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Long-term precommercial thinning effects on *Larix occidentalis* (western larch) tree and stand characteristics

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Abstract

Precommercial thinning (PCT) is used to increase tree size and shorten harvest rotation time. Short-term results from PCT studies often show a trade-off between individual tree growth and net stand yield, while longer-term effects of PCT on tree growth and stand yield are less well documented. We used a 54-year old PCT study to test long-term effects of forest density and thinning schedules on stand yield and tree-level characteristics in even-aged *Larix occidentalis* (western larch) stands. The study has three target densities (494 trees ha⁻¹, 890 trees ha⁻¹, and 1680 trees ha⁻¹) crossed with three thinning schedules (target density achieved through one, two, or four entries). Analysis of variance and linear contrasts were used to test the effects of density and number of entries on tree- and stand-level attributes. Thinning before stand age 10 years leads to long-term constant yield (219.0-269.5 m³ ha⁻¹; $P > 0.05$) across the tested densities. We also found constant volume growth across stand densities during the most recent measurement interval (5.42-6.41 m³ ha⁻¹ year⁻¹; $P > 0.05$). Number of entries did not affect any tree- or stand-level attribute. The primary effect of early PCT is to control whether wood volume and growth are concentrated on few large, stable trees or spread over many small, unstable trees.

Keywords: density management, stand density, competition, stand dynamics, growth and yield

1. Introduction

Forest stand density affects the timing and intensity of competitive interactions between neighboring trees (Oliver and Larson, 1996; Long et al. 2004; Harrington et al. 2009). In high density stands tree crowns rapidly occupy the site and trees begin to compete for limited resources such as light, water, and nutrients early in stand development. The result of competitive interactions is slower growth for all trees (Sjolte-Jorgensen 1967; Reukema, 1979). In lower density stands, more space and resources are allocated to each individual tree, the result of which is delayed onset of intense inter-tree competition, leading to an increase in tree growth and a decrease in time required to reach merchantable size (Assmann, 1970; Reukema, 1975; Smith et al. 1997; Tappeiner et al. 2007). However, the trade-off for rapid individual tree growth at lower densities is a period where trees do not fully occupy the site, and therefore stand yield may lag behind yields obtained from high-density stands.

While it is well established that individual tree size and growth increase at lower stand densities (Sjolte-Jorgensen 1967, Smith et al. 1997, Marshall and Curtis 2002, Tappeiner et al. 2007) there is still uncertainty over how long-term yield, defined as total net cubic stem wood volume per unit ground area, responds to early density management (Oliver and Larson, 1996). Stand yield is the sum of the individual trees in a stand, but does the increase in individual tree size at lower densities make up for fewer trees? Current wisdom generally suggests that yield increases with increasing density (Zeide, 2001, Curtis et al. 1997, Marshall and Curtis, 2002). However, at least one long-term precommercial thinning study has found the opposite result. Forty-two years after thinning, thinned plots contained 15% more total gross volume than unthinned plots in mixed *Abies balsamea* (balsam fir) – *Picea rubens* (red spruce) forest in northwestern New Brunswick, Canada (Pitt and Lanteigne, 2008). This may be due to the greater

individual tree growth rates caused by greater crown sizes of large trees grown at lower density (Stephenson et al. 2014) combined with the deleterious effects of tight spacing on these same attributes, as well as elevated mortality in high-density stands causing a decrease in net cubic volume (Drew and Flewelling, 1979; Oliver and Larson 1996; Newton, 1997).

The volume of a tree stem depends on tree height, diameter, and stem taper (Flewelling and Ernst, 1996), so a reduction of height growth at higher density would be expected to reduce total cubic volume. For two trees of equal diameter, volume is roughly proportional to height (Drew and Flewelling, 1979). It is a near axiomatic concept in forest density management that the height of dominant conifer trees in a stand, referred to here as top height and defined here as the height of the tallest 100 trees ha^{-1} , is independent of stand density (Sjolte-Jorgensen 1967, Lanner 1985, Smith et al. 1997, Marshall and Curtis 2002, Tappeiner et al. 2007). However, early results from some thinning trials show top height sorting along a density gradient with low-density stands having greater top height (Schmidt and Seidel 1988, Schmidt 1997, Martin and Barber, 1995). If top height increases faster in low density stands, this will have strong effect on yields of both total cubic volume and merchantable volume.

Tree height variability, or height differentiation, is an important indicator of stand development processes. This is especially true in evenly spaced even-aged stands where differentiation may be weak, leading to an earlier loss of height growth at higher densities (Oliver and Larson, 1996, O'Hara and Oliver 1999). In single-species, even-aged stands, tree size differentiation trends through time can reveal a dominant role of size asymmetric competition (indicated by increasing size variation, Weiner 1990) or of size symmetric competition (indicated by stable or declining size variation, Weiner 1990, Stoll et al. 1994). Size asymmetric competition is most strongly associated with intense competition for light, while size

symmetric competition is typical of belowground competition for nutrients (Weiner 1990, Schwinning and Weiner 1998).

Height to diameter ratio of the largest 200 trees ha^{-1} ($H:D_{200}$), an indicator of tree stability and resistance to physical damage (Cremer et al. 1982; Wilson and Oliver, 2000; Wonn and O'Hara, 2001), may indirectly affect stand yield. Stands with high $H:D_{200}$ are more susceptible to windthrow and stem breakage, and stands grown at higher densities have higher $H:D_{200}$ (Cremer et al. 1982; Wilson and Oliver, 2000; Wonn and O'Hara, 2001). This predisposes a greater proportion of the standing volume to damage and mortality, which reduces net stand yield.

Finally, mortality rates affect total net yield. Measures of competition such as relative density, the proportion of the maximum stand density index for a species (*sensu* Drew and Flewelling 1979), identify thresholds where the probability of mortality increases. Relative density can also be used to identify levels of competition where volume growth is highest. Newton (1997) identified relative densities between 40% and 55% of maximum as the zone of peak forest growth. Growth rates for relative densities below 40% were lower as the trees did not fully occupy the site, and net growth rates (gross growth minus mortality) above 55%, the beginning of the zone of imminent competition mortality, were lower due to a loss of volume to mortality (Drew and Flewelling, 1979; Newton 1997).

A target stand density may be achieved through many alternative thinning schedules. Is there a benefit to achieving a final target density with multiple light thinnings over single heavy thinning? From an operations and cost perspective, the most advantageous system may be a single thinning directly to a target density, which will allow trees to grow to a merchantable size before competition reaches a level where volume is lost to mortality. However, there are

potential benefits to making multiple thinning entries in a stand. If the stand has not yet begun to differentiate when it is initially thinned, moving the stand to an intermediate density, and allowing trees to begin to express dominance may result in a larger tree size than if stands were initially thinned to a low density (O'Hara and Oliver, 1988). Multiple light thinnings also preserve the potential to replace damaged or killed trees. However, the benefit of the ability to select ideal trees must be weighed against the increased levels of competition that the stand experiences while it is at higher densities, as well as increased costs of multiple entries.

The primary objective of this study was to evaluate long-term precommercial thinning effects on tree size and form, as well as stand growth and yield. We analyze data from a *Larix occidentalis* (western larch) density management experiment in northwestern Montana, USA. The long-term post-treatment response period (54 years) and well-replicated design (four blocks spanning a productivity gradient) allow for a rigorous investigation of long-term precommercial thinning effects. A secondary objective is to analyze and report tree- and stand-level characteristics of this experiment at nominal full rotation age (62 years from stand initiation). We ask two research questions which guide our statistical analyses.

1. How does stand density affect tree- and stand-level attributes fifty-four years after one PCT treatment?
2. Do multiple precommercial thinning entries result in tree and stand attributes that differ from those resulting from a single entry?

2. Methods

2.1 Study sites and treatments

The Western Larch Density Management Study (WLDMS) was established by US Forest Service research scientists in 1961 (Schmidt, 1964). Four study sites (blocks) with similar initial

stocking and topo-edaphic conditions (Table 1) were chosen to capture the *Larix occidentalis* productivity gradient in northwestern Montana (Fig. 1). All sites were harvested using even-aged methods between 1951 and 1953 (Table 1) and regenerated naturally in the good *Larix occidentalis* seed years of 1952 and 1954 (Schmidt, 1964), resulting in even-aged populations of *Larix occidentalis* at all sites. This resulted in high densities (25,000 to 63,000 trees ha⁻¹) of primarily *Larix occidentalis*, but included lesser amounts of *Picea engelmannii* (Engelmann spruce), *Pseudotsuga menziesii* v. *glauca* (interior Douglas-fir), *Abies lasiocarpa* (subalpine fir) and *Betula papyrifera* (paper birch) (Schmidt, 1964).

Treatment plots (experimental units) were established at each site between the summer of 1961 and winter of 1962. The stand age at initial treatment was nine years for two of the sites and seven years for the other two (Table 1), so a mean age of eight was used as the age of initial treatment. Treatment plots are square 20.12 m × 20.12 m plots surrounded by a buffer of at least 10 to 20 m that was thinned with the same treatment (Fig. 1). Thinning treatments were randomly assigned to each plot. Treatments included a core 3 × 3 factorial design, which was replicated once at all four study sites. The core treatments consisted of three different target densities (spacing): 494 trees ha⁻¹ (4.6 m × 4.6 m), 890 trees ha⁻¹ (3.6 m × 3.6 m), and 1680 trees ha⁻¹ (2.4 m × 2.4 m). These three densities were chosen in 1961 to test proposed ideal densities at which to grow *Larix occidentalis* (Schmidt and Shearer, 1961). These densities were achieved with three different thinning schedules (hereafter referred to as entries): one-entry, two-entry, or four-entry (Fig. 2). One-entry treatment plots were thinned directly to the target density in 1961. Two-entry plots were thinned to an intermediate density in 1961 then to the final target density in 1981. Four-entry plots were thinned to progressively lower densities in 1961, 1971, and 1981, then thinned to the final target density in 1991. The different number of entries created a

gradient of competition pathways by which stands reached the final target density. Within a target final density, one-entry treatments experienced low levels of competition while four-entry treatments experienced much higher levels of competition (Fig. 2). Thinnings were from below, removing small and damaged trees. All cut material was left on site. During the initial thinning in 1961 all shrubs were cut in all thinned plots. Unthinned plots (shrubs not cut) and a very low density one-entry treatment (272 trees ha⁻¹, 6.1 m × 6.1 m, single thinning in 1961) were installed at the Coram 1 and Coram 2 sites.

2.2 Measurements

All trees inside each treatment plot were tagged. In the unthinned plots trees were not tagged, rather all trees within 10 systematically located 4.05 m² permanent subplots were measured. Tree growth was measured on a 5-year cycle for the original 40-year duration of the study: 1961, 1966, 1971, 1976, 1981, 1986, 1991, and 2001. All tagged trees in treated plots were measured, as were each of the trees in the 4.05 m² subplots within the unthinned plots. The 1996 measurement was missed for all plots and the 2001 measurement was missed for just the unthinned plots. All plots were remeasured in 2015, yielding 54 years of post-treatment data. Tree measurements included dbh (stem diameter at 1.37 m), total height, crown base height (defined as the height to the lowest live whorl), height to the widest point in the crown, and crown width at two perpendicular axes.

2.3 Data reduction

Plot level averages were calculated for several response variables. Response variables include quadratic mean diameter (QMD), mean height, top height (defined as the mean height of the tallest 100 trees ha⁻¹), H:D₂₀₀, and crown volume. We used the coefficient of variation (CV)

to characterize tree height variation (i.e., stand differentiation) within treatment plots, as recommended (McGown et al. 2016). Crown volume, which has been linked to tree photosynthetic capacity (Biging and Dobertin 1992, Burkhart and Tome, 2012), was modeled as the sum of two cones, one right-side up the other upside down, calculated from measurements of total height, crown base height, height to widest point in the crown, and crown width. Measurements of dbh and height were applied to the equations of Flewelling and Ernst (1996) to calculate per tree total cubic volume of stem wood from the ground to the tip of the trunk, which was summed per plot and expanded to a stand level value expressed as $\text{m}^3 \text{ha}^{-1}$. Net periodic annual increment (PAI) of total cubic volume, expressed as $\text{m}^3 \text{ha}^{-1} \text{yr}^{-1}$, was calculated from 2001 to 2015 (1991 to 2015 for the unthinned plots). Merchantable cubic volumes were calculated using the taper profile equations of Flewelling and Ernst (1996) for the merchantable portion of the bole from a 0.3 m stump to two minimum merchantable top diameters common in the Northern Rockies (volume to a 11.4 cm (4.5") top and to a 15.2 cm (6") top).

Stand density index (SDI; Reineke, 1933) was calculated for each plot using the stand density at the time of measurement and QMD. SDI was then converted to relative density (RD; *sensu* Drew and Flewelling 1979) by relativizing SDI to a percent of maximum SDI. Maximum SDI (Table 1) was calculated for each site using a stochastic frontier model that incorporates species composition, topo-edaphic factors, and climate variables (Kimsey 2013). This was done because maximum SDI values for *Larix occidentalis* are poorly established in the literature and because maximum SDI may vary by site quality (Jack and Long, 1996). Annual mortality rates for the period of 2001 to 2015 (1991 to 2015 for unthinned plots) were calculated as a percent using the following annual compounding equation

$$(1) \quad m = 1 - [1 - (M_1/N_0)]^{1/t}$$

where N_0 is the number of trees alive at the time of previous measurement, M_1 is the number of trees that died between the previous measurement and the current measurement, and t is the number of years between measurements (Larson and Franklin, 2010).

2.4 Statistical analysis

Statistical analysis was completed using the 2015 (stand age 62) measurements. Data were analyzed for the fully replicated nine experimental treatments: three densities (494, 890, and 1680 trees ha⁻¹) crossed with the three different thinning schedules. The low-density treatment (272 trees ha⁻¹ via one thinning) and the unthinned plots are graphically presented but were not statistically analyzed due to their low replication ($n = 2$).

For this experimental design, the number of thinnings factor is nested within the target density factor. In other words, the intensity of intermediate thinnings (the number of trees removed) depended on the final target density (Fig. 2). Due to this nested design we analyzed the data as a one-way randomized block ANOVA, with site as the blocking variable and treatment as a composite variable of both target density and entries (Schaedel et al. 2017). The resulting explanatory variable was a factor with nine levels (three entries x three target densities). Once a significant result was discovered in the omnibus ANOVA test, we used linear contrasts to test our specific research questions. To examine how density in once-thinned stands affected tree and stand-level variables we used two linear contrasts: the first contrast compared the 1680 trees ha⁻¹ density with the 890 trees ha⁻¹ and the 494 trees ha⁻¹ densities, the second compared the 890 trees ha⁻¹ density with the 494 trees ha⁻¹ density. The last two densities most closely represent the current management zone for *Larix occidentalis* in the Northern Rockies and Inland Northwest so were of high interest. To evaluate the effect of the number of entries within each of the three target densities we tested two contrasts: (1) the one-entry treatment against the two-

and four-entry treatments and (2) the two-entry treatment against the four-entry treatment. All statistical analyses were conducted using R 3.2.4 (R Development Core Team 2014). The multcomp (Hothorn et al. 2014) package was used to implement the linear contrasts and Bonferroni corrections were applied to ensure family-wide type I error rates of 0.05.

3. Results

3.1 Long-term trends of tree size and stand yield

Most trends in tree-level attributes diverged by density early in the experiment, and the effect of density on tree size was obvious by stand age 62 years (Figs. 3-5). QMD differentiated rapidly by density, where lower density stands had much larger tree diameters (Supplementary Fig. S1). The QMD of unthinned plots increased much slower than that of any of the thinned plots (Supplementary Fig. S1). By stand age 62 the 272 trees ha⁻¹ treatment had a QMD nearly four times greater than that of unthinned stands (Table 4; Fig.4). Differences in diameter between the tested densities were significant at stand age 62 ($p < 0.001$; Table 2).

Mean tree height showed similar trends to QMD, where low density plots had greater mean heights than the high-density plots (Table 4, Fig. 4, $p = 0.003$). Top height followed a different pattern (Fig 6). Top height decreased along the gradient of increasing competition created by the treatments early in the experiment, but differences were relatively small until stand age 38, after which differences in top height became significant ($p = 0.0159$; Fig 6d; Table 2). H:D₂₀₀ separated by density early in the experiment (Fig. 7), with denser stands having higher H:D₂₀₀ as early as age 18 years (10 years after treatment). These differences stayed relatively constant throughout the experiment but H:D₂₀₀ continued to increase with time across all plots (Fig. 7) and differences were significant at stand age 62 years ($p < 0.001$; Table 2).

Relative variability of tree height as measured by coefficient of variation (CV_{ht}) decreased through time in all thinned treatments (Fig. 8). CV_{ht} reached minima in most stands at the 1991 measurement (35 years after initial treatment), then either was stable after 1991, or increased slightly between 1991 and 2001, then stabilized between 2001 and 2015. CV_{ht} was markedly higher and followed a different trajectory in the unthinned stands (Fig 8). In the unthinned stands, CV_{ht} increased during the first measurement interval, then subsequently declined. In the 2015 measurement CV_{ht} increased with increasing relative density across all thinned and unthinned treatments (Fig 8D). Results were nearly identical for CV_{dbh} (Supplementary Fig. S2).

Stand-level attributes exhibited different temporal trajectories compared to the tree-level attributes. Early in stand development plots with higher density had higher basal area and total cubic volume (Fig. 9), with unthinned stands having the highest value for both variables. However, with time, basal area and total cubic volume of the 890 and 1680 trees ha^{-1} plots surpassed the unthinned plots, while lower density plots continued to have lower total cubic volume. However, at stand age 62 differences in cubic volume were not significant ($p = 0.449$; Table 2). PAI of total cubic volume peaked early in the higher density stands, and both the unthinned and 1680 trees ha^{-1} stands have declined below peak levels. Stands with 890 and 494 trees ha^{-1} initially had lower PAI values but continued to increase through stand age 62, such that at age 62 differences in volume PAI are not significant ($p = 0.818$; Table 2). The low density 272 trees ha^{-1} have much lower PAI values than the other thinned stands.

Trends in merchantable volume were highly dependent on the utilization standard (minimum top diameters inside bark) that was used (11.4 cm top versus 15.2 cm top; Fig. 10). When a 11.4 cm top was used the 272 trees ha^{-1} treatment initially had the highest volume but

was rapidly surpassed by the 890, 494, and 1680 trees ha⁻¹ densities (Fig. 10A). The 890 trees ha⁻¹ had the greatest merchantable volume throughout the majority of the experiment, while the 1680 and 494 trees ha⁻¹ treatments were lower but quite similar to each other. The differences in merchantable volume to an 11.4 cm top were not significant ($p = 0.149$; Table 2). The 272 trees ha⁻¹ density had lower merchantable volume than the core densities, and the unthinned treatments had the lowest merchantable volumes in 2015 (Fig. 10A). Merchantable volume to a 15.2 cm top was substantially less than merchantable volume to an 11.4 cm top in the 1680 trees ha⁻¹ treatment. Differences in merchantable volume to a 15.2 cm top between the tested densities were significant ($p = 0.002$; Table 2). The unthinned plot had no merchantable volume that meets the 15.2 cm top utilization standard (Fig. 10B).

3.2 Effects of stand density in once-thinned treatments

3.2.1 Tree-level attributes

Quadratic mean diameter (QMD) differed significantly among the one-entry core target densities ($p < 0.001$). QMD was inversely related to stand density (Table 4). Among the tested densities at stand age 62 years, QMD was 26.8 cm, 22.4 cm, and 18.1 cm for the 494 trees ha⁻¹, 890 trees ha⁻¹, and 1680 trees ha⁻¹, respectively, and the differences in QMD between all levels were significant. The effect of density on mean tree height was also significant ($p < 0.003$; Table 3). Mean tree height increased as density decreased where the 1680 tree ha⁻¹ treatment had significantly lower heights than the 890 and 494 trees ha⁻¹ treatments ($p < 0.003$; Table 3), while the difference between the 890 and 494 trees ha⁻¹ was not significant ($p = 0.30$; Table 3). Mean tree height included all trees in a plot and so higher density stands, which had a greater number of trees in subordinate crown classes, were expected to have lower mean heights than low

density stands. Top height within the one-entry treatments decreased with increasing density, but differences were not significant ($p = 0.269$; Table 3).

H:D₂₀₀ was significantly affected by density in the one-entry treatments ($p < 0.001$; Table 3). The lower density plots had lower average H:D₂₀₀, with 494 tree ha⁻¹ ratios 6.8 units smaller than the 890 tree ha⁻¹ ratios and 13.4 units less than the ratios of 1680 tree ha⁻¹ density; all contrasts were significant.

Average crown volume per tree increased significantly with decreasing target density (Fig 5; $p < 0.001$). Crowns were approximately twice as large in the 494 trees ha⁻¹ treatment as they were in the 890 trees ha⁻¹ treatment and more than three times larger than the 1680 trees ha⁻¹ treatment (Fig 5; Table 4).

3.2.2 Stand-level attributes

Total cubic volume of stem wood from the ground to the tip of the tree was not significantly affected by density ($p = 0.244$) in the one-entry treatments. It is clear from graphical representation, (Fig. 9 A-C) that by stand age 62, cubic volume was greater for the three core densities than it was for the 272 trees ha⁻¹ density and the unthinned plots.

Merchantable volume in m³ ha⁻¹ to an 11.4 cm top of the one-entry treatments followed the same trend as the total cubic volume: 890 tree ha⁻¹ plots had the highest merchantable volume (Table 5), but differences due to density were not significant ($p = 0.421$; Table 3). Merchantable volume to a 15.2 cm top showed the same trend as the merchantable volume to a 11.4 cm top and the differences due to density were significant ($p = 0.002$; Table 2). Merchantable volumes of both the 890 trees ha⁻¹ and 494 trees ha⁻¹ densities were significantly greater than the 1680 trees ha⁻¹ density ($p < 0.05$, Table 3) but the 890 trees ha⁻¹ and 494 trees ha⁻¹ densities were not significantly different from each other (Table 3).

Relative density in 2015 increased with density and ranged from 23.5 % in the 272 trees ha^{-1} to 70.0% in the unthinned treatments (Table 5). Between 1991 and 2001 the 1680 trees ha^{-1} treatment crossed the threshold of 55% relative density (Figure 11), which was proposed by Drew and Flewelling (1979) as the onset of competitive mortality for *Pseudotsuga menziesii* var. *menziesii* (coast Douglas-fir), also known as the zone of imminent competition mortality (ZICM). By 2015 the 890 trees ha^{-1} density had also crossed into the ZICM. Crossing into the ZICM coincided with an increase in mortality in the 1680 trees ha^{-1} density to 0.86 % year^{-1} (Fig. 11; Table 4) which was higher than the 890 (0.16 % year^{-1}) or 494 (0.00 % year^{-1}) tree ha^{-1} treatments during the 2001-2015 measurement interval.

Current PAI (2001 to 2015) in the one-entry treatments was highest in the 890 trees ha^{-1} density at 6.41 $\text{m}^3 \text{ha}^{-1} \text{year}^{-1}$ but differences between the core densities were small and non-significant (Table 5, Fig. 12, $p = 0.7917$).

3.3 Effect of number of entries within density

3.3.1 Tree-level attributes

The effect of the number of entries within a given target density was not significant for any of the response variables tested. For QMD, within the 494 and 1680 trees ha^{-1} , densities there was no significant effect of the number of thinning entries ($p < 0.43$ and $p < 0.29$, respectively; Table 3), however there was suggestive evidence of a difference between the one-entry and two- or four-entry treatments in the 890 trees ha^{-1} target density ($p = 0.06$; Table 3). In the 890 trees ha^{-1} and 1680 trees ha^{-1} densities QMD decreased as the number of thinning entries increased (Table 4). It was notable that the pattern was different for the different number of entries within the 494 trees ha^{-1} density. While differences were non-significant, QMD was

nearly constant for the one- and two-entry treatments then declined in the four-entry treatment. The number of entries did not significantly affect mean height ($p = 0.8229$; Table 3). The effect of the numbers of entries factor on top height was not significant and showed a similar pattern to that of mean tree height.

3.3.2 Stand-level attributes

The effect of number of entries was not significant for any of the stand-level attributes (total cubic volume, PAI of total cubic volume, merchantable volume to an 11.4 or 15.2 cm top, and relative density; Table 3). The effect of each the number of entries on each variable generally parallels that of QMD and top height; in the 890 and 1680 trees ha^{-1} densities the volume (total cubic or merchantable) decreased as the number of entries increased, whereas in the 494 trees ha^{-1} cubic volume peaked in the two-entry treatment, but these trends were not significant.

4. Discussion

Our analysis of this long-term experiment indicates that net stand yield (total live cubic wood volume at the final measurement) converges to similar values across a wide range of target stand densities when thinning is applied early in stand development (<10 years after stand initiation). At stand age 62, the primary effect of early PCT was to control whether volume is concentrated on few large trees or distributed across many small trees (see also: Schaedel et al. 2017). After 54-years of post-thinning growth, the three tested densities (494, 890, and 1680 trees ha^{-1}) did not have significant differences in total cubic volume. This indicates that while early in stand development volumes may be driven largely by stand density, by 54 years after thinning those differences disappear (Fig. 9). In fact, very high density plots may contain less

volume than lower density plots (Fig. 9), as suggested by graphical analysis of the unthinned plots, and similar results were found in another long-term PCT study (Pitt and Lanteigne 2008). Many effects of density management cannot be extrapolated from short duration studies, highlighting the value of long-term studies, such as this 54-year-old experiment, for demonstrating outcomes obtainable with early PCT (Schaedel et al. 2017).

A second important finding is that top height was sensitive to the competition gradient created by the experimental treatments (Table 4; Fig 7). While the magnitude of the effect of density on QMD is much larger than the effect on top height, as expected, a decrease in top height has strong implications for yield. A decrease in top height has similar effects on volume accumulation as a decrease in site productivity (which is often estimated with top height, e.g. site index (King, 1966)). Increases in factors related to tree instability, such as $H:D_{200}$, may also act to increase non-competitive mortality and decrease yield at higher densities (Wonn and O'Hara, 2001). In other words, 54 years after thinning, significantly larger tree size and greater tree stability at lower densities compensated for fewer trees, resulting in no significant difference in total cubic volume across a gradient of stand density.

Stand growth and yield

A constant yield of total cubic volume been seen in other long-term studies of shade-intolerant *Pseudotsuga menziesii* (Reukema, 1979), *Pinus taeda* (Peet and Christensen, 1987), *Pinus ponderosa* (Cochran and Barrett, 1993), as well as more shade-tolerant *Abies balsamea* and *Picea rubens* (Pitt and Lanteigne, 2008). Short-term results of most PCT and spacing studies generally show that yield is proportional to density (Seidel 1987, Schmidt and Seidel 1988, Harrington et al. 2009) indicating reduced stand-level volume increment while trees initially do not fully occupy the site in the first years after treatment. Early in stand development

it is common to see PAI of cubic volume highest at high densities (Harrington et al. 2009) then converge across a wide range of stand densities (Pitt and Lanteigne, 2008; McLeod, 2012), as was found in this study. Intermediate-density stands may have greater yields than high density stands as the higher density stands enter the ZICM and some volume growth is lost to mortality (Harrington et al. 2009). Other studies showed that age at which a stand is thinned plays an important role in long-term growth and yield; early thinning can lead to smaller reductions in yield than later thinnings (Varmola and Salminen, 2004).

Our results suggest that the size-density and growth relationships proposed by Drew and Flewelling (1979) hold for *Larix occidentalis* (Fig. 12). As trees at a given density grow in diameter, their relative density (SDI/maximum SDI) increases. Drew and Flewelling (1979) suggested that the zone of maximum volume increment for *Pseudotsuga menziesii* var. *menziesii* occurs across the range of 40% to 55% relative density (RD), and that within that range, stand-level growth is unaffected by density. Subsequent studies show that this proposed zone of maximum volume increment of 40% to 55% RD holds true for other tree species (Newton, 1997). Our results suggest that the zone of maximum growth for *Larix occidentalis* may extend beyond a RD of 55% to approximately RD 65% (Fig 12; Cochran and Seidel, 1999). As high-density stands grow, they near the maximum size density relationship (Reineke 1933, Yoda et al. 1963, Drew and Flewelling, 1979), the point at which some of the accumulated gross volume is lost due to mortality (Newton, 1997). This may contribute to the long-term convergence of stand yield across different initial stocking levels (Reukema, 1979; Peet and Christensen, 1987; Marshall and Curtis, 2002; Harrington et al. 2009).

Tree size and form

Over the entire range of thinning treatments, top height was sensitive to competitive history (Fig. 6). When the stands were thinned directly to the three target densities in 1961, top height was not significantly sensitive to density (Fig. 6). However, stands that took multiple entries to reach the target density experienced much higher levels of competition early in stand development than stands that were thinned directly to the target density in one entry (Fig. 2). Top height can be significantly affected by extremes of stand density (Sjolte-Jorgensen, 1967; Lanner, 1985) and shade-intolerant species, such as *Pinus radiata*, *Pinus resinosa*, *Pinus sylvestris* and *Pseudotsuga mesziesii*, have shown greater height reductions at high densities than shade-tolerant species such as *Picea abies* (Sjolte-Jorgensen, 1967). Top height growth was adversely affected in 14-year-old *Pinus contorta* at densities greater than 15,000 tree ha⁻¹ (Mitchell and Goudie, 1997). The densities of the intermediate thinnings (up to 6,700 trees ha⁻¹, Fig. 2) in this study may represent density levels where *Larix occidentalis* height growth is reduced and certainly the densities of the unthinned plots (up to 63,000 trees ha⁻¹) cause height growth repression (Fig. 6).

We propose two potential explanations for why we found a significant effect of density on top height: 1) *Larix occidentalis* height growth is more sensitive to competition than some other conifers, and 2) decreases in top height at high densities were partially the result of high H:D₂₀₀ leading to elevated levels of top breakage. There is evidence from past work examining the effect of stand density on *Larix occidentalis* that height growth is sensitive to competition (Schmidt and Seidel, 1988; Schmidt, 1997; Martin and Barber, 1995; McLeod, 2012), this is particularly clear in studies where thinning manipulated density early in stand development. By contrast, when thinning is delayed to later stand ages, the effects of density are conflated with the effects of thinning. Top height of *Larix occidentalis* was not affected by density in studies where

PCT was delayed past stand age 30 years (Cole, 1986; Seidel 1987; Cochran and Seidel, 1999; Barber, 2007). In a study where thinning did not occur until stand age 50 years, there were no differences in top height among stands of differing densities, rather trees in all densities showed very slow height growth, roughly 7.6 cm year^{-1} , suggesting that all trees in the study were experiencing reduced height growth due to past competition (Barber, 2007). In contrast, in a study where *Larix occidentalis* was thinned at age 7, by age 13 top height was lower in unthinned stands and stands with high density ($12,000 \text{ trees ha}^{-1}$) than stands thinned to lower densities (Martin and Barber, 1995). In the same study, at age 36 there were large differences in top height among treatments, with unthinned and high-density stands having shorter top heights by over 6 m compared to low-density stands (McLeod, 2012).

Reduced top height at higher levels of competition may result in part from $H:D_{200}$. High $H:D_{200}$ has been connected with increased risk of stem breakage due to wind and snow loading (Cremer et al. 1982, Wilson and Oliver, 2000, Wonn and O'Hara 2001) and a $H:D_{200}$ of 80 has been suggested as a threshold above which there is increased risk of stem breakage for *Larix occidentalis* (Wonn and O'Hara, 2001). The time period when differences in top height occurred in this study aligned with a region-wide late-season heavy snow event in 1996 (Wonn and O'Hara, 2001) and stands with target densities of 890 and $1680 \text{ trees ha}^{-1}$ exceeding the $H:D_{200}$ of 80 (Fig. 7A). Many of the tallest trees in $1680 \text{ trees ha}^{-1}$ density plots experienced stem breakage while little damage occurred to trees in low density plots. Therefore, the decrease in top height may not entirely be a direct result of inter-tree competition but also the indirect effect of high density plots producing trees of lower stability (King 1986).

Our results for temporal trends of height differentiation (Fig. 8) are strikingly similar to those recently reported for long-term *Pinus ponderosa* spacing trials in eastern Oregon and

Washington, USA (McGown et al. 2016). The unthinned plots exhibited the classic predicted trend for high-density stands undergoing self-thinning due to asymmetrical competition (Fig. 8): an initial increase in height differentiation followed by a subsequent decrease in CV_{ht} due to differential mortality of the smallest trees (Weiner and Thomas 1986, Brand and Magnussen 1988, Knox et al. 1989). The mortality and relative density trajectories for the unthinned stands (Fig. 11) corroborate this interpretation. In contrast, the CV_{ht} was lower in all thinned stands, and declined through time, with no initial peak (Fig. 8). We attribute the subtle increase in CV_{ht} between the 1991 and 2001 measurements (Fig. 8) to a region-wide late-season heavy snow event in 1996 (Wonn and O'Hara 2001), which caused top breakage (without mortality) of many trees across our experimental units. CV_{ht} at the 2015 measurement was positively correlated with relative density (Fig 8D; *c.f.* Fig. 7 in McGown et al. 2016), indicating greater size variability at higher levels of competition, which is predicted by theory (Weiner and Thomas 1986, Bonan 1988) and consistent with recent long-term spacing trial results in *Pinus ponderosa* stands (McGown et al. 2016). Declining CV_{ht} through time in thinned stands cannot be explained by self-thinning mortality, because mortality was very low in those treatments (Fig. 11). Rather, in the once-thinned plots, this trend is most clearly explained by converging growth rates (Stoll et al., 1994). In the multiple-entry treatments the intermediate thinnings also contributed to declining CV_{ht} through time, because subordinate and damaged trees were targeted for removal, reducing size variation in the residual population. Thinned stands are obviously experiencing competition because mean tree size decreased (Fig. 5) while CV_{ht} increased (Fig. 8D) with increasing stand density. However, the CV_{ht} trajectories (declining to stable) for all thinned treatments is indicative of relatively weak competition overall (especially in low density

treatments), and of a dominant role of symmetrical competition, most likely for belowground resources (Brand and Magnussen 1988, Stoll et al. 1994).

5. Management Implications and Conclusions

This study shows the strong and long-lasting effects of thinning *Larix occidentalis* early in stand development. Our results complement other studies that have found that *Larix occidentalis* responds weakly or not at all to thinning treatments applied later in stand development (Roe and Schmidt, 1965, Cochran and Seidel, 1999, Martin and Barber, 1995, Barber, 2007). Individual tree size is maximized at lower density. We did not detect a stand density (competition) threshold below which no additional increases in individual tree size occurred (*sensu* Drew and Flewelling, 1979); trees in the 272 trees ha⁻¹ were substantially larger than trees in the 494 trees ha⁻¹ treatments. If a rotation age of 62 years is used to manage *Larix occidentalis*, the maximum merchantable volume is realized in a the one-entry 890 trees ha⁻¹ PCT treatment, but the differences are not large enough to be significantly different from the other thinned densities if a high utilization standard is used (11.4 cm top). Stand densities lower than 494 trees ha⁻¹ may be appropriate for some landowner objectives, for example if rapid growth of individual large diameter trees is prioritized over maximizing stand-level wood production. Densities below 494 trees ha⁻¹ may fail to fully occupy the site, and densities above 890 trees ha⁻¹ may result in mortality before many trees reach merchantable size, particularly if larger top diameters are required to meet merchantability specifications. There is no evidence of a benefit of multiple precommercial thinning entries.

Our results support the conclusion that at densities as low as 494 trees ha⁻¹ the increase in individual tree growth and stability will eventually compensate for lower initial stand growth and yield relative to higher-density stands. Across the tested range of densities, the primary effect of

early thinning is to control whether volume is concentrated on few large, stable trees or spread over many small, unstable trees. At lower densities tree stability increases, indicating that volume as well as volume increment may continue to stay high. We also found that top height was affected by a broad range of initial densities (up to 6,700 trees ha⁻¹) which has strong implications for long-term stand yield. Increasing tree instability (H:D₂₀₀) may also increase mortality, which will lead to decreased yield at higher densities. Said simply, the long-term effect of lower stand density was to produce trees of larger size and greater stability while not sacrificing stand yield.

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Table 1. Characteristics of the four study sites of the Western Larch Density Management Study. Reported aspects and slopes are site averages.

Study site	Harvest date	Harvest method	Site preparation	Habitat type ^a	SDI Max ^b	SI (m) ^c	Elevation (m)	Aspect (°)	Slope (%)
Coram 1	1951	Clearcut/ Seed-tree	Dozer piled, Broadcast burn	<i>Abies lasiocarpa</i> / <i>Clintonia uniflora</i> , <i>Aralia nudicaulis</i> phase	496	24	1200	350	21
Coram 2	1951	Shelterwood	Broadcast burn	<i>Abies lasiocarpa</i> / <i>Clintonia uniflora</i> , <i>Aralia nudicaulis</i> phase	496	23	1200	300	25
Cottonwood Lakes	1953	Clearcut	Dozer piled, scarified, piles burned	<i>Abies lasiocarpa</i> / <i>Clintonia uniflora</i> , <i>Vaccinium caespitosum</i> phase	456	19	1450	355	20
Pinkham Creek	1953	Clearcut	Dozer piled, scarified, piles burned	<i>Abies lasiocarpa</i> / <i>Clintonia uniflora</i> , <i>Clintonia uniflora</i> phase	518	24	1475	65	20

^a Habitat types described in Pfister et al. (1977).

^b SDI maximum was calculated using a stochastic frontier model (Kimsey, 2013) which incorporates species composition, topo-edaphic factors, and climate variables and is reported in English units.

^c Site index (SI) was calculated with the *Larix occidentalis* equation from Milner et al. 1992.

Table 2. The analysis of variance results for tree and stand level variable for *Larix occidentalis* thinned to different target densities with different number of thinning entries. The results for the blocking variable are not shown, but block effects were large for every variable.

Variable	Treatment	Error df	Model MS	Error MS	F	Prob. > F
	df					
QMD	8	24	67.66	2.18	31.05	<0.001
Mean height	8	24	15.53	2.04	7.61	<0.001
Top height	8	24	8.71	2.84	3.06	0.0159
H:D ratio ₂₀₀	8	24	119.12	10.27	11.60	<0.001
Crown volume	8	24	1154.99	75.06	15.39	<0.001
Total cubic volume	8	24	1947.00	1912.00	1.02	0.449
Cubic volume PAI ^a	8	24	0.10	1.86	0.54	0.818
Merchantable volume (11.4 cm (4.5") top)	8	24	3196.00	1875.00	1.70	0.149
Merchantable volume (15.2 cm (6") top)	8	24	8218	1902	4.32	0.002

^a Cubic volume PAI is for the period of stand age 48-62.

684 **Table 3.** Test results of the linear contrasts for tree- and stand-level attributes. Values are the
685 differences between the compared treatments.

Contrast	Stand attribute									
	QMD (cm) ^a	Mean height (m)	Top height (m) ^b	MCRV (m ³) ^c	TCSV (m ³) ^d	PAI (m ³ ha ⁻¹ year ⁻¹) ^e	MV 11.4 (m ³ ha ⁻¹) ^f	MV 15.2 (m ³ ha ⁻¹) ^g	TCRV (m ³ ha ⁻¹) ^h	HD ₂₀₀ ⁱ
Density:										
Once thinned stands										
1680 vs 890 and 494	-6.5***	-3.08**	-1.67	-25.83***	15.08	-0.69	-24.25	-63.88*	-4648	8.7***
890 vs 494	-4.4***	-1.51	-0.49	-26.88***	50.55	0.61	30.00	3.25	-2468	6.1*
Number of entries										
1680: 1 vs 2 and 4	1.3	0.36	1.18	0.92	30.82	-0.47	36.00	35.37	119	-3.2
1680: 2 vs 4	0.6	0.48	0.22	0.06	44.39	1.45	47.50	36.75	865	-2.0
890: 1 vs 2 and 4	2.1	0.71	0.75	2.99	50.86	0.57	49.50	61.37	2240	-3.8
890: 2 vs 4	1.3	0.40	0.51	-4.60	10.55	-0.25	12.00	14.25	-5122	-3.3
494: 1 vs 2 and 4	0.6	-0.61	-0.68	2.97	-10.27	-0.42	-9.125	-6.13	279	-3.4
494: 2 vs 4	1.2	-0.12	1.17	3.31	17.39	0.65	13.75	16.75	-1775	-3.4

686 Significance codes (p-value): 0 < *** < 0.001 < ** < 0.01 < * < 0.05

687 ^a Quadratic mean diameter at breast height

688 ^b Mean height of the tallest 100 trees ha⁻¹

689 ^c Crown volume of the average tree

690 ^d Total cubic stem volume of live trees

691 ^e Periodic annual increment of cubic stem volume from 2001 to 2015

692 ^f Merchantable cubic volume to a 11.4 cm (4.5 inch) top

693 ^g Merchantable cubic volume to a 15.2 cm (6 inch) top

694 ^h Total crown volume ha⁻¹

695 ⁱ Height to diameter ratio of the 200 largest trees ha⁻¹

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Table 4. Tree-level variables 54 years post-treatment for *Larix occidentalis* thinned to different target densities with different numbers of entries to achieve those densities. The reported values are means (standard errors).

Target density	Thinning entries	QMD (cm)	Mean height (m)	Top height (m)	Mean tree volume ^a (m ³)	Height: diameter ratio	Live crown ratio (%)	Mean tree crown volume (m ³)
272	1	34.0 (1.4)	24.4 (0.6)	24.3 (1.0)	0.78 (0.03)	70 (2.3)	57 (5.3)	119.52 (41.78)
494	1	26.8 (1.3)	21.9 (1.5)	23.5 (1.6)	0.47 (0.08)	77 (2.6)	47 (4.7)	54.81 (8.29)
	2	26.9 (1.6)	22.5 (1.9)	24.8 (1.6)	0.49 (0.08)	78 (4.5)	43 (3.4)	50.19 (8.53)
	4	25.7 (1.4)	22.6 (1.9)	23.6 (1.6)	0.45 (0.08)	81 (2.7)	43 (3.9)	53.50 (4.72)
	Mean	26.4 (0.8)	22.3 (0.9)	24.0 (0.9)	0.47 (0.04)	79 (1.9)	44 (2.2)	52.83 (3.91)
890	1	22.4 (1.3)	20.4 (2.1)	23.0 (2.0)	0.33 (0.06)	83 (3.9)	38 (2.9)	27.93 (3.85)
	2	21.0 (1.0)	19.9 (1.6)	22.5 (1.2)	0.27 (0.04)	86 (3.7)	35 (2.8)	22.64 (4.61)
	4	19.7 (1.7)	19.5 (2.2)	22.0 (2.2)	0.25 (0.06)	89 (2.2)	39 (2.5)	27.24 (8.02)
	Mean	21.0 (0.8)	20.0 (1.1)	22.5 (1.0)	0.28 (0.03)	86 (1.9)	37 (1.5)	25.94 (3.10)
1680	1	18.1 (1.2)	18.1 (2.0)	21.6 (1.8)	0.20 (0.05)	90 (3.8)	32 (1.6)	15.54 (4.75)
	2	17.1 (1.8)	18.0 (2.5)	20.5 (2.7)	0.18 (0.05)	88 (5.7)	32 (2.3)	14.59 (3.59)
	4	16.4 (1.4)	17.5 (1.7)	21.6 (1.6)	0.16 (0.04)	92 (5.8)	33 (2.0)	14.65 (2.80)
	Mean	17.2 (0.8)	17.9 (1.1)	20.8 (1.2)	0.18 (0.03)	90 (2.8)	32 (1.0)	14.92 (1.99)
Unthinned	0	8.7 (0.4)	10.4 (0.6)	19.1 (1.2)	0.11 (0.02)	107 (3.3)	29 (0.1)	6.45 (1.12)

^a Mean height of the tallest 100 trees ha⁻¹

^b Total cubic stem volume from ground-level to tip of the tree

^c Height to diameter ratio of the 200 largest trees ha⁻¹

Table 5. Stand-level variables 54 years post-treatment for *Larix occidentalis* stands thinned to different target densities with different numbers of entries to achieve those densities. The reported values are means (standard errors).

Target density	Thinning entries	Basal area (m ² ha ⁻¹)	Total cubic volume ^a (m ³ ha ⁻¹)	Total cubic volume PAI ^b (m ³ ha ⁻¹ year ⁻¹)	Merchantable volume 11.4 cm top ^c (m ³ ha ⁻¹)	Merchantable volume ^d 15.2 cm top (m ³ ha ⁻¹)	Stand level crown volume (m ³ ha ⁻¹)	Relative density ^e	Annual mortality ^f (%)
272	1	16.46 (4.26)	142.95 (42.55)	3.59 (0.56)	127.50 (35.50)	120.00 (34.00)	19,569 (361)	23.5 (6.5)	0.00 (0)
494	1	26.46 (2.84)	219.00 (36.22)	5.80 (1.05)	187.25 (34.55)	163.75 (35.07)	25,535 (4,094)	41.8 (3.1)	0.00 (0)
	2	27.78 (2.92)	237.96 (39.34)	6.55 (0.87)	203.25 (37.35)	178.25 (38.13)	24,368 (3,877)	43.8 (2.8)	0.09 (0.10)
	4	25.44 (2.84)	220.57 (38.56)	5.90 (1.00)	189.50 (35.62)	161.50 (37.23)	26,144 (2,475)	41.0 (2.7)	0.00 (0)
	Mean	26.56 (1.52)	225.84 (20.05)	6.08 (0.52)	193.33 (18.85)	167.83 (19.36)	25,349 (1,870)	42.1 (1.5)	0.03 (0.03)
890	1	32.98 (3.75)	269.55 (53.34)	6.41 (1.50)	217.25 (50.45)	167.00 (49.31)	23,067 (3,043)	56.0 (4.0)	0.16 (0.16)
	2	28.38 (2.98)	223.96 (38.83)	5.71 (1.00)	173.75 (35.85)	112.75 (34.65)	18,266 (3,451)	49.3 (3.4)	0.43 (0.16)
	4	26.77 (4.24)	213.42 (47.70)	5.96 (1.28)	161.75 (46.09)	98.50 (35.04)	23,388 (6,941)	47.3 (5.3)	0.10 (0.10)
	Mean	29.38 (2.09)	235.64 (25.62)	6.03 (0.67)	184.25 (24.35)	126.08 (22.83)	21,574 (2,608)	50.8 (2.5)	0.23 (0.09)
1680	1	34.27 (4.31)	259.35 (54.45)	5.42 (1.51)	178.00 (54.38)	101.50 (47.53)	19,653 (5,142)	62.8 (5.0)	0.86 (0.32)
	2	32.78 (5.66)	250.73 (63.97)	6.61 (1.60)	165.75 (59.70)	84.50 (38.80)	19,967 (4,514)	61.3 (7.5)	0.40 (0.16)
	4	28.52 (2.73)	206.33 (36.48)	5.16 (0.80)	118.25 (37.16)	47.75 (24.58)	19,102 (2,159)	54.8 (3.73)	0.63 (0.30)
	Mean	31.86 (2.41)	238.80 (28.49)	5.73 (0.73)	154.00 (27.91)	77.92 (21.04)	18,892 (3,148)	59.6 (3.1)	0.63 (0.15)
Unthinned	0	28.70 (6.21)	175.98 (54.23)	1.75 (0.12)	44.50 (15.50)	0.00 (0.00)	12,566 (3,740)	70.0 (14.0)	4.34 (0.05)

^a Total cubic stem volume of live trees

^b Cubic volume PAI is for the period of stand age 48-62 (ages 38-62 for unthinned plots).

^c Merchantable cubic volume to a 11.4 cm (4.5 inch) top

734 ^d Merchantable cubic volume to a 15.2 cm (6 inch) top

735 ^e Relative density was calculated with the methods of Drew and Flewelling (1979). SDI maximum was calculated using a stochastic
736 frontier model (Kimsey, 2013)

737 ^f Annual mortality rates for the period of 2001 to 2015 (1991 to 2015 for unthinned plots). Calculated as a percent using an annual
738 compounding equation.

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Fig. 1. A. Map showing locations of the four blocks across the northwest portion of Montana that make up the Western Larch Density Management Study. The black stars are the study sites. There are two sites located relatively close to each other in Coram Experimental Forest, which are represented by one star. B. Map of the Pinkham Creek study site. The solid squares are the 20.12 m $\times$ 20.12 m treatment plots and the dashed lines are the buffers that were thinned with the same treatment. (Map credit: Brian Battaglia).

Fig. 2. The experimental design of the Western Larch Density Management Study. Panel A

shows the three number-of-entry pathways for achieving the 494 trees ha⁻¹ target density. The x-axis shows the both stand age and the calendar year. Years marked in grey indicate years that thinnings occurred. Note that all three pathways all converge by 1991, the date of the final thinning in the four-entry pathway. While all treatments achieve the same final density, trees experienced different amounts of competition depending on the number of entries, with multiple-entry treatments developing for longer times at high stand densities. Panels B and C show the 890 trees ha⁻¹ target density treatments and 1680 trees ha⁻¹ target density treatments respectively. Note that the magnitudes of the thinnings are different depending on the final target density. This shows why the experimental factors have been nested and are being treated as nine separate treatments.

Fig. 3. A. Photo of the unthinned stand at Coram 2 at the initiation of the study in 1961. Stand density was 47,500 trees ha⁻¹. B. Photo of the same stand in 2015, where stand density was 4,200 trees ha⁻¹. The white arrows point at the same tree in panels A and B. C. Photo of a tree in the 494 trees ha⁻¹, one-entry treatment at Coram 2 in 1961 and D is the same tree in 2015. The white arrows point at the same tree in panels C and D. For each pairing the photos were taken from the same permanently marked photo point at the same distance from the tree.

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Fig. 4. Mean crown and stem form of trees of two differing densities (494 trees ha⁻¹ and 1680 trees ha⁻¹) thinned in one entry to the target densities at age 8 years. Trees from the lower density plots (light green) show much larger crowns, greater height, and greater diameter than trees from the higher density plots. The shapes of the crowns were drawn from the treatment mean values for total height, crown base height, height to the widest point in the crown, and crown width (mean of two perpendicular measurements). Stems were drawn using mean total

791 height and QMD. Diameter at root collar was calculated using the principle of triangles of equal
792 proportion. Figures are drawn to scale in both the horizontal and vertical dimensions.

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Fig 5. Mean crown and stem form at stand age 62 years for *Larix occidentalis* stands thinned at stand age 8 with one entry to different target densities. Crowns and stems were drawn using the same methods as in Fig. 4 and are drawn to scale in both the horizontal and vertical dimensions.

Fig 6. Top height (defined as the mean height of the tallest 100 trees ha⁻¹) through time by target density for all treatments. All panels include the unthinned treatment (grey) and 272 trees ha⁻¹ density treatment (orange) to serve as reference. Panel A shows top height for all three thinning schedules (target density achieved through one, two, or four entries) for the 494 trees ha⁻¹ target density. Panels B and C show top height for all three thinning schedules of the 890 trees ha⁻¹ and 1680 trees ha⁻¹ target densities respectively. Panel D shows the top height means for all

treatments in 2015. Error bars are equal to one standard error of the mean. The x-axis describes the treatment: the target density is before the period and the number of thinnings is after the period. The p-value of 0.0159 is the result of the omnibus ANOVA test, indicating that there is a significant treatment effect.

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Fig. 7. A. Height to diameter ratio of the largest diameter 200 trees ha⁻¹ (H:D₂₀₀) for all densities thinned once. The dashed line represents the 80:1 ratio suggested as a threshold of stability for *Larix occidentalis* by Wonn and O'Hara (2001). Values above the 80:1 threshold indicate that stands are at an elevated risk for stem breakage due to wind and snow loading, both of which have been reported to cause high levels of damage to *Larix occidentalis* stands (Schmidt et al. 1976; Wonn and O'Hara, 2001). B. An interaction plot showing 2015 H:D₂₀₀ for the tested densities at all three numbers of entries. The figure shows that stands left at higher densities for longer do not recover low height to diameter ratios for many years after thinning, if at all.

Fig 8. Coefficient of variation of height (CV_{ht}) through time by target density for all treatments. All panels include the unthinned treatment (grey) and 272 trees ha^{-1} density treatment (orange) to serve as reference. Panel A shows CV_{ht} for all three thinning schedules (target density achieved through one, two, or four entries) for the 494 trees ha^{-1} target density. Panels B and C show CV_{ht} for all three thinning schedules of the 890 trees ha^{-1} and 1680 trees ha^{-1} target densities, respectively. Panel D shows relationship of 2015 relative density to the 2015 CV_{ht} means for all

treatments. Relative density for stands thinned once calculated as % of maximum SDI (Drew and Flewelling, 1979). The canopy closure line, at 15% relative density indicates the beginning of inter-tree competition. The gray band, between a relative density of 40% and 55%, identifies the zone of maximum stand volume growth. The zone of imminent competition mortality (ZICM; *sensu* Drew and Flewelling, 1979), where mortality due to self-thinning begins, is defined by the line at 55% relative density.

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Fig 9. Total cubic volume through time by target density for all treatments. All panels include the unthinned treatment (grey) and 272 trees ha⁻¹ density treatment (orange) to serve as reference. Panel A shows total cubic volume for all three thinning schedules (target density achieved through one, two, or four entries) for the 494 trees ha⁻¹ target density. Panels B and C show the total cubic volume for all three thinning schedules of the 890 trees ha⁻¹ and 1680 trees ha⁻¹ target densities, respectively. Panel D shows the cubic volume means for all treatments in

2015. Error bars are equal to one standard error of the mean. The x-axis describes the treatment: the target density is before the period and the number of thinnings is after the period. The p-value of 0.449 is the result of the omnibus ANOVA test, indicating that there are no significant differences in any of the tested treatments.

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Fig 10. Merchantable cubic volume for all densities thinned once for two utilization standards common in the Northern Rockies. A. Merchantable volume up to an 11.4 cm (4.5 in) top. B. Merchantable volume up to a 15.2 cm (6 in) top.

Fig. 11. A. Annual mortality rate for stands thinned once in percent of stems $\text{ha}^{-1} \text{year}^{-1}$ calculated via annual compounding. B. Relative density for stands thinned once calculated as %

of maximum stand density index. Note that the increase in the mortality rate of the 1680 trees ha^{-1} density increases as it passes into the zone of imminent competition mortality (ZICM; *sensu* Drew and Flewelling, 1979) which begins at a relative density of 55%. The canopy closure line indicates the beginning of inter-tree competition (Drew and Flewelling, 1979). The gray band, between a relative density of 40% and 55%, identifies the zone of maximum stand volume growth.

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Fig. 12. The relationship of 2015 relative density to periodic annual increment of total cubic volume for the period from 2001 to 2015. The clustering of points of the three tested densities (494, 890, and 1680 trees ha⁻¹) around a PAI of 6 m³ ha⁻¹ year⁻¹ across the zone of maximum growth (RD of 40% to 55%) show constant volume growth across stand densities during the most recent measurement interval (5.42-6.41 m³ ha⁻¹ year⁻¹; $P > 0.05$). The lower value of the 272 trees ha⁻¹ and unthinned treatments show lower volume growth at RD values below 40% or above 55%.