
	Density	4	0.9502	0.2376	143.10	<0.0001
	Site × density	8	0.0400	0.0050	3.01	0.0420
	Site × block × density(site)	12	0.0199	0.0017	2.13	0.0128
Gregg84	Site	2	0.2992	0.1496	456.27	<0.0001
	Block(site)	3	0.0030	0.0010	3.10	0.0259
	Density	3	0.0958	0.0319	5.91	0.0164
	Site × density	6	0.0448	0.0075	1.38	0.3179
	Site × block × density(site)	9	0.0486	0.0054	16.48	<0.0001
Teepee Pole	Site	1	0.0015	0.0015	0.69	0.4050
	Block(site)	2	0.0138	0.0069	3.18	0.0421
	Density	4	0.3641	0.0910	46.20	<0.0001
	Site × density	4	0.0526	0.0131	6.67	0.0116
	Site × block × density(site)	8	0.0158	0.0020	0.90	0.5118
MacKay	Block	2	0.3334	0.1667	6.78	0.0012
	Density	4	12.7060	3.1765	36.06	<0.0001
	Block × density	6	0.5286	0.0881	3.58	0.0016

DF = degrees of freedom; Pr > F = the probability of getting by chance an F-value greater than the estimated value.

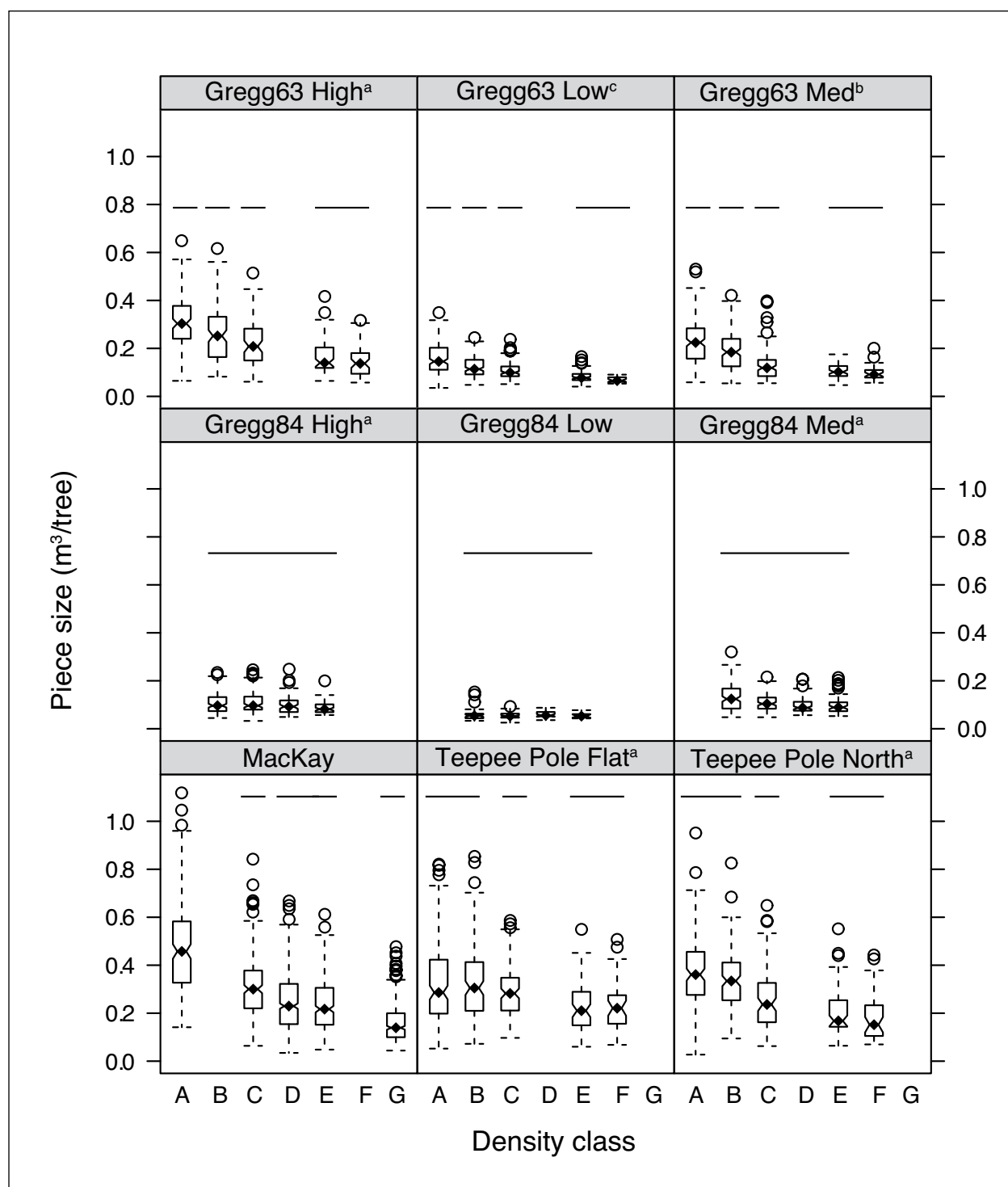


Figure 10. Piece size of merchantable trees (13/7 standard) at latest measurement for four lodgepole pine precommercial thinning trials. See caption for Figure 6 for explanation of treatment design.

Stand-Level Properties

The results reported in this section are closely related to the diameter and height variables reported above, and are included because they are commonly used in growth and yield analysis. Note that the height and diameter variables reported above were means of all trees in the treatment, whereas these variables are the means of plot-level values, averaged across two or three blocks.

Quadratic Mean Diameter

As with DBH, quadratic mean diameter was sensitive to site productivity and density treatment (Figure 11, Tables 12 and A10). The values of the arithmetic means and the quadratic means differed little in these stands.

Top Height

Top height was calculated from a subsample of the trees with the largest diameter in each plot. The number of trees included was determined by plot size, and therefore the sample size was very small (and the estimate less precise) in the smallest area plots (Figure 12, Tables 13 and A11). As expected, top height reflected site productivity, although not slope aspect, and was not significantly different among density treatments. Most top heights were from 13 m to 23 m, except for the Gregg84 low-productivity site, where top heights in all treatments were about 10 m or less.

Stand Yield

Basal Area

Basal area (BA) more strongly reflected the effect of stand density than of tree size, increasing with increasing density treatments (Figure 13, Tables 14 and A12). However, mean BA reflects the small tree size in the low-productivity site of the Gregg84 trial, where the BA in all plots is low (7–23 m²/ha) compared with other sites where the lowest values are about 12 m²/ha and the highest about 35 m²/ha. Basal area in other trials ranged as high as 40–50 m²/ha, and, in the case of the Gregg63 high-productivity site, exceeded 50 m²/ha.

Total Volume

Stand total volume was very similar to basal area but also reflected differences in height (Figure 14, Tables 15 and A13). Total volume ranged from 100 to 300 or 400 m³/ha in the Gregg63 and Teepee Pole Creek trials, but did not exceed 250 m³/ha in the Gregg84 trial. Total volume was higher in the MacKay trial, which also had the highest total volume for the A and C treatments (300 and 332 m³/ha, respectively). Total volume increased with increasing density treatment, as did BA, but there was some inconsistency among blocks, and there was no significant difference among the density treatments in the MacKay trial.

Merchantable Volume

The higher-productivity sites in the Gregg63, Teepee Pole Creek, and MacKay trials produced at best between 300 and 400 m³/ha of merchantable volume at the 13/7 standard (Figure 15, Tables 16 and A14). The lower-productivity sites in Gregg63 and all of Gregg84 produced less than half that volume. Slope aspect had no significant influence on merchantable volume.

The interaction between site and density in the Gregg63 trial resulted from an increase in merchantable volume with stand density treatment in the faster-growing high-productivity site, whereas, in the medium- and low-productivity sites, the trees had not yet grown large enough to create much merchantable volume in the higher-density treatments (E and F).

Merchantable volume at the 15/10 standard showed the same effects and patterns of significance as merchantable volume at the 13/7 standard, but the declines in volume at higher densities, in stands where the trees were still small, was exacerbated by the larger threshold of the merchantability standard (Figure 16, Tables 17 and A15). The top values of volume were still 300–400 m³/ha, but the lowest values were at or near zero in some cases.

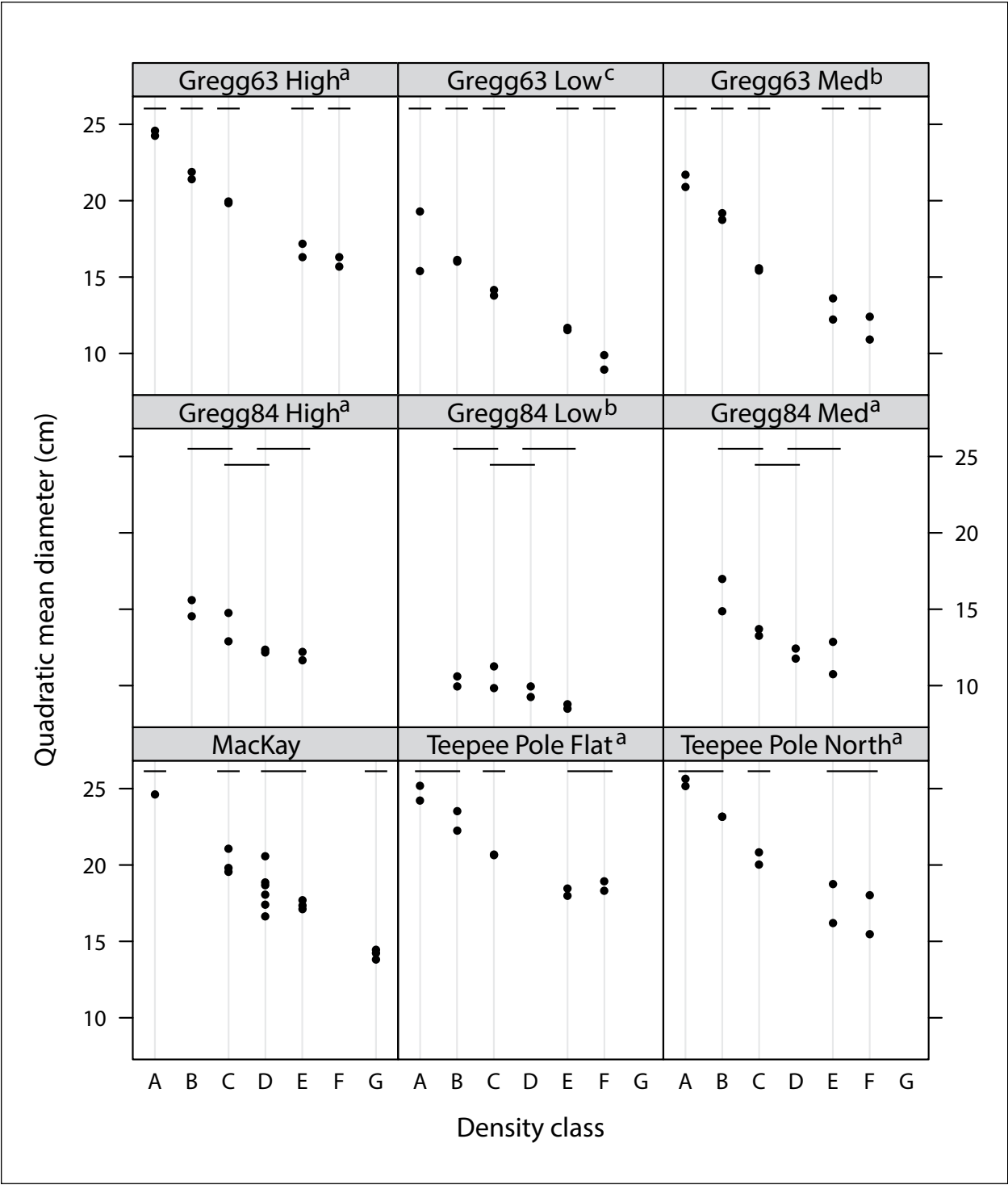


Figure 11. Quadratic mean diameter at latest measurement for four lodgepole pine precommercial thinning trials. See caption for Figure 2 for explanation of treatment design.

Table 12. Results of analysis of variance of the effect of site and density treatments on quadratic mean diameter at the latest measurement in four lodgepole pine precommercial thinning trials

Trial	Source	DF	Type III sum of squares	Mean squares	F value	Pr > F
Gregg63	Site	2	182.2011	91.1006	161.87	0.0009
	Block(site)	3	1.6884	0.5628	1.71	0.2184
	Density	4	320.5933	80.1483	243.15	<0.0001
	Site × density	8	5.7993	0.7249	2.20	0.1056
Gregg84	Site	2	94.9172	47.4586	74.48	0.0028
	Block(site)	3	1.9115	0.6372	0.67	0.5906
	Density	3	34.6976	11.5659	12.19	0.0016
	Site × density	6	5.1983	0.8664	0.91	0.5265
Teepee Pole	Site	1	0.1901	0.1901	0.18	0.7155
	Block(site)	2	2.1582	1.0791	1.27	0.3314
	Density	4	152.0163	38.0041	44.79	<0.0001
	Site × density	4	6.6796	1.6699	1.97	0.1925
MacKay	Block	2	1.4150	0.7075	1.06	0.3847
	Density	4	98.2461	24.5615	36.94	<0.0001

DF = degrees of freedom; Pr > F = the probability of getting by chance an F-value greater than the estimated value.

Table 13. Results of analysis of variance of the effect of site and density treatments on top height at the latest measurement in four lodgepole pine precommercial thinning trials

Trial	Source	DF	Type III sum of squares	Mean squares	F value	Pr > F
Gregg63	Site	2	39.2866	19.6433	50.04	0.0050
	Block(site)	3	1.1778	0.3926	0.37	0.7755
	Density	4	12.7036	3.1759	3.00	0.0625
	Site × density	8	10.1534	1.2692	1.20	0.3747
Gregg84	Site	2	135.8911	67.9456	351.69	0.0003
	Block(site)	3	0.5796	0.1932	0.26	0.8556
	Density	3	1.7891	0.5964	0.79	0.5300
	Site × density	6	1.6403	0.2734	0.36	0.8858
Teepee Pole	Site	1	1.2567	1.2567	0.35	0.6139
	Block(site)	2	7.1721	3.5860	2.52	0.1415
	Density	4	7.5779	1.8945	1.33	0.3373
	Site × density	4	2.7500	0.6875	0.48	0.7481
MacKay	Block	2	3.2162	1.6081	4.34	0.0479
	Density	4	8.0032	2.0008	5.40	0.0169

DF = degrees of freedom; Pr > F = the probability of getting by chance an F-value greater than the estimated value.

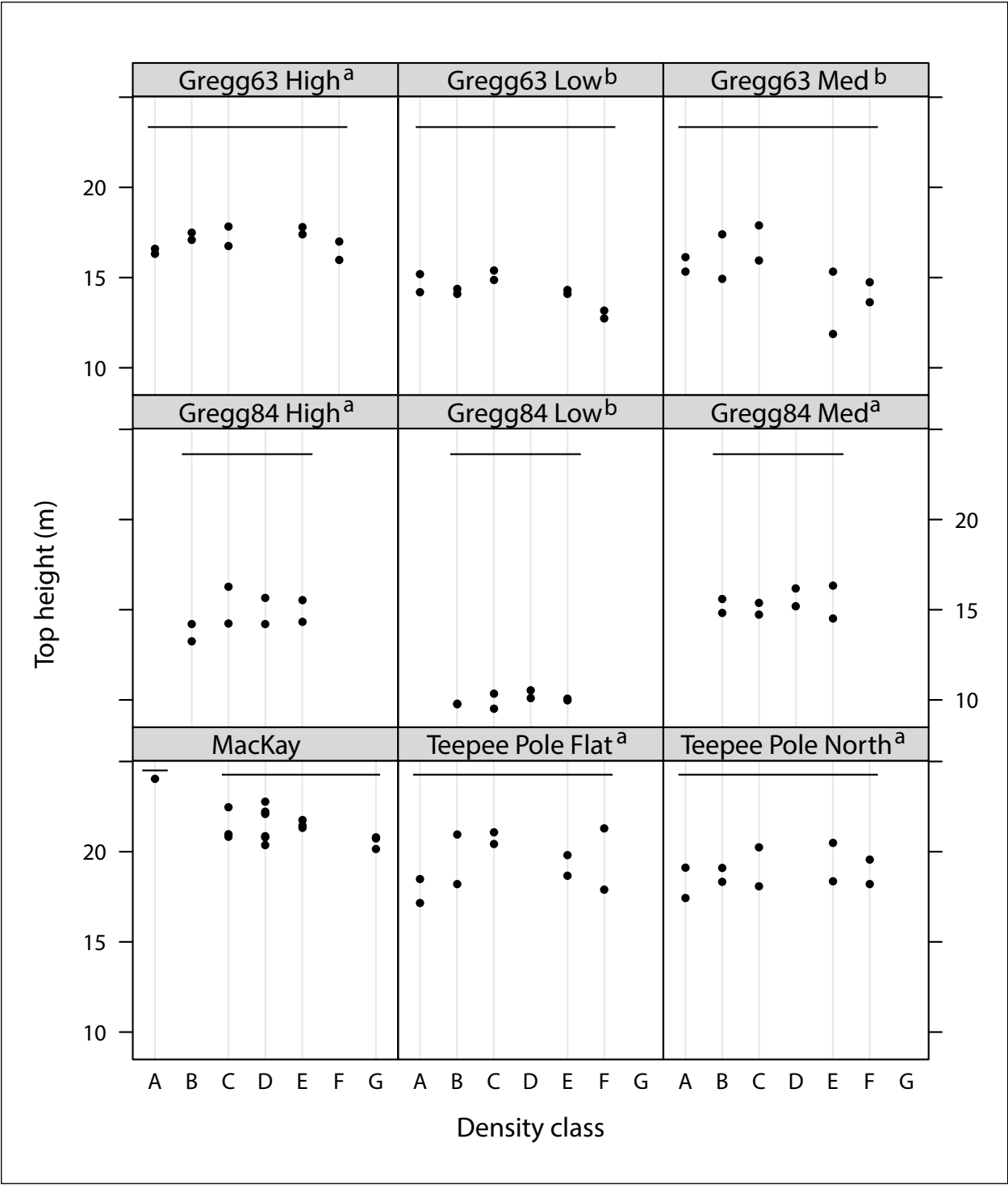


Figure 12. Top height at latest measurement for four lodgepole pine precommercial thinning trials. See caption for Figure 2 for explanation of treatment design.

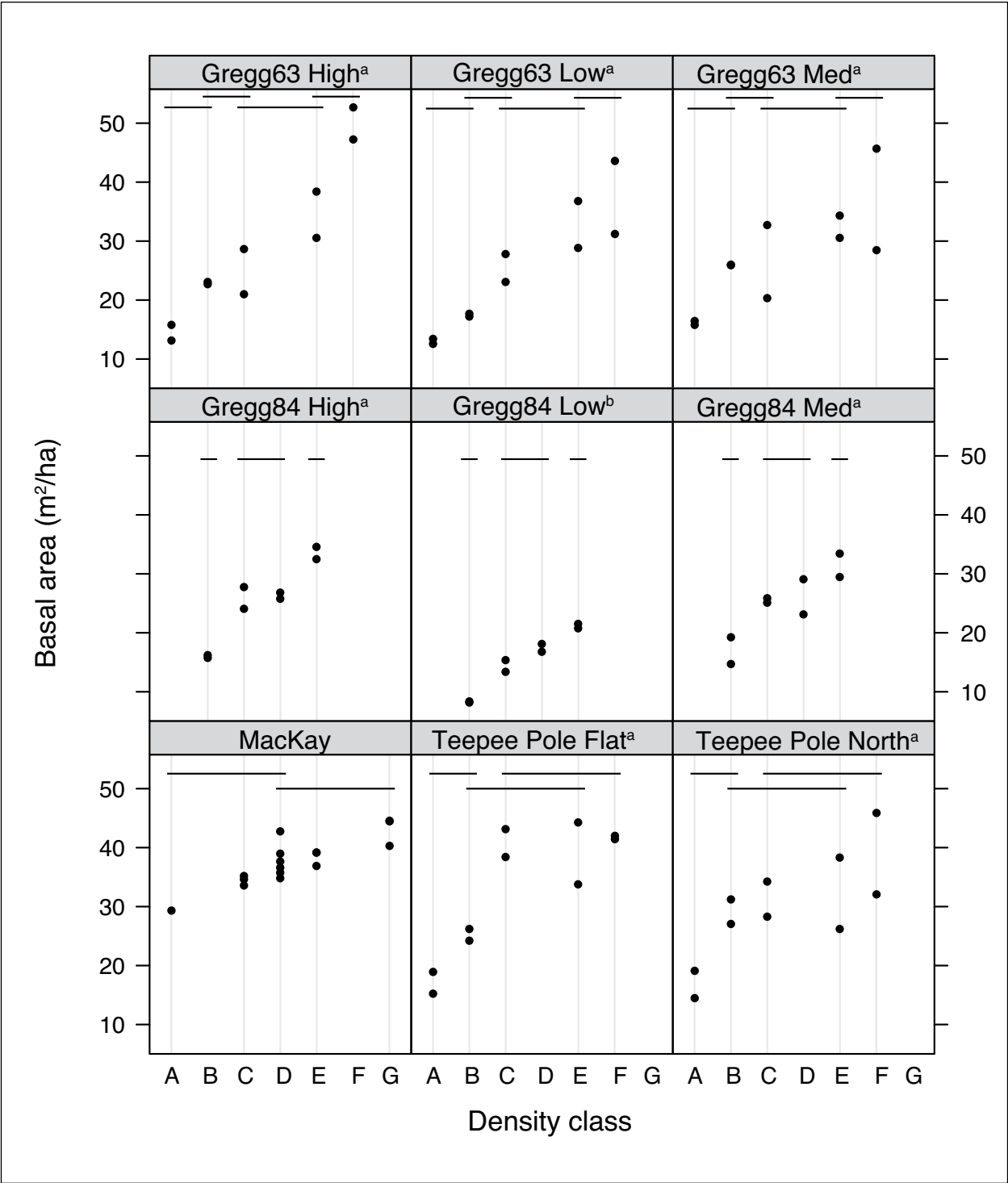


Figure 13. Basal area at latest measurement for four lodgepole pine precommercial thinning trials. See caption for Figure 2 for explanation of treatment design.

Table 14. Results of analysis of variance of the effect of site and density treatments on basal area at the latest measurement in four lodgepole pine precommercial thinning trials

Trial	Source	DF	Type III sum of squares	Mean squares	F value	Pr > F
Gregg63	Site	2	65.43	32.72	0.91	0.4917
	Block(site)	3	108.10	36.03	1.48	0.2703
	Density	4	2 519.89	629.97	25.83	<0.0001
	Site × density	8	163.94	20.49	0.84	0.5862
Gregg84	Site	2	451.53	225.76	83.31	0.0024
	Block(site)	3	8.13	2.71	0.68	0.5882
	Density	3	767.69	255.90	63.84	<0.0001
	Site × density	6	10.51	1.75	0.44	0.8371
Teepee Pole	Site	1	51.28	51.28	1.45	0.3523
	Block(site)	2	70.96	35.48	1.36	0.3103
	Density	4	1 342.19	335.55	12.86	0.0015
	Site × density	4	102.40	25.60	0.98	0.4695
MacKay	Block	2	49.69	24.85	3.81	0.0631
	Density	4	146.12	36.53	5.61	0.0151

DF = degrees of freedom; Pr > F = the probability of getting by chance an F-value greater than the estimated value.

Table 15. Results of analysis of variance of the effect of site and density treatments on total stand volume at the latest measurement in four lodgepole pine precommercial thinning trials

Trial	Source	DF	Type III sum of squares	Mean squares	F value	Pr > F
Gregg63	Site	2	20 035	10 017	5.31	0.1035
	Block(site)	3	5 664	1 888	1.22	0.3453
	Density	4	106 102	26 525	17.12	<0.0001
	Site × density	8	17 552	2 194	1.42	0.2830
Gregg84	Site	2	53 809	26 904	137.47	0.0011
	Block(site)	3	587	195	0.47	0.7088
	Density	3	27 944	9 314	22.50	0.0002
	Site × density	6	2 363	393	0.95	0.5056
Teepee Pole	Site	1	6 535	6 535	3.94	0.1857
	Block(site)	2	3 320	1 660	0.76	0.4993
	Density	4	112 486	28 121	12.85	0.0015
	Site × density	4	10 775	2 693	1.23	0.3707
MacKay	Block	2	614	307	0.50	0.6228
	Density	4	3 842	960	1.56	0.2655

DF = degrees of freedom; Pr > F the probability of getting by chance an F-value greater than the estimated value.

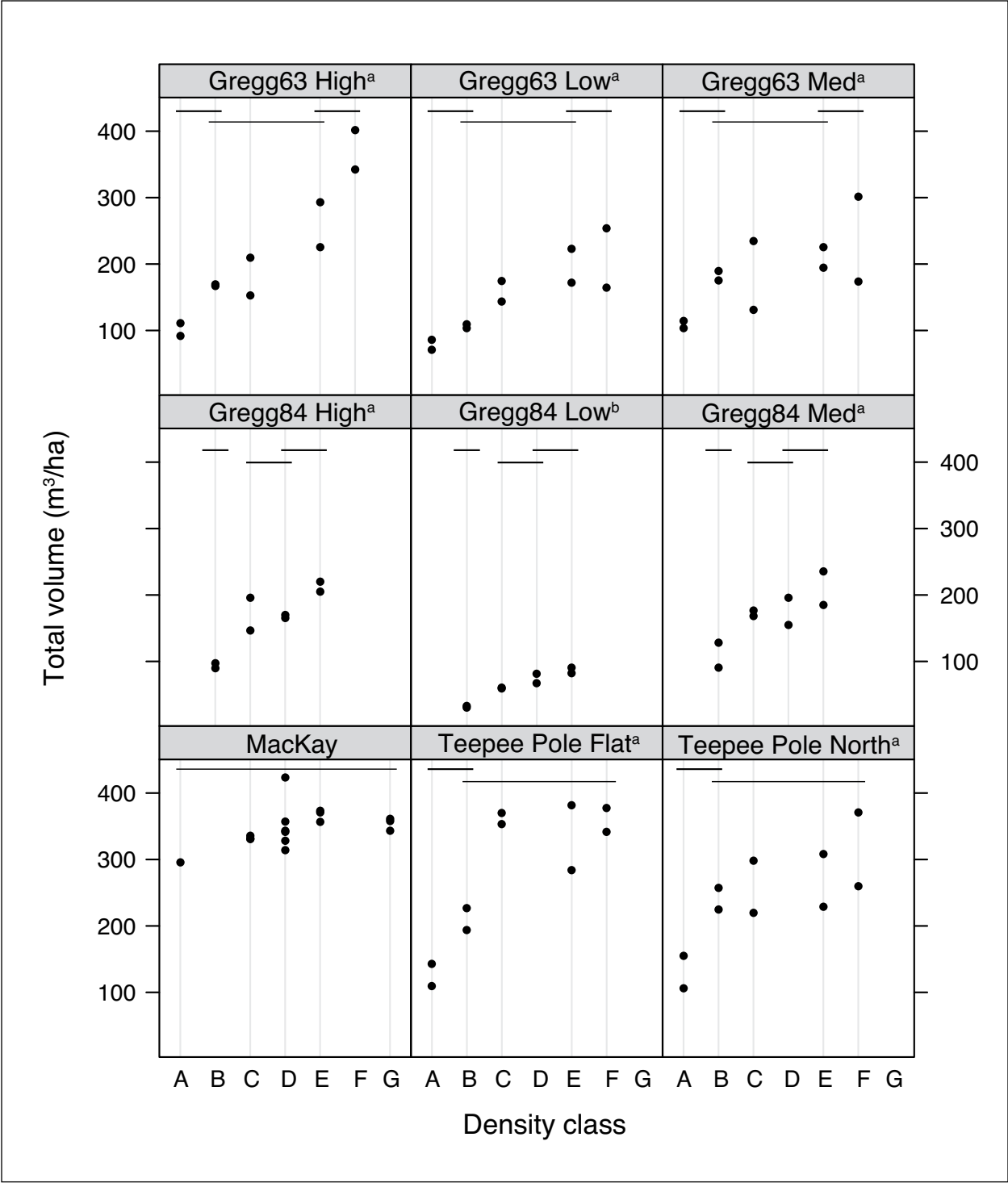


Figure 14. Total volume at latest measurement for four lodgepole pine precommercial thinning trials. See caption for Figure 2 for explanation of treatment design.

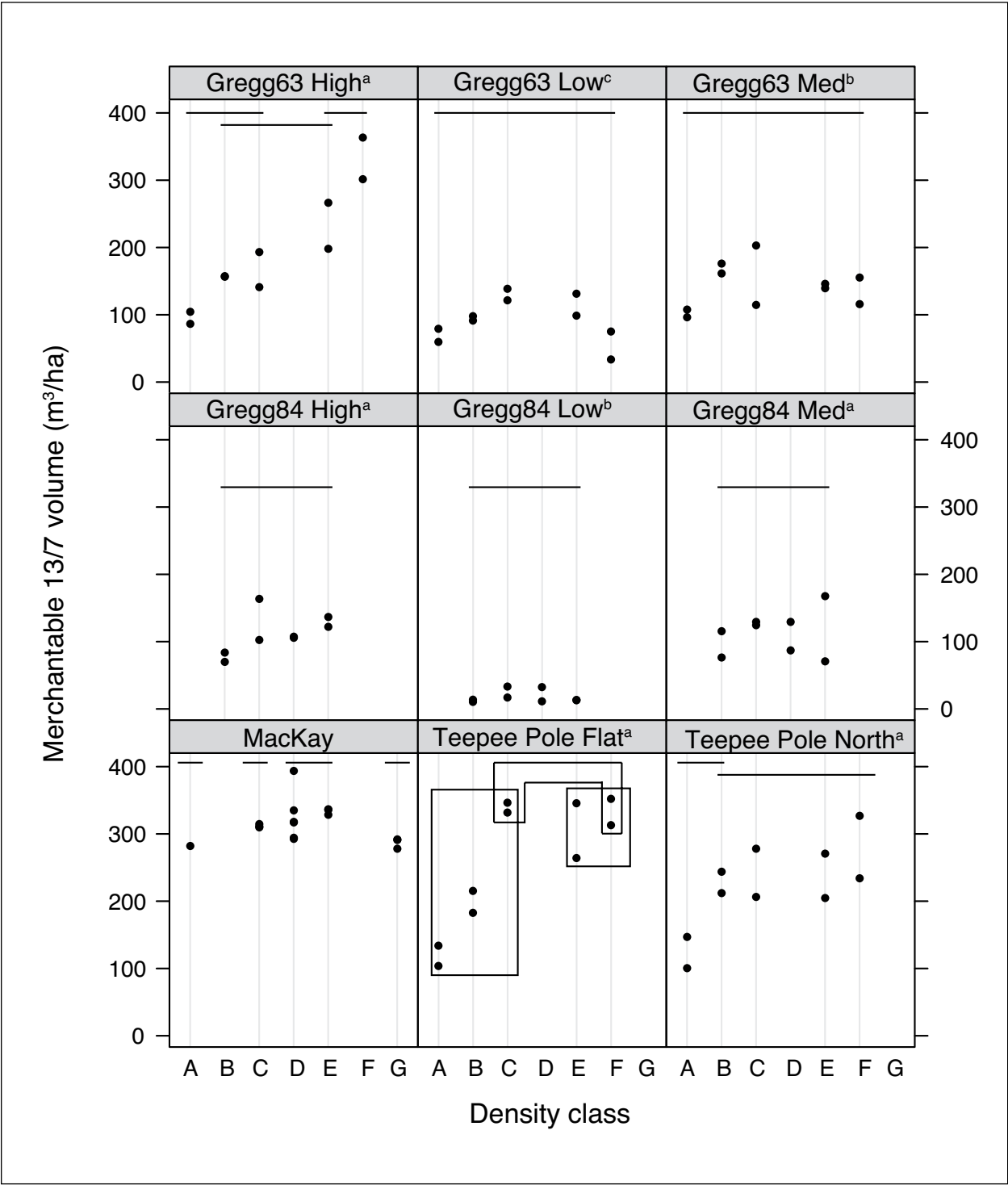


Figure 15. Merchantable volume (13/7 standard) at latest measurement for four lodgepole pine precommercial thinning trials. See caption for Figure 2 for explanation of treatment design.

Table 16. Results of analysis of variance of the effect of site and density treatments on merchantable volume (13/7 standard) at the latest measurement in four lodgepole pine precommercial thinning trials

Trial	Source	DF	Type III sum of squares	Mean squares	F value	Pr > F
Gregg63	Site	2	52 250	26 125	85.65	0.0023
	Block(site)	3	915	305	0.35	0.7914
	Density	4	25 637	6 409	7.31	0.0032
	Site × density	8	49 379	6 172	7.04	0.0015
Gregg84	Site	2	47 998	23 999	95.18	0.0019
	Block(site)	3	756	252	0.27	0.8436
	Density	3	3 730	1 243	1.35	0.3200
	Site × density	6	1 667	277	0.30	0.9214
Teepee Pole	Site	1	6 794	6 794	5.66	0.1404
	Block(site)	2	2 400	1 200	0.72	0.5180
	Density	4	89 718	22 429	13.36	0.0013
	Site × density	4	10 208	2 552	1.52	0.2841
MacKay	Block	2	224	112	0.23	0.8013
	Density	4	2 591	647	1.31	0.3364

DF = degrees of freedom; Pr > F = the probability of getting by chance an F-value greater than the estimated value.

Table 17. Results of analysis of variance of the effect of site and density treatments on merchantable volume (15/10 standard) at the latest measurement in four lodgepole pine precommercial thinning trials

Trial	Source	DF	Type III sum of squares	Mean squares	F value	Pr > F
Gregg63	Site	2	61 016	30 508	161.45	0.0009
	Block(site)	3	566	188	0.27	0.8469
	Density	4	7 227	1 806	2.57	0.0922
	Site × density	8	37 356	4 669	6.63	0.0020
Gregg84	Site	2	21 928	10 964	37.99	0.0074
	Block(site)	3	865	288	0.43	0.7396
	Density	3	1 660	553	0.82	0.5169
	Site × density	6	1 270	211	0.31	0.9151
Teepee Pole	Site	1	7 960	7 960	7.30	0.1141
	Block(site)	2	2 181	1 090	1.01	0.4051
	Density	4	65 396	16 349	15.19	0.0008
	Site × density	4	10 772	2 693	2.50	0.1254
MacKay	Block	2	211	105	0.24	0.7949
	Density	4	10 718	2 679	5.98	0.0125

DF = degrees of freedom; Pr > F = the probability of getting by chance an F-value greater than the estimated value.

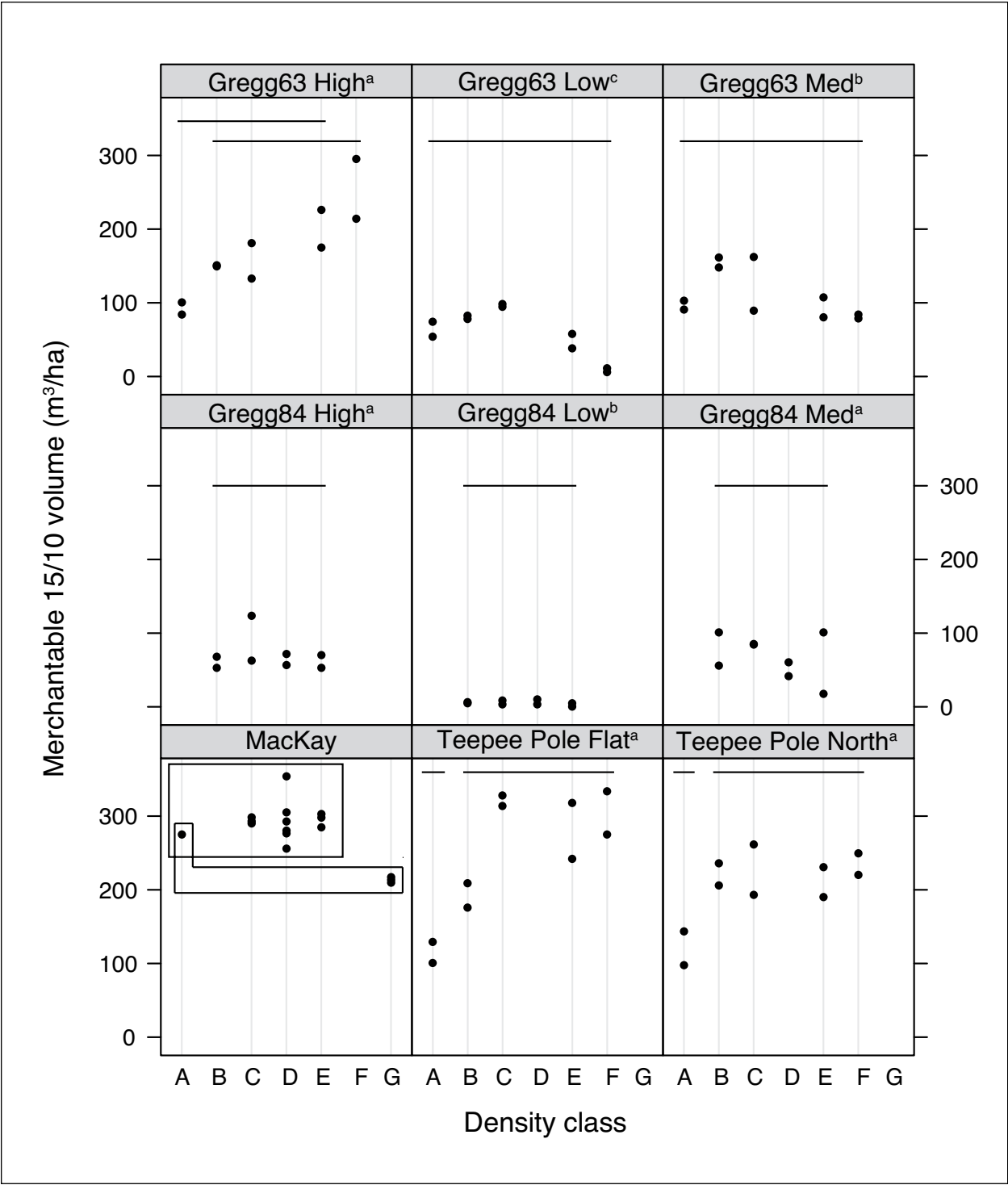


Figure 16. Merchantable volume (15/10 standard) at latest measurement for four lodgepole pine precommercial thinning trials. See caption for Figure 2 for explanation of treatment design.

Mean Annual Increment of Total Volume

Visual inspection of mean annual increment (MAI) of total volume shows that the Gregg84 trial is still in its mid-rotation phase, while the other trials are nearing their rotation age, at least for some of the density treatments (Figure 17, Tables 18 and A16). The MAI for each treatment in Gregg84 shows a consistently rising trend, regardless of site or density. Although the Gregg84 trial is the same stand age as the Gregg63 trial, the density treatments were applied later in the Gregg84 trial, and the stands have had two decades less to respond to the differences in density. The lower-density treatments in the other trials also seem to be in a similar mid-rotation phase, with the exception of the Gregg63 high-productivity site, where the MAI seems to be starting to plateau. Volume MAI also appears to be approaching or have reached a plateau in the higher-density treatments of the MacKay and Gregg63 trials. The higher-density treatments of the Teepee Pole Creek trial show MAI declining in the past few measurements, indicating that the stands have passed their optimal rotation age.

In the last measurement interval, MAI was significantly affected by site productivity in the Gregg84 trial, with higher MAI in the higher-productivity sites. MAI was also significantly affected by density treatment in the Gregg and Teepee Pole Creek trials, where MAI increased with increasing stand density at establishment. In some cases, MAI for plots of adjacent treatment levels have followed the same trajectory over the decades (e.g., Gregg63 and Gregg84 trials), and in other cases the MAI started at different values and have converged over time (MacKay and Teepee Pole Creek trials).

Mean Annual Increment of Merchantable Volume

Mean annual increment of merchantable volume based on the 13/7 standard shows most of the same influences as MAI of total volume. However, there is one major difference: with respect to merchantability, all of the stands are in an earlier

phase of stand development (Figure 18, Tables 19 and A17). With only a few exceptions, the MAI is rising in all trials, with little or no indication of slowing. Only the two highest-density treatments in the Teepee Pole Creek trial suggest that MAI has reached a plateau.

As with total volume MAI, merchantable volume MAI was significantly affected by site productivity; however, it was affected by density treatment only in the Gregg63 and Teepee Pole Creek trials. Only in the Gregg63 high-productivity site was there a consistent linear increase in MAI with increasing density treatment, whereas it was at maximum in the intermediate-density treatments in the other two sites, which accounts for the significant site \times density interaction term for the Gregg63 trial. There were only two significantly different levels of MAI in the Teepee Pole Creek trial: one for the A and B treatments, and the other spanning all of the remaining treatments. MAI values ranged from 2 to 6 m³/ha per year in most treatments, except for the Gregg84 low-productivity site, where very few trees in any treatment were large enough to have any merchantable volume.

Trends in MAI of merchantable volume based on the 15/10 standard were similar to those in MAI based on the 13/7 standard, being affected by both site productivity and by density treatment, although the latter was not significant in the Gregg84 trial (Figure 19, Tables 20 and A18). Differences observed arise from the fact that the trees are in an earlier part of their development of merchantable volume at this larger standard. Most treatments are following more or less the same trajectory within each site, except for the most extreme treatments; namely, the A treatment and the unthinned controls (G treatment). Only in the Gregg63 high-productivity site and the Teepee Pole Creek flat site do the different treatments follow different trajectories of development of merchantable volume. The interaction effect seen in the Gregg63 trial for the 15/10 standard is the same as for the 13/7 merchantable volume MAI.

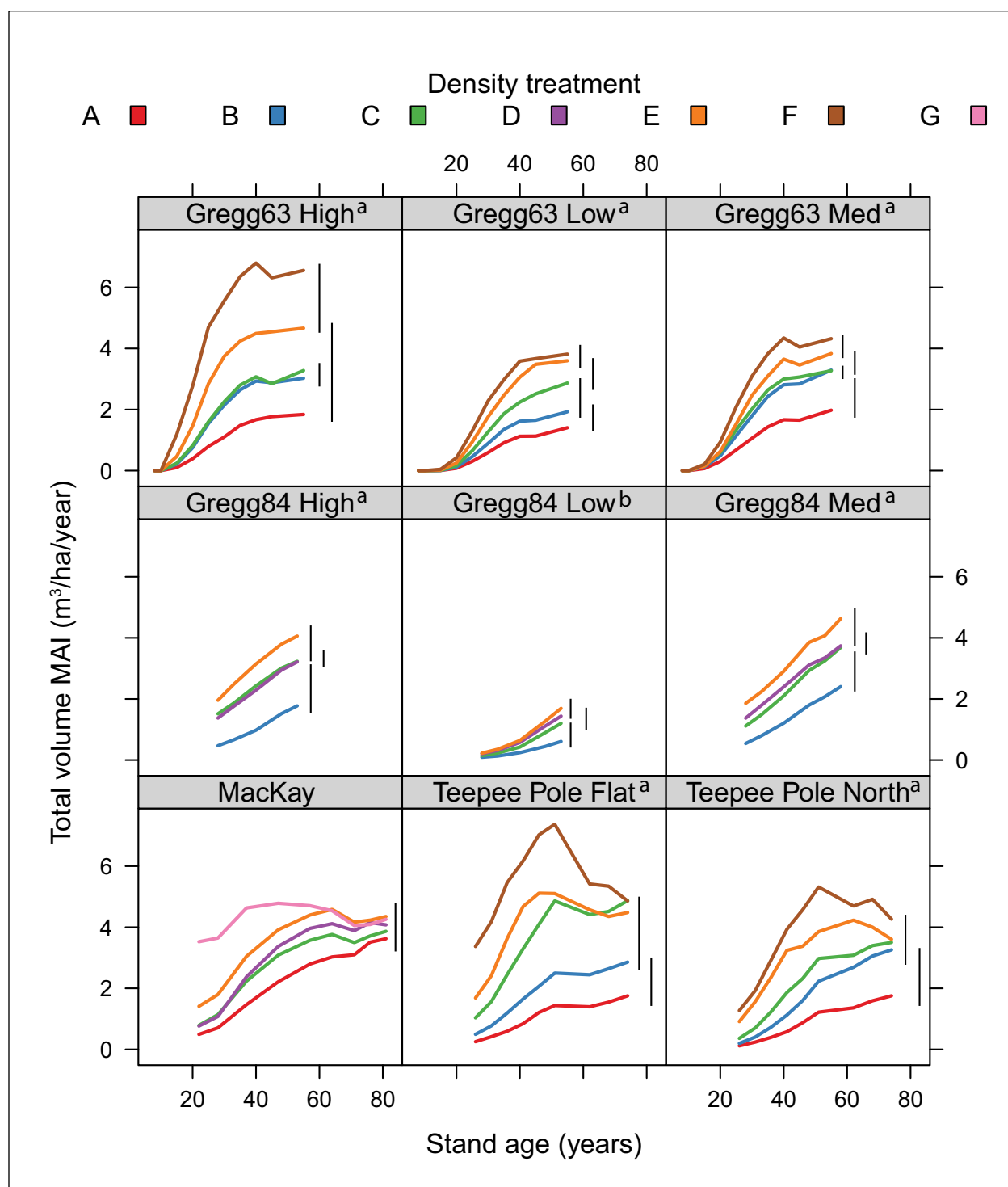


Figure 17. Mean annual increment (MAI) for total volume for four lodgepole pine precommercial thinning trials.

Table 18. Results of analysis of variance of the effect of site and density treatments on mean annual increment of total stand volume over time in four lodgepole pine precommercial thinning trials

Trial	Source	DF	Type III sum of squares	Mean squares	F value	Pr > F
Gregg63	Site	2	0.3555	0.1778	5.66	0.0958
	Block(site)	3	0.0941	0.0314	1.16	0.3667
	Density	4	2.0220	0.5055	18.62	<0.0001
	Site × density	8	0.2532	0.0316	1.17	0.3912
Gregg84	Site	2	1.5150	0.7575	154.60	0.0009
	Block(site)	3	0.0147	0.0049	0.56	0.6523
	Density	3	0.7450	0.2483	28.58	<0.0001
	Site × density	6	0.0270	0.0045	0.52	0.7818
Teepee Pole	Site	1	0.0568	0.0568	4.12	0.1795
	Block(site)	2	0.0276	0.0138	0.63	0.5585
	Density	4	1.2659	0.3165	14.39	0.0010
	Site × density	4	0.1013	0.0253	1.15	0.3994
MacKay	Block	2	0.0083	0.0041	1.18	0.3689
	Density	4	0.0262	0.0065	1.87	0.2356

DF = degrees of freedom; Pr > F = the probability of getting by chance an F-value greater than the estimated value.

Table 19. Results of analysis of variance of the effect of Site and Density treatments on mean annual increment of merchantable volume (13/7 standard) over time in four lodgepole pine precommercial thinning trials

Trial	Source	DF	Type III sum of squares	Mean squares	F value	Pr > F
Gregg63	Site	2	1.1272	0.5636	86.18	0.0022
	Block(site)	3	0.0196	0.0065	0.34	0.7952
	Density	4	0.5362	0.1341	7.02	0.0037
	Site × density	8	0.9292	0.1161	6.08	0.0029
Gregg84	Site	2	1.9649	0.9824	115.73	0.0014
	Block(site)	3	0.0255	0.0085	0.32	0.8110
	Density	3	0.1184	0.0395	1.49	0.2831
	Site × density	6	0.0470	0.0078	0.30	0.9243
Teepee Pole	Site	1	0.0628	0.0628	5.81	0.1375
	Block(site)	2	0.0216	0.0108	0.59	0.5768
	Density	4	1.0719	0.2680	14.63	0.0009
	Site × density	4	0.1016	0.0254	1.39	0.3210
MacKay	Block	2	0.0046	0.0023	1.05	0.4074
	Density	4	0.0194	0.0049	2.22	0.1831

DF = degrees of freedom; Pr > F = the probability of getting by chance an F-value greater than the estimated value.

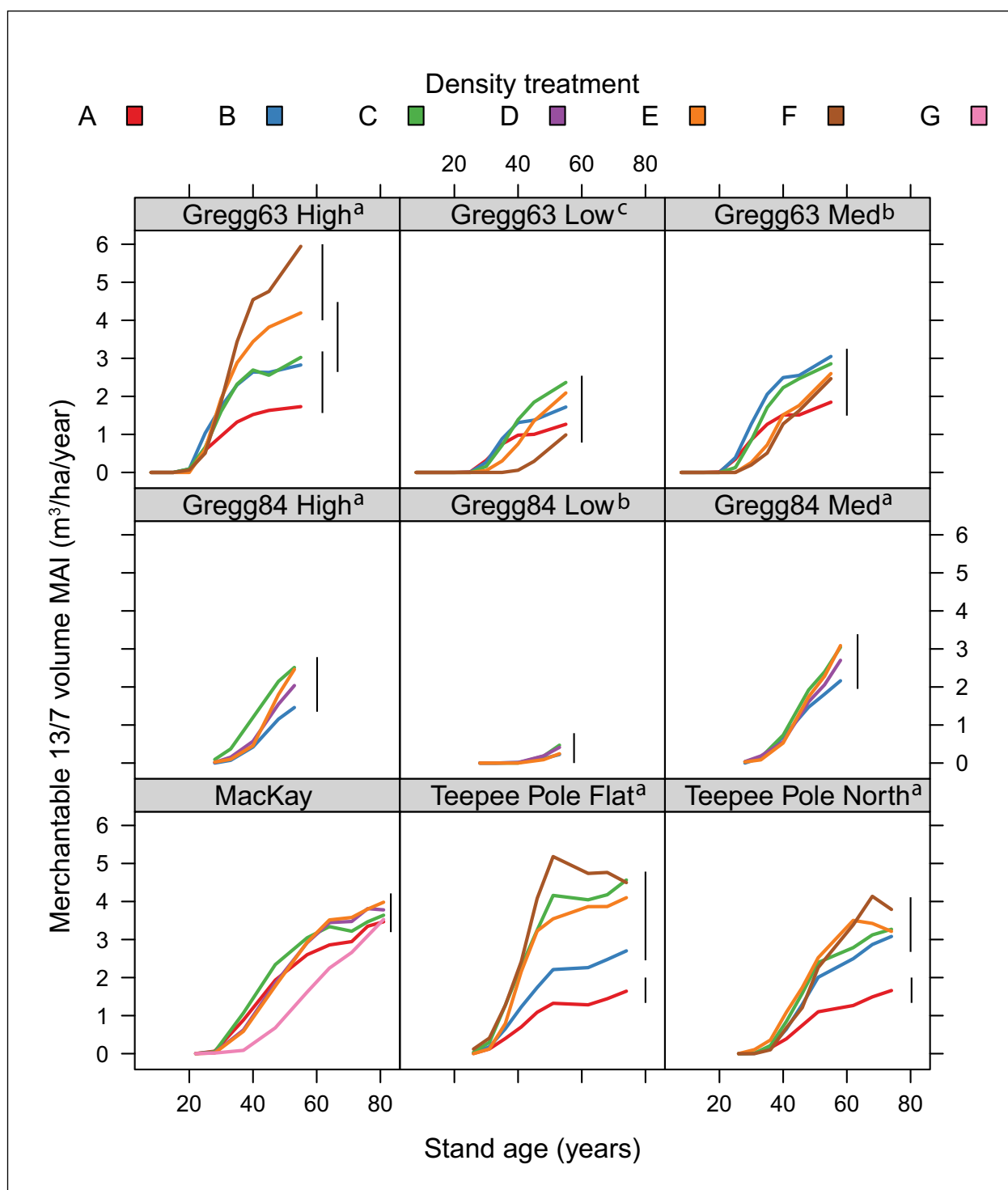


Figure 18. Mean annual increment (MAI) for merchantable volume (13/7 merchantability standard) for four lodgepole pine precommercial thinning trials.

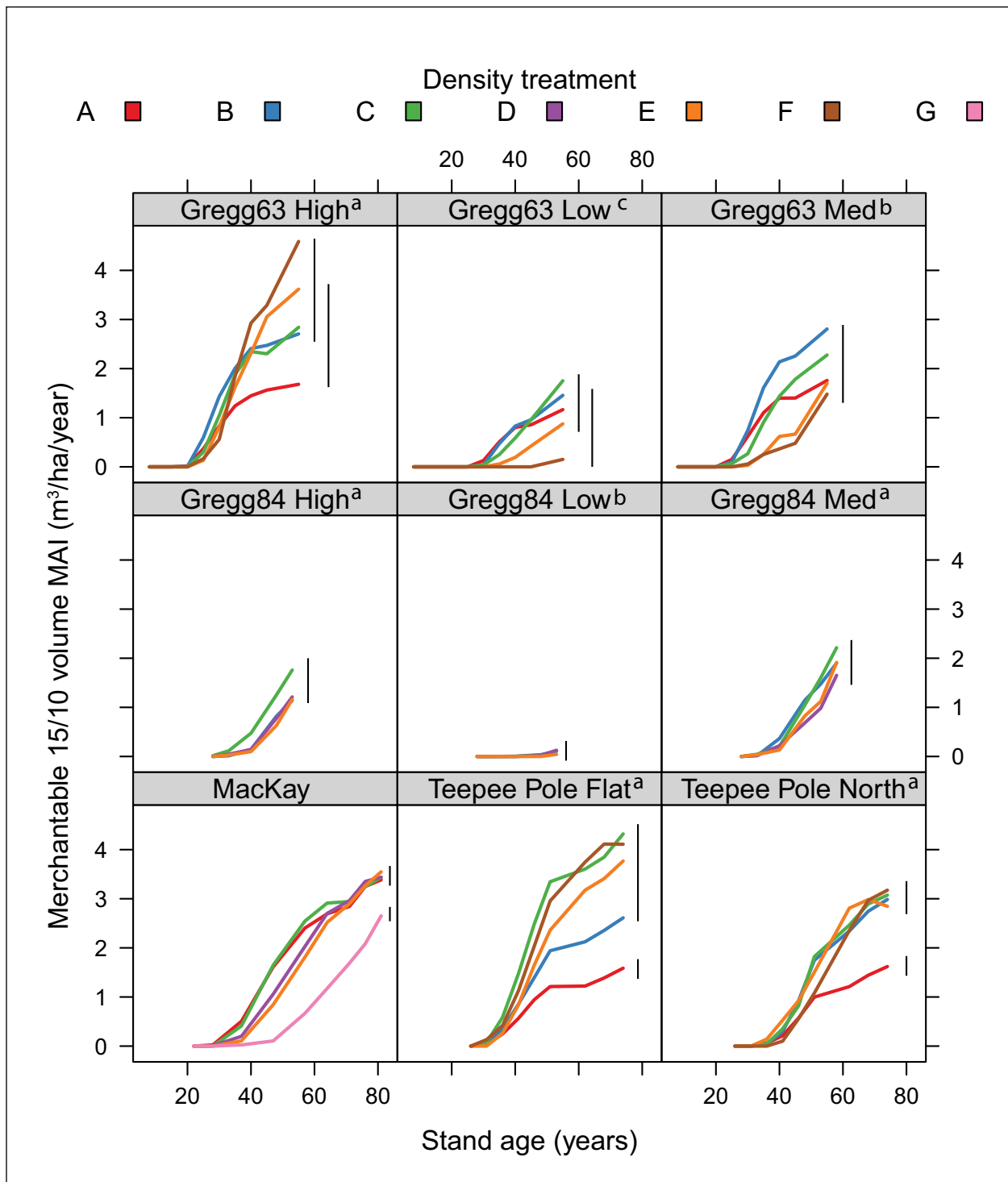


Figure 19. Mean annual increment (MAI) for merchantable volume (15/10 merchantability standard) for four lodgepole pine precommercial thinning trials.

Table 20. Results of analysis of variance of the effect of site and density treatments on mean annual increment of merchantable volume (15/10 standard) over time in four lodgepole pine precommercial thinning trials

Trial	Source	DF	Type III sum of squares	Mean squares	F value	Pr > F
Gregg63	Site	2	1.6678	0.8339	176.50	0.0008
	Block(site)	3	0.0142	0.0047	0.31	0.8158
	Density	4	0.2157	0.0539	3.57	0.0386
	Site × density	8	0.9535	0.1192	7.89	0.0009
Gregg84	Site	2	1.1480	0.5740	51.77	0.0047
	Block(site)	3	0.0333	0.0111	0.41	0.7502
	Density	3	0.0659	0.0220	0.81	0.5190
	Site × density	6	0.0467	0.0078	0.29	0.9284
Teepee Pole	Site	1	0.0775	0.0775	6.95	0.1188
	Block(site)	2	0.0223	0.0112	0.89	0.4468
	Density	4	0.8263	0.2066	16.52	0.0006
	Site × density	4	0.1121	0.0280	2.24	0.1541
MacKay	Block	2	0.00403	0.00202	1.51	0.2938
	Density	4	0.09765	0.02441	18.32	0.0016

DF = degrees of freedom; Pr > F = the probability of getting by chance an F-value greater than the estimated value.

Discussion

These four trials represent a long-term investment; there are considerable costs for protecting and maintaining the field installations, in addition to the initial establishment costs. The measurement datasets span from three decades in the Gregg84 trial to six decades in the MacKay trial, during which a wide range of climate variation has been integrated in the tree growth and stand development, to an extent seen in few other trials. The trials also represent different environmental conditions, the trial locations being in both the Lower and Upper Foothills ecological subregions, as well as the specific site conditions tested in the trials, namely site productivity and slope aspect.

Despite the range of conditions covered by these trials, there are still limitations to what they can tell us about lodgepole pine stand development after thinning. The trials are situated in a small area relative to the entire range of lodgepole pine, although the site conditions represent a

common type of site for lodgepole pine. The stand types represent only a few of those that exist for lodgepole pine; however, these stand types represent a large part of the total area of lodgepole pine forest. These results are most relevant for the northeastern part of the lodgepole pine range, that is, the eastern slopes of the Rocky Mountains in Canada. These results, in terms of their absolute sizes and rates, should be applied with caution to other regions of the lodgepole pine range. However, we expect the trends and patterns to hold for lodgepole pine as a species.

Lastly, these results can be applied to lodgepole pine stands only in similar conditions, and growth models will still be appropriate for forecasting the results of different scenarios of management. However, these results remain an important touchstone to check the validity of these models and to validate the conventional wisdom in density management of lodgepole pines. The

long-term datasets from these trials have been used to develop and validate the TASS model for lodgepole pine. Other growth and yield simulators (e.g., GYPSY, MGM) have made limited use of this dataset; however, it remains one of few such multi-decadal datasets for lodgepole pine under different densities that is available for model validation.

Stand Development after Density Treatments

Density treatments were distinct at establishment; the precision with which the treatments were carried out made it possible to have several levels of density established at relatively close intervals. The differentiation among treatments at establishment has been largely maintained over time, despite some convergence in stand density due to mortality.

The setup of the trials provides an opportunity to compare the timing of thinning between trials. The Gregg Burn trials contrast spacing at stand age seven years with spacing at stand age 28 years in stands of the same origin year. The MacKay and Teepee Pole Creek trials were also thinned at the late juvenile stage (stand ages 22 and 26 years, respectively), but at the latest measurement the latter stands are decades older than those of the Gregg Burn trials. Despite the differences in the length of time that mortality has reduced stand density, rates of mortality have been different enough in the different treatments of the four trials that almost all of the low-density treatments have similar stand density, whereas the differences in stand density in the high-density treatments vary widely. It is difficult to detect a consistent pattern in development of stand density, or to connect these results to some other variable that would allow prediction of stand density development. This adds an element of uncertainty to subsequent growth and yield results and application. Understanding mortality dynamics is still a major challenge in managing lodgepole pine and has been specifically studied elsewhere (Lee 1971; Yao et al. 2001; Temesgen and Mitchell 2005; Thorpe and Daniels 2012; Yang and Huang 2013).

Convergence in stand density between density treatments might be expected to result in convergence in tree size or stand yield as well. However, we found that, despite higher mortality rates in the denser treatments, the overall gradient of stand density has been maintained across the range of treatment densities within each trial, although the Tukey–Kramer tests often show no significant difference between adjacent levels of density treatment, especially in the older stands (MacKay and Teepee Pole Creek). The competition factors, SF and SDI, also show that there has been convergence in the density treatments, and the convergence is greater in the higher-density treatments than in the lower-density ones. Spacing factor in the A treatment is significantly different from all others in every trial but the MacKay, and the same is true of the B treatments in both Gregg Burn trials. This suggests that adjacent treatment levels at the high-density end of the gradient tend to converge first, and those in the lowest-density treatments converge last. This was also seen in a trial of level of growing stock in Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco), in which the highest density levels appeared to converge before the less dense stands, although they all eventually converged (Cochran and Dahms 2000).

Stand density index, based on quadratic mean diameter rather than height, shows more overlap between treatments at the lower densities than at the higher densities. In the MacKay and Gregg Burn trials, SDI in the highest density treatments (F and G) were still significantly different from those in other treatments, whereas there was overlap in SDI between all other density treatments. Since competition indices have different sensitivities at either end of the density gradient, the selection of an index to inform thinning prescriptions should be determined, in part, by the objectives of the thinning program. SF responds mainly to the changes in stand density, because height differences tend to be small between thinning levels in lodgepole pine stands, as shown in our results and in other studies of thinning lodgepole pine (Alexander 1965; Lanner 1985). In contrast,

while SDI responds to the density changes as well, the changes in diameter with changes in growing space also strongly affect SDI. Our results showed diameter to be more dynamic and significantly different among treatments.

Is There an Optimal Stand Density?

There has long been interest in determining whether there is an optimal precommercial thinning regime that maximizes yield. The breadth of site condition and treatments, along with the long timespan of the dataset, allows us at least to address, if not resolve, this issue. The question can be broken down into two aspects: volume yield and value. We will address mainly the former in this report, and leave the value analysis for another study to be published separately. Before we look at yields from our study, we first need to assess whether our results truly reflect the yields at rotation. It is clear from our MAI results that most of the treatment plots have not yet reached a technical rotation based on merchantable volume, since the MAI curves are still ascending, except for the highest-density treatments in the Teepee Pole Creek trial. It appears that the culmination of MAI is still some years away, or possibly even decades in the case of the Gregg Burn trials. However, MAI curves for the various volume standards follow similar trajectories, just shifted to older stand ages as they go from total volume to the larger merchantable standard. Therefore, we can use the total volume results as an indicator of the trends in merchantable yield at maturity. Judging by the trends in MAI for the Teepee Pole Creek site, merchantable volume according to the 13/7 standard appears to culminate about 20 years after the culmination for total volume.

Total volume results show that maximum yield is in the highest-density treatments, suggesting that thinning should not be prescribed if maximizing yield is the objective. Previous studies by Mitchell and Goudie (1998) and CCSMAF (2002) have reached the same conclusion. Although most other studies have shown that unthinned plots

maintain their BA and total volume well above those of thinned plots, the differential decreases over time. In contrast to our results, in one central British Columbia trial the most lightly thinned plots surpassed the unthinned plots with respect to merchantable volume after 10–15 years (Johnstone and van Thienen 2004).

Our results show that precommercial thinning regimes reduced volume at establishment, and that this was never made up by subsequent growth. At best, the resulting volumes would not be significantly different between any thinning treatment and unthinned plots after sufficient time had elapsed, as shown in the MacKay trial. Disregarding the lowest-density treatments, there was little or no difference among the other thinning treatments in the next oldest stand, the Teepee Pole Creek trial. This suggests that, if there are reasons to thin other than maximizing yield, there may not be a yield disadvantage in doing so.

Potential advantages of thinning are mainly connected with having larger trees (piece size) in the same rotation time. This allows for (1) lower handling costs (in part due to fewer trees to handle), (2) larger-dimension lumber (if this brings a premium price in the market), and (3) shorter technical rotations based on a tree size threshold. Another reason for thinning is to adjust rotation times in order to even out fibre flow where there is an age-class gap. Effects on operating costs are beyond the scope of this paper, and will be the subject of a subsequent report. As has been demonstrated elsewhere in lodgepole pine (Alexander 1956, 1960, 1965; Johnstone 1981a, b, 1982, 1985, 2005; Johnstone and Cole 1988; Johnstone and Pollack 1990; Johnstone and van Thienen 2004, 2011a, b), larger piece size is definitely achieved in the thinning treatments, and increased significantly with each decrease in stand density. This is seen in our diameter results. To effect a significant change in quadratic mean diameter, our results suggest that a relatively large change in density is needed, i.e., thinning to at least C or D treatment levels. If shorter rotations

are desired, it is clear from our diameter results that thinning can reduce rotation age by years or decades. Precommercial thinning can also be part of a regime that lengthens rotations, if that is desired to fill an age-class gap, or to set up a stand for later commercial thinning (Cole and Koch 1995; Johnstone 2005).

Mean annual increment for total volume at rotation is likely to be 3.5–4.5 m³/ha per year for most sites and thinning regimes, except for the most severe thinning regimes and the lowest-productivity sites. There is no evidence that early thinning is any better or worse than late juvenile thinning. Comparing the results from the medium-productivity sites from two Gregg Burn trials, which are adjacent to each other, it appears that postponing thinning might result in higher MAI at rotation, but with the disadvantage of lengthening the rotation and probably increasing thinning costs. These outcomes of postponing thinning are not as evident in comparing the Gregg Burn 1963 trial with the Teepee Pole Creek trial, which was also thinned later, similar to the Gregg Burn 1984 trial. However, in this case the differences in site productivity and climate between the two trials also influence the outcome and make the comparison more difficult to interpret.

Effect of Precommercial Thinning on Non-yield Characteristics

The lower-density treatments provide more growing space and less competition, resulting in faster-growing trees with greater live crown ratios. These characteristics are related to greater taper, larger branches, more large knots, and a larger proportion of juvenile wood, all of which can reduce the quality and value of the wood produced (Ballard and Long 1988; Johnstone and Pollack 1990; Middleton et al. 1995). Wood density has not been found to vary strongly with stand density in pines generally (Brazier 1977) and in lodgepole pine specifically (Ballard and Long 1988).

Does lower density improve stand health? Thinning can increase the susceptibility of residual trees to damage from wind and snow as a result of greater

exposure and lack of support from neighbouring trees (Valinger et al. 1994); however, in some lodgepole pine stands the damage was greater in the unthinned stands, disproportionately affecting the smaller stems (Teste and Lieffers 2011). This suggests that, if the thinned stands can avoid serious damage in the first few years after treatment, the increased diameter growth will lead to lower height–diameter ratios, making the trees more resistant to snow and wind damage (Johnstone and van Thienen 2004). Wind-caused sway after thinning can reduce xylem-specific conductivity, suggesting functional damage to sapwood, at least in the short term, despite the advantages of increased diameter growth and leaf area in the residual trees (Liu et al. 2003).

Thinning can reduce the risk of some types of insect and disease damage, and increase the risk for other types. Thinning, both early and late in rotation, can be used as part of a preventative management program to control mountain pine beetle infestation and spread, and make lodgepole pine stands less susceptible to attack (Whitehead et al. 2006). Thinning usually sanitizes the stands of western gall rust (*Endocronartium harknessii* [J.P. Moore] Y. Hiratsuka), but is less effective at reducing Atropellis canker (*Atropellis piniphila* [Weir] Lohman and Cash) (Johnstone and van Thienen 2004). In a study of operational forestry blocks, precommercial thinning resulted in fewer undamaged trees than in unthinned plots, due to significant increases in western gall rust, lodgepole terminal weevil (*Pissodes terminalis* [Hopping]), pitch twig moth (*Petrova albicapitana* [Busck]), and several species of needle cast (Bella 1985a). The incidence of damage due to western gall rust, lodgepole terminal weevil, and pitch twig moth were all strongly correlated with tree size, in both thinned and unthinned stands (Bella 1985b). Precommercial thinning operations should include identification and removal of trees already showing damage and disease, especially gall rust (Bella 1985b, Blenis and Duncan 1997). Delayed thinning should also reduce post-thinning mortality from gall rust (Blenis and Duncan 1997) but can increase the

risk of damage from wind and snow (Johnstone and van Thienen 2011b). Our data on tree condition are insufficient to draw any conclusions about the role of insect and disease attack in stand development, or about the effect of stand density on susceptibility to attack, since the incidence of attack is so high in these lodgepole pine stands. A more intensive survey of tree condition and damage agents that includes an assessment of the severity of the attack is required to address this issue in any meaningful way.

Johnstone's General Principles Revisited

Based on results from numerous thinning and spacing trials for lodgepole pine, the following six general principles have been suggested (Johnstone 1985; Johnstone and Cole 1988; Johnstone and van Thienen 2004). Our results have largely supported these principles.

- (1) Thinning can significantly enhance the merchantable yield and value of excessively dense stands.

This aspect was only addressed in the MacKay trial, since it is the only trial with unthinned controls. In MacKay, the merchantable volumes appeared higher in all treatments compared with the controls (though not significantly so); however, the MAI trajectories suggest that merchantable volume in the controls might match those of the thinned plots by rotation age. The other trials had pseudocontrol plots installed in the last decade or two in unthinned areas adjacent to the thinned plots; however, there is no plot history available and no guarantee that these areas were similar to the treated areas at the time of establishment. Anecdotally, there are unthinned areas that did not self-thin effectively and remained as dense areas of small trees, while others more closely resembled the high-density treatment plots. Observation of these pseudocontrols suggests that precommercial thinning would be beneficial, compared with not thinning at all, in lower-productivity stands; however, this must be verified by further study.

- (2) Higher-productivity sites have a larger absolute response to thinning and lower-productivity sites have a greater relative response.

This principle is difficult to address because it is based on the idea that thinning will provide a yield advantage, which it does not in this analysis; we found that yield either was the same or actually decreased as thinning intensity increased. It is clear that the greatest absolute differences in volume were found in the higher-productivity treatments. This negative response supports the guideline that thinning is better done in the lower-productivity sites, although the absolute differences between treatments are less.

- (3) Younger trees have a larger thinning response than older ones.

This principle addresses the concern that, as a stand ages, it may become less responsive to thinning, an issue to which our results are not applicable. However, we can compare the results of thinning at two different ages early in stand development by examining the medium-productivity sites in the two Gregg Burn trials, which are adjacent to each other. It appears that MAI was higher in the plots thinned at the earlier age when compared with the later-thinned plots at the same stand age. However, the treatments thinned early subsequently showed a slowing of the increase in MAI, which the later-thinned plots did not. As a result, growth rates were higher in the Gregg84 than the Gregg63 trial, at least in the higher-density plots where total volume is currently about 200 m³/ha per year in both trials. In the lower-density treatments, where there is still a difference in volume, the higher growth rates in the Gregg84 plots may allow it to catch up with the Gregg63 plot over time. So it appears that the timing of the thinning treatment may affect the outcome.

- (4) Larger dominant and co-dominant trees have the largest growth response.

This principle is more relevant to commercial thinning treatments, in which the larger trees (thinning from above), or the smaller trees (thinning

from below), or some combination of the two, can be removed. In the juvenile spacing trials reported on here, all residual trees were small, and appropriate spacing took precedence over tree size.

- (5) Individual tree response generally increases with increased thinning weight.

Our results confirm this; the relationship between

density (stems per hectare) and DBH is not a straight line.

- (6) Thinning may increase some risks and reduce others associated with managing lodgepole pine.

Our data on risk factors in this study is insufficient to address this principle.

Conclusions

Our analysis of precommercial thinning in lodgepole pine in the Alberta foothills supports the conventional wisdom that thinning is unlikely to increase yields. However, if there are other reasons to thin, then judicious choice of a thinning regime may not result in a yield loss (cf. Johnstone and van Thienen 2011b). Thinning to an initial

density of 2 000–3 000 stems per hectare appears to be optimal, maximizing the positive effect on tree growth without major losses in volume. The use of SDI as the competition index in thinning prescriptions is recommended, as it appears to be more sensitive than SF in this density range.

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Appendix

Table A1. Least-square means of stand density at the latest measurement for site and density treatments in four lodgepole pine precommercial thinning trials

Trial	Site	Density	Stems/ha, least square mean	Standard error	Pr > t
Gregg63	High	A-494	303.7	326.1	0.3701
	High	B-988	607.7	326.1	0.0870
	High	C-1977	790.5	326.1	0.0321
	High	E-3954	1521.7	326.1	0.0005
	High	F-7907	2283.5	326.1	<0.0001
	Low	A-494	496.3	326.1	0.1540
	Low	B-988	835.0	326.1	0.0250
	Low	C-1977	1571.1	326.1	0.0004
	Low	E-3954	3102.8	326.1	<0.0001
	Low	F-7907	5393.7	326.1	<0.0001
	Med	A-494	446.9	326.1	0.1957
	Med	B-988	899.2	326.1	0.0174
	Med	C-1977	1353.8	326.1	0.0013
	Med	E-3954	2588.9	326.1	<0.0001
	Med	F-7907	3661.4	326.1	<0.0001
Gregg84	High	B-988	909.1	277.5	0.0096
	High	C-1977	1729.2	277.5	0.0002
	High	D-2965	2270.3	277.5	<0.0001
	High	E-3954	3102.8	277.5	<0.0001
	Low	B-988	1166.0	277.5	0.0023
	Low	C-1977	2164.0	277.5	<0.0001
	Low	D-2965	2992.1	277.5	<0.0001
	Low	E-3954	4743.1	277.5	<0.0001
	Med	B-988	854.7	277.5	0.0131
	Med	C-1977	1768.8	277.5	0.0001
	Med	D-2965	2296.6	277.5	<0.0001
	Med	E-3954	3043.5	277.5	<0.0001
Teepee Pole	Flat	A-494	397.5	242.7	0.1401
	Flat	B-988	627.5	242.7	0.0324
	Flat	C-1977	1205.5	242.7	0.0011
	Flat	E-3954	1482.2	242.7	0.0003
	Flat	F-7907	1535.4	242.7	0.0002
	North	A-494	328.4	242.7	0.2131
	North	B-988	691.7	242.7	0.0215
	North	C-1977	958.5	242.7	0.0042
	North	E-3954	1363.6	242.7	0.0005
	North	F-7907	1889.8	242.7	<0.0001
MacKay	None	A-750	642.3	218.2	0.0164
	None	C-1680	984.3	118.3	<0.0001
	None	D-2990	1346.7	83.67	<0.0001
	None	E-4330	1515.5	118.3	<0.0001
	None	G-no_thin	2454.2	118.3	<0.0001

Pr > |t| = the probability of getting by chance, an absolute value of the t-statistic greater than the estimated value.

Table A2. Least-square means of mortality rate at the latest measurement for site and density treatments in four lodgepole pine precommercial thinning trials

Trial	Site	Density	Lambda, least square mean	Standard erro	Pr > t
Gregg63	High	A-494	1.0252	0.2423	0.0012
	High	B-988	1.0142	0.2423	0.0013
	High	C-1977	1.9334	0.2423	<0.0001
	High	E-3954	1.9937	0.2423	<0.0001
	High	F-7907	2.5889	0.2423	<0.0001
	Low	A-494	-0.0096	0.2423	0.9689
	Low	B-988	0.3509	0.2423	0.1731
	Low	C-1977	0.5092	0.2423	0.0574
	Low	E-3954	0.5174	0.2423	0.0540
	Low	F-7907	0.7996	0.2423	0.0063
	Med	A-494	0.2090	0.2423	0.4052
	Med	B-988	0.1963	0.2423	0.4335
	Med	C-1977	0.8367	0.2423	0.0048
	Med	E-3954	0.9149	0.2423	0.0026
	Med	F-7907	1.7266	0.2423	<0.0001
Gregg84	High	B-988	0.3389	0.2663	0.2204
	High	C-1977	0.5466	0.2663	0.0558
	High	D-2965	1.0695	0.2663	0.0009
	High	E-3954	0.9718	0.2663	0.0020
	Low	B-988	-0.6155	0.2663	0.0336
	Low	C-1977	-0.3037	0.2663	0.2700
	Low	D-2965	0.0199	0.2663	0.9413
	Low	E-3954	-0.7042	0.2663	0.0170
	Med	B-988	0.5313	0.1883	0.0118
	Med	C-1977	0.4035	0.1883	0.0469
	Med	D-2965	0.9791	0.1883	<0.0001
	Med	E-3954	1.0490	0.1883	<0.0001
Teepee Pole	Flat	A-494	0.4823	0.3712	0.2300
	Flat	B-988	0.9464	0.3712	0.0342
	Flat	C-1977	1.0331	0.3712	0.0238
	Flat	E-3954	2.0759	0.3712	0.0005
	Flat	F-7907	3.4151	0.3712	<0.0001
	North	A-494	0.8721	0.3712	0.0467
	North	B-988	0.7481	0.3712	0.0786
	North	C-1977	1.5271	0.3712	0.0034
	North	E-3954	2.3191	0.3712	0.0002
	North	F-7907	3.1046	0.3712	<0.0001
MacKay	None	A-750	0.4589	0.1961	0.0440
	None	C-1680	0.6898	0.1064	0.0001
	None	D-2990	1.1625	0.0752	<0.0001
	None	E-4330	1.5054	0.1064	<0.0001
	None	G-no_thin	2.5021	0.1064	<0.0001

Pr > |t| = the probability of getting by chance, an absolute value of the t-statistic greater than the estimated value.

Table A3. Least-square means of spacing factor at the latest measurement for site and density treatments in four lodgepole pine precommercial thinning trials

Trial	Site	Density	Spacing factor, least square mean	Standard error	Pr > t
Gregg63	High	A-494	0.3504	0.0165	<0.0001
	High	B-988	0.2347	0.0165	<0.0001
	High	C-1977	0.2083	0.0165	<0.0001
	High	E-3954	0.1460	0.0165	<0.0001
	High	F-7907	0.1271	0.0165	<0.0001
	Low	A-494	0.3059	0.0165	<0.0001
	Low	B-988	0.2431	0.0165	<0.0001
	Low	C-1977	0.1689	0.0165	<0.0001
	Low	E-3954	0.1269	0.0165	<0.0001
	Low	F-7907	0.1053	0.0165	<0.0001
	Med	A-494	0.3009	0.0165	<0.0001
	Med	B-988	0.2075	0.0165	<0.0001
	Med	C-1977	0.1649	0.0165	<0.0001
	Med	E-3954	0.1503	0.0165	<0.0001
	Med	F-7907	0.1228	0.0165	<0.0001
Gregg84	High	B-988	0.2418	0.0085	<0.0001
	High	C-1977	0.1583	0.0085	<0.0001
	High	D-2965	0.1409	0.0085	<0.0001
	High	E-3954	0.1205	0.0085	<0.0001
	Low	B-988	0.3023	0.0085	<0.0001
	Low	C-1977	0.2185	0.0085	<0.0001
	Low	D-2965	0.1789	0.0085	<0.0001
	Low	E-3954	0.1456	0.0085	<0.0001
	Med	B-988	0.2251	0.0085	<0.0001
	Med	C-1977	0.1583	0.0085	<0.0001
	Med	D-2965	0.1333	0.0085	<0.0001
	Med	E-3954	0.1181	0.0085	<0.0001
Teepee Pole	Flat	A-494	0.2857	0.0205	<0.0001
	Flat	B-988	0.2049	0.0205	<0.0001
	Flat	C-1977	0.1389	0.0205	0.0001
	Flat	E-3954	0.1371	0.0205	0.0002
	Flat	F-7907	0.1311	0.0205	0.0002
	North	A-494	0.3059	0.0205	<0.0001
	North	B-988	0.2034	0.0205	<0.0001
	North	C-1977	0.1709	0.0205	<0.0001
	North	E-3954	0.1437	0.0205	0.0001
	North	F-7907	0.1267	0.0205	0.0003
MacKay	None	A-750	0.1702	0.0053	<0.0001
	None	C-1680	0.1494	0.0029	<0.0001
	None	D-2990	0.1273	0.0020	<0.0001
	None	E-4330	0.1193	0.0029	<0.0001
	None	G-no_thin	0.0986	0.0029	<0.0001

Pr > |t| = the probability of getting by chance, an absolute value of the t-statistic greater than the estimated value.

Table A4. Least-square means of stand density index at the latest measurement for site and density treatments in four lodgepole pine precommercial thinning trials

Trial	Site	Density	Stand density index, least square mean	Standard error	Pr > t
Gregg63	High	A-494	294.8	92.14	0.0076
	High	B-988	484.4	92.14	0.0002
	High	C-1977	549.9	92.14	<0.0001
	High	E-3954	808.8	92.14	<0.0001
	High	F-7907	1153.5	92.14	<0.0001
	Low	A-494	293.3	92.14	0.0079
	Low	B-988	418.5	92.14	0.0007
	Low	C-1977	638.4	92.14	<0.0001
	Low	E-3954	908.7	92.14	<0.0001
	Low	F-7907	1131.7	92.14	<0.0001
	Med	A-494	346.8	92.14	0.0027
	Med	B-988	581.5	92.14	<0.0001
	Med	C-1977	638.3	92.14	<0.0001
	Med	E-3954	873.5	92.14	<0.0001
	Med	F-7907	1035.0	92.14	<0.0001
Gregg84	High	B-988	402.7	30.41	<0.0001
	High	C-1977	668.5	30.41	<0.0001
	High	D-2965	725.3	30.41	<0.0001
	High	E-3954	938.5	30.41	<0.0001
	Low	B-988	256.9	30.41	<0.0001
	Low	C-1977	468.4	30.41	<0.0001
	Low	D-2965	566.9	30.41	<0.0001
	Low	E-3954	736.3	30.41	<0.0001
	Med	B-988	415.8	30.41	<0.0001
	Med	C-1977	663.3	30.41	<0.0001
	Med	D-2965	720.1	30.41	<0.0001
	Med	E-3954	895.6	30.41	<0.0001
Teepee Pole	Flat	A-494	368.3	93.36	0.0043
	Flat	B-988	538.0	93.36	0.0004
	Flat	C-1977	890.4	93.36	<0.0001
	Flat	E-3954	894.8	93.36	<0.0001
	Flat	F-7907	956.6	93.36	<0.0001
	North	A-494	337.1	93.36	0.0069
	North	B-988	612.1	93.36	0.0002
	North	C-1977	690.7	93.36	<0.0001
	North	E-3954	753.7	93.36	<0.0001
	North	F-7907	945.3	93.36	<0.0001
MacKay	None	A-750	622.9	68.78	<0.0001
	None	C-1680	715.3	37.30	<0.0001
	None	D-2990	821.1	26.38	<0.0001
	None	E-4330	866.2	37.30	<0.0001
	None	G-no_thin	1037.4	37.30	<0.0001

Pr > |t| = the probability of getting by chance, an absolute value of the t-statistic greater than the estimated value.

Table A5. Least-square means of tree diameter at the latest measurement for Site and Density treatments in four lodgepole pine precommercial thinning trials

Trial	Site	Density	Diameter at breast height, least square mean	Standard error	Pr > t
Gregg63	High	A-494	24.1873	0.3057	<0.0001
	High	B-988	21.2385	0.3042	<0.0001
	High	C-1977	19.5205	0.3813	<0.0001
	High	E-3954	16.4890	0.3850	<0.0001
	High	F-7907	16.0400	0.4430	<0.0001
	Low	A-494	17.5788	0.2378	<0.0001
	Low	B-988	16.0218	0.2594	<0.0001
	Low	C-1977	14.0540	0.2713	<0.0001
	Low	E-3954	11.2602	0.2707	<0.0001
	Low	F-7907	9.1109	0.2884	<0.0001
	Med	A-494	21.0302	0.2506	<0.0001
	Med	B-988	18.7258	0.2499	<0.0001
	Med	C-1977	15.3109	0.2947	<0.0001
	Med	E-3954	12.4319	0.2992	<0.0001
	Med	F-7907	11.0742	0.3708	<0.0001
Gregg84	High	B-988	14.7846	0.2089	<0.0001
	High	C-1977	13.5757	0.2145	<0.0001
	High	D-2965	11.8849	0.2153	<0.0001
	High	E-3954	11.5270	0.2260	<0.0001
	Low	B-988	9.3495	0.1864	<0.0001
	Low	C-1977	9.2629	0.1940	<0.0001
	Low	D-2965	8.4467	0.1901	<0.0001
	Low	E-3954	7.3772	0.1838	<0.0001
	Med	B-988	15.6341	0.2152	<0.0001
	Med	C-1977	13.3038	0.2119	<0.0001
	Med	D-2965	11.7766	0.2141	<0.0001
	Med	E-3954	11.4084	0.2293	<0.0001
Teepee Pole	Flat	A-494	23.2566	0.3617	<0.0001
	Flat	B-988	22.2731	0.4016	<0.0001
	Flat	C-1977	20.2825	0.4102	<0.0001
	Flat	E-3954	17.8530	0.5305	<0.0001
	Flat	F-7907	18.1771	0.7248	<0.0001
	North	A-494	25.0395	0.3964	<0.0001
	North	B-988	22.8116	0.3834	<0.0001
	North	C-1977	19.9247	0.4636	<0.0001
	north	E-3954	17.0650	0.5718	<0.0001
	North	F-7907	16.0500	0.6927	<0.0001
MacKay	None	A-750	- ^a	-	-
	None	C-1680	20.1679	0.2561	<0.0001
	None	D-2990	17.9188	0.1548	<0.0001
	None	E-4330	17.2028	0.2053	<0.0001
	None	G-no_thin	14.2154	0.1636	<0.0001

^aDashes indicate non-estimable.

Pr > |t| = the probability of getting by chance, an absolute value of the t-statistic greater than the estimated value.

Table A6. Least-square means of tree height at the latest measurement for site and density treatments in four lodgepole pine precommercial thinning trials

Trial	Site	Density	Tree height, squared least square mean	Standard error	Pr > t
Gregg63	High	A-494	242.950	4.275	<0.0001
	High	B-988	252.662	4.255	<0.0001
	High	C-1977	236.994	5.332	<0.0001
	High	E-3954	242.501	5.385	<0.0001
	High	F-7907	243.683	6.195	<0.0001
	Low	A-494	162.647	3.326	<0.0001
	Low	B-988	163.212	3.628	<0.0001
	Low	C-1977	161.959	3.795	<0.0001
	Low	E-3954	137.554	3.785	<0.0001
	Low	F-7907	110.082	4.034	<0.0001
	Med	A-494	215.638	3.505	<0.0001
	Med	B-988	223.261	3.495	<0.0001
	Med	C-1977	195.913	4.122	<0.0001
	Med	E-3954	160.911	4.185	<0.0001
	Med	F-7907	150.601	5.186	<0.0001
Gregg84	High	B-988	142.657	2.699	<0.0001
	High	C-1977	175.559	2.771	<0.0001
	High	D-2965	153.933	2.781	<0.0001
	High	E-3954	151.003	2.919	<0.0001
	Low	B-988	50.072	2.408	<0.0001
	Low	C-1977	59.426	2.507	<0.0001
	Low	D-2965	58.163	2.456	<0.0001
	Low	E-3954	50.259	2.3740	<0.0001
	Med	B-988	172.383	2.780	<0.0001
	Med	C-1977	182.912	2.738	<0.0001
	Med	D-2965	171.140	2.766	<0.0001
	Med	E-3954	166.448	2.962	<0.0001
Teepee Pole	Flat	A-494	256.402	5.940	<0.0001
	Flat	B-988	316.670	6.596	<0.0001
	Flat	C-1977	351.934	6.736	<0.0001
	Flat	E-3954	308.595	8.712	<0.0001
	Flat	F-7907	317.056	11.903	<0.0001
	North	A-494	291.615	6.510	<0.0001
	North	B-988	319.430	6.296	<0.0001
	North	C-1977	300.998	7.614	<0.0001
	North	E-3954	292.721	9.391	<0.0001
	North	F-7907	256.490	11.376	<0.0001
MacKay	None	A-750	- ^a	-	-
	None	C-1680	409.571	5.480	<0.0001
	None	D-2990	357.943	3.313	<0.0001
	None	E-4330	376.476	4.394	<0.0001
	None	G-no_thin	278.904	3.502	<0.0001

^aDashes indicate non-estimable.

Pr > |t| = the probability of getting by chance, an absolute value of the t-statistic greater than the estimated value.

Table A7. Least-square means of height–diameter ratio at the latest measurement for site and density treatments in four lodgepole pine precommercial thinning trials

Trial	Site	Density	Log height– diameter ratio, least square mean	Standard error	Pr > t
Gregg63	High	A-494	0.2184	0.0028	<0.0001
	High	B-988	0.2466	0.0028	<0.0001
	High	C-1977	0.2553	0.0035	<0.0001
	High	E-3954	0.2926	0.0035	<0.0001
	High	F-7907	0.2988	0.0040	<0.0001
	Low	A-494	0.2372	0.0022	<0.0001
	Low	B-988	0.2552	0.0024	<0.0001
	Low	C-1977	0.2811	0.0025	<0.0001
	Low	E-3954	0.3123	0.0025	<0.0001
	Low	F-7907	0.3352	0.0026	<0.0001
	Med	A-494	0.2311	0.0023	<0.0001
	Med	B-988	0.2565	0.0023	<0.0001
	Med	C-1977	0.2833	0.0027	<0.0001
	Med	E-3954	0.3082	0.0027	<0.0001
	Med	F-7907	0.3323	0.0034	<0.0001
Gregg84	High	B-988	0.2582	0.0023	<0.0001
	High	C-1977	0.2972	0.0023	<0.0001
	High	D-2965	0.3145	0.0023	<0.0001
	High	E-3954	0.3188	0.0025	<0.0001
	Low	B-988	0.2431	0.0020	<0.0001
	Low	C-1977	0.2616	0.0021	<0.0001
	Low	D-2965	0.2767	0.0021	<0.0001
	Low	E-3954	0.2905	0.0020	<0.0001
	Med	B-988	0.2645	0.0023	<0.0001
	Med	C-1977	0.3072	0.0023	<0.0001
	Med	D-2965	0.3280	0.0023	<0.0001
	Med	E-3954	0.3317	0.0025	<0.0001
Teepee Pole	Flat	A-494	0.2303	0.0027	<0.0001
	Flat	B-988	0.2563	0.0030	<0.0001
	Flat	C-1977	0.2880	0.0031	<0.0001
	Flat	E-3954	0.3004	0.0040	<0.0001
	Flat	F-7907	0.2962	0.0054	<0.0001
	North	A-494	0.2268	0.0030	<0.0001
	North	B-988	0.2539	0.0029	<0.0001
	North	C-1977	0.2760	0.0035	<0.0001
	North	E-3954	0.3071	0.0043	<0.0001
	North	F-7907	0.3027	0.0052	<0.0001
MacKay	None	A-750	– ^a	–	–
	None	C-1680	0.3000	0.0034	<0.0001
	None	D-2990	0.3019	0.0021	<0.0001
	None	E-4330	0.3160	0.0030	<0.0001
	None	G-no_thin	0.3289	0.0023	<0.0001

^aDashes indicate non-estimable.

Pr > |t| = the probability of getting by chance, an absolute value of the t-statistic greater than the estimated value.

Table A8. Least-square means of live crown ratio at the latest measurement for site and density treatments in four lodgepole pine precommercial thinning trials

Trial	Site	Density	Log live crown ratio, least square mean	Standard error	Pr > t
Gregg63	High	A-494	0.1828	0.0029	<0.0001
	High	B-988	0.1537	0.0029	<0.0001
	High	C-1977	0.1533	0.0036	<0.0001
	High	E-3954	0.1244	0.0036	<0.0001
	High	F-7907	0.1213	0.0042	<0.0001
	Low	A-494	0.2057	0.0022	<0.0001
	Low	B-988	0.1764	0.0024	<0.0001
	Low	C-1977	0.1606	0.0026	<0.0001
	Low	E-3954	0.1376	0.0026	<0.0001
	Low	F-7907	0.1146	0.0027	<0.0001
	Med	A-494	0.1914	0.0024	<0.0001
	Med	B-988	0.1589	0.0023	<0.0001
	Med	C-1977	0.1379	0.0028	<0.0001
	Med	E-3954	0.1174	0.0028	<0.0001
	Med	F-7907	0.1106	0.0035	<0.0001
Gregg84	High	B-988	0.1890	0.0024	<0.0001
	High	C-1977	0.1349	0.0024	<0.0001
	High	D-2965	0.1239	0.0024	<0.0001
	High	E-3954	0.1158	0.0026	<0.0001
	Low	B-988	0.2026	0.0021	<0.0001
	Low	C-1977	0.2003	0.0022	<0.0001
	Low	D-2965	0.1789	0.0022	<0.0001
	Low	E-3954	0.1766	0.0021	<0.0001
	Med	B-988	0.1779	0.0024	<0.0001
	Med	C-1977	0.1390	0.0024	<0.0001
	Med	D-2965	0.1200	0.0024	<0.0001
	Med	E-3954	0.1152	0.0026	<0.0001
Teepee Pole	Flat	A-494	0.1808	0.0035	<0.0001
	Flat	B-988	0.1728	0.0039	<0.0001
	Flat	C-1977	0.1257	0.0039	<0.0001
	Flat	E-3954	0.1432	0.0051	<0.0001
	Flat	F-7907	0.1229	0.0070	<0.0001
	North	A-494	0.2107	0.0038	<0.0001
	North	B-988	0.1675	0.0037	<0.0001
	North	C-1977	0.1654	0.0045	<0.0001
	North	E-3954	0.1259	0.0055	<0.0001
	North	F-7907	0.1319	0.0067	<0.0001
MacKay	None	A-750	- ^a	-	-
	None	C-1680	0.0948	0.0035	<0.0001
	None	D-2990	0.1135	0.0022	<0.0001
	None	E-4330	0.1027	0.0031	<0.0001
	None	G-no_thin	0.1018	0.0024	<0.0001

^aDashes indicate non-estimable.

Pr > |t| = the probability of getting by chance, an absolute value of the t-statistic greater than the estimated value.

Table A9. Least-square means of piece size at the latest measurement for site and density treatments in four lodgepole pine precommercial thinning trials

Trial	Site	Density	Log piece size, least square mean	Standard error	Pr > t
Gregg63	High	A-494	0.1167	0.0025	<0.0001
	High	B-988	0.0970	0.0025	<0.0001
	High	C-1977	0.0813	0.0032	<0.0001
	High	E-3954	0.0600	0.0032	<0.0001
	High	F-7907	0.0576	0.0037	<0.0001
	Low	A-494	0.0560	0.0020	<0.0001
	Low	B-988	0.0462	0.0021	<0.0001
	Low	C-1977	0.0346	0.0022	<0.0001
	Low	E-3954	0.0154	0.0022	<0.0001
	Low	F-7907	0.0042	0.0024	0.0820
	Med	A-494	0.0878	0.0021	<0.0001
	Med	B-988	0.0733	0.0021	<0.0001
	Med	C-1977	0.0462	0.0024	<0.0001
	Med	E-3954	0.0235	0.0025	<0.0001
	Med	F-7907	0.0163	0.0031	<0.0001
Gregg84	High	B-988	0.0352	0.0013	<0.0001
	High	C-1977	0.0322	0.0014	<0.0001
	High	D-2965	0.0196	0.0014	<0.0001
	High	E-3954	0.0175	0.0014	<0.0001
	Low	B-988	0.0045	0.0012	0.0002
	Low	C-1977	0.0053	0.0012	<0.0001
	Low	D-2965	0.0034	0.0012	0.0050
	Low	E-3954	0.0012	0.0012	0.3207
	Med	B-988	0.0455	0.0014	<0.0001
	Med	C-1977	0.0296	0.0014	<0.0001
	Med	D-2965	0.0195	0.0014	<0.0001
	Med	E-3954	0.0173	0.0015	<0.0001
Teepee Pole	Flat	A-494	0.1125	0.0037	<0.0001
	Flat	B-988	0.1174	0.0041	<0.0001
	Flat	C-1977	0.1053	0.0042	<0.0001
	Flat	E-3954	0.0794	0.0055	<0.0001
	Flat	F-7907	0.0834	0.0075	<0.0001
	North	A-494	0.1348	0.0041	<0.0001
	North	B-988	0.1218	0.0040	<0.0001
	North	C-1977	0.0953	0.0048	<0.0001
	North	E-3954	0.0710	0.0059	<0.0001
	North	F-7907	0.0614	0.0071	<0.0001
MacKay	None	A-750	- ^a	-	-
	None	C-1680	0.1125	0.0028	<0.0001
	None	D-2990	0.0874	0.0017	<0.0001
	None	E-4330	0.0818	0.0022	<0.0001
	None	G-no_thin	0.0467	0.0018	<0.0001

^aDashes indicate non-estimable.

Pr > |t| = the probability of getting by chance, an absolute value of the t-statistic greater than the estimated value.

Table A10. Least-square means of quadratic mean diameter at the latest measurement for site and density treatments in four lodgepole pine precommercial thinning trials

Trial	Site	Density	Quadratic mean diameter, least square mean	Standard error	Pr > t
Gregg63	High	A-494	24.5585	0.4060	<0.0001
	High	B-988	21.7078	0.4060	<0.0001
	High	C-1977	19.9302	0.4060	<0.0001
	High	E-3954	16.8154	0.4060	<0.0001
	High	F-7907	16.3270	0.4060	<0.0001
	Low	A-494	17.9904	0.4060	<0.0001
	Low	B-988	16.2377	0.4060	<0.0001
	Low	C-1977	14.3177	0.4060	<0.0001
	Low	E-3954	11.5998	0.4060	<0.0001
	Low	F-7907	9.3868	0.4060	<0.0001
	Med	A-494	21.3413	0.4060	<0.0001
	Med	B-988	19.0388	0.4060	<0.0001
	Med	C-1977	15.5887	0.4060	<0.0001
	Med	E-3954	12.7927	0.4060	<0.0001
	Med	F-7907	11.5591	0.4060	<0.0001
Gregg84	High	B-988	15.0520	0.6887	<0.0001
	High	C-1977	13.8544	0.6887	<0.0001
	High	D-2965	12.2554	0.6887	<0.0001
	High	E-3954	11.8489	0.6887	<0.0001
	Low	B-988	9.8013	0.6887	<0.0001
	Low	C-1977	9.7005	0.6887	<0.0001
	Low	D-2965	8.9482	0.6887	<0.0001
	Low	E-3954	7.8276	0.6887	<0.0001
	Med	B-988	15.9203	0.6887	<0.0001
	Med	C-1977	13.5594	0.6887	<0.0001
	Med	D-2965	12.0924	0.6887	<0.0001
	Med	E-3954	11.7179	0.6887	<0.0001
Teepee Pole	Flat	A-494	23.9350	0.6513	<0.0001
	Flat	B-988	22.7180	0.6513	<0.0001
	Flat	C-1977	20.6854	0.6513	<0.0001
	Flat	E-3954	18.2856	0.6513	<0.0001
	Flat	F-7907	18.6064	0.6513	<0.0001
	North	A-494	25.4373	0.6513	<0.0001
	North	B-988	23.1622	0.6513	<0.0001
	North	C-1977	20.4226	0.6513	<0.0001
	North	E-3954	17.5938	0.6513	<0.0001
	North	F-7907	16.6397	0.6513	<0.0001
MacKay	None	A-750	25.1367	0.8681	<0.0001
	None	C-1680	20.5456	0.4708	<0.0001
	None	D-2990	18.4238	0.3329	<0.0001
	None	E-4330	17.6241	0.4708	<0.0001
	None	G-no_thin	14.6290	0.4708	<0.0001

Pr > |t| = the probability of getting by chance, an absolute value of the t-statistic greater than the estimated value.

Table A11. Least-square means of top height at the latest measurement for site and density treatments in four lodgepole pine precommercial thinning trials

Trial	Site	Density	Top height, least square mean	Standard error	Pr > t
Gregg63	High	A-494	16.4550	0.7275	<0.0001
	High	B-988	17.2900	0.7275	<0.0001
	High	C-1977	17.2800	0.7275	<0.0001
	High	E-3954	17.6000	0.7275	<0.0001
	High	F-7907	16.4833	0.7275	<0.0001
	Low	A-494	14.6900	0.7275	<0.0001
	Low	B-988	14.2400	0.7275	<0.0001
	Low	C-1977	15.1300	0.7275	<0.0001
	Low	E-3954	14.2000	0.7275	<0.0001
	Low	F-7907	12.9500	0.7275	<0.0001
	Med	A-494	15.7300	0.7275	<0.0001
	Med	B-988	16.1600	0.7275	<0.0001
	Med	C-1977	16.9200	0.7275	<0.0001
	Med	E-3954	13.6000	0.7275	<0.0001
	Med	F-7907	14.1833	0.7275	<0.0001
Gregg84	High	B-988	13.7350	0.6149	<0.0001
	High	C-1977	15.2500	0.6149	<0.0001
	High	D-2965	14.9250	0.6149	<0.0001
	High	E-3954	14.9333	0.6149	<0.0001
	Low	B-988	9.7750	0.6149	<0.0001
	Low	C-1977	9.9300	0.6149	<0.0001
	Low	D-2965	10.3125	0.6149	<0.0001
	Low	E-3954	10.0167	0.6149	<0.0001
	Med	B-988	15.2050	0.6149	<0.0001
	Med	C-1977	15.0600	0.6149	<0.0001
	Med	D-2965	15.6875	0.6149	<0.0001
	Med	E-3954	15.4167	0.6149	<0.0001
Teepee Pole	Flat	A-494	17.8275	0.8432	<0.0001
	Flat	B-988	19.5700	0.8432	<0.0001
	Flat	C-1977	20.7500	0.8432	<0.0001
	Flat	E-3954	19.2333	0.8432	<0.0001
	Flat	F-7907	19.6000	0.8432	<0.0001
	North	A-494	18.2775	0.8432	<0.0001
	North	B-988	18.7200	0.8432	<0.0001
	North	C-1977	19.1600	0.8432	<0.0001
	North	E-3954	19.4333	0.8432	<0.0001
	North	F-7907	18.8833	0.8432	<0.0001
MacKay	None	A-750	24.0084	0.6480	<0.0001
	None	C-1680	21.4122	0.3514	<0.0001
	None	D-2990	21.5068	0.2485	<0.0001
	None	E-4330	21.5373	0.3514	<0.0001
	None	G-no_thin	20.5968	0.3514	<0.0001

Pr > |t| = the probability of getting by chance, an absolute value of the t-statistic greater than the estimated value.

Table A12. Least-square means of basal area at the latest measurement for site and density treatments in four lodgepole pine precommercial thinning trials

Trial	Site	Density	Basal area/ha, least square mean	Standard error	Pr > t
Gregg63	High	A-494	14.3668	3.4923	0.0014
	High	B-988	22.4687	3.4923	<0.0001
	High	C-1977	24.6497	3.4923	<0.0001
	High	E-3954	33.9064	3.4923	<0.0001
	High	F-7907	47.7517	3.4923	<0.0001
	Low	A-494	12.6326	3.4923	0.0035
	Low	B-988	17.2861	3.4923	0.0003
	Low	C-1977	25.0309	3.4923	<0.0001
	Low	E-3954	32.8164	3.4923	<0.0001
	Low	F-7907	37.6420	3.4923	<0.0001
	Med	A-494	15.9823	3.4923	0.0006
	Med	B-988	25.5963	3.4923	<0.0001
	Med	C-1977	25.9626	3.4923	<0.0001
	Med	E-3954	32.7204	3.4923	<0.0001
	Med	F-7907	37.0898	3.4923	<0.0001
Gregg84	High	B-988	16.1352	1.4157	<0.0001
	High	C-1977	25.9257	1.4157	<0.0001
	High	D-2965	26.7695	1.4157	<0.0001
	High	E-3954	34.1786	1.4157	<0.0001
	Low	B-988	8.6569	1.4157	0.0002
	Low	C-1977	15.7086	1.4157	<0.0001
	Low	D-2965	18.4131	1.4157	<0.0001
	Low	E-3954	22.6937	1.4157	<0.0001
	Med	B-988	17.0792	1.4157	<0.0001
	Med	C-1977	25.4836	1.4157	<0.0001
	Med	D-2965	26.4581	1.4157	<0.0001
	Med	E-3954	32.4775	1.4157	<0.0001
Teepee Pole	Flat	A-494	17.7391	3.6126	0.0012
	Flat	B-988	25.4211	3.6126	0.0001
	Flat	C-1977	40.5193	3.6126	<0.0001
	Flat	E-3954	38.7231	3.6126	<0.0001
	Flat	F-7907	41.7250	3.6126	<0.0001
	North	A-494	16.6544	3.6126	0.0017
	North	B-988	29.1425	3.6126	<0.0001
	North	C-1977	31.2427	3.6126	<0.0001
	North	E-3954	31.9545	3.6126	<0.0001
	North	F-7907	39.1213	3.6126	<0.0001
MacKay	None	A-750	30.4309	2.7169	<0.0001
	None	C-1680	32.4315	1.4734	<0.0001
	None	D-2990	35.6562	1.0419	<0.0001
	None	E-4330	36.9787	1.4734	<0.0001
	None	G-no_thin	41.0658	1.4734	<0.0001

Pr > |t| = the probability of getting by chance, an absolute value of the t-statistic greater than the estimated value

Table A13. Least-square means of total stand volume at the latest measurement for site and density treatments in four lodgepole pine precommercial thinning trials

Trial	Site	Density	Total stand volume/ha, least square mean	Standard error	Pr > t
Gregg63	High	A-494	101.203	27.833	0.0034
	High	B-988	166.463	27.833	<0.0001
	High	C-1977	180.299	27.833	<0.0001
	High	E-3954	256.589	27.833	<0.0001
	High	F-7907	360.508	27.833	<0.0001
	Low	A-494	77.273	27.833	0.0168
	Low	B-988	106.025	27.833	0.0025
	Low	C-1977	157.784	27.833	0.0001
	Low	E-3954	197.914	27.833	<0.0001
	Low	F-7907	209.825	27.833	<0.0001
	Med	A-494	108.822	27.833	0.0021
	Med	B-988	180.999	27.833	<0.0001
	Med	C-1977	179.862	27.833	<0.0001
	Med	E-3954	210.857	27.833	<0.0001
	Med	F-7907	237.648	27.833	<0.0001
Gregg84	High	B-988	93.958	14.388	0.0001
	High	C-1977	171.302	14.388	<0.0001
	High	D-2965	170.302	14.388	<0.0001
	High	E-3954	215.069	14.388	<0.0001
	Low	B-988	32.297	14.388	0.0515
	Low	C-1977	63.712	14.388	0.0017
	Low	D-2965	76.144	14.388	0.0005
	Low	E-3954	89.605	14.388	0.0002
	Med	B-988	109.943	14.388	<0.0001
	Med	C-1977	172.217	14.388	<0.0001
	Med	D-2965	177.392	14.388	<0.0001
	Med	E-3954	215.755	14.388	<0.0001
Teepee Pole	Flat	A-494	129.788	33.084	0.0044
	Flat	B-988	211.559	33.084	0.0002
	Flat	C-1977	360.539	33.084	<0.0001
	Flat	E-3954	331.602	33.084	<0.0001
	Flat	F-7907	359.605	33.084	<0.0001
	North	A-494	129.792	33.084	0.0044
	North	B-988	241.133	33.084	<0.0001
	North	C-1977	259.109	33.084	<0.0001
	North	E-3954	266.734	33.084	<0.0001
	North	F-7907	315.563	33.084	<0.0001
MacKay	None	A-750	298.313	26.410	<0.0001
	None	C-1680	313.133	14.323	<0.0001
	None	D-2990	330.177	10.128	<0.0001
	None	E-4330	352.421	14.323	<0.0001
	None	G-no_thin	344.943	14.323	<0.0001

Pr > |t| = the probability of getting by chance, an absolute value of the t-statistic greater than the estimated value.

Table A14. Least-square means of merchantable volume (13/7 standard) at the latest measurement for site and density treatments in four lodgepole pine precommercial thinning trials

Trial	Site	Density	Merchantable volume/ha (13/7 standard), least square mean	Standard error	Pr > t
Gregg63	High	A-494	95.153	20.937	0.0007
	High	B-988	155.381	20.937	<0.0001
	High	C-1977	166.360	20.937	<0.0001
	High	E-3954	230.693	20.937	<0.0001
	High	F-7907	326.954	20.937	<0.0001
	Low	A-494	69.641	20.937	0.0060
	Low	B-988	94.588	20.937	0.0007
	Low	C-1977	130.139	20.937	<0.0001
	Low	E-3954	114.965	20.937	0.0001
	Low	F-7907	54.337	20.937	0.0234
	Med	A-494	101.618	20.937	0.0004
	Med	B-988	167.723	20.937	<0.0001
	Med	C-1977	157.149	20.937	<0.0001
	Med	E-3954	142.979	20.937	<0.0001
	Med	F-7907	135.626	20.937	<0.0001
Gregg84	High	B-988	77.364	21.499	0.0058
	High	C-1977	133.220	21.499	0.0002
	High	D-2965	107.972	21.499	0.0007
	High	E-3954	130.466	21.499	0.0002
	Low	B-988	11.860	21.499	0.5946
	Low	C-1977	24.894	21.499	0.2767
	Low	D-2965	21.869	21.499	0.3356
	Low	E-3954	12.986	21.499	0.5607
	Med	B-988	95.985	21.499	0.0016
	Med	C-1977	127.090	21.499	0.0002
	Med	D-2965	109.060	21.499	0.0007
	Med	E-3954	120.964	21.499	0.0003
Teepee Pole	Flat	A-494	121.506	28.971	0.0030
	Flat	B-988	199.972	28.971	0.0001
	Flat	C-1977	337.821	28.971	<0.0001
	Flat	E-3954	303.380	28.971	<0.0001
	Flat	F-7907	332.788	28.971	<0.0001
	North	A-494	122.815	28.971	0.0028
	North	B-988	228.014	28.971	<0.0001
	North	C-1977	241.979	28.971	<0.0001
	North	E-3954	237.835	28.971	<0.0001
	North	F-7907	280.514	28.971	<0.0001
MacKay	None	A-750	284.014	23.658	<0.0001
	None	C-1680	294.820	12.830	<0.0001
	None	D-2990	306.128	9.072	<0.0001
	None	E-4330	322.443	12.830	<0.0001
	None	G-no_thin	285.721	12.830	<0.0001

Pr > |t| = the probability of getting by chance, an absolute value of the t-statistic greater than the estimated value.

Table A15. Least-square means of merchantable volume (15/10 standard) at the latest measurement for site and density treatments in four lodgepole pine precommercial thinning trials

Trial	Site	Density	Merchantable volume/ha (15/10 standard), least square mean	Standard error	Pr > t
Gregg63	High	A-494	92.4132	18.7599	0.0004
	High	B-988	148.8566	18.7599	<0.0001
	High	C-1977	156.2299	18.7599	<0.0001
	High	E-3954	198.9437	18.7599	<0.0001
	High	F-7907	252.3556	18.7599	<0.0001
	Low	A-494	64.0780	18.7599	0.0051
	Low	B-988	80.0825	18.7599	0.0011
	Low	C-1977	96.3768	18.7599	0.0002
	Low	E-3954	48.1521	18.7599	0.0247
	Low	F-7907	8.3309	18.7599	0.6649
	Med	A-494	96.7229	18.7599	0.0002
	Med	B-988	154.3867	18.7599	<0.0001
	Med	C-1977	125.1965	18.7599	<0.0001
	Med	E-3954	93.5546	18.7599	0.0003
	Med	F-7907	81.4181	18.7599	0.0010
Gregg84	High	B-988	60.4672	18.4197	0.0095
	High	C-1977	93.2657	18.4197	0.0007
	High	D-2965	64.2910	18.4197	0.0068
	High	E-3954	61.5099	18.4197	0.0087
	Low	B-988	5.5547	18.4197	0.7698
	Low	C-1977	6.0567	18.4197	0.7498
	Low	D-2965	6.6836	18.4197	0.7251
	Low	E-3954	2.2844	18.4197	0.9040
	Med	B-988	78.2104	18.4197	0.0022
	Med	C-1977	84.8895	18.4197	0.0013
	Med	D-2965	52.0407	18.4197	0.0199
	Med	E-3954	59.3831	18.4197	0.0104
Teepee Pole	Flat	A-494	117.3641	23.1953	0.0010
	Flat	B-988	193.2319	23.1953	<0.0001
	Flat	C-1977	319.7477	23.1953	<0.0001
	Flat	E-3954	278.8595	23.1953	<0.0001
	Flat	F-7907	304.1387	23.1953	<0.0001
	North	A-494	119.8585	23.1953	0.0009
	North	B-988	220.9400	23.1953	<0.0001
	North	C-1977	227.4714	23.1953	<0.0001
	North	E-3954	210.6511	23.1953	<0.0001
	North	F-7907	234.9122	23.1953	<0.0001
MacKay	None	A-750	276.8220	22.5357	<0.0001
	None	C-1680	278.3855	12.2217	<0.0001
	None	D-2990	278.6498	8.6420	<0.0001
	None	E-4330	287.4046	12.2217	<0.0001
	None	G-no_thin	214.7190	12.2217	<0.0001

Pr > |t| = the probability of getting by chance, an absolute value of the t-statistic greater than the estimated value.

Table A16. Least-square means of mean annual increment of total stand volume over time for site and density treatments in four lodgepole pine precommercial thinning trials

Trial	Site	Density	Mean annual increment of total stand volume over time, least square mean	Standard error	Pr > t
Gregg63	High	A-494	1.6845	0.1165	<0.0001
	High	B-988	2.0066	0.1165	<0.0001
	High	C-1977	2.0648	0.1165	<0.0001
	High	E-3954	2.3769	0.1165	<0.0001
	High	F-7907	2.7477	0.1165	<0.0001
	Low	A-494	1.5498	0.1165	<0.0001
	Low	B-988	1.7110	0.1165	<0.0001
	Low	C-1977	1.9655	0.1165	<0.0001
	Low	E-3954	2.1419	0.1165	<0.0001
	Low	F-7907	2.1867	0.1165	<0.0001
	Med	A-494	1.7256	0.1165	<0.0001
	Med	B-988	2.0712	0.1165	<0.0001
	Med	C-1977	2.0542	0.1165	<0.0001
	Med	E-3954	2.1976	0.1165	<0.0001
	Med	F-7907	2.2931	0.1165	<0.0001
Gregg84	High	B-988	1.6650	0.0659	<0.0001
	High	C-1977	2.0543	0.0659	<0.0001
	High	D-2965	2.0526	0.0659	<0.0001
	High	E-3954	2.2488	0.0659	<0.0001
	Low	B-988	1.2686	0.0659	<0.0001
	Low	C-1977	1.4839	0.0659	<0.0001
	Low	D-2965	1.5606	0.0659	<0.0001
	Low	E-3954	1.6400	0.0659	<0.0001
	Med	B-988	1.7505	0.0659	<0.0001
	Med	C-1977	2.0613	0.0659	<0.0001
	Med	D-2965	2.0832	0.0659	<0.0001
	Med	E-3954	2.2490	0.0659	<0.0001
Teepee Pole	Flat	A-494	1.6579	0.1049	<0.0001
	Flat	B-988	1.9637	0.1049	<0.0001
	Flat	C-1977	2.4232	0.1049	<0.0001
	Flat	E-3954	2.3367	0.1049	<0.0001
	Flat	F-7907	2.4201	0.1049	<0.0001
	North	A-494	1.6567	0.1049	<0.0001
	North	B-988	2.0629	0.1049	<0.0001
	North	C-1977	2.1179	0.1049	<0.0001
	North	E-3954	2.1425	0.1049	<0.0001
	North	F-7907	2.2884	0.1049	<0.0001
MacKay	None	A-750	2.1776	0.0639	<0.0001
	None	C-1680	2.2058	0.0342	<0.0001
	None	D-2990	2.2528	0.0342	<0.0001
	None	E-4330	2.3128	0.0342	<0.0001
	None	G-no_thin	2.2917	0.0342	<0.0001

Pr > |t| = the probability of getting by chance, an absolute value of the t-statistic greater than the estimated value.

Table A17. Least-square means of mean annual increment of merchantable volume (13/7 standard) over time for site and density treatments in four lodgepole pine precommercial thinning trials

Trial	Site	Density	Annual increment of merchantable volume (13/7 standard) over time,		
			least square mean	Standard error	Pr > t
Gregg63	High	A-494	1.6516	0.0977	<0.0001
	High	B-988	1.9558	0.0977	<0.0001
	High	C-1977	2.0028	0.0977	<0.0001
	High	E-3954	2.2755	0.0977	<0.0001
	High	F-7907	2.6338	0.0977	<0.0001
	Low	A-494	1.5042	0.0977	<0.0001
	Low	B-988	1.6491	0.0977	<0.0001
	Low	C-1977	1.8342	0.0977	<0.0001
	Low	E-3954	1.7560	0.0977	<0.0001
	Low	F-7907	1.4036	0.0977	<0.0001
	Med	A-494	1.6872	0.0977	<0.0001
	Med	B-988	2.0120	0.0977	<0.0001
	Med	C-1977	1.9533	0.0977	<0.0001
	Med	E-3954	1.8972	0.0977	<0.0001
	Med	F-7907	1.8592	0.0977	<0.0001
Gregg84	High	B-988	1.5677	0.1152	<0.0001
	High	C-1977	1.8681	0.1152	<0.0001
	High	D-2965	1.7428	0.1152	<0.0001
	High	E-3954	1.8601	0.1152	<0.0001
	Low	B-988	1.1061	0.1152	<0.0001
	Low	C-1977	1.2107	0.1152	<0.0001
	Low	D-2965	1.1857	0.1152	<0.0001
	Low	E-3954	1.1158	0.1152	<0.0001
	Med	B-988	1.6728	0.1152	<0.0001
	Med	C-1977	1.8433	0.1152	<0.0001
	Med	D-2965	1.7453	0.1152	<0.0001
	Med	E-3954	1.7924	0.1152	<0.0001
Teepee Pole	Flat	A-494	1.6240	0.0957	<0.0001
	Flat	B-988	1.9234	0.0957	<0.0001
	Flat	C-1977	2.3590	0.0957	<0.0001
	Flat	E-3954	2.2548	0.0957	<0.0001
	Flat	F-7907	2.3439	0.0957	<0.0001
	North	A-494	1.6282	0.0957	<0.0001
	North	B-988	2.0195	0.0957	<0.0001
	North	C-1977	2.0631	0.0957	<0.0001
	North	E-3954	2.0499	0.0957	<0.0001
	North	F-7907	2.1841	0.0957	<0.0001
MacKay	None	A-750	2.1352	0.0505	<0.0001
	None	C-1680	2.1540	0.0270	<0.0001
	None	D-2990	2.1860	0.0270	<0.0001
	None	E-4330	2.2315	0.0270	<0.0001
	None	G-no_thin	2.1269	0.0270	<0.0001

Pr > |t| = the probability of getting by chance, an absolute value of the t-statistic greater than the estimated value.

Table A18. Least-square means of mean annual increment of merchantable volume (15/10 standard) over time for site and density treatments in four lodgepole pine precommercial thinning trials

Trial	Site	Density	Annual increment of merchantable volume (15/10 standard) over time, least square mean	Standard error	Pr > t
Gregg63	High	A-494	1.6365	0.0869	<0.0001
	High	B-988	1.9252	0.0869	<0.0001
	High	C-1977	1.9568	0.0869	<0.0001
	High	E-3954	2.1464	0.0869	<0.0001
	High	F-7907	2.3593	0.0869	<0.0001
	Low	A-494	1.4701	0.0869	<0.0001
	Low	B-988	1.5671	0.0869	<0.0001
	Low	C-1977	1.6590	0.0869	<0.0001
	Low	E-3954	1.3679	0.0869	<0.0001
	Low	F-7907	1.0728	0.0869	<0.0001
	Med	A-494	1.6606	0.0869	<0.0001
	Med	B-988	1.9509	0.0869	<0.0001
	Med	C-1977	1.8004	0.0869	<0.0001
	Med	E-3954	1.6418	0.0869	<0.0001
	Med	F-7907	1.5748	0.0869	<0.0001
Gregg84	High	B-988	1.4623	0.1164	<0.0001
	High	C-1977	1.6521	0.1164	<0.0001
	High	D-2965	1.4869	0.1164	<0.0001
	High	E-3954	1.4688	0.1164	<0.0001
	Low	B-988	1.0511	0.1164	<0.0001
	Low	C-1977	1.0554	0.1164	<0.0001
	Low	D-2965	1.0607	0.1164	<0.0001
	Low	E-3954	1.0211	0.1164	<0.0001
	Med	B-988	1.5675	0.1164	<0.0001
	Med	C-1977	1.6130	0.1164	<0.0001
	Med	D-2965	1.4067	0.1164	<0.0001
	Med	E-3954	1.4296	0.1164	<0.0001
Teepee Pole	Flat	A-494	1.6069	0.0791	<0.0001
	Flat	B-988	1.8995	0.0791	<0.0001
	Flat	C-1977	2.3066	0.0791	<0.0001
	Flat	E-3954	2.1803	0.0791	<0.0001
	Flat	F-7907	2.2588	0.0791	<0.0001
	North	A-494	1.6159	0.0791	<0.0001
	North	B-988	1.9958	0.0791	<0.0001
	North	C-1977	2.0152	0.0791	<0.0001
	North	E-3954	1.9600	0.0791	<0.0001
	North	F-7907	2.0426	0.0791	<0.0001
MacKay	None	A-750	2.1111	0.0394	<0.0001
	None	C-1680	2.1064	0.0211	<0.0001
	None	D-2990	2.1071	0.0211	<0.0001
	None	E-4330	2.1323	0.0211	<0.0001
	None	G-no_thin	1.9102	0.0211	<0.0001

Pr > |t| = the probability of getting by chance, an absolute value of the t-statistic greater than the estimated value.

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