FOREST GROWTH
ORGANIZATION OF WESTERN CANADA

Regenerated Lodgepole Pine Trial

Final Regeneration Phase Report

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Abstract

The FGrOW Regenerated Lodgepole Pine Trial was established in the year 2000 to monitor, under experimentally controlled conditions, the effects of planting, weeding, and pre-commercial thinning on the development of lodgepole pine stands following harvesting. This report summarizes analyses of data collected at the end of the trial's regeneration phase, between 2017 and 2020.

Planting of lodgepole pine improved stocking and increased projected growth and yield. On modal sites planted trees were often greatly outnumbered by natural regeneration; but on some sites, with either poor or nutrient-rich soils, planting was essential to achieve satisfactory re-stocking.

Herbicide application was demonstrated to be essential for restoration of pine on competitive sites, depending on levels of hardwood competition and associated site factors. It did not usually increase projected total timber production (pine plus hardwoods).

Pre-commercial thinning increased the growth of retained trees, especially in dense stands, and has good potential for reducing pine rotations. It is projected to increase mean annual volume increment of pine in stands with more than 6000 – 7000 stems per ha, and at lower densities in some situations. Thinning on competitive sites, in the absence of chemical hardwood control, was found to stimulate aspen suckering, with uncertain consequences for future stand development.

Responses to the treatments varied greatly depending on soil nutrient and moisture regimes, and other climatic, ecological and treatment factors. As a result, planting, weeding or thinning may be effective to meet management objectives on some sites, but unnecessary on others. A decision support tool has been developed to help managers apply the results to specific site and stand conditions.

Projections of the long-term effects of planting, weeding and thinning cannot currently be verified. Ongoing monitoring is essential to validate, defend and improve predictions over time. Recommendations are made for continued re-measurement of the trial during the growth phase of the rotation.

1 Introduction

The Foothills Growth and Yield Association (FGYA) established the Regenerated Lodgepole Pine (RLP) trial in the year 2000 to monitor, under experimentally controlled conditions, the effects of planting, weeding, and pre-commercial thinning on the development of lodgepole pine stands following harvesting.

The RLP trial consists of 102 installations planted with regular lodgepole pine nursery stock at six different target densities: 0, 816, 1111, 1600, 2500 and 4444 stems per ha. The installations are distributed across 10 forest management areas, with the number allocated to each approximately proportional to pine-leading area. All installations are located in Upper and Lower Foothills natural sub-regions, between latitudes 51.5 and 54.7 ^{O} N, and between elevations 840 and 1620 m above sea level. Figure 1 shows the layout of plots and sub-plots within installations. Each installation was split two ways to create 4 treatment plots: control (C), weed (W), thin (T), and weed-plus-thin (WT). Sixteen regeneration / sapling sub-plots, and 4 sub-plots for assessing top height, were placed in each treatment plot.

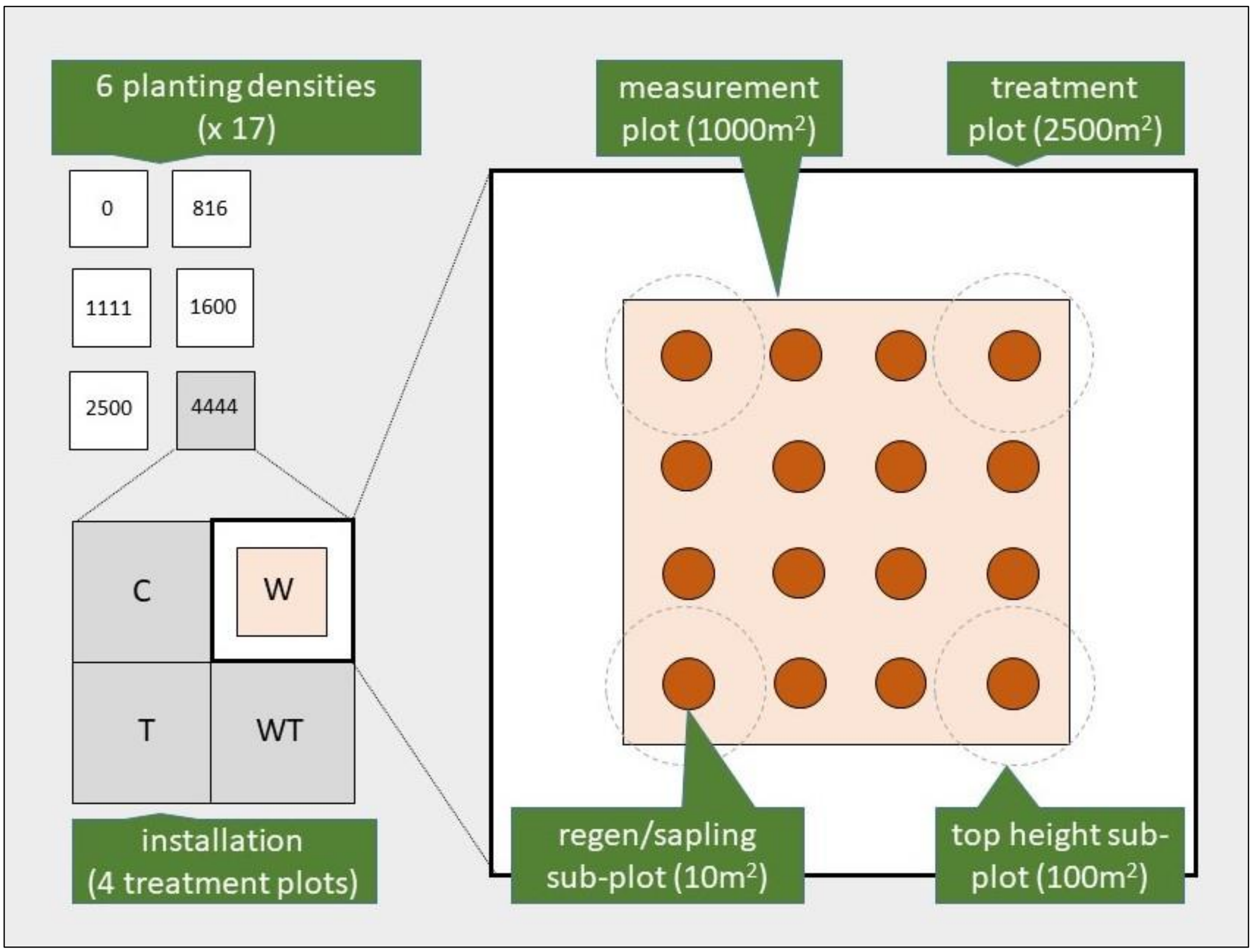

Figure 1. Layout of installations, treatment plots and sub-plots

The W and WT plots were weeded during the first 8 years after cut, as required to control non-tree vegetation and keep hardwood densities below 1000 stems per ha. Weeding usually involved chemical spraying at normal operational rates of glyphosate per ha on plots subject to hardwood competition; but was not required where competition was below threshold levels. Some plots, usually those with marginally competitive hardwood densities, were weeded manually.

The T and WT plots were thinned at stand ages between 11 and 15 years (average 13 years), when crowns were approaching closure and the average height of pine was 3 – 5 m. Where ingress of natural regeneration resulted in the target density being exceeded, planted installations were thinned to their target planting densities. In non-planted installations the target post-thinning density was set at 4444 stems per ha. Hardwoods and shrubs over 30cm in height were also cut down. Retained trees were, to the extent possible, well-spaced, healthy, co-dominant or dominant lodgepole pine with good form and vigour, and no serious disease or damage.

The trial was measured at two-year intervals throughout the first 18 years after cut. All planted trees throughout each 1000 m^2 measurement plot were checked for vigour, health and mortality, and natural regeneration was counted by species on the 16 sub-plots. During the first 14 years, detailed tree measurements were largely restricted to sub-samples of planted trees, except on non-planted installations where naturally regenerated pine was sampled. In 2015 an expanded protocol was introduced, involving detailed measurement of all live trees $\geq$ 1.3 m in height occurring on the 16 sub-plots, as well as continued tracking of all planted trees throughout the measurement plot. Measurements were made of top height on 100m^2 sub-plots as per the Regeneration Standard of Alberta[1]. The last complete set of measurements for all installations was acquired during 2017 and 2018, 17 growing seasons following planting and (on average) 18 years after harvest. Measurements for a further two years were acquired from a sub-set of plots, with emphasis on those occurring in stands with persistently high levels of aspen competition.

The following report focuses on analyses of the primary lodgepole pine stand component at the end of the regeneration phase of stand development. It includes assessments of conditions at the last full measurement (17 growing seasons after planting), rates of change (periodic annual increment) between growing seasons 15 and 19), and GYPSY[2] projections of future growth and yield. Description of earlier analyses of stand development, included in previous annual crop performance reports and published papers[3,4], will not be repeated in this report.

Results of the RLP trial regeneration phase, and data from other sources, have been consolidated into FRIPSY (Foothills Reforestation Interactive Planning System). This easy-to-use planning tool, run in Microsoft Excel, was developed to encourage and facilitate application of research undertaken by the FGrOW Foothills Pine Project. The analyses required to develop FRIPSY were more comprehensive in scope than those described in the following report. The system includes site preparation as well as density management. It contains sub-models for mortality, ingress, stocking, growth, secondary tree species, and western gall rust, which are described in detail in the user guide [5].

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[1] Alberta Environment and Sustainable Resource Development. (2021). *Reforestation standard of Alberta*. Government of Alberta Department of Agriculture and Forestry, Edmonton, Alberta.
[2] Huang, S., Meng, S., & Yang, Y. (2009). *A growth and yield projection system (GYPSY) for natural and post-harvest stands.* Alberta Sustainable Resource Development Tech. Report Pub. No. T/216, Edmonton, Alberta.
[3] Dempster, W.R., & Meredith, S. (2014). *A discussion of best management practices for reforestation following harvesting of lodgepole pine in the Alberta foothills.* Forestry Chronicle, 90:6, 763-770.
[4] Dempster, W.R. (2017) *Impact of climate on juvenile mortality and Armillaria root disease in lodgepole pine*. Forestry Chronicle, 93:12, 148-160.
[5] Dempster, W.R., Gulyas, G. (2021). *Foothills reforestation interactive planning system: user guide (version 210908).* At: https://fgrow.friresearch.ca/resource/foothills-reforestation-interactive-planning-system

2 Analytical methods

Treatment effects were analyzed with a mixed-effects analysis of variance (ANOVA) model. The REML (Restricted Maximum Likelihood) method was used for model fitting.[6] The RLP trial has a two-layered split-plot design. (In split-plot terminology, the installations are considered as "whole-plots" and the treatment plots as "sub-plots".) The effects of planting density were tested with respect to the variation from installation to installation. The effects of weeding and pre-commercial thinning were tested with the respect to the variation within installations. Note that in this design, the weeding and thinning effects use the residual error for the denominator of their F-statistics, whereas the F-statistics for the planting effect are tested against the nested effect of the installation within planting density. The installation effect was declared as random, while planting, weeding and thinning were all fixed effects.

Planting and thinning treatments are not independent of each other, because planted plots were thinned to the target planting density. This option was selected in the original experimental design and layout, because a full factorial design (i.e. with each planting density replicated against each post-thinning density) was not achievable. In order to distinguish planting from thinning effects, analyses of variance were conducted with and without splitting the data into thinned and non-thinned sub-sets.

Variables investigated and reported below are, unless otherwise stated, confined to lodgepole pine, and measured 17 full growing seasons after planting (on average 18 years after harvest). They include:

- Age: average total age, in years since germination, of the 100 largest-diameter stems per ha;
- Top height: average height of the 100 largest-diameter stems per ha;
- Average height: average total height of all trees $\geq$ 1.3 m in height;
- Live crown ratio: average ratio of crown length to total height;
- DBH: quadratic means diameter breast-height, measured 1.3 m above ground level;
- % stocking: percentage of $10m^2$ regeneration sub-plots occupied by at least on live tree $\geq$ 1.3 m in height;
- Density: number of live stems per ha $\geq$ 1.3 m in height;
- Basal area: total basal area per ha of live trees, measured at 1.3m above ground level.

Repeat measurements taken between 15 and 17 growing seasons after planting were used to examine rates of change in the above variables during the transition from regeneration to growth phases of stand development.

In addition, the following variables were projected by GYPSY from age, top height, % stocking, density, and basal area, measured as above;

- Site index: top height at 50 years breast-height age;
- MAI: maximum gross merchantable mean annual volume increment (15/10 utilization standard at culmination age);
- Culmination age: years after harvest at which MAI culminates.

[6] SAS Institute Inc. (2002*). Statistics and graphics guide*, version 5. Cary, NC.

Table 1. Treatment effects on lodgepole pine stand variables 17 growing seasons after planting – means and standard deviations

Variable	Thinning	Planting (target density) and weeding											
		0		816		1111		1600		2500		4444	
		No weed	Weed	No weed	Weed	No weed	Weed	No weed	Weed	No weed	Weed	No weed	Weed
Age	No thin	15.7	16.3	18.2	18.2	18.2	18.2	18.2	18.2	18.2	18.2	18.2	18.2
(years)		*2.7*	*1.6*	*0.5*	*0.5*	*0.5*	*0.5*	*0.5*	*0.5*	*0.5*	*0.5*	*0.5*	*0.5*
	Thin	15.8	16.5	18.2	18.2	18.2	18.2	18.2	18.2	18.2	18.2	18.2	18.2
		2.7	*1.9*	*0.5*	*0.5*	*0.5*	*0.5*	*0.5*	*0.5*	*0.5*	*0.5*	*0.5*	*0.5*
Top ht.	No thin	580	657	684	704	692	727	692	701	686	722	719	724
(cm)		*149*	*146*	*129*	*134*	*128*	*141*	*136*	*132*	*114*	*140*	*119*	*137*
	Thin	559	638	698	714	679	749	667	694	699	724	712	738
		155	*149*	*98*	*116*	*130*	*123*	*123*	*139*	*109*	*137*	*107*	*133*
Av. ht.	No thin	370	445	430	459	427	479	439	458	425	474	502	519
(cm)		*75*	*123*	*109*	*137*	*108*	*113*	*164*	*161*	*113*	*153*	*114*	*142*
	Thin	409	479	531	581	515	622	525	579	547	573	543	587
		121	*111*	*124*	*141*	*133*	*135*	*127*	*164*	*122*	*160*	*111*	*145*
Live	No thin	0.64	0.68	0.65	0.67	0.60	0.66	0.62	0.66	0.61	0.64	0.60	0.60
crown		*0.10*	*0.13*	*0.13*	*0.11*	*0.12*	*0.13*	*0.13*	*0.11*	*0.12*	*0.11*	*0.11*	*0.11*
ratio	Thin	0.74	0.75	0.82	0.84	0.76	0.81	0.79	0.79	0.76	0.76	0.68	0.68
		0.06	*0.07*	*0.08*	*0.08*	*0.11*	*0.07*	*0.10*	*0.11*	*0.08*	*0.09*	*0.11*	*0.11*
DBH	No thin	4.16	5.38	5.51	6.16	5.41	6.26	5.33	5.92	5.22	6.05	6.10	6.38
(cm)		*0.86*	*1.87*	*2.35*	*2.48*	*1.93*	*1.78*	*2.35*	*2.92*	*1.50*	*2.16*	*1.42*	*1.68*
	Thin	5.32	6.34	9.20	9.98	8.72	10.36	8.14	9.01	8.07	8.26	7.31	7.73
		1.81	*1.25*	*2.17*	*2.19*	*2.44*	*1.89*	*1.95*	*2.54*	*1.53*	*1.63*	*1.12*	*1.59*
%	No thin	75.4	83.3	87.9	84.8	79.3	93.0	90.6	96.5	91.4	96.9	96.5	99.2
stocked		*34.4*	*28.1*	*17.1*	*18.8*	*25.1*	*9.6*	*17.7*	*6.4*	*19.1*	*4.6*	*7.6*	*3.1*
	Thin	80.4	81.7	69.5	76.2	80.5	88.7	90.6	91.8	95.3	97.3	98.4	98.4
		29.9	*27.8*	*18.4*	*11.7*	*15.6*	*8.6*	*11.2*	*8.1*	*7.7*	*4.5*	*3.6*	*4.3*
Density	No thin	7858	8621	7954	6770	6878	7150	8797	8945	6689	7660	6551	7194
(trees per		*6213*	*7679*	*6794*	*5808*	*8001*	*6045*	*8857*	*7915*	*5441*	*5908*	*4447*	*4075*
ha)	Thin	3621	3517	906	962	1131	1239	1679	1718	2221	2486	3990	3828
		1824	*1827*	*302*	*218*	*333*	*243*	*345*	*245*	*550*	*273*	*687*	*444*
Basal	No thin	10.4	14.1	12.3	12.5	10.9	15.9	11.9	15.6	11.9	16.4	16.8	20.0
area		*7.8*	*8.2*	*8.1*	*6.6*	*7.7*	*6.5*	*7.4*	*5.1*	*7.2*	*5.9*	*5.9*	*6.4*
(m^2 / ha)	Thin	9.7	11.3	5.8	7.6	7.6	10.4	9.1	11.2	11.7	13.6	17.3	18.5
		6.1	*6.6*	*2.6*	*3.2*	*4.8*	*3.2*	*4.9*	*5.7*	*5.2*	*5.0*	*6.3*	*7.0*

3 Results and discussion

3.1 Effects of experimental treatments on regeneration performance

Table 1 summarizes means (normal text) and standard deviations (italics) by experimentally controlled treatments (planting, weeding and thinning) for pine stand variables measured at the end of the regeneration phase, 17 growing seasons after planting of the trial. (“Pine” from here on refers to lodgepole pine.)

Table 2 shows the significance probabilities (“Prob>F”) of the F-tests for the main treatment effects (planting density, weeding and thinning), and their interactions. Prob>F values of less than 0.05 are considered to indicate rejection of the null hypothesis (that there was no effect of the treatment, or combination of treatments, on the stand variable). Bolded values in the table highlight the significant effects and interactions. The second-order interaction (*Plant x Thin x Weed*) was not found significant for any response variable. The only first-order interaction to show high levels of significance was *Plant x Thin*. This interaction was attributable to the planting and thinning treatments not being independent of each other, as explained in Section 2. Tests for age were confined to non-planted installations, because ages on planted installations varied very little.

Table 2. Significance probabilities (Prob>F values) for treatment effects on regeneration

Effect	Age	Top ht.	Av. ht.	LCR	DBH	% stocked	Density	Basal area
Plant	n/a	0.0904	0.1691	0.0569	**0.0015**	**0.0002**	**0.0003**	**<.0001**
Weed	**0.0275**	**<.0001**	**<.0001**	**0.0015**	**<.0001**	**0.0003**	**0.0443**	**<.0001**
Thin	0.5311	0.8801	**<.0001**	**<.0001**	**<.0001**	0.0666	**<.0001**	**<.0001**
Thin*Weed	0.9183	0.4916	0.2021	0.0666	0.7299	0.3460	0.4580	0.1196
Plant*Weed	n/a	**0.0408**	0.2551	0.1153	0.265	0.2000	0.7331	0.5685
Plant*Thin	n/a	0.7474	**0.0044**	**<.0001**	**<.0001**	**0.0013**	**<.0001**	**0.0121**
Plant*Thin*Weed	n/a	0.9103	0.6987	0.9034	0.6816	0.3586	0.82	0.8292

3.1.1 Planting

Percent stocking of pine increased with planting density (see Figure 2). The effect was significant for both thinned and non-thinned plots, and influenced by site. Figure 3 contrasts stocking responses of planted and non-planted plots between soil nutrient classes.

The effect of planting density on overall density of pine 17 growing seasons after planting tended to be masked by generally high and variable amounts of natural regeneration. Although shown as significant in Table 2, the effect was not statistically significant when assessed only for non-thinned plots. Planting effects on average height and live crown ratio (LCR) were also non-significant, although the test value indicated marginal significance for the latter.

Planted plots had greater average top height and quadratic mean diameter (DBH) than did non-planted plots. The effect on top height was not quite significant when assessed across the whole experiment (as shown in Table 2), but was statistically significant in non-thinned plots. These effects were attributed to age differences, since they became non-significant when age was added to the ANOVA model.

Accumulation of pine basal area per ha increased with planting density in both thinned and non-thinned plots (see Figure 4).

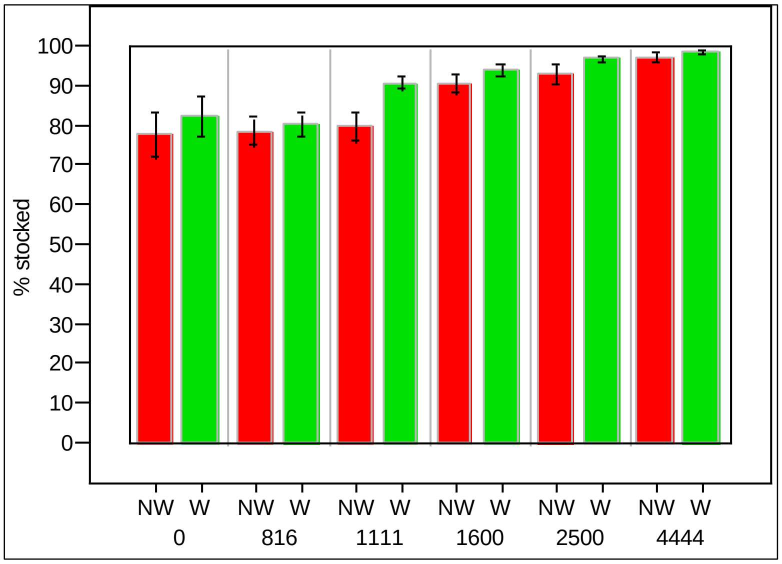

Figure 2. Effects of planting density and weeding on percent stocking
The target planting densities were 0, 816, 1111, 1600, 2500 and 4444 stems per ha. The weeding treatments are shown as NW (no weed) and W (weed). Average % stocking increased with planting density and weeding. The treatment effects were statistically significant and independent of each other.

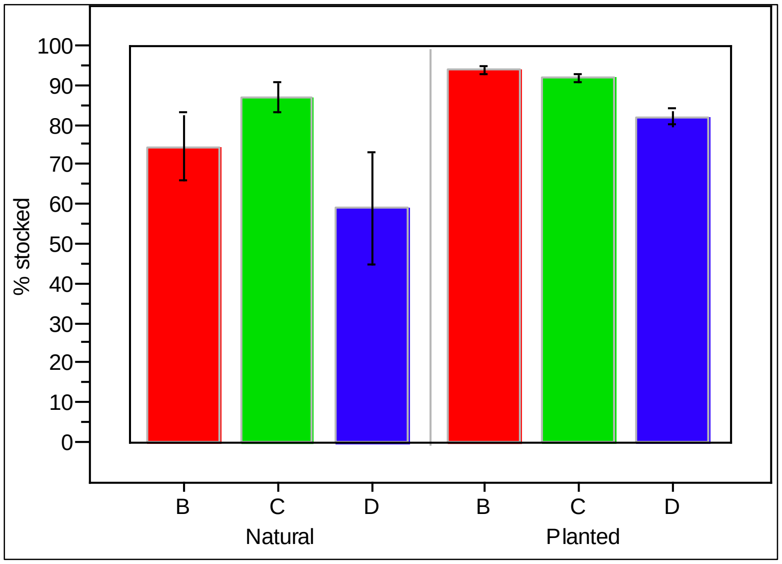

Figure 3. Influence of soil nutrient regime on response of percent stocking to planting
Percent stocking is shown averaged by soil nutrient class (B = poor, C = medium, D = rich) for non-planted ("natural") and planted plots (target densities 816 to 4444 stems per ha). Averages include both non-weeded and weeded plots.

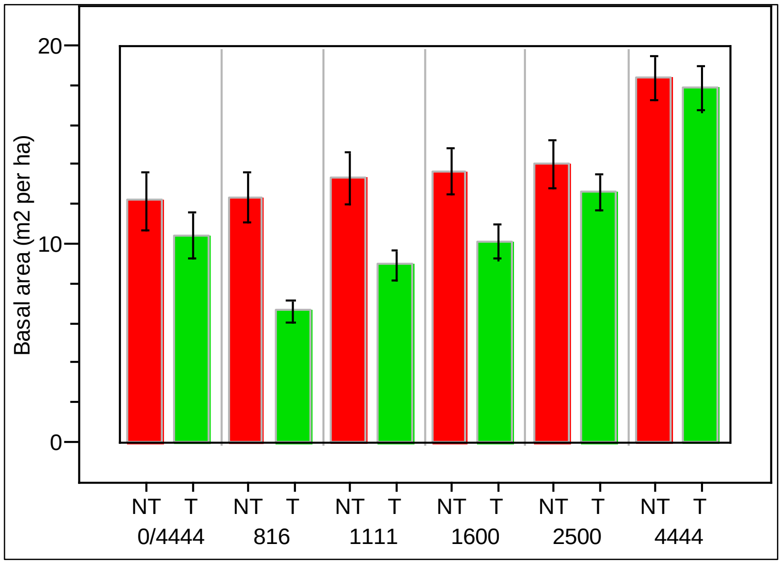

Figure 4. Effects of planting and thinning on basal area
The target planting densities were 0, 816, 1111, 1600, 2500 and 4444 stems per ha. Target post-thinning densities were the same, except for the non-planted ("0/4444") treatment, where the thinning target was 4444 stems per ha. The thinning treatments are shown as NT (no thin) and T (thin). Average basal area increased significantly with planting density in non-thinned plots, and with post-thinning density in thinned plots.

3.1.2 Weeding

Weeding significantly increased top height, average height, LCR, DBH, percent stocking, density and basal area. It also increased the average age (i.e. reduced the regeneration delay) of ingress occurring in non-planted installations.

The pine responses to weeding were related to aspen and balsam poplar competition. ("Aspen" from here on refers to combined aspen and balsam poplar.) Figure 5 compares average basal areas of non-weeded and weeded plots in installations with high and low densities of aspen in the control plots (i.e. treatment plots "C"). Figure 6 shows the zero-tending trend of pine basal area with aspen density for control plots with aspen densities exceeding 1000 stems per ha.

As mentioned previously, weeding in the RLP trial usually involved chemical spraying at normal operational rates of glyphosate per ha on plots subject to hardwood competition, but was not required where competition was below threshold levels; and some W or WT plots were weeded manually or not at all. Figure 7 illustrates the effect of weeding method (chemical, manual, none) on aspen density, comparing C and W plots. Where chemical treatment was considered unnecessary, and tending was either manual or not at all, little hardwood competition was evident in either the control or weeded plots. (No statistical difference in hardwood densities were found between control and weeded plots where the weeding method was either "manual" or "none".) In installations where chemical weeding was undertaken, the difference in hardwood densities between control and weeded plots was high in both magnitude and statistical significance.

It should be noted that, although weeding had positive effects on pine development, it reduced total basal area (pine plus aspen) in installations containing aspen (see Figure 8).

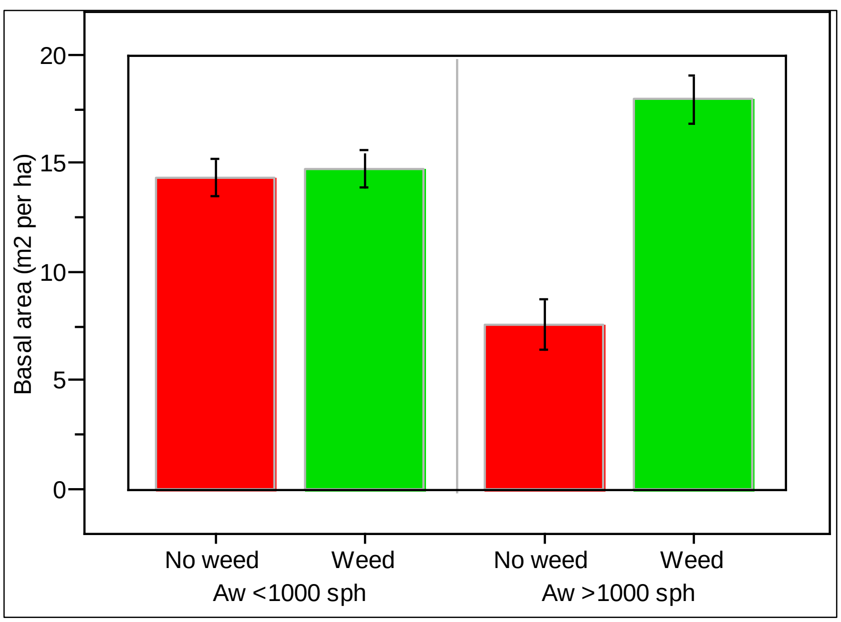

Figure 5. Influence of aspen competition on response of pine basal area to weeding
Average basal area of pine is shown averaged by weeding treatment in non-thinned plots. Averages are compared between stands with low (Aw <1000 sph) and higher (Aw >1000 sph) levels of aspen (Aw) competition, as indicated by the stems per ha (sph) of aspen occurring in the control plots.

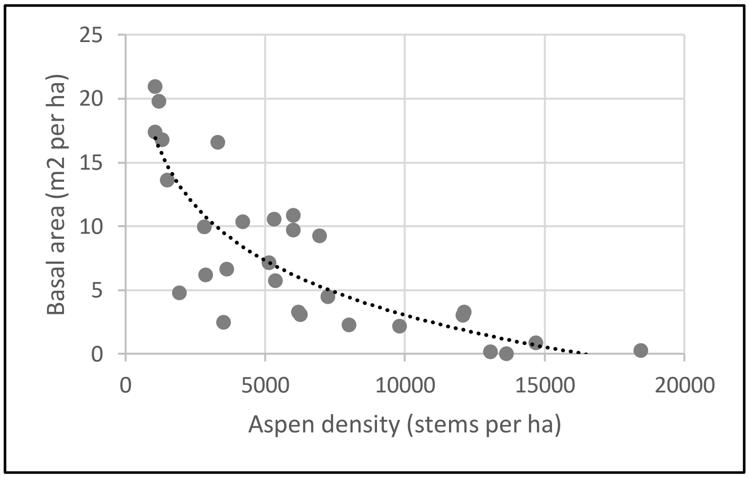

Figure 6. Trend of pine basal area with aspen density
Pine basal area is displayed on the Y-axis against aspen density (on the X-axis) for control plots with more than 1000 aspen stems per ha. Data points for individual plots are shown relative to a trend line based on the equation:
Y = 59.902 – 6.1721 (ln X)
(R^2 = 0.697)

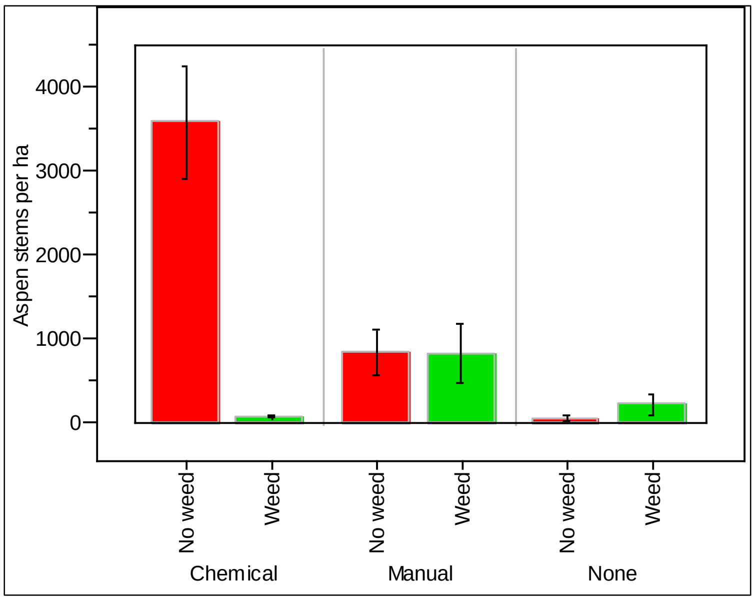

Figure 7. Effect of weeding method on aspen density
Average number of aspen stems (>1.3 m in height) are shown by weeding treatment (No weed, Weed), and weeding method (Chemical, Manual and None). Note that plots designated for weeding, that had very low aspen densities, were not required to be treated (method = None); and plots designated for weeding, with generally <1000 sph, were sometimes weeded manually instead of chemically.

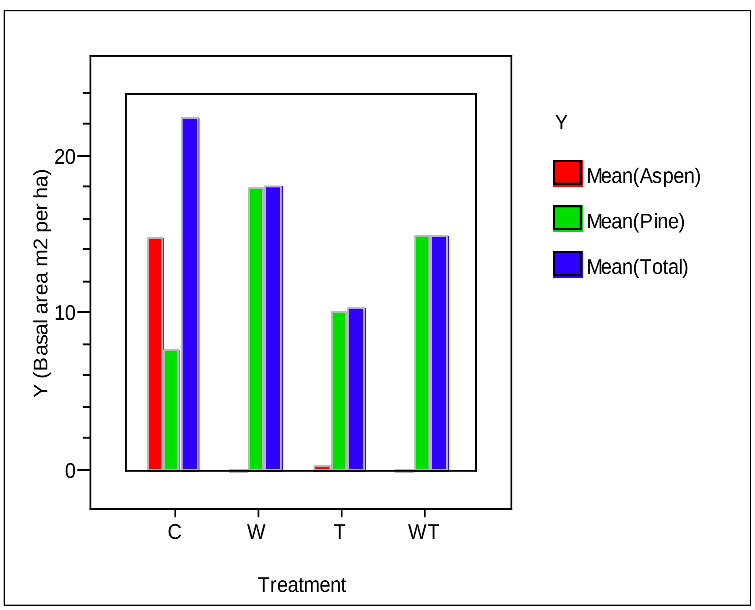

Figure 8. Effects of weeding and thinning on pine and aspen basal area
Average aspen, pine and total basal areas are displayed by treatment for installations where aspen exceeded 1000 stems per ha in the control plot. Treatments codes are: Control, Weed, Thin, and Weed-plus-Thin (WT).

3.1.3 Thinning

Significant effects of thinning were observed on DBH, LCR, average height, density and basal area. These variables also showed statistically significant interactions between planting and thinning (see Table 2). The nature of the interaction is illustrated in Figure 9 for DBH. The declining trend of DBH with target post-thinning density was statistically significant in thinned plots, but there was no significant trend of DBH with planting density in non-thinned plots. This result was interpreted to suggest a significant effect of thinning on DBH, but no demonstrated effect of planting density. Similarly, average height and LCR showed no significant trends with planting density in non-thinned plots, but were significantly increased by both thinning and weeding (see Figure 10), and inversely related to post-thinning density. The thinning treatment unsurprisingly reduced both density and basal area. The extent to which this effect may be compensated by increased tree growth is discussed below.

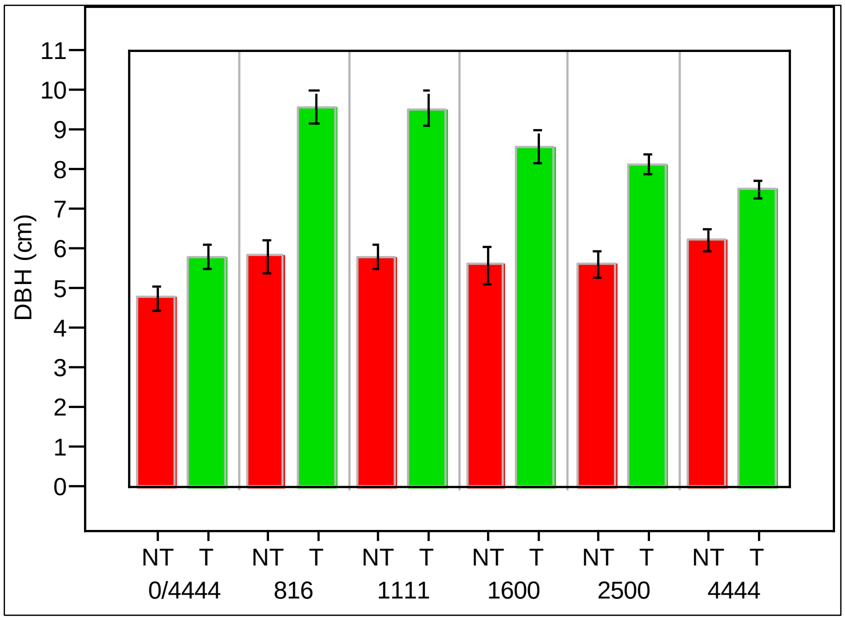

Figure 9. Effects of planting and thinning on tree diameter
The target planting densities were 0, 816, 1111, 1600, 2500 and 4444 stems per ha. Target post-thinning densities were the same, except for the non-planted ("0/4444") treatment, where the thinning target was 4444 stems per ha. The trend of quadratic mean diameter (DBH) with post-thinning target density in thinned (T) plots was significant; but there was no significant trend with target density in non-thinned (NT) plots.

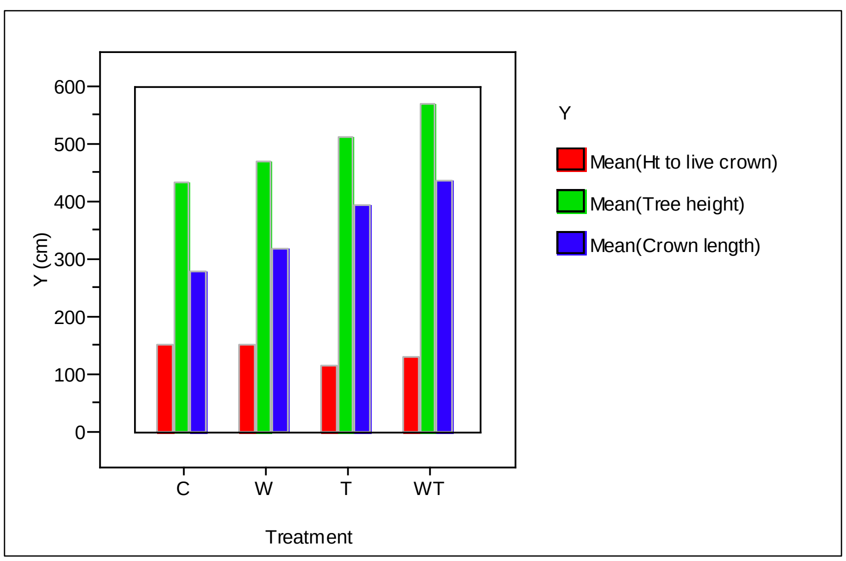

Figure 10. Effects of weeding and thinning on height and crown development
Treatment codes are: Control, Weed, Thin, and Weed +Thin (WT). Mean height and crown length significantly increased with both weeding and thinning. Crown recession, as indicated by means of height to live crown, was greater in non-thinned than thinned plots.

3.2 Rates of change during transition from regeneration to growth phases

The last two complete re-measurements of the trial allowed examination of periodic annual increments over the two-year period between 15 and 17 growing seasons after planting. No effects of planting were demonstrated. Annual increments are shown averaged by weeding and thinning treatment combinations in Table 3 (standard deviations are shown in italics).

Increases in growth increment shown by weeding for top height, average height, DBH and basal area per ha were all statistically significant, with and without taking age into account, and even though the short interval between measurements resulted in standard deviations being high.

Thinning increased DBH increment significantly. Basal area increment per ha remained lower in thinned versus non-thinned plots, indicating that the increase in diameter growth was not yet sufficient to offset the treatment's reduction of basal area. The rate of LCR decline in thinned plots was about half that in the non-thinned. The observed changes in stand density indicate that in non-thinned plots mortality exceeded any continued ingress; in thinned plots mortality and ingress were approximately balanced.

Table 3. Effects of weeding and thinning on periodic annual increment of lodgepole pine between 15 and 17 growing seasons after planting – means and standard deviations

Variable	No weed		Weed	
	No thin (C)	Thin (T)	No thin (W)	Thin (WT)
Top height (cm)	46.5	46.7	47.7	48.8
	15.7	*15.3*	*18.6*	*15.4*
Average height (cm)	32.2	33.3	37.6	39.9
	17.3	*17.6*	*20.1*	*16.8*
Live crown ratio	-0.04	-0.02	-0.04	-0.02
	0.03	*0.03*	*0.03*	*0.02*
DBH (cm)	0.35	0.52	0.40	0.53
	0.19	*0.20*	*0.19*	*0.17*
Density (stems per ha)	-100	29	-160	7
	579	*134*	*777*	*131*
Basal area (m^2 per ha)	1.40	1.29	1.66	1.40
	0.87	*0.69*	*0.86*	*0.71*

Significant changes were also observed in aspen over the same two-year period. Aspen densities were observed to be increasing in some thinned plots, rather than decreasing as observed in the control plots. Figure 11 shows average rates of change computed from a sub-set of plots where measurements were taken over a further two years (17 to 19 growing seasons after planting). The persistent and significant increase in density attributable to thinning would seem to suggest that thinning may extend the regeneration phase of aspen, with uncertain implications for pine development.

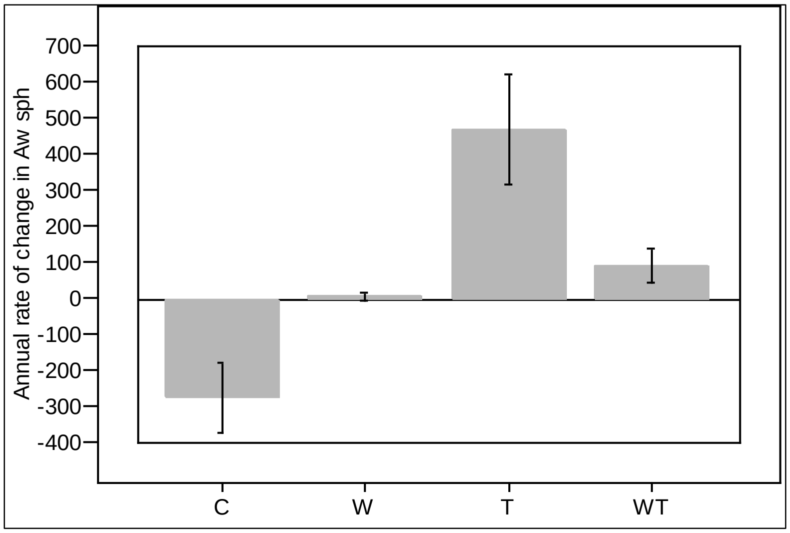

Figure 11. Effects of weeding and thinning on increment of aspen density late in the regeneration phase
Average rates of change computed for a sub-set of plots measured 17 to 19 growing seasons after planting (18 to 20 years since cut). Density increases in thinned plots (T), and decreases in control plots (C), were statistically significant.

3.3 Uncontrolled site and stand variables

The effects of experimental treatments were influenced and complicated by site and stand factors. Table 4 indicates co-variates that were found to be consistently significant when added to the ANOVA model. Categorical covariates included mechanical site preparation (drag scarification and mounding treatments prior to planting), and site classes based on ecosite classifications for west-central and southwestern Alberta.[7] Continuous covariates found to influence responses included elevation, latitude, organic soil depth, and ground cone density (measured after harvesting and site preparation, and before the experimental treatments).

Table 4. Site and stand factors influencing treatment response

Response variable	Categorical covariates				Other covariates				
	Prep	SNC	SMC	NSR	Elev	Lat	LFH	Slope	Cones
Top ht.		*	*		*			*	
% stocked	*	*	*				*		*
Density	*	*	*	*		*	*		*
DBH		*							

Prep = mechanical site preparation, *SNC* = soil nutrient class, *SMC* = soil moisture class, *NSR* = natural sub-region, *Elev* = elevation, *Lat* = latitude, *LFH* = depth of organic soil (litter, fungus, humus), *Slope* = percent slope, *Cones* = ground cone density at establishment.

Both top height and DBH increased from poor to rich soil nutrient classes. Top height was also affected by soil moisture, elevation, and slope. Percent stocking and density were both influenced by site preparation, soil conditions, and cone density. Pine density is predicated by the initial planting density, and the subsequent mortality of planted stock and ingress of natural regeneration. Uncontrolled variables found to influence planted stock mortality included natural sub-region, latitude, soil moisture, and site preparation. Variables influencing ingress included soil moisture and nutrient status, depth of organic soil, site preparation, and ground cone density.

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[7] Archibald, J. H., Klappstein, G. D., & Corns, I. G. (1996). *Field guide to ecosites of southwestern Alberta.* Special Report 8, Canadian Forest Service, Northwest Region, Northern Forestry Centre, Edmonton, Alberta.
- Beckingham, J. D., Corns, I. G., & Archibald, J. H. (1996). *Field guide to ecosites of west-central Alberta.* Special Report 9. Canadian Forest Service, Northwest Region, Northern Forestry Centre, Edmonton, Alberta.

3.4 Projections of future growth and yield

Table 5 summarizes means (normal text) and standard deviations (italics) by treatment combinations (planting, weeding and thinning) for pine site index, maximum mean annual volume increment (MAI), and age of MAI culmination, as projected by GYPSY from measurements taken 17 growing seasons after harvest. Table 6 shows significance probabilities ("Prob>F") of the F-tests for the treatment effects and their interactions. Bolded values in the table highlight the significant effects.

Projected MAI is predicted to increase significantly with planting density (see Table 5, and trend for non-thinned plots in Figure 12).

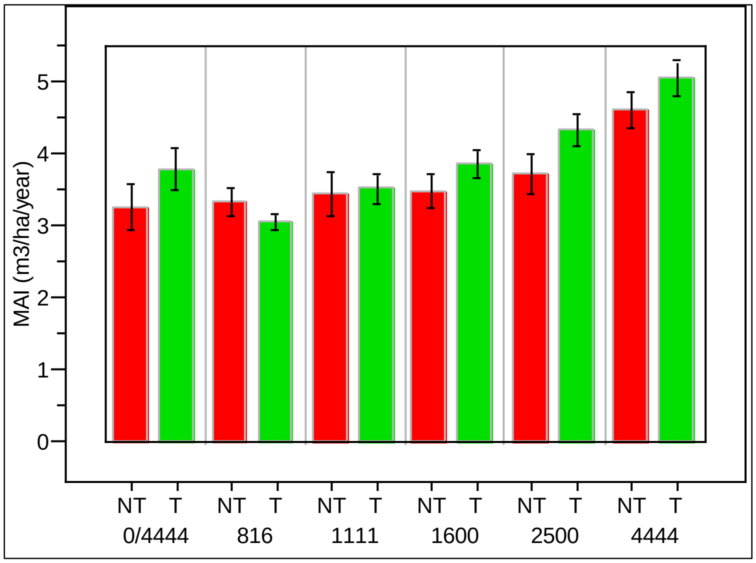


Figure 12. Projected effects of planting and thinning on mean annual increment
The target planting densities were 0, 816, 1111, 1600, 2500 and 4444 stems per ha. Target post-thinning densities were the same, except for the non-planted ("0/4444") treatment, where the thinning target was 4444 stems per ha. Averages of maximum mean annual increment (MAI) increase significantly with planting density in non-thinned (NT) plots, and with post-thinning density in thinned (T) plots.

Weeding is predicted to increase site index and MAI averages across all planting and thinning treatment combinations, and slightly reduces MAI culmination age (see Tables 5 and 6). The increases in site index are small but statistically significant. MAI increases are larger and also statistically significant. The decrease in culmination age is slight, and its overall statistical significance is marginal (prob>F = 0.0568). The large increases in MAI attributed to weeding may be explained by the relationship between MAI of pine and density of aspen (see Figure 13).

Pre-commercial thinning is predicted to substantially reduce MAI culmination age across all planting and weeding treatment combinations (see Tables 5 and 6). This may be largely attributed to the strong relationship shown in Figure 14 between culmination age and regeneration density. The relationship between MAI and regeneration density is more variable. Figure 15 shows the predicted trend of maximum MAI with regeneration density. Projected MAI increases with regeneration density to between 6000 and 7000 stems per ha, and then declines. Thinning is likely to be beneficial in stands with higher pine densities. It may also increase MAI in well-stocked planted stands having lower densities (see Figures 12 and 15).

Weeding and thinning under most site conditions are not predicted to increase total combined production of pine and aspen, and may decrease it (see Figure 16). The likely exceptions are where regeneration of tree cover is precluded by excessive grass, herbaceous or shrub competition. However, the incidence of these conditions was too irregular in the RLP trial to quantify or predict their effect. In stands subject to aspen competition, thinning is less beneficial for pine MAI than is chemical weeding.

Table 5. Effects of treatments on projected productivity of lodgepole pine: means and standard deviations

Variable	Thinning	Planting (target density) and weeding											
		0		816		1111		1600		2500		4444	
		No weed	Weed	No weed	Weed	No weed	Weed	No weed	Weed	No weed	Weed	No weed	Weed
Site index (m @ 50 years BH age)	No thin	20.0	20.9	19.7	20.2	19.8	20.4	19.9	20.0	19.7	20.4	20.3	20.4
		1.8	*2.8*	*2.6*	*2.4*	*2.5*	*2.5*	*2.6*	*2.4*	*2.2*	*2.5*	*2.3*	*2.4*
	Thin	19.3	20.3	20.1	20.4	19.7	20.9	19.3	19.9	20.0	20.4	20.2	20.6
		2.3	*2.7*	*2.1*	*2.2*	*2.5*	*2.3*	*2.5*	*2.4*	*2.1*	*2.5*	*2.0*	*2.3*
MAI (m^3/ha/year)	No thin	2.78	3.76	3.05	3.64	2.82	4.10	2.97	4.01	3.21	4.28	4.33	4.94
		2.78	*3.76*	*3.05*	*3.64*	*2.82*	*4.10*	*2.97*	*4.01*	*3.21*	*4.28*	*4.33*	*4.94*
	Thin	3.51	4.09	2.89	3.25	3.11	3.96	3.60	4.14	4.04	4.66	4.80	5.31
		3.51	*4.09*	*2.89*	*3.25*	*3.11*	*3.96*	*3.60*	*4.14*	*4.04*	*4.66*	*4.80*	*5.31*
Culm. age (years)	No thin	100	99	97	90	100	89	102	100	92	90	85	85
		17	*35*	*31*	*24*	*36*	*25*	*41*	*45*	*20*	*25*	*17*	*18*
	Thin	86	80	69	68	72	67	73	70	73	72	76	74
		15	*7*	*7*	*6*	*8*	*6*	*7*	*7*	*6*	*6*	*6*	*6*

Table 6. Significance probabilities (Prob>F values) for treatment effects on projected productivity

Effect	Site index	MAI	Culm. age
Plant	0.9801	**0.0002**	0.3436
Weed	**<.0001**	**<.0001**	0.0568
Thin	0.8135	**0.0052**	**<.0001**
Thin*Weed	0.5085	0.0847	0.8047
Plant*Weed	0.4208	0.6244	0.8617
Plant*Thin	0.2943	0.1290	**0.0220**
Plant*Thin*Weed	0.8873	0.9935	0.9168

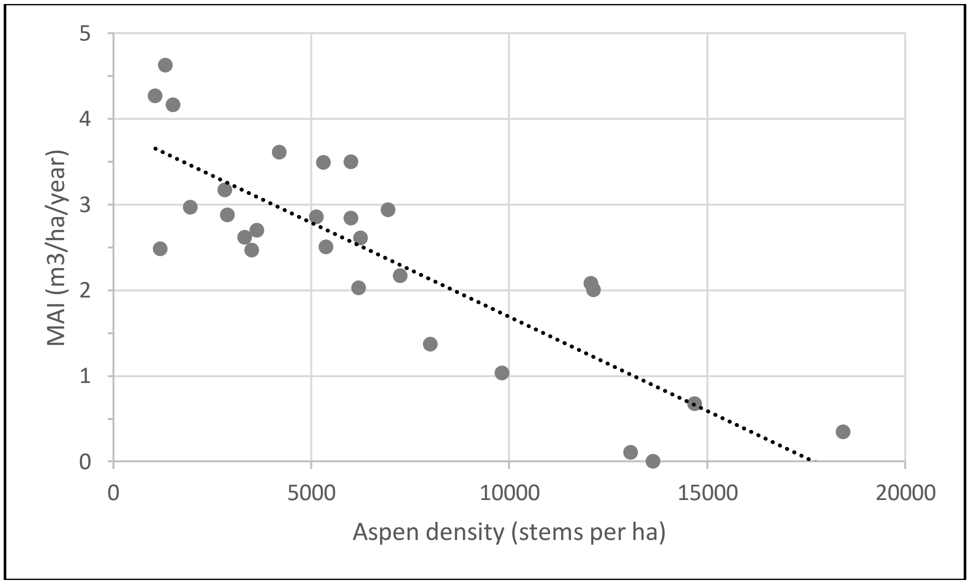


Figure 13. Trend of projected pine mean annual increment with aspen density
MAI is displayed on the Y-axis against aspen density at 17 growing seasons after planting (on the X-axis) for plots with more than 1000 aspen stems per ha. Data points for individual plots are shown relative to a trend line based on the equation: Y = 3.8882 – 0.0002 (X) (R^2 = 0.7112)

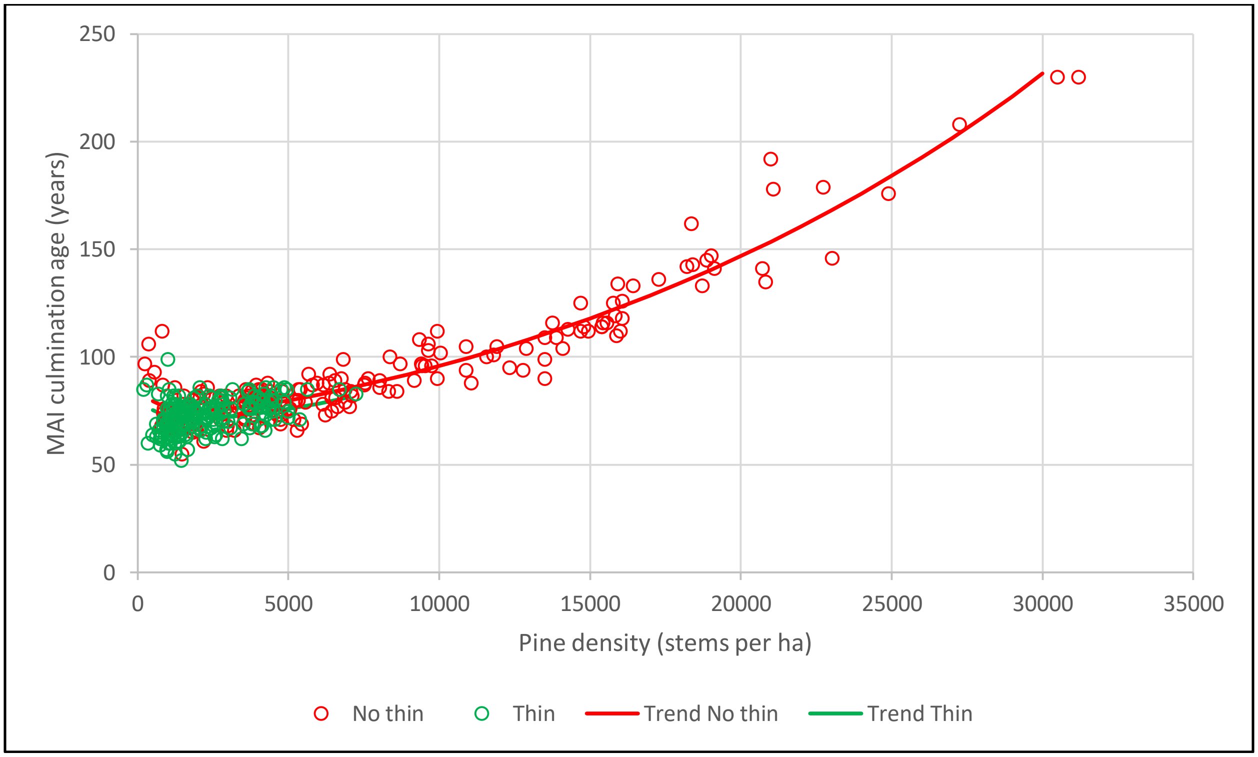


Figure 14. Trend of projected MAI culmination age with pine density
Culmination age of pine is displayed on the Y-axis against pine density at 17 growing seasons after planting (on the X-axis). Data points for individual plots are shown relative to trend lines based on the equation:

$$\ln Y = 4.9065 - 0.0937 (\ln X) + 0.00005 (X) + 0.0254 (\text{Thin[No]}) \quad (R^2 = 0.7914)$$

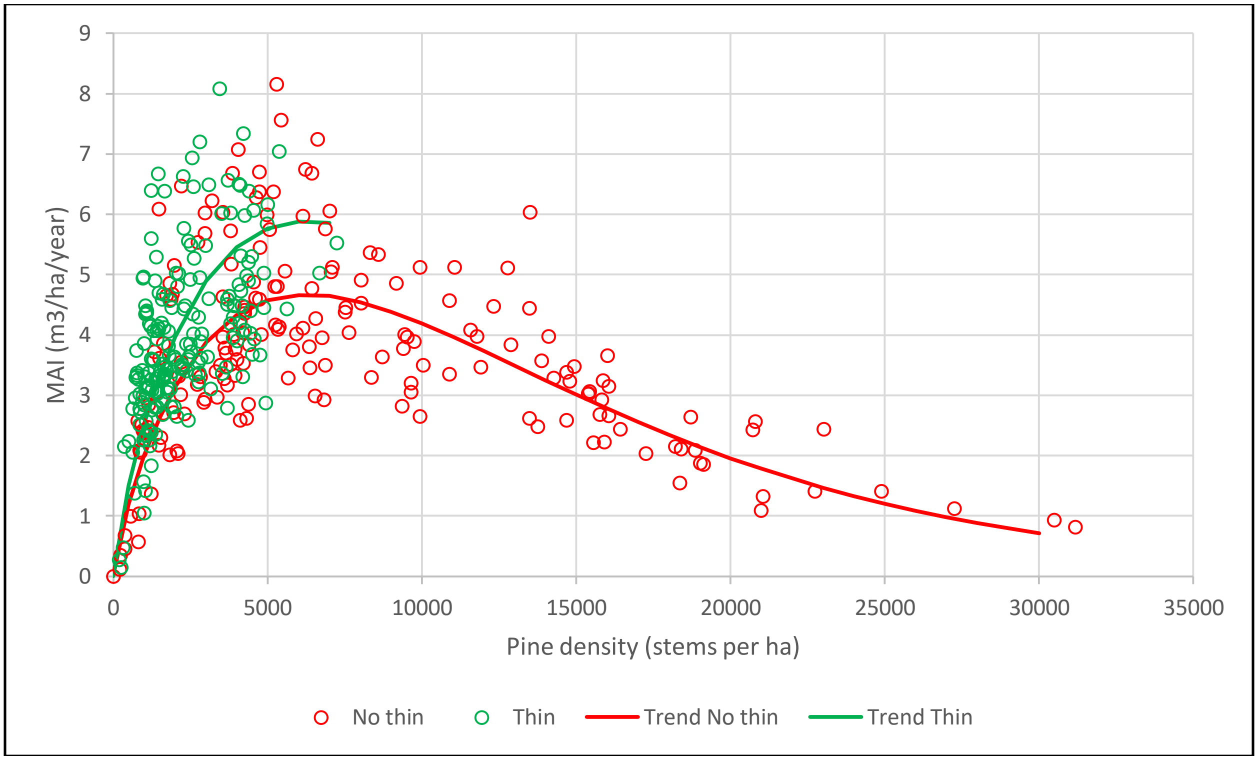


Figure 15. Trend of projected mean annual increment with pine density

Maximum MAI of pine is displayed on the Y-axis against pine density at 17 growing seasons after planting (on the X-axis). Data points for individual plots are shown relative to trend lines based on the equation:

ln Y = – 4.9274 + 0.8498 (ln X) – 0.00014 (X) – 0.1158 (Thin[No]) (R^2 = 0.0.6041)

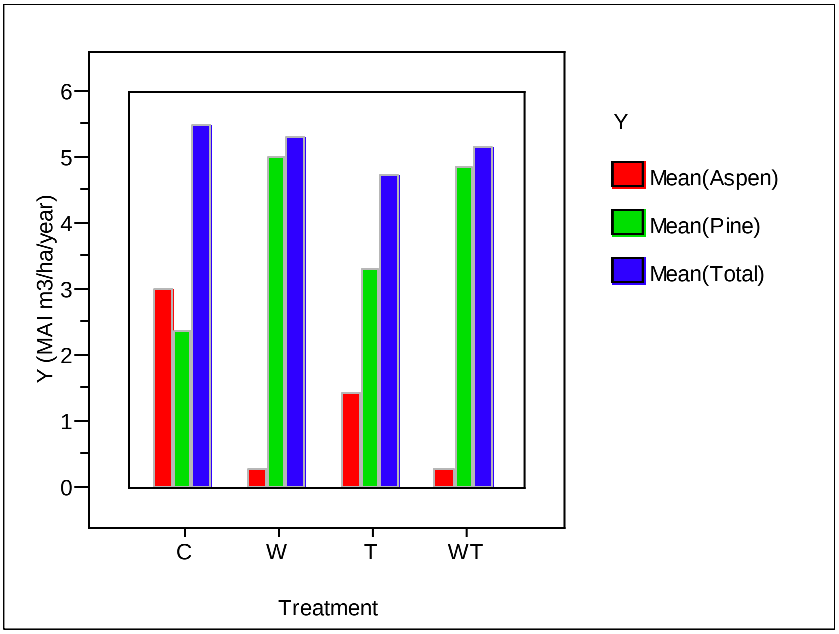


Figure 16. Effects of weeding and thinning on projected mean annual increment of pine and aspen

Averages of aspen and pine MAI's at age of pine culmination are displayed by treatment for installations where aspen exceeded 1000 stems per ha in the control plot. Treatments codes are: Control, Weed, Thin, and Weed +Thin (WT).

4 Conclusions and recommendations

4.1 Planting

On the most commonly occurring lodgepole pine site types, densities from natural regeneration exceed those achievable by planting, and planting may not be necessary. However, stocking of natural regeneration is variable. Planting improves site occupancy (i.e. it fills gaps that would otherwise occur in natural regeneration) and reduces the risk of reforestation failure. On some sites it may be essential to achieve satisfactory stocking, particularly those with either poor soil nutrient and moisture conditions, or with rich soils where the favourable nutrient status leads to high levels of inter-specific competition. Increasing planting densities improves the accumulation of basal area at the end of the regeneration phase, and this is predicted to result in increased mean annual volume increment throughout the rotation.

4.2 Weeding

Weeding under most site conditions is not expected to increase the total (combined) MAI of conifers and hardwoods, except where regeneration of tree cover is precluded by excessive grass, herbaceous or shrub competition. However, control of hardwoods is essential for restoration of pine on competitive sites, particularly lowland sites with high levels of aspen density. Chemical herbicide application is effective on such sites in improving survival, stocking and growth of pine. Weeding is seldom necessary for hardwood control on upland sites with medium to low soil nutrient status.

4.3 Pre-commercial thinning

Carefully planned pre-commercial thinning has the potential to accelerate growth and thereby shorten rotations, especially in dense stands, by providing more space for crown development and growth of retained trees. It can also increase MAI of pine in dense stands with more than 6000 – 7000 stems per ha, and may increase pine MAI at lower densities, particularly in planted stands where crop trees are well spaced. The increased rate of aspen suckering, observed following thinning of non-weeded plots, has uncertain consequences for future stand development, and requires ongoing monitoring.

4.4 Factors influencing treatment responses

Responses to the treatments described above vary greatly depending on soil nutrient and moisture regimes, and other climatic, ecological and treatment factors. As a result, planting, weeding or thinning may be essential to meet management objectives on some sites, but unnecessary or counter-productive on others. This report has focused on statistically testing the significance of treatment effects across a broad range of site and stand conditions. Readers interested in treatment responses to particular combinations of site and treatment factors are recommended to explore them with the FRIPSY regeneration model, as noted and referenced on page 3.

4.5 Continued monitoring

Measurements of the RLP trial have been completed for the entire regeneration phase of stand development. Results have provided insights, under controlled experimental conditions, into how pine regeneration develops in response to reforestation treatments. However, predictions of the long-term effects of these treatments currently relies on growth models like GYPSY, which are not based on controlled data definitively representing the different reforestation treatments. Ongoing monitoring is essential to verify, defend and improve predictions over time. Recommendations for achieving this have already been reviewed and approved by the FGrOW Foothills Pine Project Team, and are included in Appendix 1.

Appendix 1. Recommendations for continued re-measurement of the RLP trial (April 19, 2021)

Introduction

The Regenerated Lodgepole Pine (RLP) trial was established in 2000 to monitor, under experimentally controlled conditions, the effects of planting, weeding and pre-commercial thinning on the growth and yield of lodgepole pine regenerated after harvesting. At that time, the participating companies considered these effects to be the inadequately understood and therefore the highest priority for research by the newly formed Foothills Growth and Yield Association. During the 20 years since establishment of the trial, the project has focused on quantifying relationships between treatments, site and regeneration performance during the regeneration phase of stand development. This resulted in FRIPSY, which forecasts stand development to the end of the regeneration phase, and inputs the results into GYPSY, which projects growth and yield to rotation.

Having completed measurements and analyses for the entire regeneration phase of the rotation, the Foothills Pine Project Team now needs to consider what ongoing measurements are required for monitoring stand development during the growth phase. None of the models presently available for projection during the growth phase are based directly on controlled data representing different reforestation treatments. Ongoing monitoring is essential if we wish to verify, defend and improve predictions made by FRIPSY, GYPSY, or other growth models.

Objectives

1. Conduct sufficient and suitable re-measurements on an ongoing basis to verify predicted effects of reforestation treatments on growth and yield.
2. Adjust measurement procedures and schedules for this purpose, recognizing that those adopted for the regeneration phase are not all suitable or necessary for the growth phase.
3. Comply with minimum provincial standards for measuring permanent sample plots.
4. Minimize costs, within the constraints imposed by 1 to 3 above.

Current design

Figure 1 illustrates the RLP design as applied from establishment of the trial in 2000 to the latest measurements taken in 2020. Each installation was planted at one of 6 densities, and divided into 4 treatment plots. The 6 planting densities were replicated 17 times, resulting in a total of 102 installations.
A 1000m^2 measurement plot was placed centrally in each treatment plot, and sub-sampled with 16 circular 10m^2 sub-plots. All planted lodgepole pine within the measurement plot were tagged and assessed bi-annually for health and mortality. Natural regeneration in the 16 subplots was monitored by species for % stocking, density and height class. In addition, since 2015, all saplings and trees within the 16 sub-plots, plus sample planted trees previously designated outside the sub-plots, were assessed individually for species, height, DBH, DSH, crown class, height to live crown, and health. Top height and age was measured by species on 4 sub-plots, each 100m^2.

Recommendations

Figure 2 illustrates the recommended changes to the current design. The modified design relies largely on the existing plot layout and demarcation. The proposed reduction in the measurement plot size would require only two additional boundary posts per plot.

Figure 1. Current design (regeneration phase)

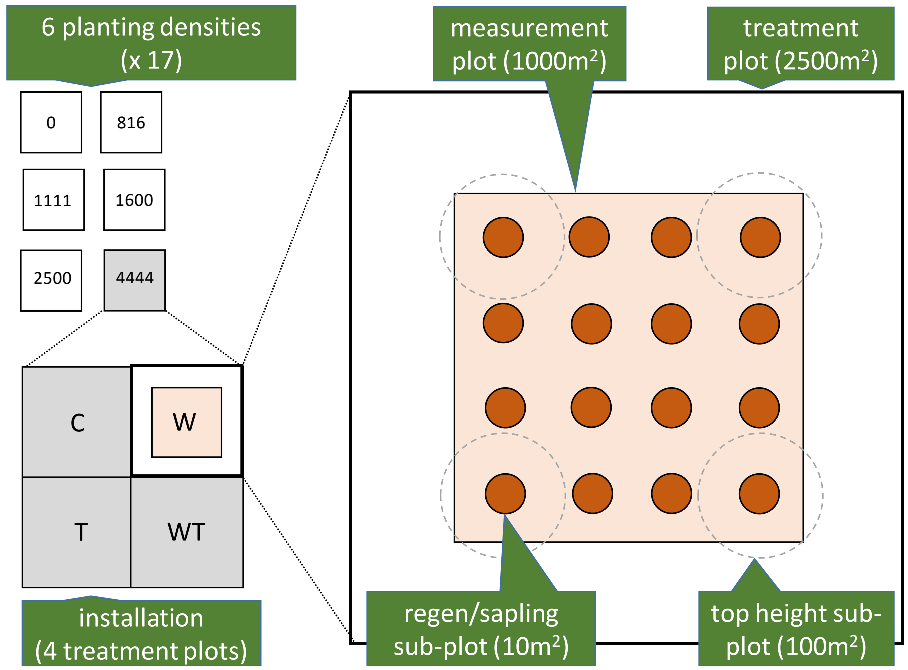
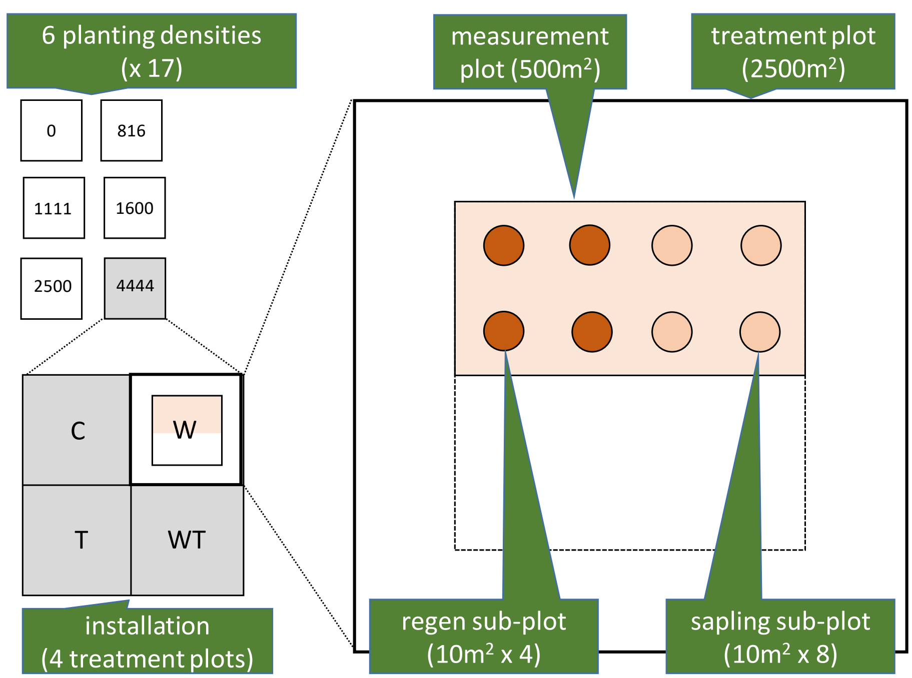


Figure 2. Recommended design (early growth phase)



The recommended standards and requirements for measurement are summarized as follows:

Plot sizes	
Tree (measurement)	500 m^2
Sapling	80 m^2 (8 x 10 m^2)
Regeneration	40 m^2 (4 x 10 m^2)
Tagging limits	
Trees	>5 cm DBH
Saplings	$\geq$1.3 m in height
Seedlings	$\geq$ 0.3 m in height (conifers only)
Ages and top height	
Selection	5 largest DBH trees per species
Planted trees	Height only (age is known)
Natural regeneration	Height and age
Tree and sapling measurements	
DBH	All trees and saplings on respective plots
Height	Every 4^{th} tagged tree or sapling on respective plots
Tree condition code	All trees and saplings on respective plots
Seedling measurements	
Count by species	All seedlings on regeneration plots
Height	Maximum 10 trees per species
Tree condition code	Maximum 10 trees per species

Table 1 indicates the estimated average number of trees, saplings and seedlings to be sampled. The estimates are based on the last measurements made on 53 installations measured in 2019 and 2020, 20 years after harvest. Actual numbers of trees measured will obviously vary between installations and over time. Nevertheless, the table indicates that the proposed plot design should result in an adequate, but not excessive, number of trees being measured during the early part of the growth phase. Reversion to the original tree plot size of 1000m^2 may be necessary at later stages of the rotation, depending on the extent to which self-thinning reduces stand densities.

Table 1. Estimated average number of trees, saplings and seedlings to be sampled per installation

Treatment	Pine			All species		
plot	Trees	Saplings	Seedlings	Trees	Saplings	Seedlings
Control	98	34	2	182	49	6
Thin	79	4	3	80	25	5
Weed	138	33	2	140	38	6
Weed & Thin	89	3	3	91	6	6
Average per plot	101	19	3	123	30	6
Total per installation	404	74	10	493	118	23

A re-measurement interval of 5 years is suggested. Some flexibility could be provided by permitting installations to be measured a year before or after the default scheduled year. Ensuring that all plots on all installations are adequately demarcated and maintained should be given high priority, to allow for the extended measurement interval and to prevent irreversible loss of future measurement opportunities. This would include maintenance of the original buffer and plot corner posts. Tree tagging, and centre stakes for sapling and regeneration sub-plots, need be retained, and refreshed as necessary, only within the revised 500m^2 tree measurement plots.