Regenerated Lodgepole Pine Trial

CROP PERFORMANCE REPORT
18-YEAR RESULTS

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FOREST GROWTH
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Abstract

Between 2015-2018 all 102 installations of the FGrOW Regenerated Lodgepole Pine (RLP) trial were each re-measured at the ends of the 15th and 17th growing seasons following planting. An expanded measurement protocol introduced in 2015 allowed current annual increment and other changes in stand conditions to be assessed in more detail than had been previously possible. The measurements provided, for the first time, an opportunity to investigate thinning response. This report describes growth and yield responses to experimentally controlled silvicultural treatments, including projections of future mean annual increment at culmination age.

Analyses of stand development to date and current rates of change in stand conditions quantified responses to planting (at a range of densities from 0 to 4,444 trees per ha), weeding (chemical and mechanical vegetation control during establishment phase), and pre-commercial thinning (including mechanical hardwood removal).

Projections of future growth suggest that substantial potential gains in timber yield, and reductions in rotations, are possible, especially as the result of competition control brought about by weeding and thinning in high density stands and stands subject to hardwood competition. However, repeat measurements over a two-year period indicated that some projections are not stable and can change progressively over time. The instabilities are confined to certain stand conditions and at least partially explainable; and recommendations are made for rectifying them.

Suggestions are made for finalization of the FRIPSY regeneration model representing the regeneration phase of the RLP trial now ending, and for transition of the RLP trial for ongoing monitoring of stand development during the growth phase.

1. Introduction

The Regenerated Lodgepole Pine (RLP) trial was established between 2000 and 2002 to assess site and treatment effects on stand development following harvesting and planting of lodgepole pine. It was laid out on a split-plot design involving 102 whole-plots (“installations”) established at six different planting densities. Each installation is divided into four tending treatment plots.

During the four-year period 2015-2018, all installations were each re-measured at the end of the 15th and 17th growing seasons following planting. The measurements provided, for the first time, an opportunity to investigate thinning response, and to assess current annual increment and other changes in stand conditions since an expanded measurement protocol was introduced in 2015.

The scope of this report is limited to the dynamics of lodgepole pine and aspen (the latter including balsam poplar as well as trembling aspen). The main objective and focus are to assess:

1. Growth and yield responses to controlled treatments: planting density, weeding and pre-commercial thinning, including mean annual increment as projected by GYPSY;
2. The stability of growth and yield projections to the age of MAI (merchantable mean annual increment) culmination;

and the implications of these responses for development of FRIPSY[1] (including incorporation of GYPSY[2]) and continuation of the RLP trial. Responses to site factors have been addressed previously[3], and will be investigated and documented in more detail before the finalization of FRIPSY. A previous attempt was also made to assess the stability of MAI projections by GYPSY[3], but the results were based on a small number of simulations, and possibly biased by the sampling of pine ingress growth being limited to trees selected at an early stage of natural regeneration. The current attempt reported here was based on a large number of GYPSY simulations and entirely on the refined measurement protocol introduced in 2015, with projections being made for 408 treatment plots from each of the two identical re-measurements, with and without the basal area adjustment option offered by GYPSY.

Results are presented below for:

- Stand development to date;
- Latest rates of change (as represented by the periodic annual increment of stand and tree variables measured over the two-year period between the ends of the 15th and 17th growing seasons);
- Projected growth and yield (including changes between projections based on the 15th and 17th growing season measurements).

A mixed-effects split-plot model was used to analyse the significance of effects. The model has two layers: the between-installation planting density effect, and the within-installation tending effects. Planting densities were 0, 816, 1111, 1600, 2500 and 4444 stems per ha. The tending treatments are annotated as C (control), W (weed), T (thin), and WT (weed and thin). Changes in variables between repeated measurements were also examined by matched pairs analysis. Differences between means of treatment levels were evaluated by the Tukey-Kramer HSD (honestly significantly difference) test.

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[1] Dempster, W.R., & Gulyas, G. FRIPSY: *Foothills reforestation interactive planning system - technical description and user’s guide.* July 2017. Forest Growth Organization of Western Canada.

[2] Huang, S., Meng, S., & Yang, Y. (2009). *A growth and yield projection system (GYPSY) for natural and post-harvest stands in Alberta.* Alberta Sustainable Resource Development Technical Report Pub. No. T/216.

[3] *Regenerated lodgepole pine trial crop performance report – 16-year results*, March 2018.

2. Stand development to date

Statistics were extracted from the latest plot measurements made during 2017 and 2018 (17 growing seasons after planting) on 94 installations each containing 4 treatment plots. (Eight installations with historic treatment violations were excluded.) Average stand age (the greater of growing seasons since germination of planted stock or operating years since cut) is 18 years. Average numbers of years since weeding and thinning are 13 and 5 respectively. Trends were investigated for total age (of site trees selected for top height measurement), top height, percent stocking, density, basal area per ha, and average tree height and diameter.

Total age

- Average age of planted pine is constant at about 18 years; ingress averages 16 years;
- Aspen age is affected by weeding and thinning (C > W > T, WT) – see Figure 1.

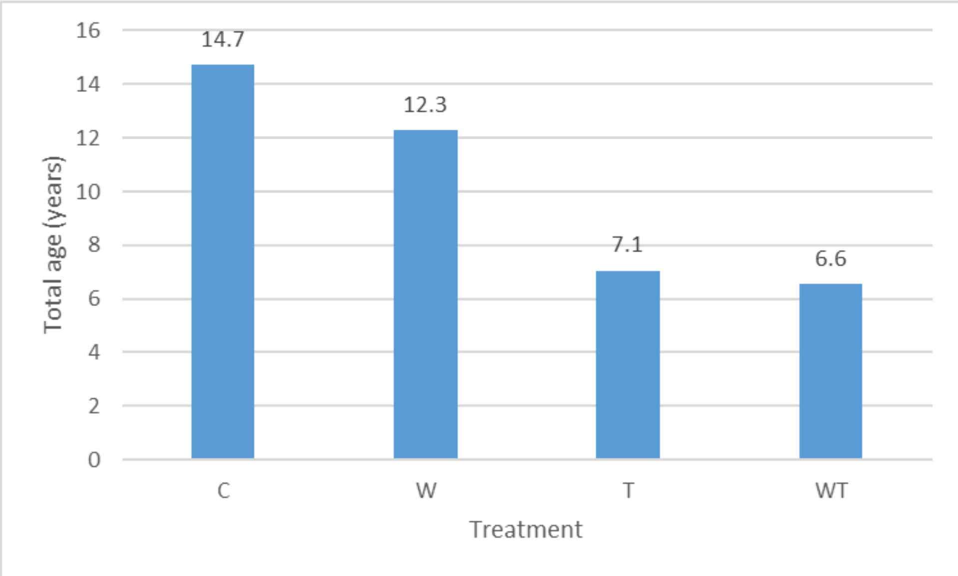


Figure 1. Average total age of aspen by tending treatment

Top height

- No significant planting density effect and no difference between planted stock and ingress were found;
- Pine shows a small but significant average response to weeding, but not to thinning – see Figure 2;
- Aspen shows a response to weeding and thinning that parallels age differences shown in Figure 1.

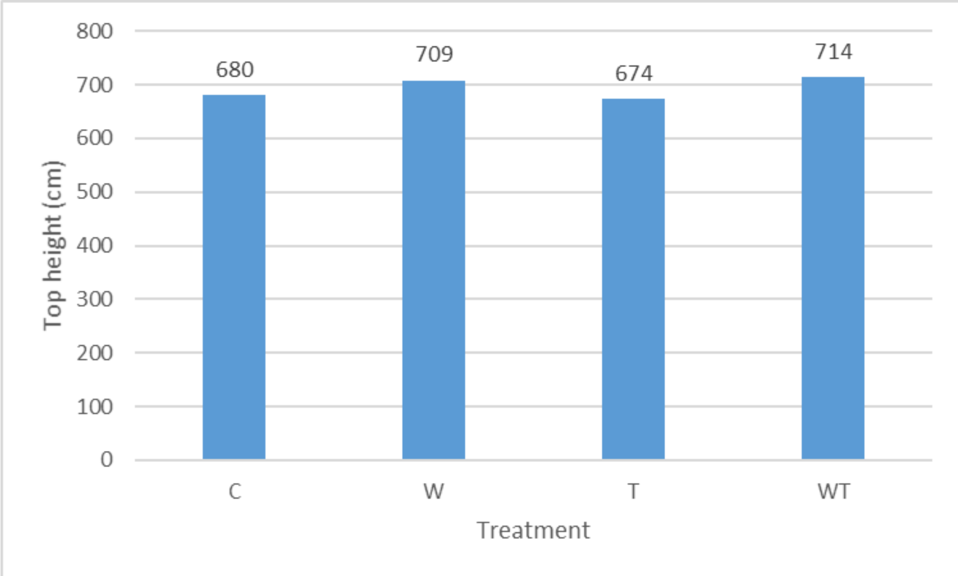


Figure 2. Average top height of pine by tending treatment

Percent stocking

- Average stocking of pine increases with planting density, from 81% in non-planted plots to 98% at the 4444 stems per ha density;
- Average pine stocking is slightly higher in weeded versus non-weeded treatments (W, WT > C, T); there is no thinning effect;
- Aspen stocking is affected by weeding and thinning (C > T > W, WT) – see Figure 3.

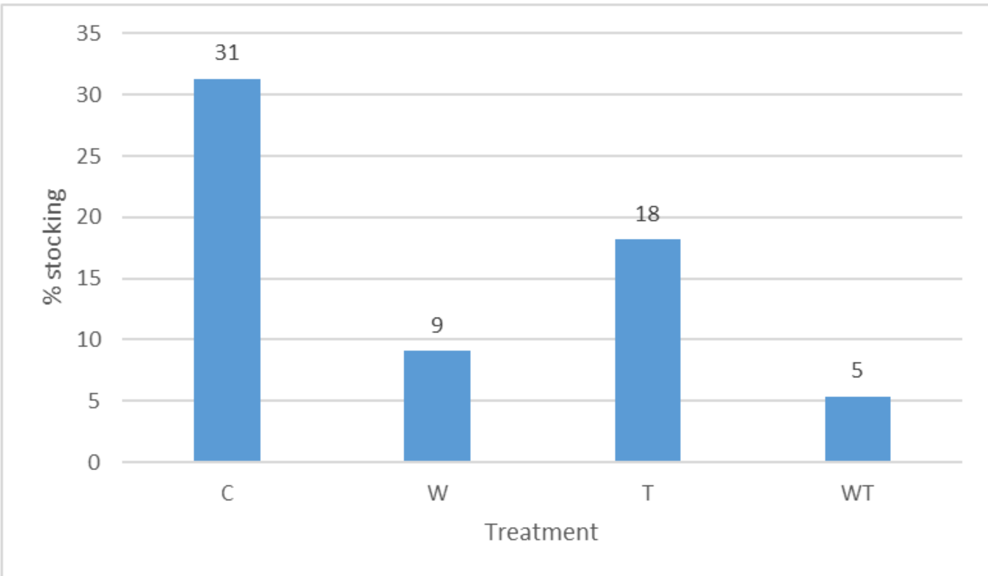


Figure 3. Average percent stocking of aspen by tending treatment

Stand density

- The effect of planting density is not statistically significant! This probably reflects the masking effect of ingress density, which is highly variable, and the reduction in ingress densities at the higher planting densities owing to intra-specific competition.
- Pine shows the expected effects of low-thinning, but no significant weeding response;

- Aspen density is greatly affected by weeding and thinning (C > T > W, WT). The response is shown in Figure 4 averaged across installations most likely to be subject to aspen competition, as evidenced by the control plot having more than 1000 stems per ha of aspen. About 30 installations meet this condition.

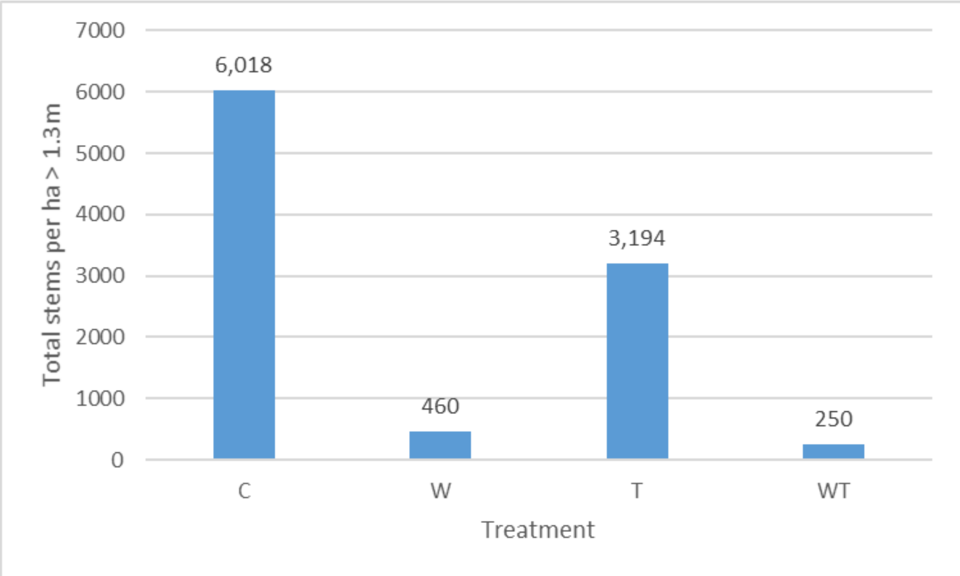


Figure 4. Average density of aspen by tending treatment in installations with more than 1000 stems per ha in control plot

Basal area

- Pine basal area is affected by weeding and thinning (W > C, WT > T) – see Figure 5, and increases with planting density;
- Average aspen basal area is far higher in the control plots than in the treated plots (C > W, T, WT). In the treated plots the aspen regrowth is generally too young to yet have much basal area, and averages less than 0.3 m^2 per ha.

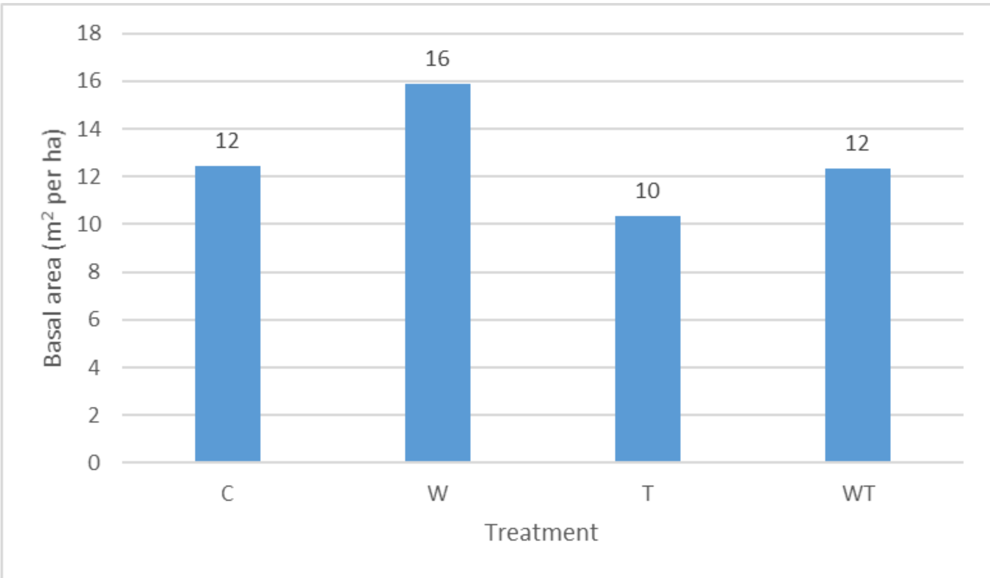


Figure 5. Average basal area per ha of pine by tending treatment

Average tree diameter

- Planting and tending effects interact in pine – see Figure 6; the main significant differences being:
    - between treatments (WT > T > W > C);
    - between planting densities (0 < 816,1111).
- Aspen average diameter is reduced by both weeding and tending (C > W > T, WT) – see Figure 7.

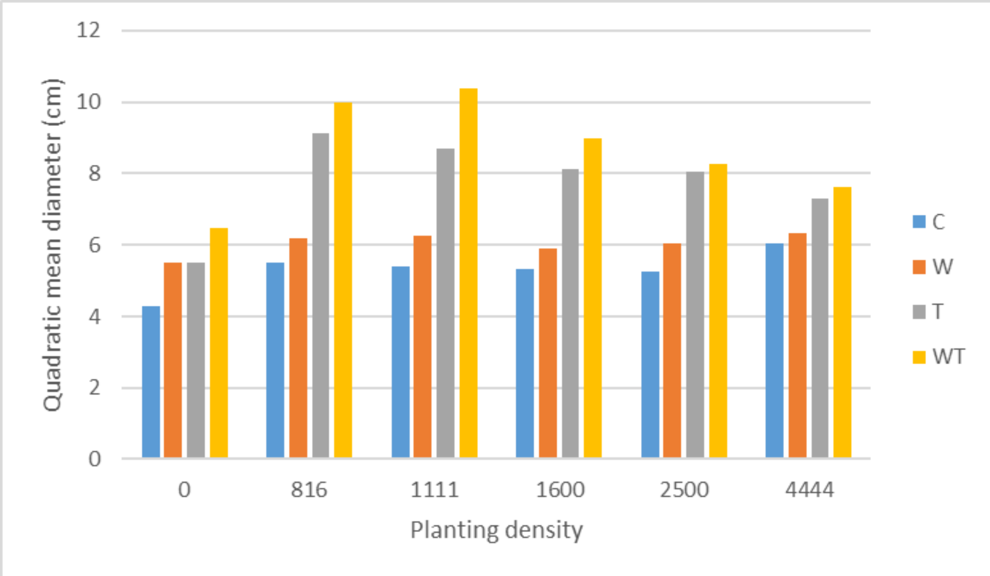


Figure 6. Average pine diameter by planting density and tending treatment

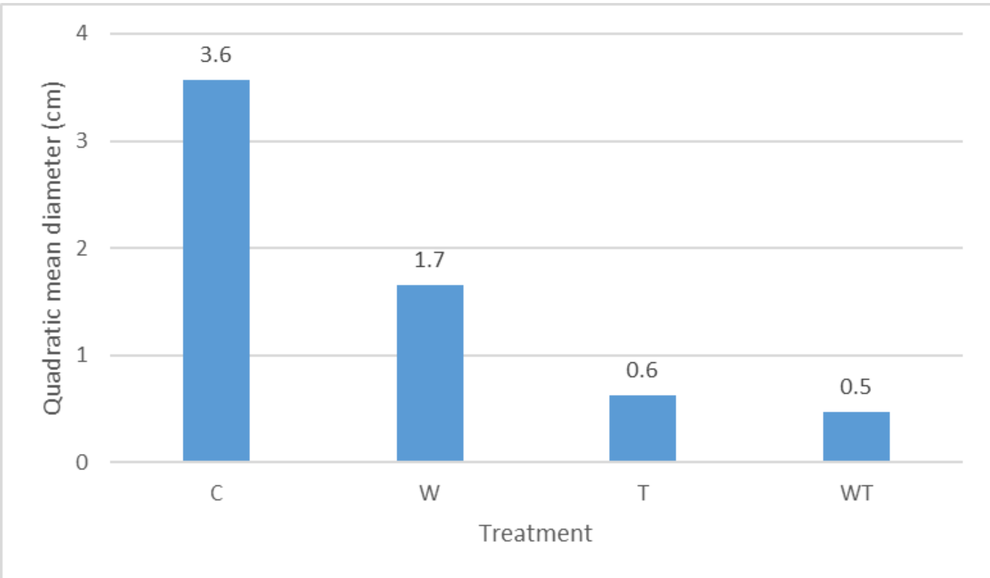


Figure 7. Average aspen diameter by tending treatment

Average height

- Pine shows a weak planting density x treatment interaction, with average height in trees > 1.3m in height tending to be lower in non-planted plots;
- Pine average height increases with weeding and thinning (WT > T > W > C) – see Figure 8;
- Aspen average height decreases with weeding and thinning (C > W > T, WT) – see Figure 9.

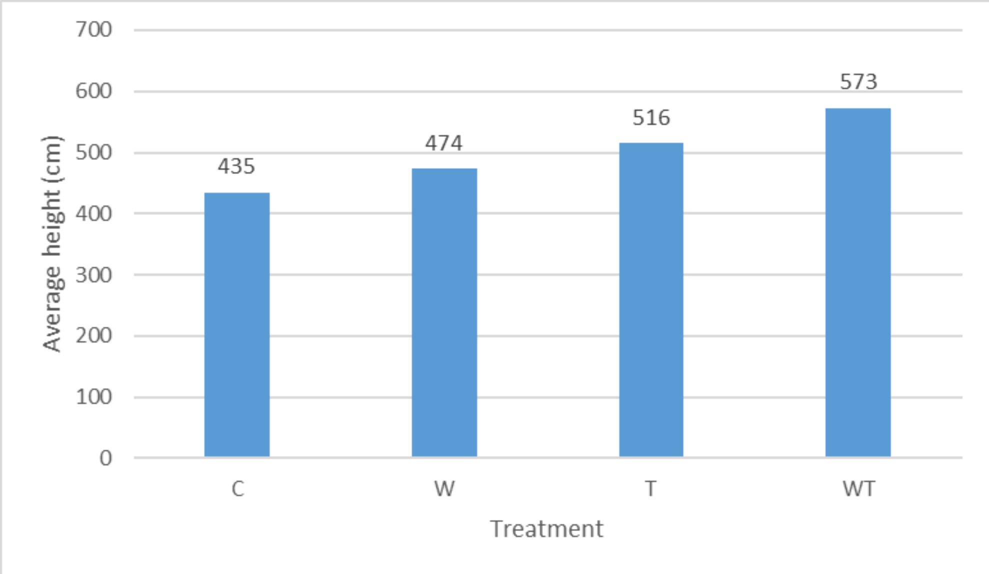


Figure 8. Average pine height by tending treatment

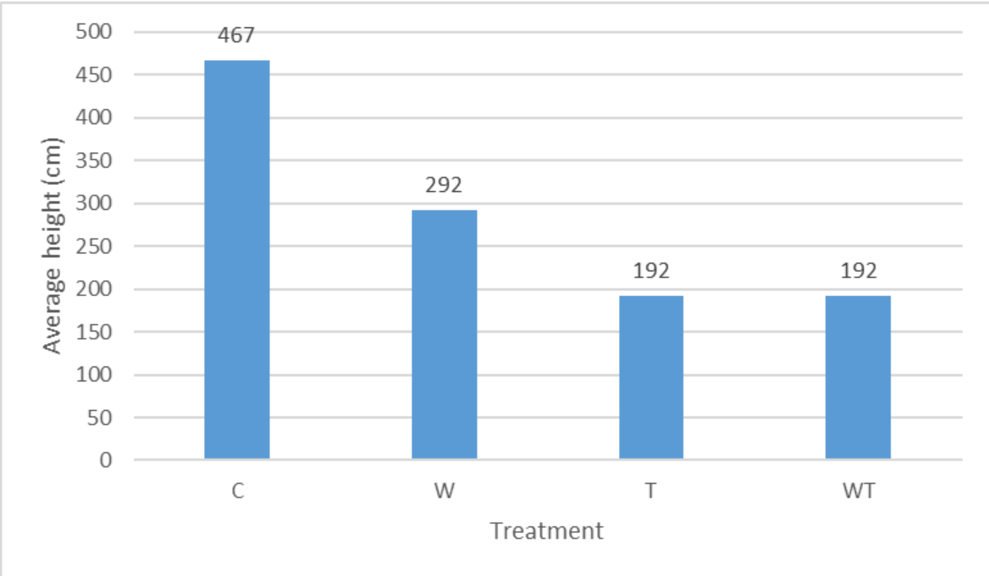


Figure 9. Average aspen height by tending treatment

3. Rates of change

The above results reflect the combined direct effects of treatments in adding and removing trees from the stand, and the stand responses to these changes. In order to better understand the responses, rates of change in stand variables were calculated over the two-year re-measurement period between growing seasons 15 and 17. Because exactly the same procedures were used at each measurement, sensitive assessment of changes in stand conditions was possible.

3.1 Net change

Net changes at the stand level are the combined effects of ingress, mortality and growth.

Top height and age

- Significant top height increment differences were not detected between treatments;
- Age increment differences were not observed in aspen or in planted pine;
- In naturally regenerated pine on non-planted plots, average age was observed to increase by 0.67 years per year, instead of the expected one year per year.

Percent stocking

- In pine a small average decline was detected in control plots (< 1% per year), but significant changes were not found in other treatments;
- In aspen stocking increases substantially in thinned non-weeded plots (T > C, W) – see Figure 10.

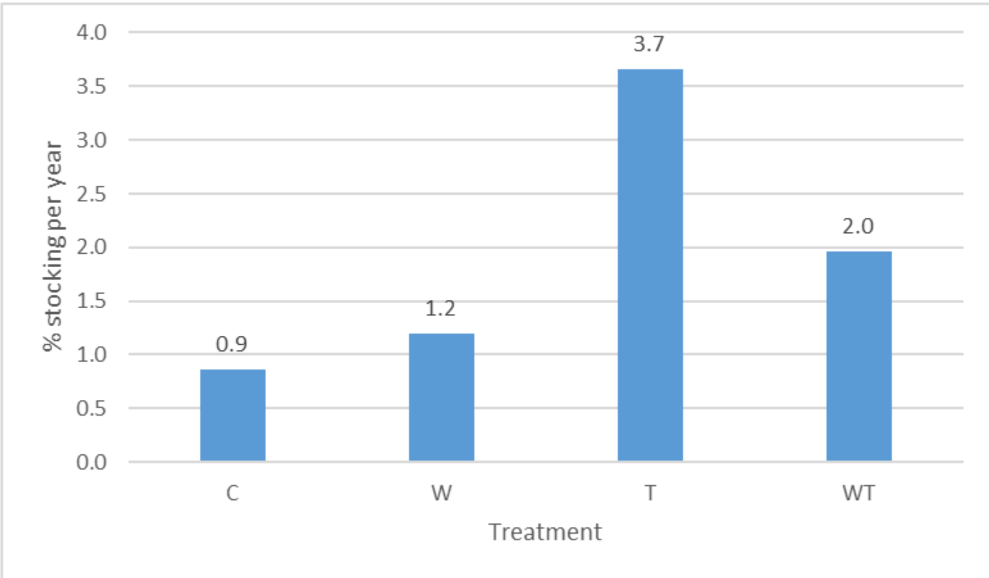


Figure 10. Average annual change in aspen percent stocking by tending treatment

Density

- In pine the change in density is predominantly negative, with the decline occurring mainly in non-thinned versus thinned plots (C, W < T, WT) – see Figure 11;
- In aspen there is generally little change except in thinned non-weeded plots, where average density is increasing rapidly (T > C, W, WT) – see Figure 12.

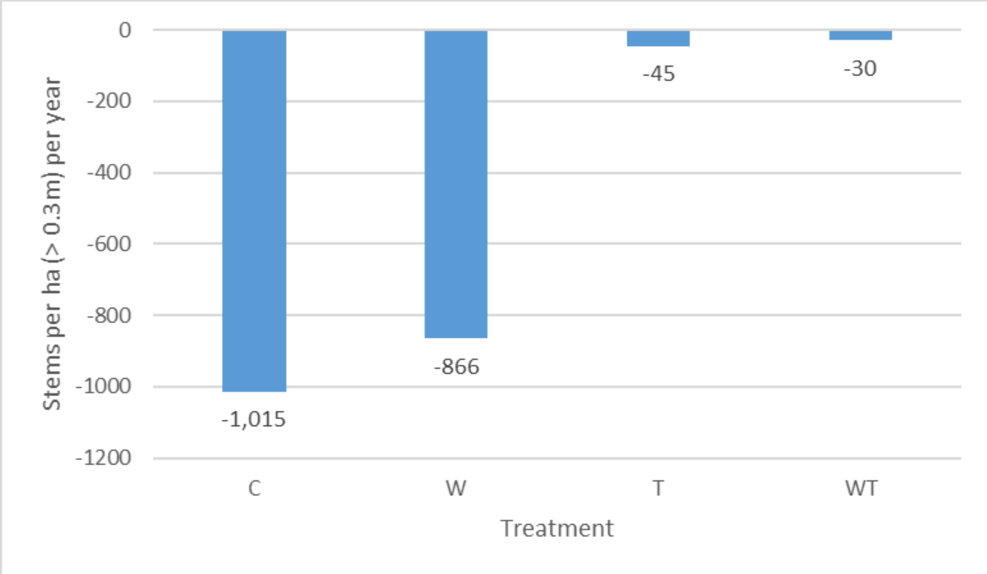


Figure 11. Average annual change in pine density by tending treatment

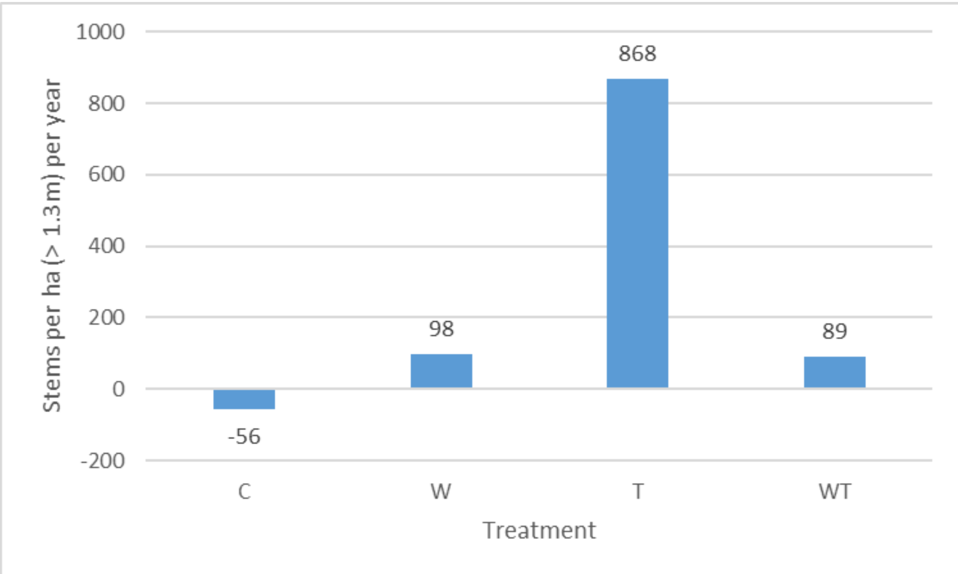


Figure 12. Average annual change in aspen density by tending treatment in installations with more than 1000 stems per ha in control plot

Basal area per ha

- In pine basal area increment is greatest in weeded non-thinned plots (W > C, T), but in weeded thinned plots average increment is already surpassing that in control plots – see Figure 13;
- Aspen basal area increment is greatest in control plots, with generally little increment yet evident in treated plots.

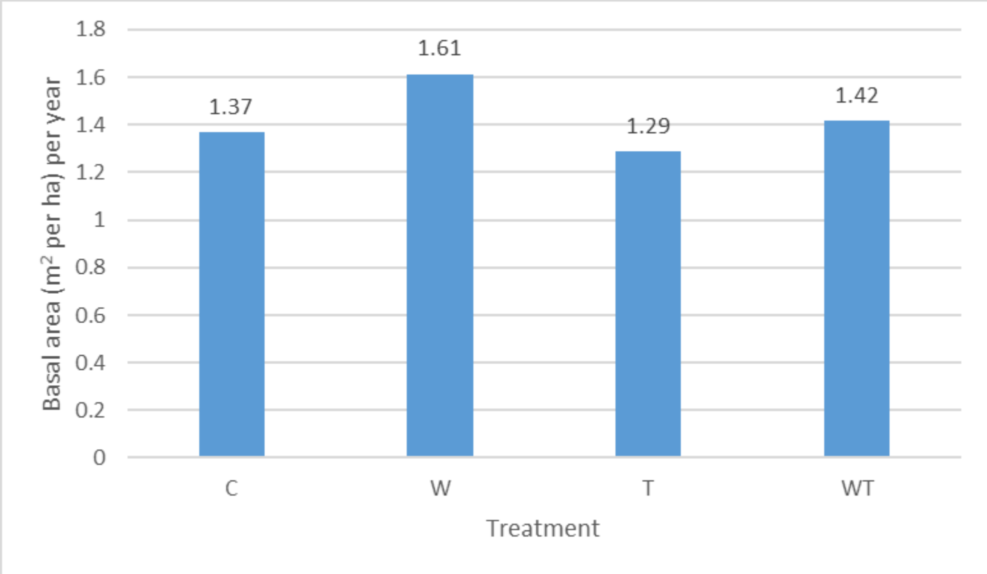


Figure 13. Average annual change in pine basal area by tending treatment

3.2 Tree growth rates in pine

Net changes do not indicate actual tree growth rates, because they are the combined effects of ingress, mortality and growth. In order to assess responses of tree growth rates to treatments, changes were calculated for pine trees which were alive and $\geq$ 1.3m at the first (GS15) measurement, and still alive at the second (GS17) measurement. The resulting estimates of periodic mean annual increment answer the question: in which treatments are trees growing the fastest?

Periodic annual height increment (see Figure 14):

- In planted stock is increased by weeding (W, WT > C, T);
- In natural regeneration increases with both weeding and thinning (C < W < T, WT). The latter response probably reflects the fact that slower growing trees were removed during thinning under the T and WT treatments.

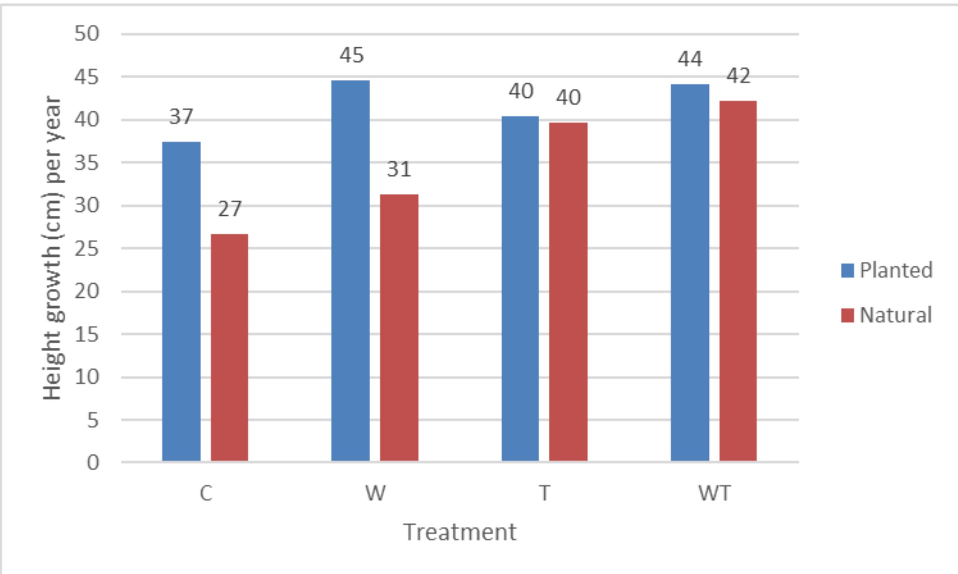


Figure 14. Periodic annual height growth of pine by tending treatment

Diameters measured at stump height (0.3m) were used to analyze trends in tree diameter growth, because breast-height diameters were not measured in trees less than 2.0 m tall, and the assessment of tree increment at breast height (1.3m) was complicated by this transition.

- Periodic annual diameter increment of both planted stock and ingress decreases at higher planting densities (see Figure 15);
- Periodic annual increment of planted stock increases with both weeding and thinning, while that of ingress is significantly increased only by thinning (Figure 16).

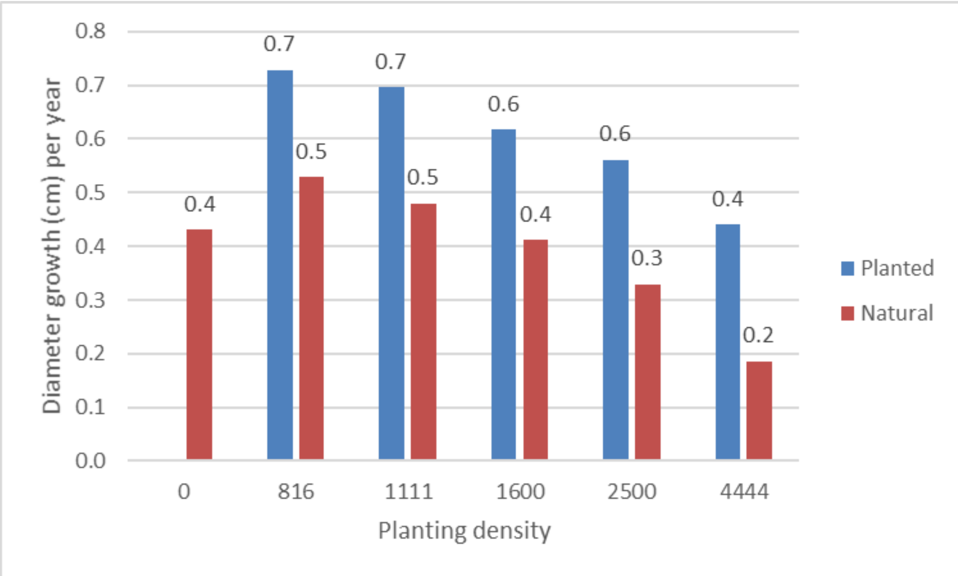


Figure 15. Average periodic annual increment of stump diameter by planting density and stock origin

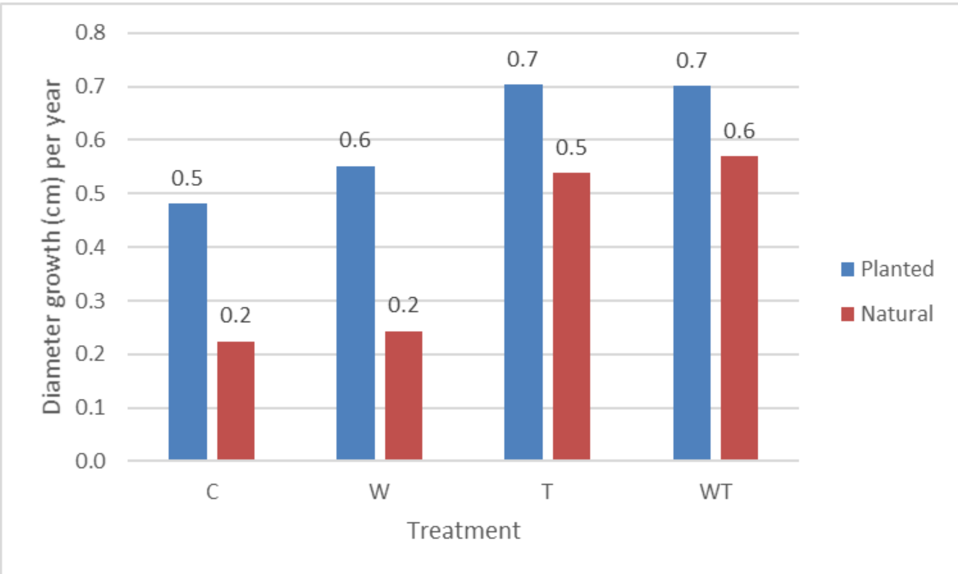


Figure 16. Average periodic annual increment of stump diameter by tending treatment and stock origin

4. Projected growth and yield

GYPSY simulations were made individually for all treatment plots in the trial, using data on stand age, total age, top height, density, percent stocking and basal area collected at the ends of growing seasons 15 and 17 (“GS 15” and “GS 17”) as described previously. Projections are summarized below by planting density and tending treatments, for 94 installations each containing 4 treatment plots. (Eight installations with historic treatment violations are excluded as in Section 1.) Culmination ages and MAI’s are all based on the following utilization limits: stump DOB 15 cm, top DIB 10 cm, stump height: 0.3m. Stand age at the time of projection was computed as the greater of growing seasons since germination or operating years since cut. Simulations were spatial and with basal area adjustment, and included only two species groups: lodgepole pine and aspen (including black poplar). Note that the summaries do not attempt to differentiate the effects of site or non-controlled treatments such as site preparation, and are designed to illustrate the prevailing projected effects of planting density and tending treatments across the whole trial.

Figure 17 shows an overall slight reduction in pine culmination age in response to weeding, and a much greater reduction in response to thinning. Note however that, while ages forecast in response to thinning appear stable (i.e. unchanged whether based on GS15 or GS17 input data), those forecast for the non-thinned C and W treatments decline from GS 15 to GS17 input ages. The reduction of culmination age following thinning is much more pronounced at higher than lower ingress densities (see Figure 18).

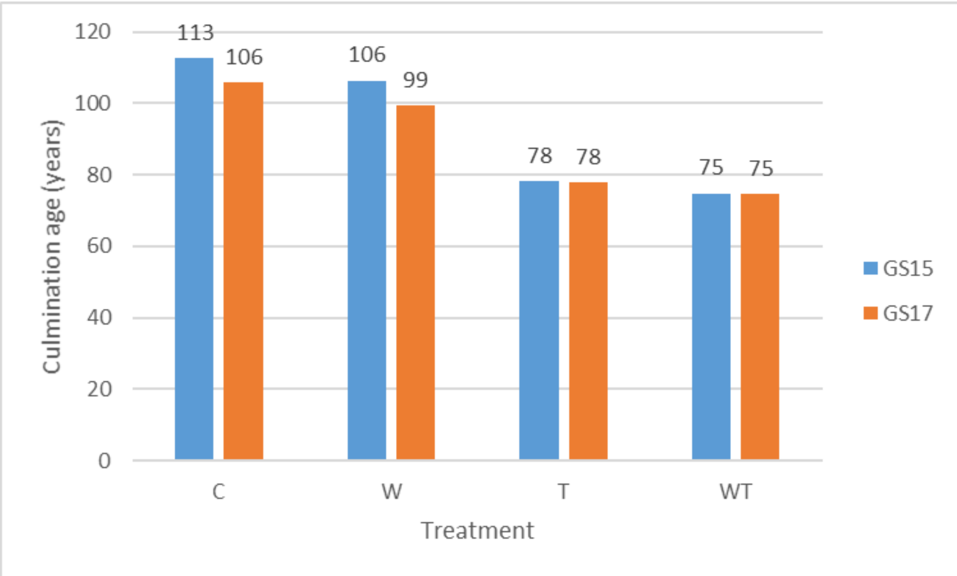


Figure 17. Pine culmination age averaged by tending treatment and input age

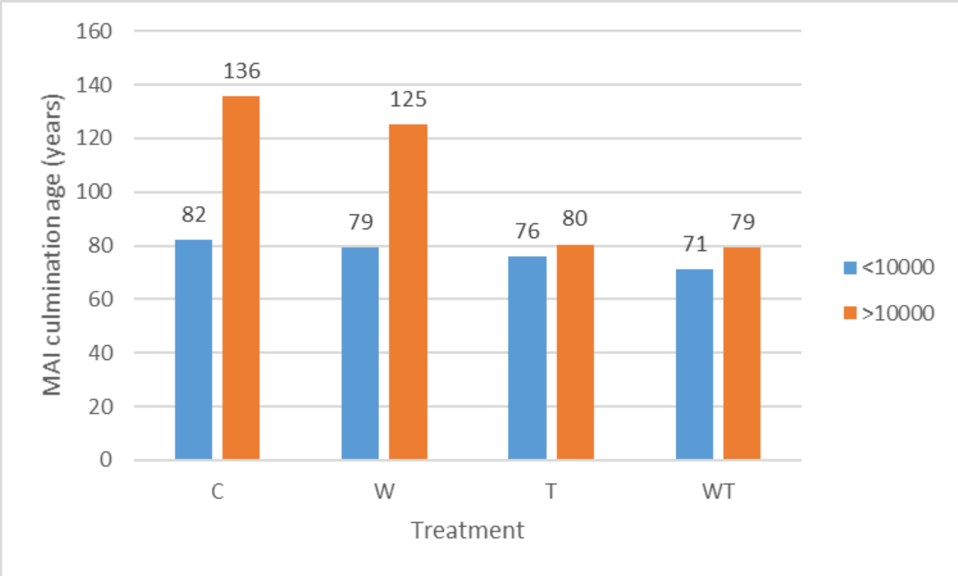


Figure 18. Pine MAI culmination age averaged by tending treatment, comparing installations with high and lower pine total densities (> and < 10,000 stems per ha in the control plot)

In Figure 19 mean annual increment (MAI) at culmination age increases with weeding ("W" versus "C") by about 30%, with thinning ("T" versus "C" by a similar proportion, and shows an overall increase of about 50% between no treatment ("C") and combined weeding and thinning ("WT"). Again, note that while yields forecast in response to thinning appear relatively stable, those forecast for the non-thinned C and W treatments increase slightly between GS 15 and GS 17 inputs. Results shown in Figure 19 are averaged across the whole trial and include treatment plots designated as "W" or "WT", but never weeded because no aspen competition was present.

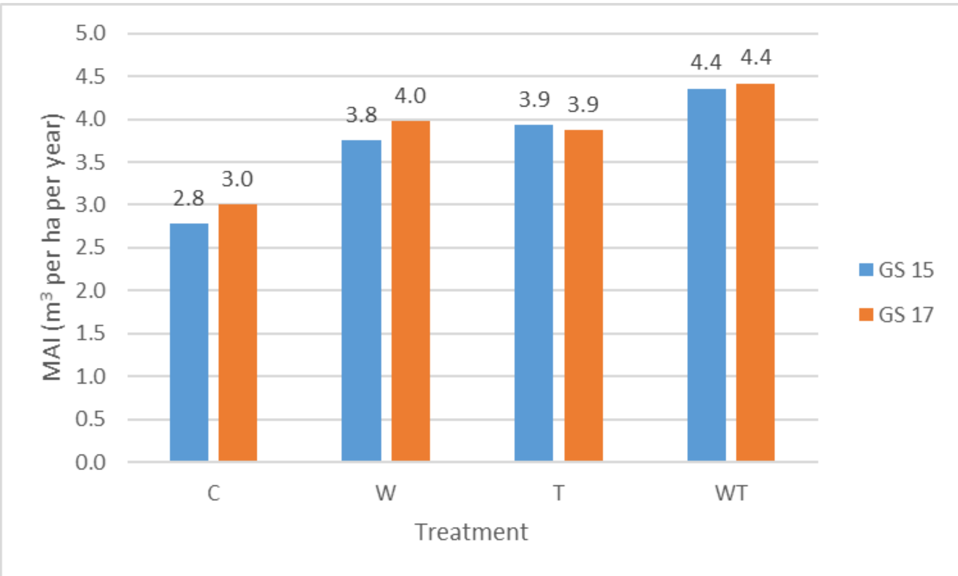


Figure 19. Pine MAI at culmination age averaged across the whole trial by tending treatment and input age

Figure 20 compares the MAI treatment response between installations with high and lower levels of pine density. “High” density installations are those with pine densities in GS 15 greater than 10,000 stems per ha. Note that below densities of 10,000 stems per ha weeding results in a large MAI improvement, but thinning does not. At higher densities both weeding and thinning increase MAI.

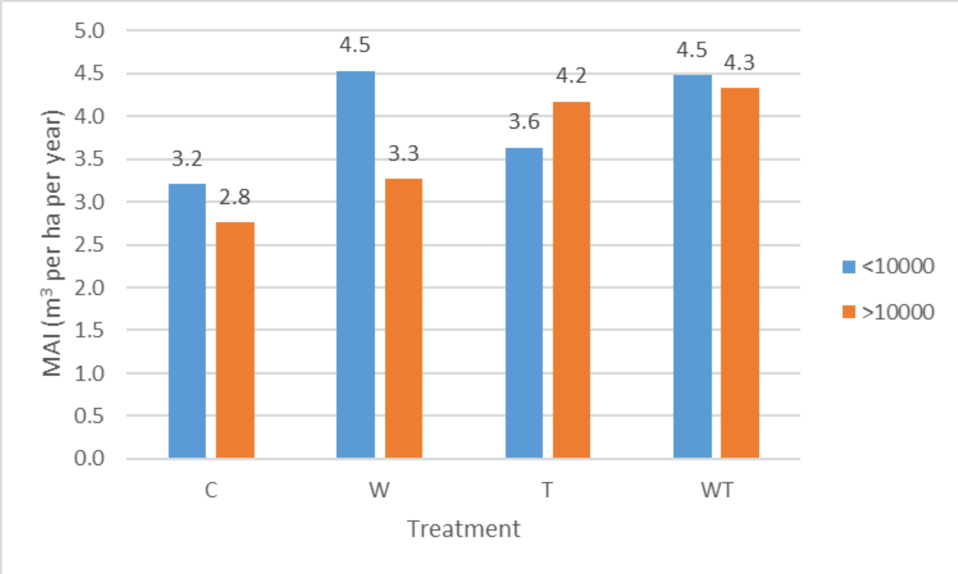


Figure 20. Pine MAI at culmination age averaged by tending treatment, comparing installations with high and lower pine total densities (> and < 10,000 stems per ha in the control plot)

The increase in MAI attributable to weeding is greatest in stands subject to aspen competition (see Figure 21). The average increase demonstrated by installations with more than 1000 aspen stems per ha in the control plots is 50%, and in these plots thinning does not appear to provide additional benefit.

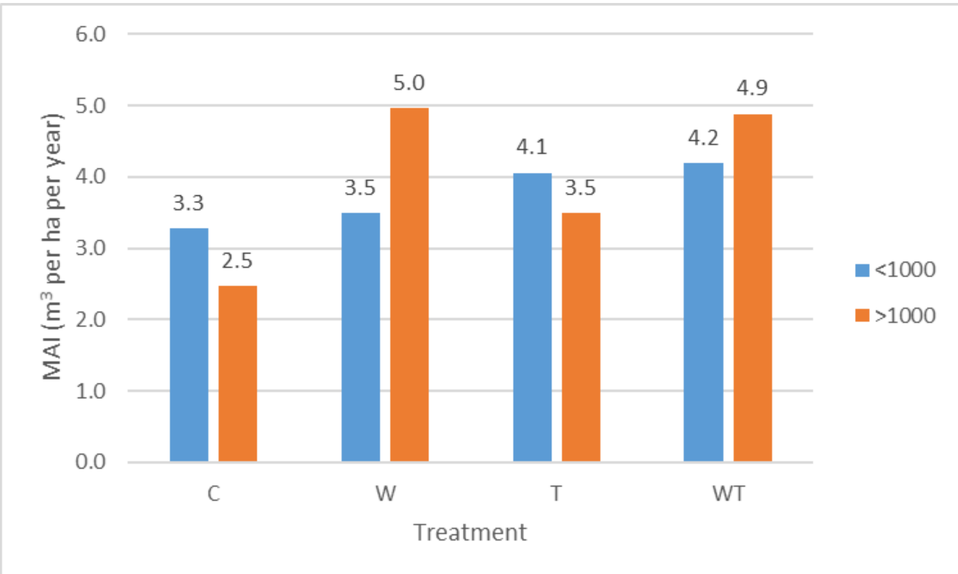


Figure 21. Pine MAI at culmination age averaged by tending treatment, comparing installations with higher and lower aspen densities (> and < 1000 stems per ha in control plot)

Of the plots weeded in the RLP trial, 24% were treated only mechanically and the remainder were sprayed by glyphosate ground application. The average MAI of the mechanically weeded plots is forecast to be less than 50% that of those chemically treated. This may underestimate the reduction in yield resulting from mechanical versus chemical weeding, because the choice of treatment was not controlled in the trial experimental design, and mechanical weeding tended to be confined to plots with lower levels of aspen competition.

Figure 22 indicates a general upward trend of MAI with planting density under most tending treatments. Without weeding or thinning, the increase is shown only at the highest planting density (4444 stems per ha).

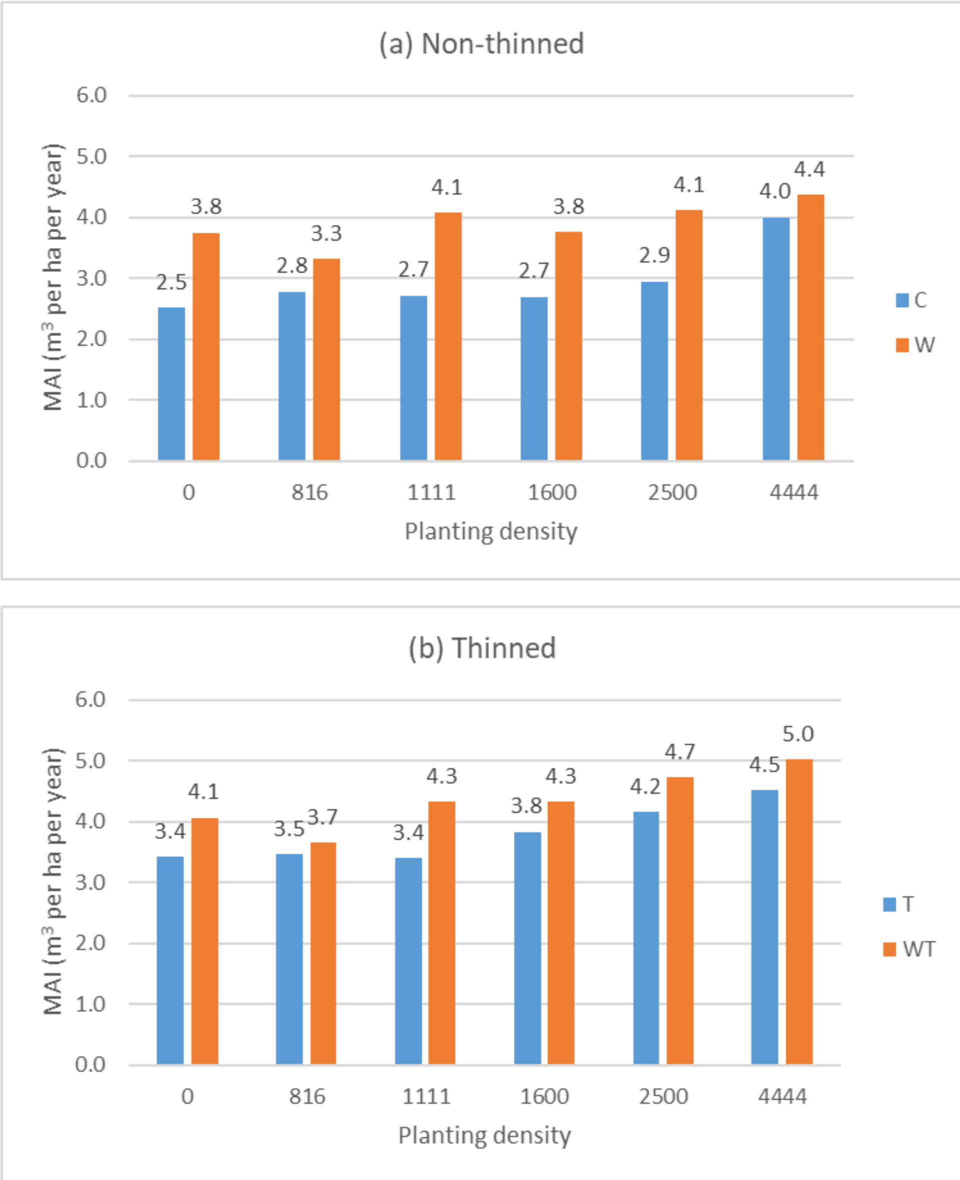


Figure 22. Average pine MAI at culmination age by planting density in (a) non-thinned and (b) thinned plots

Figure 23 indicates a much higher MAI of aspen in treated versus non-treated plots. MAI is reduced by weeding, but in all treatments is increasing with age of input particularly under thinning without weeding (treatment "T"). The figure illustrates aspen MAI's averaged across the whole trial, including plots without any aspen. Aspen site index, as projected by GYPSY from top height and age, is reduced by the weeding but not by thinning.

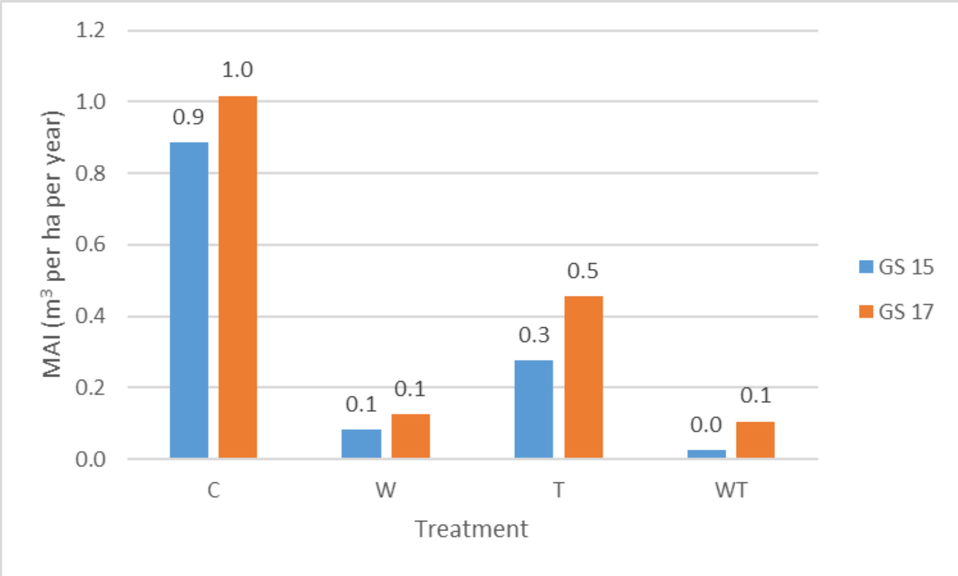


Figure 23. Average aspen MAI at pine culmination age by tending treatment

5. Stability of growth and yield projections

5.1 The problem

Projected pine and aspen MAI, and associated culmination age, if stable, should remain constant and not show any statistically significant upward or downward trend between measurements. Over the two-year measurement interval between growing season 15 and 17, average changes in these variables were statistically significant. Annual rates of change, averaged across the trial but excluding installations with treatment violations (8) or missing data (5), are as follows:

- Pine culmination age decreases by 1.84 years (2.0 %) per year;
- Pine MAI increases by 0.06 m^3 per ha (1.5 %) per year;
- Aspen MAI (at pine culmination age) increases by 0.06 m^3 per ha (17.1 %) per year.

Even though the overall average rate of MAI change in pine is relatively low, it cannot be assumed that yield predictions made at these ages are stable. High rates of increase in pine MAI tend to occur on dragged, non-thinned, upper foothills, medium nutrient, dry-mesic sites. Elsewhere changes are generally small and insignificant. Increases tend to be larger in non-planted plots, and at higher planting densities.

Above total (planted and ingress) densities at GS 15 of more than 30,000 stems per ha the average projected MAI is very low (in spite of the fact that these stands generally exhibit good top height with site indices averaging in excess of 18m); and almost doubles between input of data to GYPSY at GS 15 and 17. In densities of less than 10,000 stems per ha there is little change in the average with input age (see Figure 24).

The instability in average projected MAI of aspen, with an annual rate of change of 17%, is clearly of concern. Increases in MAI tend to be lowest in plots that have been site prepared and weeded, and highest in thinned plots that have not been site prepared or weeded.

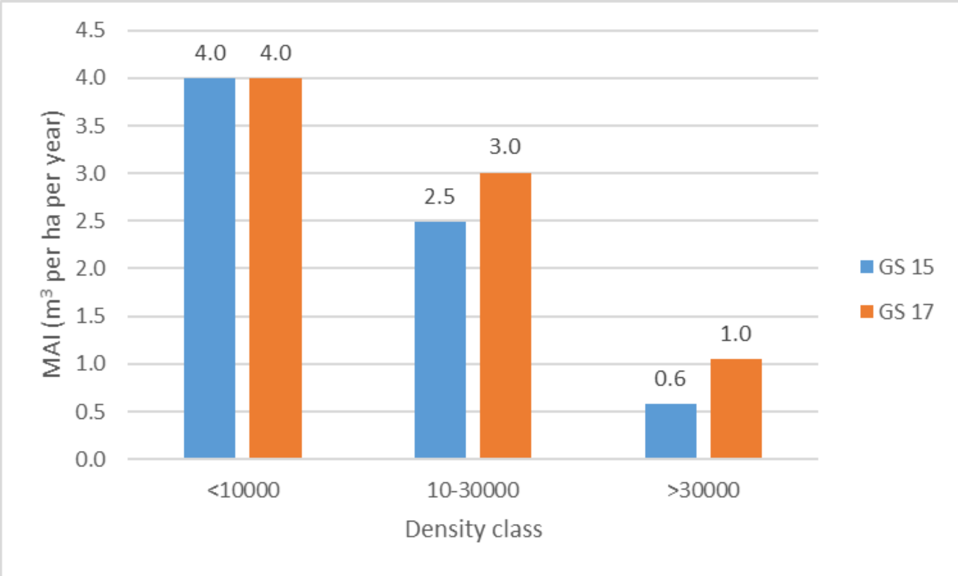


Figure 24. Average pine MAI by density class and input age

5.2 Possible causes

GYPSY projections of volume yield are based on sub-models for top height, density, percent stocking and basal area increment. Top height, density and stocking are indexed at age 50 years by site index (SI), stand density factor (SDF), and percent stocking index (PSI) respectively. Repeat measures and matched pairs analyses indicated that the effect of input age (time) is statistically significant for all three with the exception of pine site index, where the main effect of time is replaced by an interaction between time and planting treatment.

For pine, in order to help identify which sub-models are implicated in the instability of MAI projection, plots occurring in strata with high average rates of MAI change were separated from other plots. The "high" change group includes dragged, non-thinned plots on Upper Foothills, medium nutrient, dry-mesic sites. Changes in the GYPSY indices and other stand variables over the two-years' time between measurements were compared between plots in the "high" change group and other plots, with the following results.

- Site index does not show an overall effect of input age, and the rate of change does not differ between the "high" and "other" groups. It appears stable in planted plots, but shows a slight increase in time in non-planted plots (see Figure 25).
- Percent stocking index appears stable, and the rate of change does not differ significantly between groups.
- Stand density factor drops by almost 1200 stems per ha (16%) over the two-year period in the "high" change group, but shows little change in the "other" group (see Figure 26).
- The reduction in projected SDF appears to reflect decreases in total pine density that have occurred over the two-year period in plots with high densities at the time of the GS 15 measurement (see Figure 27).
- The decline in stand density factor between GS 15 and 17 increases with total stand density at GS 15 and, as for MAI, there is little average change at densities below 10,000 stems per ha (see Figure 28).
- Analyses were run with and without basal area input. Without basal area input, there is no significant change with input age in projected MAI across averaged across the whole trial. However, there is still a substantial change in the "high" group.

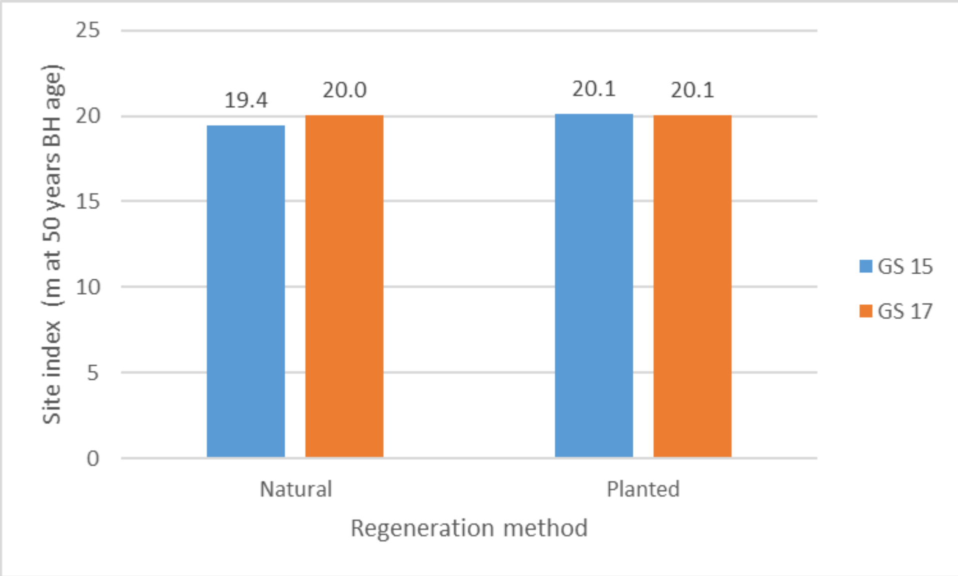


Figure 25. Average site index by regeneration method and input age

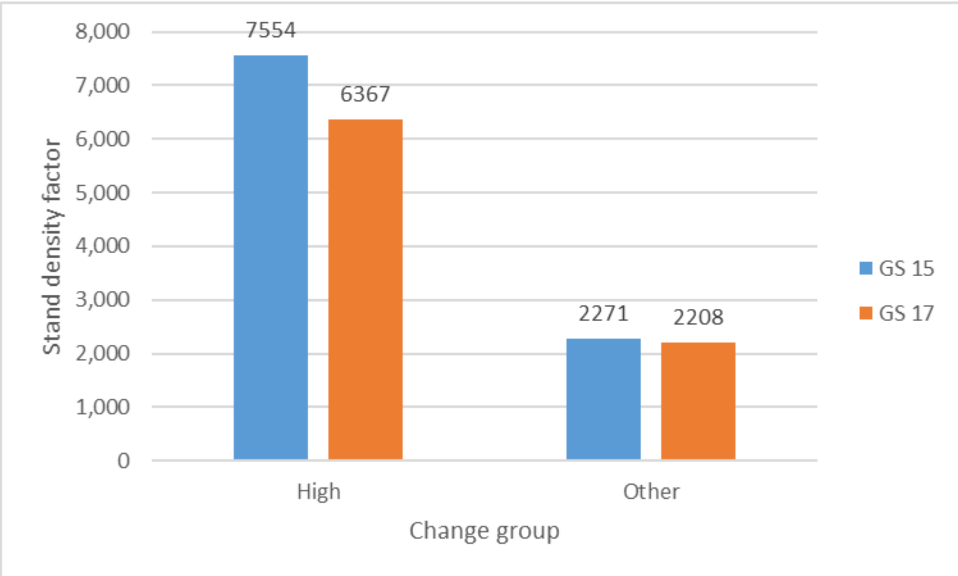


Figure 26. Average stand density factor of pine by change group and input age.[4]

[4] The "high" group includes dragged, non-thinned plots on medium-mesic Upper Foothills sites.

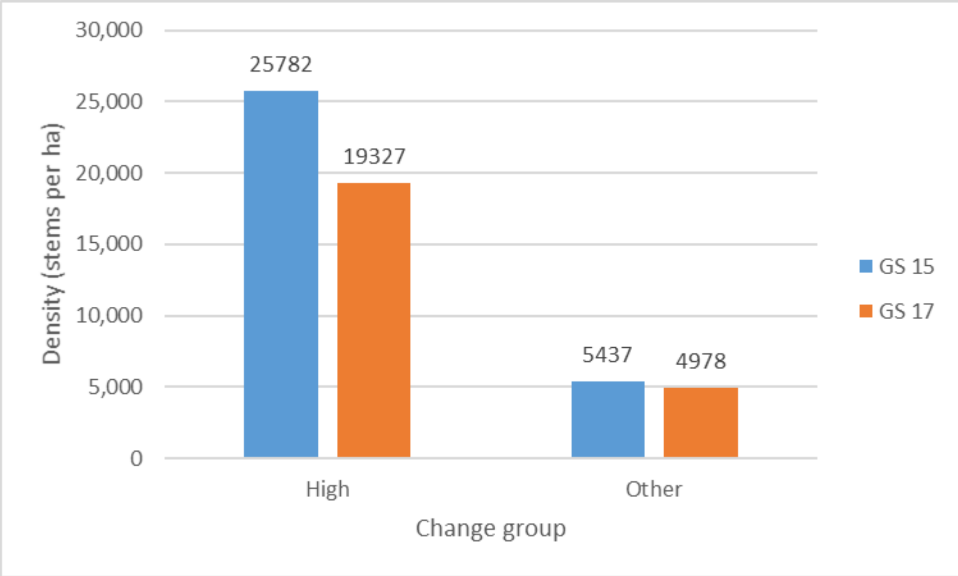


Figure 27. Average total stand density of pine by change group and growing season

Figure 28. Average stand density factor of pine by density class

In aspen, the following trends were observed in installations where aspen is present in the control plots:

- Site index is lower in weeded versus non-weeded stands, does not appear to be reduced by thinning, and has a low average rate of change with input age.
- Percent stocking index shows an overall increase with input age, which is most noticeable and significant in thinned plots that have not been weeded (see Figure 29). It closely reflects observed levels of aspen percent stocking, and changes therein (see also Figure 10).

- Stand density factor shows similar patterns to PSI of increase with input age (see Figure 30 and also 12).
- MAI projections for aspen made by GYPSY are almost the same with and without basal area inputs, suggesting that the change in projected MAI over time may not be attributable to the localized basal area increment model.

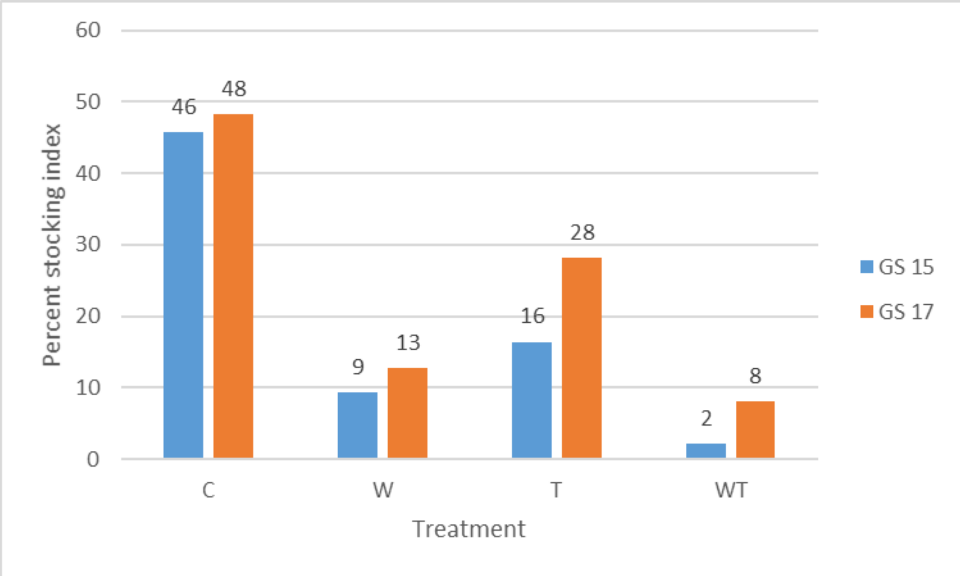


Figure 29. Average percent stocking index for aspen by tending treatment and input age

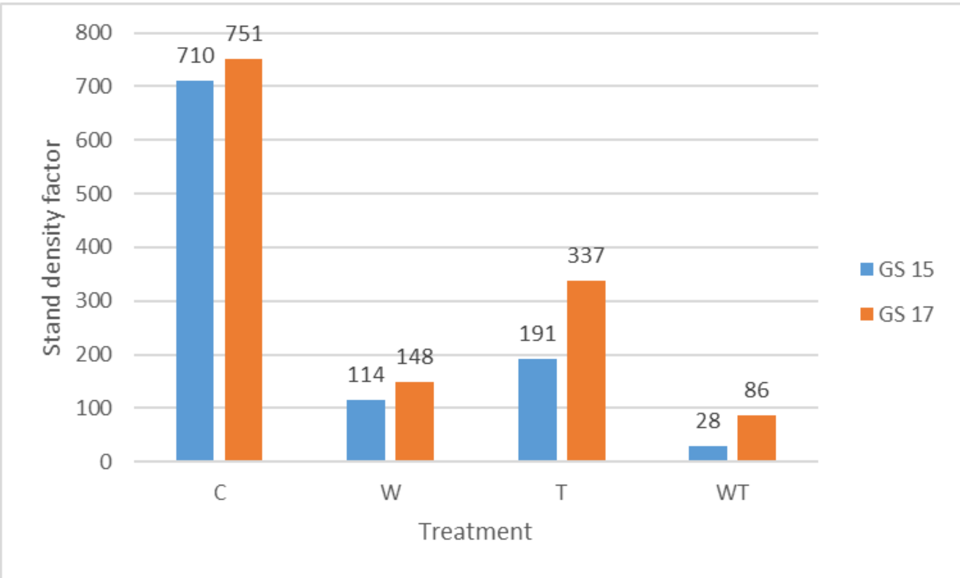


Figure 30. Average stand density factor for aspen by tending treatment and input age

In pine the increase in projected MAI with input age, after allowance for normal variation and error, is primarily confined to plots with high densities (exceeding 10,000 stems per ha at GS 15) where density appears to be declining faster than predicted by the GYPSY stand density sub-model. The resulting reduction in stand density factor when calculated two years later at the GS 17 measurement could increase predicted MAI, because GYPSY reduces basal area increment as SDF increases in dense stands. The effect on MAI could result from the SDF bias rather than bias in the basal area increment model itself, since any error in SDF is likely to be amplified during basal area projection.

There is also a slight increase in projected site index of pine with input age, but this is confined to natural regeneration in non-planted plots and not shown in planted plots. The increase may result from measurement bias rather than the site index sub-model, because (a) the sub-model appears to perform well for planted stock where age is known accurately and (b) in the non-planted plots there is a small but unexplained discrepancy between measurements of the average age of trees selected for top height / site index estimation (see Section 3 above).

In aspen the increase in projected MAI appears to result from situations where stocking and density are increasing at stand ages where the GYPSY stand density sub-model is predicting a decrease.

It is often assumed that instability in growth and yield projection is inevitable until stands have grown through the basal area measurement threshold established by the conventional measurement of diameter at 1.3m. Interestingly, in this study no significant correlation was found between the proportion of trees > 1.3m in height and the change of projected MAI with input age.

For both pine and aspen changes in projected MAI with input age appear to be related to changes in stand density. SDF decreases with input time in pine, particularly in high density plots, but increases in aspen, particularly in non-weeded and thinned plots. Figure 31 illustrates conceptually a possible explanation for the decrease in high density pine stands. The blue line indicates the decline in pine total density assumed by GYPSY for a high density naturally regenerated stand, to an SDF value which is the predicted density at 50 years' age. The blue density curve commences declining at year zero, which is biologically illogical. The red density curve indicates a more logical trajectory ending at the same SDF at 50 years, but culminating at around 10 to 15 years as has been observed in the RLP trial.

SDF projected by GYPSY from periodic measurements of the stand will increase until the age that the red curve culminates. Beyond this point actual density is declining faster than forecast by GYPSY, and predicted SDF will decrease. It is likely that the high density RLP plots (which show the greatest rates of SDF decrease and MAI increase) are at this declining density stage.

A rather different situation appears to exist for aspen whereby, in thinned and non-weeded plots particularly, densities are still increasing (i.e. to the left of culmination of the red curve), while GYPSY is forecasting them to decrease, with the result that predicted SDF and MAI increase with each re-measurement.

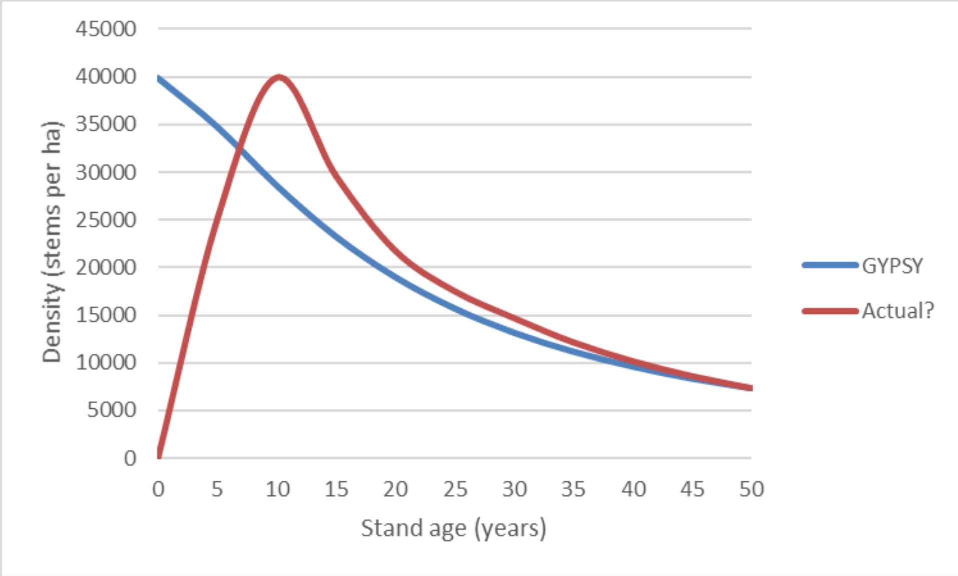


Figure 31. Density trends in a dense naturally regenerated pine stand

5.3 Implications

MAI forecast by GYPSY for stands with pine densities of greater than 10,000 stems per ha is likely to be low when forecast at performance survey age and shortly thereafter, but to increase when forecast from later stand measurements. In contrast, forecasts for lower density stands, including those where density has been reduced by pre-commercial thinning, are generally higher. They appear relatively stable and unchanging with age of input, and therefore may be considered more credible and reliable.

The decline in SDF and increase in MAI associated with input age in high-density stands, as well as suggesting that yields and contribution of such stands to AAC may be under-estimated, also implies that the need for density-control measures to offset "over-stocking" might be exaggerated. If projected yields of non-thinned plots are found to continue increasing with input age, the increase attributable to thinning may be less than indicated.

MAI's forecast for aspen generally are increasing with input age, particularly in non-weeded and thinned plots; and this appears to be the result of ingress from suckering not anticipated in the growth and yield model. This observation implies that aspen competition is currently being under-estimated, and that mechanical weeding and thinning of hardwoods may be ineffective for reducing such competition.

6. Conclusions and recommendations

6.1 Treatment effects on growth and yield

Seventeen years after planting and, on average, 13 years after weeding and 5 years after pre-commercial thinning (including mechanical brushing of hardwoods), observed responses to planting, weeding and thinning include:

- Top height, average height and current annual average height growth increase with weeding;
- Pine basal area per ha and current annual basal area growth increase with weeding and planting density;

- Current annual diameter growth increases with both weeding and thinning, is higher in planted versus non-planted stands, but decreases at higher planting densities;
- Aspen stocking and density is highest in the absence of weeding and thinning, lowest following weeding, and increases over time in non-weeded plots, especially following thinning.

Projections by GYPSY suggest the following responses of mean annual increment at age of culmination:

- Over the range of sites represented by the RLP trial, average pine MAI increases with weeding and thinning. In stands with less than 10,000 pine stems per ha, weeding can result in a large MAI improvement, but thinning shows little effect. At higher densities both weeding and thinning increase MAI, though the thinning effect may be exaggerated (see below).
- The increase from weeding is greatest in stands subject to aspen competition.
- The average MAI following mechanical weeding is much lower than that following chemical treatment (and this difference may be under-estimated).
- MAI tends to increase with planting density, but without weeding or thinning, the increase is shown only after very dense planting (4444 stems per ha).
- MAI culmination age is reduced by thinning, especially in plots with high levels of ingress density.
- MAI's forecast by GYPSY for non-thinned stands with high pine ingress densities are generally low but appear to be increasing with age of input. These results suggest that yields may be under-estimated, and increases attributed to thinning may be less than indicated in such stands.
- Aspen MAI is reduced by weeding and to a lesser extent by thinning, but conclusions drawn are made uncertain by instability in the projections. Projected aspen MAI significantly increases with age of input, suggesting that future aspen competition may currently be underestimated.

6.2 Instability of growth and yield projections

The apparent instability in pine forecasts is largely confined to high density stands that have experienced a steep rise in ingress density which is now declining. It may be necessary to calibrate the GYPSY density sub-model to better reflect this dynamic, but a quicker and easier solution might be to reduce the density values input to GYPSY by FRIPSY. This could be done in one or both of two ways.

1. In the RLP trial and current FRIPSY regeneration model, all pine regeneration is counted, included unhealthy trees likely to die. It is quite possible that such trees may not have been included in the data used to develop GYPSY. It is therefore proposed to investigate the effect of excluding trees in poor health on GYPSY projections, in a similar way to methods used in the Regeneration Standard of Alberta. This may have the effect of smoothing and lowering the steep peak in density observed in Figure 31. If this results in stabilized projections, the same approach can be taken to excluding such trees in the finalized FRIPSY regeneration model.
2. During the development of FRIPSY a statistical irregularity was encountered in modelling high densities, whereby the distribution of such densities between regeneration sub-plots tends to be non-normal and highly skewed. This results in sub-plots with very high numbers of seedlings having a potentially disproportionate impact on the plot or stand density

average, and plot averages not representing the modal stand condition. It was attempted to address the non-normality by data transformation and modelling distributions rather than averages, but these approaches may not sufficiently address the issue. Capping to remove outliers at the sub-plot level may be effective.

The observed instability in aspen growth and yield projections suggest that more data are required on suckering following tending treatments. Continued re-measurement of RLP installations subject to hardwood competition will probably provide the earliest possible solution for realistically predicting aspen development (unless alternative data sources can be found). It may be possible in the short term to build an interim allowance for increased aspen ingress into FRIPSY, that can be tested and calibrated by the further re-measurements.

6.3 FRIPSY finalization

The optimum stage of stand development for "handover" between the FRIPSY regeneration and growth models is when density culminates. Up until this point density is not correctly represented by GYPSY, and is better simulated by the regeneration model. Beyond this point the decline in density involves competition-induced mortality simulated by GYPSY and not represented in the regeneration model. In the RLP trial 73% of the sample plots reached this transition point for pine by growing season 15 (as measured in 2015 and 2016). During the subsequent two years the average density decrease in these plots was large relative to the modest increases or lack of change observed in the remaining plots. In aspen this situation is reversed, with more than half of the plots containing aspen increasing in density with uncertain but possibly significant management implications, and the remaining plots being evenly split between those showing no change and those declining.

It is proposed that the FRIPSY regeneration model not be extended beyond the RLP GS17 growing season and completed in 2020 using data collected in 2017 and 2018, with a provision for adjusting aspen projections based on additional re-measurements or external data.

6.4 RLP trial re-measurement

Now that the trial is entering the "growth" versus "regeneration" phase of stand development its utility for regeneration modelling is declining, with the exception of aspen ingress projection following tending treatments. The ongoing role of the trial to monitor development during the growth phase may be best, and most cost effectively, served by adopting the standards and protocols established for measuring permanent sample plots in Alberta by the Provincial Growth and Yield Initiative (PGYI). The current RLP protocol, while necessary and effective for monitoring and modelling regeneration, is cumbersome for quality control and analytical purposes, and the dependence on small regeneration sub-plots may not be the best approach for monitoring growth at the stand level. The transition to PGYI standards will depend on the individual priorities of companies who own the installations, but the following approach is proposed for discussion:

1. Continue to re-measure on a two-year cycle and according to the current RLP field manual, those installations that are subject to hardwood competition. This would involve at least 30 installations where the control plot contains more than 1000 stems per ha of aspen or balsam poplar.
2. On other installations consider a final measurement in 2020 using current protocols. This would, in conjunction with plots already being measured in 2019, provide a complete time series of biannual measurements to GS 19, which equates to 20 years since cut. The data collected in 2019 and 2020 may not be used directly in FRIPSY modeling, but would be valuable for validation of previous analytical results and predictions by FRIPSY and GYPSY.

3. Following the 2020 re-measurement switch all installations, with the possible exception of those continuing to incur significant aspen ingress, to the PGYI standard and protocol, on an extended re-measurement cycle.

Addendum: Effects of Minimum Height Standards on Growth and Yield Projections

Introduction

All GYPSY density models were originally developed based on a minimum height standard of 1.3m (“N13”). However, the Government of Alberta has adopted a minimum density standard of 0.3m (“N03”) for post-harvest coniferous species at performance survey age, on the assumption that stems less than 1.3m will eventually grow to exceed 1.3m. In order to maintain consistency with the Regeneration Standard of Alberta, the same assumption was adopted for FRIPSY. The current version of FRIPSY first simulates regeneration performance at 12-14 years, and then uses GYPSY to project future growth and yield based on the simulated performance.

The RLP trial, consistent with observations made by the Government of Alberta, indicates that the total density of post-harvest pine regeneration typically culminates at total stand ages between 14 and 18 years. GYPSY does not simulate increases in density over time. It is therefore intended to delay the “hand-over” between the FRIPSY regeneration model and GYPSY until 18 years, by which age the majority of stands have reached crown closure and densities are declining as a result of self-thinning.

As noted in the 18-year RLP Crop Performance Report, GYPSY projections of MAI culmination based on RLP trial measurements 15 and 17[5] growing seasons (“GS15” and GS17”) after planting were observed to vary significantly between the two input ages. This instability was observed to be confined mainly to high-density stands, and to be related to density rather than growth estimation, leading to the suggestion that it might be related to the adoption of the N03 minimum height standard. The projections were therefore repeated using the N13 standard, and compared to those based on the N03 standard, as described below.

[5] The equivalent range in total stand age, taking into account time from germination and / or harvest, is 15 to 20 years.

Results

When averaged across the trial as a whole, mean annual increments at culmination age projected by the N03 and N13 standards were very similar when projected at GS15 (average values 3.62 and 3.67 m^3/ha/year respectively), and almost identical when projected at GS17 (3.73 m^3/ha/year). Differences in MAI were not statistically significant at either input age, but average culmination ages were always significantly higher at the N03 than at the N13 standard (90 versus 84 years when projected at GS17).

Although MAI averaged across the trial showed little effect of the minimum height standard when other factors were ignored, a significant interaction was found between the effects of the standard and stand density (measured as the total number of stems per ha at GS15), whereby increments calculated by the N03 standard tended to be low relative to N13 at high densities, and similar or higher at lower densities. In order to illustrate this interaction, the continuous density variable was converted into a categorical variable with three classes (see Table 1 and Figure 1.) Note that at densities of less than 10,000 stems per ha application of the N13 standard results in a slightly smaller average MAI, while at higher densities it results in significant increases relative to the N03 standard.

Table 1. Repeat measures analysis of GYPSY projections for effects of stand density and minimum height standard on MAI culmination.

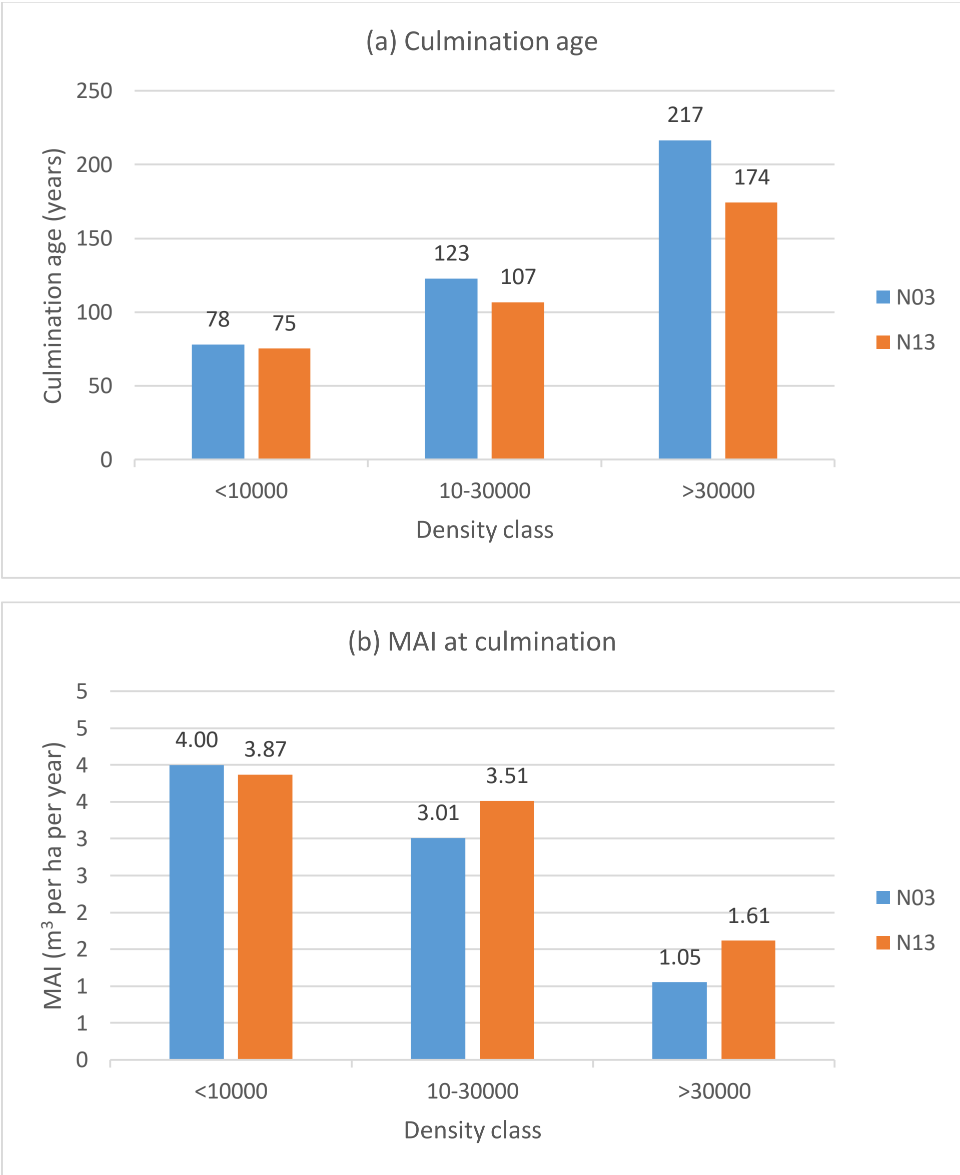
(a) Input age GS15 (15 growing seasons after planting)

Variable	Test	Effect	Exact F	Num DF	Den DF	Prob > F
Culmination age	Between plots	Density	693.043	2	348	**<.0001**
	Within plots	Minimum height	707.778	1	348	**<.0001**
		Min.ht*Density	278.479	2	348	**<.0001**
Mean annual increment	Between plots	Density	41.231	2	349	**<.0001**
	Within plots	Minimum height	244.529	1	349	**<.0001**
		Min.ht*Density	285.329	2	349	**<.0001**

(b) Input age GS17 (17 growing seasons after planting)

Variable	Test	Effect	Exact F	Num DF	Den DF	Prob > F
Culmination age	Between plots	Density	525.385	2	348	**<.0001**
	Within plots	Minimum height	343.431	1	348	**<.0001**
		Min.ht*Density	121.445	2	348	**<.0001**
Mean annual increment	Between plots	Density	26.119	2	349	**<.0001**
	Within plots	Minimum height	97.804	1	349	**<.0001**
		Min.ht*Density	137.968	2	349	**<.0001**

Figure 32. Interaction between effects of density and minimum height standard on MAI culmination projected from GS17 measurements.



When the N03 standard was applied, significant effects and interactions between input timing and stand density were observed for culmination age, MAI at culmination, and stand density factor (see Table 2a), indicating instability in projections, especially at higher densities as already noted in the Crop Performance Report. However, when the N13 standard was applied only stand density factor indicated a statistically significant interaction between input timing and density (see Table 2b and Figure 2b). This effect did not appear sufficient to influence projected growth and yield, since no significant effect of time or time-density interaction was observed for culmination age or MAI at culmination.

Table 2. Repeat measures analysis of GYPSY projections for effects of stand density and input timing.

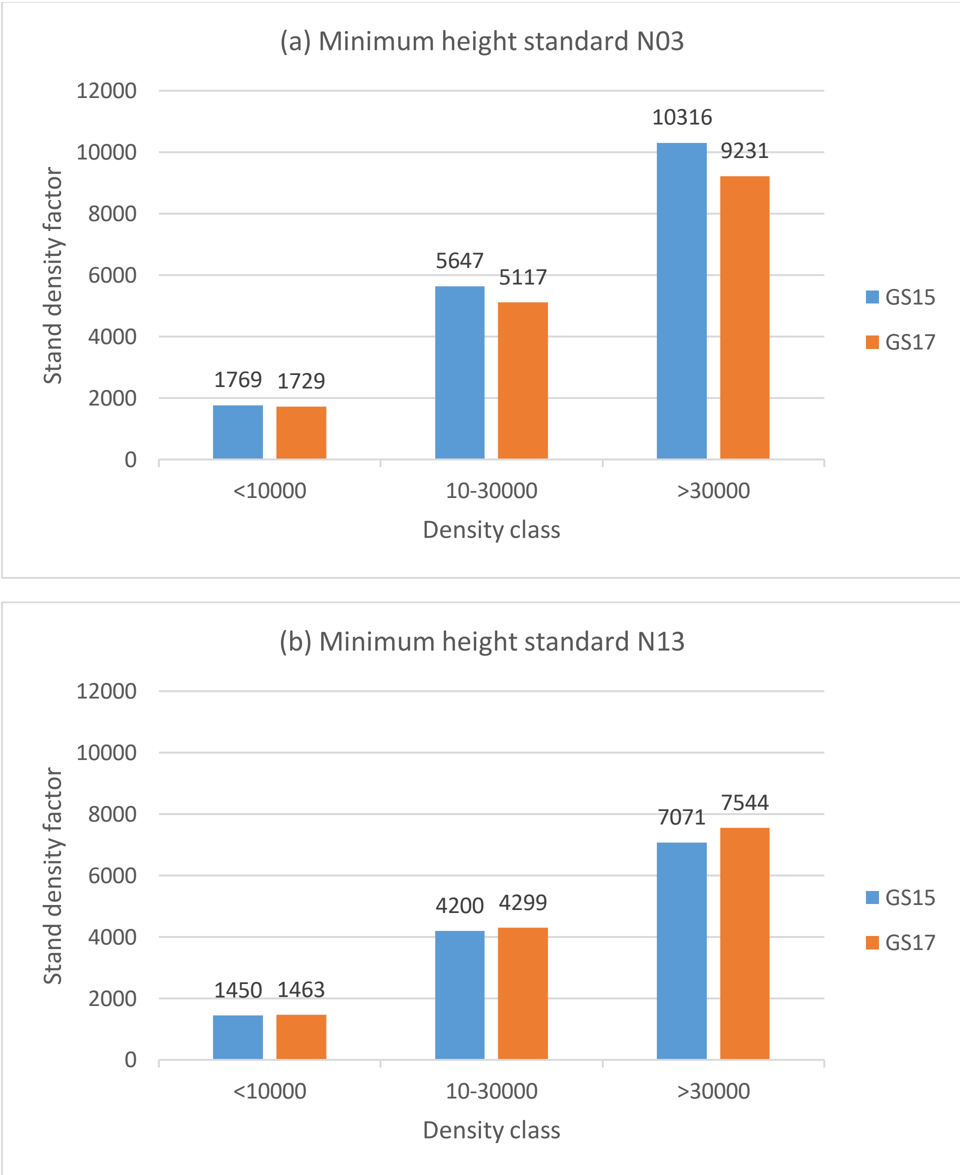
(a) Minimum height standard N03

Variable	Test	Effect	Exact F	Num DF	Den DF	Prob > F
Culmination age	Between plots	Density	683.417	2	348	**<.0001**
	Within plots	Time	137.108	1	348	**<.0001**
		Time*Density	69.051	2	348	**<.0001**
Mean annual increment	Between plots	Density	55.142	2	349	**<.0001**
	Within plots	Time	69.787	1	349	**<.0001**
		Time*Density	52.797	2	349	**<.0001**
Percent stocking index	Between plots	Density	10.917	2	349	**<.0001**
	Within plots	Time	0.237	1	349	0.6267
		Time*Density	0.815	2	349	0.4437
Stand density factor	Between plots	Density	760.872	2	349	**<.0001**
	Within plots	Time	139.972	1	349	**<.0001**
		Time*Density	59.560	2	349	**<.0001**

(b) Minimum height standard N13

Variable	Test	Effect	Exact F	Num DF	Den DF	Prob > F
Culmination age	Between plots	Density	452.1727	2	348	**<.0001**
	Within plots	Time	3.35	1	348	0.0681
		Time*Density	2.7191	2	348	0.0673
Mean annual increment	Between plots	Density	18.192	2	349	**<.0001**
	Within plots	Time	3.1441	1	349	0.0771
		Time*Density	1.1784	2	349	0.309
Percent stocking index	Between plots	Density	13.7245	2	349	**<.0001**
	Within plots	Time	0.0186	1	349	0.8917
		Time*Density	0.2774	2	349	0.7579
Stand density factor	Between plots	Density	581.0773	2	349	**<.0001**
	Within plots	Time	50.512	1	349	**<.0001**
		Time*Density	20.2371	2	349	**<.0001**

Figure 33. Interaction between effects of stand density and input timing on projected MAI culmination, percent stocking index and stand density factor.



Conclusions and Recommendations

1. Although MAI averaged across the whole RLP trial showed little effect of minimum height standard, when stand density was taken into account important differences emerged between the N03 and N13 standards, with implications for modelling and management.
2. Projections made using the N13 standard were found to be more stable over time than were projections using N03, with no significant change in forecast MAI and culmination ages over a two-year re-measurement interval.
3. Projections made using the N03 standard were less stable, showing significant changes in forecast MAI and culmination ages over the same two-year interval.
4. Projections made using the N03 standard may underestimate growth and yield in high-density stands, and overestimate it in low-density stands, potentially leading to inappropriate density management decisions.
5. The results apply to post-harvest lodgepole pine stands 15 to 20 years in total age. They do not necessarily apply to stands at performance survey age (12 to 14 years).
6. The N13 standard should be used for densities and stocking values “handed-over” from the FRIPSY regeneration model to GYPSY at age 18 years.
7. Further analysis will be undertaken to assess the relationships between densities at performance survey age (based on the N03 standard as per the RSA) and later densities based on the N13 standard.