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DENSITY MANAGEMENT IN YOUNG WESTERN LARCH STANDS:
TREE GROWTH, STAND YIELD, AND CARBON STORAGE
54 YEARS AFTER THINNING

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Density management in young western larch stands: tree growth, stand yield, and carbon storage 54 years after thinning

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Long-term silvicultural experiments can be used to test novel ecological hypotheses and answer contemporary management questions that were not envisioned at study initiation. We used a 54-year old western larch precommercial thinning (PCT) study in northwest Montana to examine two sets of questions: (1) how different PCT regimes affect long-term stand yield and tree growth, and (2) how PCT affects total aboveground carbon (C) storage and distribution among C pools. The study has three target densities (494 trees ha\(^{-1}\), 890 trees ha\(^{-1}\), and 1680 trees ha\(^{-1}\)) and three numbers of entries to achieve those target densities (1, 2, and 4 entries). We included unthinned plots for comparison in our C analysis. We measured multiple tree attributes and sampled three additional aboveground C pools: understory/mid-story vegetation, woody detritus, and forest floor material. Tree measurements were used to calculate tree- and stand-level attributes, as well as total live tree C. Carbon samples from other pools were processed in a lab. ANOVA and linear contrasts were used to test specific research questions.

Results from our yield analysis found long-term constant yield and constant volume growth over a range of densities. The primary effect of early thinning is to control whether volume and tree crown are concentrated on few large individuals or spread over a greater number of small individuals. Top height was negatively affected by higher densities. Height to diameter ratio, an attribute related to tree stability, acted to increase mortality in high density plots, decreasing yield at higher densities.

Three main conclusions follow from our examination of effects of early thinning on total aboveground C. (1) Fifty-four years after treatment total aboveground C of stands precommercially thinned to a wide range of densities is similar, due primarily to the increase in mean tree C of trees grown at lower stand densities. (2) Sixty-two years after stand replacing disturbance deadwood legacies from the pre-disturbance forest still play an important role in long-term C storage. (3) Given enough time since early thinning, there is no trade-off between managing stands to promote individual tree growth, and maximizing stand level accumulation of aboveground C.
Chapter 1.

Early precommercial thinning leads to similar yields across a wide range of stand densities 54 years after treatment

Abstract

Precommercial thinning (PCT) increases individual tree size and shortens harvest rotation time by affecting the timing and intensity of competitive interactions between trees. Short-term results from PCT and spacing trials often show that the trade-off for rapid individual tree growth at lower densities is a period of time where trees do not fully occupy the site, and stand yield lags behind yields obtained from high density stands.

While it is well established that individual tree size and growth increase at lower stand densities there is still some uncertainty over how long-term yield, defined as the total cubic stem volume per unit ground area, responds to early PCT. We re-sampled a 54-year old western larch PCT study in northwest Montana with two objectives: (1) to test how different target densities and thinning schedules affect stand yield, and (2) to analyze and report tree- and stand-level mensurational characteristics of a long-term PCT experiment at nominal full rotation age (62 years from stand initiation). The study has three target densities (494 trees ha\(^{-1}\), 890 trees ha\(^{-1}\), and 1680 trees ha\(^{-1}\)) and three numbers of entries to achieve those target densities (1, 2, and 4 entries), creating a gradient of competition pathways by which a stand achieves a final density. Analysis of variance and linear contrasts were used to test the affects of density and number of entries on tree- and stand-level attributes 54-years after treatment began. Results suggest that if thinning is done early (<10 years) we will see long-term constant yield across a range of densities. We
also found evidence supporting Langsaeter’s hypothesis, that volume growth is constant over a range of densities. There was no significant effect of the number of entries on any tree- or stand-level attribute. The primary effect of early thinning is to control whether volume and tree crown are concentrated on few large individuals or spread over a greater number of small individuals. Top height was negatively affected by higher densities, which has strong implications for long-term stand yield. Height to diameter ratio, an attribute related to tree stability, also acted to increase mortality in high density plots, which decreased yield at higher densities. Our results showed that across the tested range of densities the long-term effect of lower density was to produce trees of larger size and greater stability while not sacrificing long-term stand yield.

**Keywords:** *Larix occidentalis*, western larch, precommercial thinning, density management, stand density, competition

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. 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 inter-tree competition leading to an increase in tree growth and a decrease in time required to reach merchantable size (Assman, 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 of time 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 some uncertainty over how long-term yield, defined here as the total cubic stem 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, so does the increase in individual tree size at lower densities make up for fewer trees? Current wisdom generally suggests that the yield increases with density (Fig 1a; Zeide, 2001, Cutis et al. 1997, Marshall and Curtis, 2002) until a threshold is reached where extreme levels of competition and poor differentiation lead to height growth suppression (Lanner, 1985; Oliver and Larson, 1996) and a loss of volume increment. Alternative yield hypotheses are based on the proposition that, given enough time, stand density is not always the main driver of stand yield. One hypothesis, known at the constant yield effect, suggests that all stands will eventually grow at the same constant rate of volume increment but stands at lower density will begin growing at that rate later than stands at higher densities (Fig 1b; Oliver and Larson, 1996), leading to a constant final yield across a broad range of initial densities. Another alternative hypothesis, known as the crossover effect, suggests that early in stand development the total cubic volume of a stand is most directly governed by its density, but over time the low density stands will eventually surpass the volumes of higher density stands (Fig 1c; Oliver and
Larson, 1996). 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) and 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 crossover affect has been observed
in some thinning and spacing trials (e.g. Reukema, 1979; Peet and Christensen, 1987;
Marshall and Curtis, 2002). Very low densities may never crossover higher densities as
they may never fully occupy the site due to an upper limit of tree size (Oliver and Larson,
1996).

Several tree-level attributes may lead to the constant yield (Fig. 1b) or crossover
(Fig. 1c) effects. The volume of a tree depends on the tree’s height, diameter, and trunk
taper (Flewelling and Raynes, 1993), 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 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-Jørgensen 1967, Lanner 1985, Smith et al. 1997,
Marshall and Curtis 2002, Tappeiner et al. 2007). However, early results from some
thinnings trials show top height sorting along a density gradient with lower density stands
having greater top height (Schmidt and Seidel 1988, Schmidt 1996, Martin and Barber,
1992). This may be especially true in evenly spaced stands where differentiation is often
weak, leading to an earlier loss of height grow at higher densities (Oliver and Larson,
1996). If top height increases in low density stands this will have strong effect on yields of both total cubic volume and merchantable volume.

Height to diameter ratio of the largest 200 trees ha\(^{-1}\) (H:D\(_{200}\)), a simple measure of tree stability and resistance to physical damage (Cremer and Borough, 1982; Wilson and Oliver, 2000; Won and O’Hara, 2001) may indirectly affect stand yield. Trees with high H:D\(_{200}\) are more susceptible to wind throw and stem breakage and stands grown at higher densities have higher H:D\(_{200}\) (Cremer and Borough, 1982; Wilson and Oliver, 2000; Won and O’Hara, 2001). This predisposes a greater proportion of the standing volume to damage and mortality, which reduces stand yield.

Mortality rates also affect total yield. Measures of competition such as relative density, the proportion of the maximum stand density index for a species (\textit{sensu} Drew and Flewelling 1979), identify thresholds where the probability of mortality increases. Relative density can be used to identify levels of competition where volume growth is highest. Newton (1997), using a combination of relative density and Langsaeter’s forest productivity hypothesis (which states that volume growth is constant over a wide range of levels of growing stock [Langsaeter, 1941; Marshal and Curtis, 2002]), identified relative densities between 40% and 55% of maximum as the area of maximum 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 thinnings? From an operations and cost perspective, the most advantageous prescription 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 may begin to be 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 larger tree size than if stands were initially thinned to a low density (O’Hara and Oliver, 1988). Multiple lighter 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 is to evaluate three alternative stand yield hypotheses (Fig. 1) using a 54-year long western larch (*Larix occidentalis*) density management experiment in northwestern Montana. A secondary objective is to analyze and report tree and stand-level mensurational characteristics of this long-term experiment at nominal full rotation age (62 years from stand initiation). Tree and stand characteristics analyzed include QMD, mean height, top height, mean crown volume, height to diameter ratio, basal area, total cubic volume, periodic annual increment of cubic volume, merchantable cubic volume, relative density, and mortality rate. We ask two specific research questions which guide our statistical analyses.

1. Fifty-four years after treatment, given one precommercial thinning entry, how does stand density affect tree- and stand-level attributes?
2. Do multiple precommercial thinning entries result in tree and stand-level 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), originally titled “Spacing and precommercial thinning in young western larch stands, western Montana” and was established by US Forest Service research scientists in 1961 (Schmidt, 1964). Four study sites (blocks) were chosen to capture the western larch productivity gradient in northwestern Montana (Fig. 2). All sites had been harvested using even-aged methods between 1951 and 1953 (Table 1) and regenerated naturally in the good western larch seed years of 1952 and 1954 (Schmidt, 1964). This resulted in high densities (25,000 to 63,000 trees ha$^{-1}$) of primarily western larch, but included lesser amounts of Engelmann spruce ($Picea engelmannii$), Douglas-fir ($Pseudotsuga menziesii$ v. glauca), subalpine fir ($Abies lasiocarpa$) and paper birch ($Betula papyrifera$) (Schmidt, 1964). Sites were chosen for their even stocking and similar topo-edaphic conditions (Table 1). For a more detail description of the study sites and harvest methods see the WLDMS establishment report (Schmidt 1964).

Between the summer of 1961 and winter of 1962, 12 to 14 treatment plots were established at each site. 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 will be used as the age of initial treatment. Treatment plots (i.e., the experimental units) are square 20.12 m by 20.12 m plots surrounded by a buffer of at least 10 to 20 m that was thinned with the same treatment. Thinning treatments were randomly selected for each plot.
Treatments included a core 3 x 3 factorial design, hereafter referred to as the core, which were replicated once at all four study sites. The core treatments consisted of three different target densities (spacing): 494 trees ha\(^{-1}\) (4.6 m x 4.6 m), 890 trees ha\(^{-1}\) (3.6 m x 3.6 m), and 1680 trees ha\(^{-1}\) (2.4 m x 2.4 m). These three densities were chosen in 1961 to test proposed ideal densities to grow larch (Schmidt, 1961). These densities were achieved with three different thinning schedules (hereafter referred to as entries): one entry, two entries, or four entries (Figure 3). Single-entry treatment plots were thinned directly to the target density in 1961. If a plot was assigned two entries it was thinned to an intermediate density in 1961 then to the final target density in 1981. If a plot was assigned four entries it was thinned to progressively lower intermediate densities in 1961, 1971, and 1981, then thinned to the final target density in 1991. The different number of entries creates a gradient of competition pathways by which a treatment plot reaches the final target density; one entry treatments had low levels of competition while four entry treatments had higher levels of competition (Fig. 3). Thinnings were from below, removing small and damaged trees (J. Schmidt, personal communication 2016). All cut material was left on site. During the initial thinning in 1961 all shrubs were cut in all thinned plots. Theses nine treatments (the three core target densities crossed with three different numbers of entries) were replicated once at each of the four sites. In addition, unthinned plots and very low density once thinned treatment (272 trees ha\(^{-1}\), 6.1 m x 6.1 m achieved in a single thinning in 1961) were installed at the Coram 1 and Coram 2 sites. To explore the effects of competition from sprouting shrubs, paired plots were installed in all target densities of the four entry treatments where cut shrub stumps were sprayed with an herbicide (2-4-5-T). The results of the herbicide treatments are not presented here but
are noted for completeness. The result is 14 treatment plots at the Coram 1 and Coram 2 sites and 12 treatment plots at the Cottonwood Lakes and Pinkham Creek sites. All trees were tagged inside each treatment plot. In the unthinned plots 20 tagged crop trees were measured as well as all trees within 10 systematically located permanent 4.05 m² plots.

2.2 Measurements

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, and in the unthinned plots the crop trees and all trees in the 4.05 m² plots were measured. 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. All tree measurements were originally recorded in English units. Tree measurements included dbh (stem diameter at 1.37 m; nearest 0.25 cm), total height (nearest 0.3 m), crown base height (defined as the height to the lowest complete whorl, where lower branches were visually moved up to fill in gaps in the upper canopy; nearest 0.3 m), height to the widest point in the crown (nearest 0.3 m), crown width at two perpendicular axes (nearest 0.3 m), vigor (a qualitative call from 1 (healthy) to 4 (dead)), and Kraft crown class (dominant, codominant, intermediate, or suppressed). Physical damage and insects or disease issues were also noted at each measurement.

2.3 Data reduction

Plot level averages were calculated for a number of response variables. Response variables reported include quadratic mean diameter (QMD; defined as the diameter of the
tree of average basal area), mean height, top height (defined as the mean height of the
tallest 100 trees ha$^{-1}$), height to diameter ratio, and crown volume. 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, made up of measures 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 Raynes (1993) 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 m$^3$ ha$^{-1}$. Net periodic annual increment
(PAI) of total cubic volume, expressed as m$^3$ ha$^{-1}$ year$^{-1}$, 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 Raynes (1993) 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
actual stand density and the QMD, then converted to a relative density as a percentage of
maximum SDI (Drew and Flewelling 1979). Maximum SDI was calculated for each site
using a stochastic frontier model that incorporates species composition, topo-edaphic
factors, and climate variables (M. Kimsey, personal communication; Table 1). This was
done because maximum SDI values for western larch are poorly established in the
literature and there are suggestions that maximum SDI may vary by site quality (Jack and
unthinned plots) were calculated as a percent using the following annual compounding equation

\[ m = 1 - \left[ 1 - \left( \frac{M_1}{N_0} \right) \right]^{1/t} \]

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 for the 2015 (stand age 62) measurements, for each of the tree and stand-level variables. Data was analyzed for the fully replicated, core nine experimental treatments: 3 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 (\( n = 2 \)).

An important consideration for statistical analysis is the recognition that the number of thinnings factor is nested within the target density factor: the severity of intermediate thinnings (defined as the number of trees removed) depended on the final target density (Fig. 3). 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. The resulting explanatory variable was a factor with 9 levels (3 entries x 3 target densities). Once a significant result was discovered in the omnibus ANOVA test, we used linear contrasts to test our specific research questions: 1) if in plots with one thinning entry density had an effect on tree and
stand level attributes, and 2) whether there was a benefit of multiple thinning entries within each of the three core experimental densities. To examine how density in once-thinned stands affected tree and stand-level variables we set up two linear contrasts: the first compared the 1680 trees ha\textsuperscript{−1} density with the 890 trees ha\textsuperscript{−1} and the 494 trees ha\textsuperscript{−1} densities, the second compared the 890 trees ha\textsuperscript{−1} density with the 494 trees ha\textsuperscript{−1} density. The last two densities most closely represent the current management zone for western larch 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. Family wide P-values were adjusted using the Bonferroni correction to ensure a family-wise type I error rate of \( \alpha=0.05 \). All statistical analyses were conducted using R 3.2.4 (R Development Core Team 2016). The multcomp (Hothorn et al., 2014) package was used to test the linear contrasts.

3. Results

3.1 Long-term trends of tree size and stand yield

Most tree-level attributes differentiated by density early in the experiment, and the effect of density on tree size was visually obvious by stand age 62 years (Figs. 4-6). QMD differentiated rapidly by density, with lower density stands having much larger diameters (Appendix A). The QMD of unthinned control plots developed much more slowly than that of any of the thinned plots (Appendix A). By stand age 62 the 272 trees ha\textsuperscript{−1} treatment had a QMD nearly 4 times greater than that of unthinned stands (Table 4;
Fig. 5). 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, with low density plots having greater mean heights that the high density plots (Table 4, Fig. 5, $p = 0.003$). Top height (the mean height of the largest 100 trees ha$^{-1}$) followed a different pattern (Fig 7). Top height sorted out along the competition gradient created by the treatments relatively early in experiment, but differences were relatively small until stand age 38 after which differences in top height began to become larger as higher density stands (1680 tree ha$^{-1}$) grew at lower rates resulting in significant differences in top height due to treatment in 2015 ($p = 0.0159$; Fig 7d; Table 2). Height to diameter ratio of the 200 largest trees per plot (H:D$_{200}$) separated by density early in the experiment (Fig. 8), with denser stands having higher H:D$_{200}$ as early as age 18 (20 years after treatment). These differences have stayed relatively constant through the course of the experiment but H:D$_{200}$ have continued to increase with time across all plots (Fig. 8) and were significantly different at stand age 62 years ($p < 0.001$; Table 2).

Stand-level attributes sorted out differently over time than 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 in both of these variables. However, with time, the basal area and total cubic volume of the 890 and 1680 trees ha$^{-1}$ plots have surpassed the unthinned plots, while lower density plots have continued to have lower total cubic volume. However, at stand age 62 differences in cubic volume were not significant ($p = 0.449$; Table 2). PI of total cubic volume peaked early in the higher density stands and both the unthinned stands and 1680 trees ha$^{-1}$
stands have declined below peak levels. Stand with 890 and 494 trees ha\(^{-1}\) had lower initial PAI values but have continued to increase through stand age 62, such that at age 62 differences in volume PAI are not significant \((p = 0.818; \text{Table 2})\). The low density 272 trees ha\(^{-1}\) has much lower PAI values than the other thinned stands.

Trends in merchantable volume are highly dependent on the utilization standard that is used (11.4 cm top versus 15.2 cm top; figure 9 A and B). When using the 11.4 cm top the very 272 trees ha\(^{-1}\) stand initially has the highest volume but was rapidly surpassed by the 890, 494, and 1680 trees ha\(^{-1}\) densities. The 890 trees ha\(^{-1}\) has the greatest merchantable volume throughout the majority of the experiment period while the 1680 and 494 trees ha\(^{-1}\) treatments are lower but quite similar to each other. The differences in merchantable volume to an 11.4 cm top are not significant \((p = 0.149; \text{Table 2})\). The 272 trees ha\(^{-1}\) density has lower merchantable volumes than the core densities and the unthinned plot has the lowest merchantable volumes throughout the experiment (Fig. 9 A). When looking at merchantable volume to a 15.2 cm top the 1680 trees ha\(^{-1}\) has substantially less merchantable volume than it did when using an 11.4 cm top. The 494 and 890 trees ha\(^{-1}\) are almost identical to each other. Differences between the tested densities were significant \((p = 0.002; \text{Table 2})\). The unthinned plot has no merchantable volume that meets the 15.2 cm top utilization standard (Fig. 9 B)

3.2 Effects of stand density in once-thinned treatment plots
3.2.1 Tree-level attributes

Quadratic mean diameter (QMD) differed significantly among the one entry core target densities \((p < 0.001)\). Quadratic mean diameter was inversely related to stand
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 with the 1680 tree ha$^{-1}$ plots having significantly lower heights that the 890 and 494 trees ha$^{-1}$ plots ($p < 0.003$; Table 3), while the difference between the 890 and 494 trees ha$^{-1}$ was not significant ($p = 0.30$; Table 3). Mean tree height includes all trees in a plot and so higher density stands, which have a greater number of trees in subordinate crown classes, are expected to have lower mean heights than low density stands. Top height within the one entry treatments sorted out by density, with lower density plots having higher top heights, but differences were not significant ($p = 0.269$; Table 3).

The H:D$_{200}$ was significantly affected by density in the one entry treatments ($p < 0.001$; Table 3). The lower density plots had lower higher H:D$_{200}$ ratios with 494 tree ha$^{-1}$ 6.8 points smaller than the 890 tree ha$^{-1}$ and 13.4 points less than the 1680 tree ha$^{-1}$ density with all contrasts significant.

Average crown volume per tree increased significantly as density decreases (Fig 6; $p < 0.001$). Crowns are approximately twice as large in the 494 trees ha$^{-1}$ treatment as they are in the 890 trees ha$^{-1}$ treatment and more than three times larger than the 1680 trees ha$^{-1}$ treatment (Fig 8; Table 4).

3.2.2 Stand-level attributes

For the single entry treatments the total cubic volume of stem wood from the ground to the tip of the tree was not significantly affected by density ($p = 0.244$). It is
clear from graphical representation (Fig. 9 A-C), that by stand age 62 values of cubic volume are greater for all of the core densities than the 272 trees ha\(^{-1}\) density and the unthinned plots. PAI in the once thinned treatments in the period between 2001 and 2015 was highest in the 890 trees ha\(^{-1}\) density at 6.41 m\(^3\) ha\(^{-1}\) year\(^{-1}\) but differences between the core densities were small and non-significant (Table 5, Fig. 12, \(p = 0.7917\)).

The merchantable volume in m\(^3\) ha\(^{-1}\) to an 11.4 cm (4.5 inch) top of the once thinned treatments followed the same trend as the total cubic volume, with 890 tree ha\(^{-1}\) plots having the highest merchantable volume (Table 5), but difference between densities are not significant (\(p = 0.421\); Table 3). The merchantable volume to a 15.2 cm top showed the same trend as the merchantable volume to a 11.4 cm top but the differences due to density were significant (\(p =0.001\); Table 2). The 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 (\(p < 0.001\), 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 ranges 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\(^{-1}\) density crossed the threshold of 55% relative density (Figure 11), which is proposed by Drew and Flewellig (1979) as the onset of competitive mortality, or zone of imminent competition mortality (ZICM). By 2015 the 890 trees ha\(^{-1}\) density had also crossed into the ZICM. Crossing into the ZICM coincides with an increase in mortality in the 1680 trees ha\(^{-1}\) density to 0.86 % year\(^{-1}\) (Fig. 11; Table 4) which is higher than the 890 (0.16% year\(^{-1}\)) or 494 (0.00% year\(^{-1}\)) tree ha\(^{-1}\) treatments.
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 rarely significant. For QMD, within 494 trees ha\(^{-1}\) 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 1 entry and 2 or 4 entry treatments in the 890 trees ha\(^{-1}\) target density \((p = 0.06;\) Table 3). In the 890 trees ha\(^{-1}\) 1680 trees ha\(^{-1}\) densities the QMD decreases as the number of thinning entries increases (Table 4). It is 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 entries treatments then declined in the four entries treatment. The number of entries did not have a significant effect on mean height \((p = 0.8229;\) Table 3) but the same trend occurred that was present in QMD, as the number of entries increased the mean height decreased for all densities except the 494 tree ha\(^{-1}\) which increased with higher numbers of entries. The effects of the numbers of entries factor on top height was not significant and showed a similar pattern to that of mean tree height. The effect of number of thinnings on crown volume is non-significant.

3.3.2 Stand level attributes

The effect of the 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 increases where as in the 494 trees ha\(^{-1}\) cubic volume peaked at two thinning entries.

**4. Discussion**

We found strong support for the constant yield effect (Fig. 1, Oliver and Larson 1996) as well as evidence supporting Newton’s (1997) formulation of Langsaeter’s hypotheses. Our results suggest that if thinning is done early (<10 years) long-term net yield converges across a range of thinned densities. At stand age 62 years the primary effect of early thinning is controlling whether volume is concentrated on few large individuals or spread over a greater number of small individuals. 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 volumes may be driven largely by density early in stand development, by 54 years after thinning those differences disappear (Fig. 10). In fact, very high density plots may actually have less volume than lower density plots (Fig. 10), evidence to support the crossover effect (Oliver and Larson 1996). A second important finding is that top height was sensitive to the competition gradient created by the experimental treatments (Table 4; Fig 7). This has strong implication for yield as 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). Increases in factors related to tree instability, such as height to diameter ration (H:D\(_{200}\)), may also act to increase non-competitive mortality and decrease yield at higher densities. In other words, 54 years after thinning, significantly larger tree size and greater tree stability at lower densities made up in cubic volume for fewer trees.
Our results agree with those of other long-term PCT and spacing studies. The constant yield or crossover effects have been seen in long-term studies of Douglas-fir (Reukema, 1979), loblolly pine (Peet and Christensen, 1987), ponderosa pine (Cochran and Barrett, 1993), as well as more shade tolerant balsam fir and red spruce (Pitt and Lanteigne, 2008). Short-term results of most PCT and spacing studies generally show that yield is proportional to density (Schmidt and Seidel 1988, Harrington et al. 2009) indicating that there is a loss of volume 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 we see in this study, or potentially crossover as stands enter the ZICM and some volume growth is lost to mortality (Harrington et al. 2009). Other studies showed that the stand age of density reduction plays an important role in long-term growth and yield; early thinning leads to smaller reductions in yield than later thinnings (Varmola and Salminen, 2004).

The results of many previous long-term levels-of-growing-stock (LOGS) studies general contradict our results but, interestingly, not all always. We also reemphasize that the multiple thinning entries in this study are distinctly different from the multiple thinning entries of LOGS studies; in this study the multiple thinning entries removed the smallest trees to achieve a target density over multiple thinnings (Fig. 3), while LOGS thinnings seek to maintain a constant level of growing stock through time, defined by basal area, bole surface area, or total cubic volume (e.g. Cochran and Seidel 1999; Marshall and Curtis 2002, D’Amato et al., 2010). The results from Douglas-fir and red pine LOGS studies have shown that stand yield is always proportional to density (Curtis
et al. 1997; D’Amato et al., 2010) with the exception of long-term results of unthinned stands near the maximum size-density relationship on high productivity sites (Marshall and Curtis, 2002). However, the most directly comparable LOGS study, a western larch study in the Blue Mountains of eastern Oregon established in 1966 (Cochran and Seidel, 1999), shows that cubic volume yield at age 65 increases with growing stock level until the experiment-long average RD threshold of 55%. A growing stock levels that exceeded the ZICM, with an experiment-long average RD of approximately 63%, had a lower yield than stands with lower growing stock (Cochran and Seidel, 1999). In Douglas-fir LOGS studies volume growth rate (defined by PAI of cubic volume) consistently increases with growing stock, evidence against Langsaeter’s hypothesis (Curtis et al., 1997; Zeide, 2001). However, there is evidence that treatments in these studies may simply not have had enough growing stock to show Langsaeter’s effect (Marshall and Curtis, 2002). In comparison, LOGS studies in red pine (D’Amato et al. 2010) and western larch (Cochran and Seidel, 1999) show that as stand age increases, PAI of stands at higher levels of growing stock are equaled or surpassed by stands with lower levels of growing stock, providing evidence for Langsaeter’s hypothesis as well as the constant yield or crossover effects (Oliver and Larson, 1996).

As trees at a given density grow in diameter their relative density (SDI/maximum SDI) increases. Drew and Flewlling (1979) suggest that the zone of maximum volume increment for coastal Douglas-fir occurs across the range of 40% to 55% relative density (RD) and that within that range, growth is unaffected by density. Other studies have shown that their suggested range holds true for other species (Newton, 1997). Below 40% RD growth is proportional to density and above 55% RD net growth decreases as a
portion of gross growth is lost to mortality (Drew and Flewelling, 1979; Newton, 1997). Our results suggest that these relationships hold for western larch (Fig. 12), though the zone of maximum growth may extend beyond a RD of 55% to approximately RD 65% (Fig. 12). Our results also show that size-density relationships provide the ecological foundation for the constant yield and crossover effects. As high density stands grow, they near the maximum size density relationship (Reineke 1933, Yoda et al., 1963, Drew and Flewelling, 1979). At this point some of the gross volume that is accumulated early in stand development is lost due to mortality (Newton, 1997). As trees in subordinate crown classes die from competitive mortality there is a loss of leaf area (Smith and Long 2001) and a decreased foliar efficiency (Binkley et al., 2002) slowing stand-level growth rates of higher density stands. This leads to the either the constant yield or crossover effect found in a growing number of precommercial thinning and spacing studies (Reukema, 1979; Peet and Christensen, 1987; Marshall and Curtis, 2002; Harrington et al., 2009).

Figure 11 B shows that both the 890 and 1680 tree ha$^{-1}$ treatments are leaving the RD zone of maximum growth and entering the zone of imminent completion mortality. This indicates that their net growth rates are likely to decrease as some growth is lost to mortality with an increase in RD (Fig. 12, Fig 11 A). The 494 trees ha$^{-1}$ treatment is just entering the RD zone of maximum growth. Looking forward, this suggests that the yields of the three densities will continue to converge or perhaps crossover as the 494 trees ha$^{-1}$ treatment potentially achieves a higher growth rate than the 890 and 1680 tree ha$^{-1}$ treatments.
It is of particular note that over the entire range of thinning treatments top height was found to be sensitive to competitive history (Fig. 7). When the stands were thinned directly to the three tested target densities in 1961 top height was not significantly sensitive to density (Fig. 7). 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. 3). Figure 5 D shows that among tested densities top height differences were greatest between the 494 trees ha\(^{-1}\) density with 1 or 2 entries and the 1680 trees ha\(^{-1}\) with 2 or 4 entries. These treatments represent opposite ends of the competition gradient within the experiment. Figure 3 C shows that the 1680 tree ha\(^{-1}\) 4 entries stand was experiencing enough competition between the first and second thinnings that mortality was occurring in the plot (as indicated by the slight downward slope of the line). Top height can be significantly affected by extremes of stand density (Sjolte-Jorgensen, 1967; Lanner, 1985) and shade-intolerant species, such as Pinus radiate, Pinus resinosa, Pinus sylvestris and Pseudotsuga menziessii, tend to have greater height reductions at high densities than shade-tolerant species such as Picea abies (Sjolte-Jorgensen, 1967). Top height growth has been shown to be adversely affected in 14-year-old lodgepole pine in densities greater than 15,000 tree ha\(^{-1}\) (Mitchell and Gouldie, 1997). The densities of the initial intermediate thinnings (up to 6,700 trees ha\(^{-1}\), Fig. 3) may represent density levels where larch height growth is compromised and certainly the densities of the unthinned plots (up to 63,000 trees ha\(^{-1}\)) cause height growth repression (Fig. 7).

While it is widely accepted that top height is controlled by site environmental conditions and independent of stand densities (Sjolte-Jorgensen, 1967; Lanner, 1985;
Smith et al., 1997; Marshall and Curtis, 2002; Tappeiner et al., 2007), our results show that this assumption must be reconsidered, particularly for highly shade-intolerant species such as western larch. We propose two potential explanations for why we find a significant effect of density on top height: 1) western larch height growth is more sensitive to competition than some other conifers and 2) decreases top height at high densities are the result of high H:D leading to elevated levels of top breakage in the tallest trees. There is evidence from past work examining the effect of density on western larch growth that suggests larch height growth is sensitive to competition (Schmidt and Seidel, 1988; Schmidt, 1997; Martin and Barber, 1992; McLeod, 2012), however the stand age at which thinning takes place makes a large difference in this trend (McLeod, 2012). In studies where PCT of western larch was delayed past stand age 30 top height was not affected by density (Cole, 1986; Cochran and Seidel, 1999; Barber, 2007). In a study where thinning did not occur until stand age 50 there were no differences in top height, rather trees in all densities showed very low height growth, roughly 7.6 cm year⁻¹, suggesting that all trees in the study were experiencing reduced height growth due to past high density (Barber, 2007). In contrast, in a western larch PCT study thinned at age 7 in eastern Washington, by age 13 unthinned stands and stands with high density (12,000 trees ha⁻¹) were found to have lower top heights than stands thinned to lower densities (Martin and Barber, 1995). While the differences were non-significant at the time of measurement the authors suggest that the differences may become significant with time. By age 36 in the same study, there were larger difference in top height, with unthinned stands and high density stands having shorter top heights by over 20 feet (McLeod, 2012). McLeod attributes part of this large difference in top height to substantial
amounts of snow breakage in the higher density stands. A similar trend is apparent in the present thinning study as well with higher density stands experiencing more top breakage.

Reduced top height at higher levels of competition may result in part from H:D$_{200}$ that exceed the stability threshold. High H:D$_{200}$ have been connected with increased risk of stem breakage due to wind and snow loading (Cremer et al., 1985, Wilson and Oliver, 2000, Wonn and O’Hara 2001) and a H:D$_{200}$ of 80 has been suggested as a threshold over which there is increased risk of stem breakage for western larch (Wonn and O’Hara, 2001). Figure 5 shows that top height for all densities was tightly clustered until stand age 48 then larger differences develop by stand age 58. The period when difference in top height occurred aligns with stands at target densities of 890 and 1680 trees ha$^{-1}$ exceeding the H:D$_{200}$ of 80 (Fig. 6 A) and the occurrence of a regional late spring wet snow event in 1996 (Wonn and O’Hara 2001). Western larch has been shown to be particularly susceptible to heavy snows in late spring when they have a full complement of needles (Schmidt and Schmidt, 1979). The result was top breakage of many of the tallest trees in 1680 trees ha$^{-1}$ density plots with little damage 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). Figure 7 B shows that stands which had multiple thinnings, and therefore took longer to reach low densities, have not regained the lower H:D$_{200}$ of plots thinned to low densities early. This reinforces the findings of Wilson and Oliver (2000) that early density reduction is imperative to establish low H:D$_{200}$ and high tree stability.
High H:D\textsubscript{200} of more dense stands may also play a role in the occurrence of the constant yield and crossover effects. Stands with high densities crossed the H:D\textsubscript{200} threshold of 80:1 much earlier in stand development (Fig. 6). The result is trees that are more predisposed to stem breakage due to heavy snows and wind. Stem breakage leading to tree mortality causes a loss of crown volume and total cubic volume production. This leads to potentially significant reductions yield, as damage occurs across the tree size range and not only in suppressed trees, which make up a very small portion of the yield. This increased loss of volume at due to stem breakage higher densities may explain part of the occurrence of the constant yield effect.

5. Conclusions

Our results suggest that if thinning is done early (<10 years) we will see long-term constant yield across a range of densities. We also found evidence that Newton’s (1997) formulation Langsaeter’s hypothesis, which states that volume growth is constant over a range of relative densities, holds true in stands thinned early. Our results suggest that at densities as low as 494 trees ha\textsuperscript{-1} the increase in individual tree growth rate and crown size will allow full site occupancy by stand age 62. Across the tested range of densities the primary effect of early thinning is to control whether volume and tree crown are concentrated on few large individuals or spread over a greater number of small individuals. It also controls the stability of the 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\textsuperscript{-1}) which has strong implications for long term stand yield. Increases in factors related to tree instability (H:D\textsubscript{200}) may also act to increase mortality which will
also decrease yield at higher densities. Said simply, with the tested range of densities the long term effect of lower density was to produce trees of larger size and greater stability while not sacrificing stand yield.

6. Management Implications

The results of this study show the strong and long lasting effects of thinning western larch early in stand development, complementing the conclusions of other studies that have found that western larch does not respond readily to thinning treatments late in stand development (Roe and Schmidt, 1965, Cochran and Seidel, 1999, Martin and Barber, 1995, Barber, 2007). If a rotation age of 62 years is used to manage western larch, the maximum merchantable volume is realized in the once entered 890 trees ha\(^{-1}\) treatment but the differences are not large enough to be significantly different if a high utilization standard is used (11.4 cm top). Individual tree size is maximized at lower density. It is suggested that there is a competition threshold below which no addition increases in individual tree size occurs (Drew and Flewelling, 1979) but we did not find that point in this study; trees in the 272 trees ha\(^{-1}\) were substantially larger than trees in the 494 trees ha\(^{-1}\) treatments. At stand age 62 the primary effect of early precommercial thinning is controlling whether volume is concentrated on few large individual or spread over greater number of small individuals.

There is no evidence from our results that there is any benefit to precommercially thinning larch stands multiple times. In the 890 and 1680 tree ha\(^{-1}\) densities mean tree size and stand-level yield are always lower in stands with multiple thinnings. The 494 trees ha\(^{-1}\) saw very small increases in tree and stand-level attributes. The magnitude of
this effect is small but it suggests that 494 trees ha\(^{-1}\) is on the low end of full site occupancy. If trees in low density plots are damaged or of poor genetics there are no replacement trees available to make up for the poor quality tree. If it is desired to grow large trees but still be able to accommodate some level of damage a more operationally feasible alternative than multiple precommercial thinnings would be leaving stands at a density between 494 trees ha\(^{-1}\) and 890 trees ha\(^{-1}\).

The target density for precommercial thinning is an important decision early in the life of a stand as it regulates the resulting tree size and stand yield. This research indicates that for western larch an acceptable compromise between tree size and merchantable stand yield occurs between the densities of 494 and 890 trees ha\(^{-1}\). Densities below that may fail to occupy the site for too long to allow larger tree size to make-up for low density and higher than that may result in elevated levels of mortality occurring before many of the trees have reached merchantable size, particularly if larger top diameters are required of meet merchantability specifications.
References


Figures and tables

Table 1. Characteristics of the four study sites of the western larch thinning study.

Reported aspects and slopes are site averages.

<table>
<thead>
<tr>
<th>Study site</th>
<th>Harvest date</th>
<th>Harvest method</th>
<th>Site preparation</th>
<th>Habitat type</th>
<th>SDI max&lt;sup&gt;a&lt;/sup&gt;</th>
<th>SI (m)&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Elevation (m)</th>
<th>Aspect</th>
<th>Slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coram 1</td>
<td>1951</td>
<td>Clearcut/Seed-tree</td>
<td>Dozer piled, Broadcast burn</td>
<td>Abies lasiocarpa/Clintonia uniflora, Aralia nudicaulis phase</td>
<td>496</td>
<td>24 m</td>
<td>1200</td>
<td>350&lt;sup&gt;o&lt;/sup&gt;</td>
<td>21%</td>
</tr>
<tr>
<td>Coram 2</td>
<td>1951</td>
<td>Shelterwood</td>
<td>Broadcast burn</td>
<td>Abies lasiocarpa/Clintonia uniflora, Aralia nudicaulis phase</td>
<td>496</td>
<td>23 m</td>
<td>1200</td>
<td>300&lt;sup&gt;o&lt;/sup&gt;</td>
<td>25%</td>
</tr>
<tr>
<td>Cottonwood Lakes</td>
<td>1953</td>
<td>Clearcut</td>
<td>Dozer piled, scarified, piles burned</td>
<td>Abies lasiocarpa/Clintonia uniflora, Vaccinium caespitosum phase</td>
<td>456</td>
<td>19 m</td>
<td>1450</td>
<td>355&lt;sup&gt;o&lt;/sup&gt;</td>
<td>20%</td>
</tr>
<tr>
<td>Pinkham Creek</td>
<td>1953</td>
<td>Clearcut</td>
<td>Dozer piled, scarified, piles burned</td>
<td>Abies lasiocarpa/Clintonia uniflora, Clintonia uniflora phase</td>
<td>518</td>
<td>24 m</td>
<td>1475</td>
<td>65&lt;sup&gt;o&lt;/sup&gt;</td>
<td>20%</td>
</tr>
</tbody>
</table>

<sup>a</sup> SDI maximum was calculated using a stochastic frontier model (M. Kimsey personal communication, manuscript in preparation) which incorporates species composition, topo-edaphic factors, and climate variables and is reported in English units.

<sup>b</sup> Site index (SI) was calculated with the western larch equation from Milner et al. 1992.
Table 2. The analysis of variance results for tree and stand level variable for western larch thinned to different target densities with different number of thinning entries. The results for the blocking variable are not shown, but had 3 degrees of freedom and were significant (P <0.001) for every variable. The results are for stand age 62 unless otherwise noted.

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

<sup>a</sup>Cubic volume PAI is for the period of stand age 48-62.
Table 3. Test results of the linear contrasts for tree- and stand-level attributes.

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

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

\(^a\) Quadratic mean diameter at breast height

\(^b\) Mean height of the tallest 100 trees ha\(^{-1}\)

\(^c\) Crown volume of the average tree

\(^d\) Total cubic stem volume of live trees

\(^e\) Periodic annual increment of cubic stem volume from 2001 to 2015

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

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

\(^h\) Total crown volume ha\(^{-1}\)

\(^i\) Height to diameter ratio of the 200 largest trees ha\(^{-1}\)
**Table 4.** A comparison of 2015 (54 years post-treatment) tree-level variables for western larch thinned to different target densities with different numbers of entries to achieve those densities. The reported values are means (standard errors).

<table>
<thead>
<tr>
<th>Target density</th>
<th>Thinning entries</th>
<th>QMD (cm)</th>
<th>Mean height (m)</th>
<th>Top height (m)</th>
<th>Mean tree volume(^a) (m(^3))</th>
<th>Height: diameter ratio</th>
<th>Live crown ratio (%)</th>
<th>Mean tree crown volume (m(^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>272</td>
<td>1</td>
<td>34.0 (1.4)</td>
<td>24.4 (0.6)</td>
<td>24.3 (1.0)</td>
<td>0.78 (0.03)</td>
<td>70 (2.3)</td>
<td>57 (5.3)</td>
<td>119.52 (41.78)</td>
</tr>
<tr>
<td>494</td>
<td>1</td>
<td>26.8 (1.3)</td>
<td>21.9 (1.5)</td>
<td>23.5 (1.6)</td>
<td>0.47 (0.08)</td>
<td>77 (2.6)</td>
<td>47 (4.7)</td>
<td>54.81 (8.29)</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>26.9 (1.6)</td>
<td>22.5 (1.9)</td>
<td>24.8 (1.6)</td>
<td>0.49 (0.08)</td>
<td>78 (4.5)</td>
<td>43 (3.4)</td>
<td>50.19 (8.53)</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>25.7 (1.4)</td>
<td>22.6 (1.9)</td>
<td>23.6 (1.6)</td>
<td>0.45 (0.08)</td>
<td>81 (2.7)</td>
<td>43 (3.9)</td>
<td>53.50 (4.72)</td>
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<tr>
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<td>26.4 (0.8)</td>
<td>22.3 (0.9)</td>
<td>24.0 (0.9)</td>
<td>0.47 (0.04)</td>
<td>79 (1.9)</td>
<td>44 (2.2)</td>
<td>52.83 (3.91)</td>
</tr>
<tr>
<td>890</td>
<td>1</td>
<td>22.4 (1.3)</td>
<td>20.4 (2.1)</td>
<td>23.0 (2.0)</td>
<td>0.33 (0.06)</td>
<td>83 (3.9)</td>
<td>38 (2.9)</td>
<td>27.93 (3.85)</td>
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<td>21.0 (1.0)</td>
<td>19.9 (1.6)</td>
<td>22.5 (1.2)</td>
<td>0.27 (0.04)</td>
<td>86 (3.7)</td>
<td>35 (2.8)</td>
<td>22.64 (4.61)</td>
</tr>
<tr>
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<td>4</td>
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<td>19.5 (2.2)</td>
<td>22.0 (2.2)</td>
<td>0.25 (0.06)</td>
<td>89 (2.2)</td>
<td>39 (2.5)</td>
<td>27.24 (8.02)</td>
</tr>
<tr>
<td>Mean</td>
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<td>21.0 (0.8)</td>
<td>20.0 (1.1)</td>
<td>22.5 (1.0)</td>
<td>0.28 (0.03)</td>
<td>86 (1.9)</td>
<td>37 (1.5)</td>
<td>25.94 (3.10)</td>
</tr>
<tr>
<td>1680</td>
<td>1</td>
<td>18.1 (1.2)</td>
<td>18.1 (2.0)</td>
<td>21.6 (1.8)</td>
<td>0.20 (0.05)</td>
<td>90 (3.8)</td>
<td>32 (1.6)</td>
<td>15.54 (4.75)</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>17.1 (1.8)</td>
<td>18.0 (2.5)</td>
<td>20.5 (2.7)</td>
<td>0.18 (0.05)</td>
<td>88 (5.7)</td>
<td>32 (2.3)</td>
<td>14.59 (3.59)</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>16.4 (1.4)</td>
<td>17.5 (1.7)</td>
<td>21.6 (1.6)</td>
<td>0.16 (0.04)</td>
<td>92 (5.8)</td>
<td>33 (2.0)</td>
<td>14.65 (2.80)</td>
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<tr>
<td>Mean</td>
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<td>17.2 (0.8)</td>
<td>17.9 (1.1)</td>
<td>20.8 (1.2)</td>
<td>0.18 (0.03)</td>
<td>90 (2.8)</td>
<td>32 (1.0)</td>
<td>14.92 (1.99)</td>
</tr>
<tr>
<td>Unthinned</td>
<td>0</td>
<td>8.7 (0.4)</td>
<td>10.4 (0.6)</td>
<td>19.1 (1.2)</td>
<td>0.11 (0.02)</td>
<td>107 (3.3)</td>
<td>29 (0.1)</td>
<td>6.45 (1.12)</td>
</tr>
</tbody>
</table>
Table 5. A comparison of stand-level variables for western larch thinned to different target densities with different numbers of entries to achieve those densities. The reported values are means (standard errors).

<table>
<thead>
<tr>
<th>Target density</th>
<th>Thinning entries</th>
<th>Basal area (m² ha⁻¹)</th>
<th>Total cubic volume (m³ ha⁻¹)</th>
<th>Total cubic volume PAI (m³ ha⁻¹ year⁻¹)</th>
<th>Merchantable volume 11.4 cm top (m³ ha⁻¹)</th>
<th>Merchantable volume 15.2 cm top (m³ ha⁻¹)</th>
<th>Stand level crown volume (m³ ha⁻¹)</th>
<th>Relative density</th>
<th>Annual mortality (%)</th>
</tr>
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<tbody>
<tr>
<td>272</td>
<td>1</td>
<td>16.46 (4.26)</td>
<td>142.95 (42.55)</td>
<td>3.59 (0.56)</td>
<td>127.50 (35.50)</td>
<td>120.00 (34.00)</td>
<td>19.569 (361)</td>
<td>23.5 (6.5)</td>
<td>0.00 (0)</td>
</tr>
<tr>
<td>272</td>
<td>4</td>
<td>24.44 (2.84)</td>
<td>220.57 (38.56)</td>
<td>5.90 (1.00)</td>
<td>189.50 (35.62)</td>
<td>161.50 (37.23)</td>
<td>26.144 (2.475)</td>
<td>41.0 (2.7)</td>
<td>0.00 (0)</td>
</tr>
<tr>
<td>890</td>
<td>1</td>
<td>32.98 (3.75)</td>
<td>269.55 (53.34)</td>
<td>6.41 (1.50)</td>
<td>217.25 (50.45)</td>
<td>167.00 (49.31)</td>
<td>23.067 (3.043)</td>
<td>56.0 (4.0)</td>
<td>0.16 (0.16)</td>
</tr>
<tr>
<td>890</td>
<td>2</td>
<td>28.38 (2.98)</td>
<td>223.96 (38.83)</td>
<td>5.71 (1.00)</td>
<td>173.75 (35.85)</td>
<td>112.75 (34.65)</td>
<td>18.266 (3.451)</td>
<td>49.3 (3.4)</td>
<td>0.43 (0.16)</td>
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<tr>
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<td>34.27 (4.31)</td>
<td>259.35 (53.45)</td>
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<td>178.00 (54.38)</td>
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<td>19.653 (5.142)</td>
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<tr>
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<td>32.78 (5.66)</td>
<td>250.73 (63.97)</td>
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<td>165.75 (59.70)</td>
<td>84.50 (38.80)</td>
<td>19.967 (4.514)</td>
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</tr>
<tr>
<td>1680</td>
<td>4</td>
<td>28.52 (2.73)</td>
<td>206.33 (36.48)</td>
<td>5.16 (0.80)</td>
<td>118.25 (37.16)</td>
<td>47.75 (24.58)</td>
<td>19.102 (2.159)</td>
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<td>0.63 (0.30)</td>
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<tr>
<td>Mean</td>
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<td>29.38 (2.09)</td>
<td>235.64 (25.62)</td>
<td>6.03 (0.67)</td>
<td>184.25 (24.35)</td>
<td>126.08 (22.83)</td>
<td>21.574 (2.608)</td>
<td>50.8 (2.5)</td>
<td>0.23 (0.09)</td>
</tr>
<tr>
<td>1680</td>
<td>1</td>
<td>31.86 (2.41)</td>
<td>238.80 (28.49)</td>
<td>5.73 (0.73)</td>
<td>154.00 (27.91)</td>
<td>77.92 (21.04)</td>
<td>18.892 (3.148)</td>
<td>59.6 (3.1)</td>
<td>0.63 (0.15)</td>
</tr>
<tr>
<td>Unthinned</td>
<td></td>
<td>31.86 (2.41)</td>
<td>238.80 (28.49)</td>
<td>5.73 (0.73)</td>
<td>154.00 (27.91)</td>
<td>77.92 (21.04)</td>
<td>18.892 (3.148)</td>
<td>59.6 (3.1)</td>
<td>0.63 (0.15)</td>
</tr>
</tbody>
</table>
Fig. 1. A. Hypothetical yield curve indicating the assumption that higher density stands will always have higher densities. The roman numerals indicate stands of different densities, from I indicating very low density to V indicating very high density. B. Hypothetical yield curve demonstrating the Constant Yield Effect (Oliver and Larson, 1996), where all stands grow at the same rate but lower density stands reach that rate at a later time. C. Hypothetical yield curve demonstrating the Crossover Effect (Oliver and Larson, 1996), where high density stands initially have greater volume but are eventually exceeded by stands at lower densities. (Figures adapted from Oliver and Larson, 1996).
Fig. 2. A. Map of our four study areas across the northwest portion of Montana. 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 Cottonwood Lakes study site. The solid squares are the 20 m x 20 m treatment plots and the dashed lines are the buffers that were thinned with the same treatment.
**Fig. 3.** The experimental design of the western larch precommercial thinning study. Panel A shows the tree different 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 4 entry pathway. While all treatments achieve the same final density there is clearly different amounts of competition experienced depending on the number of entries. Panels B and C show the same trends for 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. 4. 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 is 4,200 trees ha\(^{-1}\). The white arrows point at the same tree in panels A and B and photos were taken from a photo point at the same distance from the tree. C. Photo of a tree in the 494 trees ha\(^{-1}\), 1 entry treatment at Coram 2 in 1961 and D is the same tree in 2015. Again the white arrows point at the same tree in panels C and D.
Fig. 5. Crown form of trees of two differing densities (494 trees ha\(^{-1}\) and 890 trees ha\(^{-1}\)) thinned with one entry to the target densities at age 8 years. Trees from the lower density plots (light green) show much larger crowns, greater mean stem height, and greater diameter than trees from the higher density plots. The shapes of the crowns are drawn from the mean value for all trees of the following variables: total height, crown base height, height to the widest point in the crown, and crown width (mean of two perpendicular measurements). Stems are drawn using mean total height and QMD.
Diameter at root collar was calculated using the principle of triangles of equal proportion.

Figures are drawn to scale in both the horizontal and vertical dimensions.
Fig 6. Crown form at stand age 62 years of western larch thinned at stand age 8 with one entry to different target densities. Crowns and stems were drawn using the same methods as in Fig. 5.
Fig 7. 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 the top height all three numbers of entries for the 494 trees ha\(^{-1}\) target density. Panels B and C show the top height for the 890 trees ha\(^{-1}\) and 1680 trees ha\(^{-1}\) target densities respectively. Panels 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. Largest tested differences in top height occur between 494 trees ha\(^{-1}\) two thinnings with 1680 trees ha\(^{-1}\) two thinnings and 1680 trees ha\(^{-1}\) four thinnings.
Fig. 8. A. Height to diameter ratio of the largest diameter 200 trees ha$^{-1}$ (H:D$_{200}$) for all densities thinned once. The dashed line represents the 80:1 ratio suggested as a threshold of stability for western larch 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 western larch stands (Schmidt et al. 1976). B. An interaction plot showing 2015 H:D$_{200}$ 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 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 the total cubic volume all three numbers of entries for the 494 trees ha$^{-1}$ target density. Panels B and C show the total cubic volume for 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.
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 and 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 ha$^{-1}$ 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 pass 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. The gray band, between a relative density of 40% and 55%, identifies the zone of maximum stand volume growth.
**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 m\(^3\) ha\(^{-1}\) year\(^{-1}\) across the zone of maximum growth (RD of 40\% to 55\%) as well as the lower PAI of both the 272 trees ha\(^{-1}\) treatments and unthinned treatments give support to Newton’s (1997) formulation of Langseter’s hypothesis (Compare to Fig 2b of Newton, 1997).
Fig. A1. Quadratic mean diameter through time for all densities of the once thinned treatment.
Chapter 2.

Early forest thinning changes aboveground carbon distribution among pools, but not total amount, 54 years after treatment

Abstract
Mounting concerns about global climate change have increased the interest in understanding how common forest management practices, such as precommercial thinning (PCT), affect forest carbon (C) storage. However, long-term effects of early density management on total aboveground C are not well understood. We examined total aboveground C stores in a 54-year-old western larch (*Larix occidentalis*) PCT experiment to determine whether and how different PCT treatments affect long-term aboveground C storage and distribution among aboveground C pools. Four aboveground C pools (live overstory, live understory/mid-story, woody detritus, and forest floor) were measured and separated into C produced prior to initiation of the current stand (legacy C) and C produced by the current stand (non-legacy C). Our results indicate that early PCT does not decrease total non-legacy aboveground C stores 54 years after treatment. Live tree C was nearly identical across densities due to much larger trees in low density stand compensating for few of them. Low density stands had more understory and mid-story C while unthinned plots had significantly more non-legacy woody detritus C than thinned stands. Legacy pools did not vary significantly with density, as expected, but made up a substantial proportion of aboveground C stores. Three main conclusions follow from our examination of the effects of early thinning on total aboveground C. (1) Fifty-four years after treatment total aboveground C of stands precommercially thinned to a wide range of
densities is similar, due primarily to the increase in mean tree C of trees grown at lower stand densities. (2) Sixty-two years after stand replacing disturbance deadwood legacies from the pre-disturbance forest still play an important role in long-term C storage, accounting for approximately 20-25% of aboveground C stores. (3) Given enough time since early thinning, there is no trade-off between managing stands to promote individual tree growth and development of understory vegetation, and maximizing stand level accumulation of aboveground C. We infer that there is potential to use early precommercial thinning to simultaneously achieve climate change mitigation and adaptation objectives, provided treatments are implemented early in stand development before the onset of intense intertree competition.

Keywords:

*Larix occidentalis*, western larch, carbon storage, density management, precommercial thinning, Montana, long-term studies

Introduction

Mounting concerns about anthropogenic climate change have increased interest in using forests to capture and store atmospheric CO$_2$. Forests in the United States alone store about 22 Tg of carbon (C) year$^{-1}$ (Heath and Smith 2004, Birdsey et al. 2006). In the past several decades there has been a concerted effort to understand how forests can be managed to maintain or increase forest C storage (Pregitzer and Euskirchen 2004, Birdsey et al. 2006, McKinley et al. 2011, Skog et al. 2014). Even global leaders are beginning to recognize the important role of forest ecosystems in a global C management
strategy, evidenced by the inclusion of forest C specific management strategies in the 2015 Paris Climate Agreement, (UNFCCC 2015). Despite rising policy interest and recent research, there remains uncertainty over long-term effects of common forest management practices, such as early low thinning, on C storage.

Carbon accumulates in the form of woody biomass and foliage in trees and, at the stand level, generally increases with time as trees increase in size (Pregitzer and Euskirchen 2004). Any management actions that increase tree growth also have the potential to increase forest C accumulation and storage; conversely, management actions that reduce the number trees on a site may potentially reduce forest C accumulation and storage. Thinning, a common management activity used to manipulate the growth rate, size, and form of individual trees, as well as the structure and yield of forest stands (Sjolte-Jorgensen 1967, Smith et al. 1997, Tappeiner et al. 2007), does both. Thinning involves the selective removal of some trees such that more resources and growing space are allocated to the residual trees, thereby increasing their growth rates.

Different methods of thinning—i.e., different methods of tree selection for removal and retention during thinning treatments—can have strong, differential effects on long-term forest C storage (Hoover and Stout 2007). Thinning from above (preferential removal of the largest trees) or across the diameter range decreases aboveground C storage both immediately and over the long-term (Hoover and Stout 2007, Harmon et al. 2009, Chattergee et al. 2009, D’Amato et al. 2011, Zhao et al. 2013). However, studies of low thinning (selective removal of the smallest trees), also termed precommercial thinning (PCT), implemented early in stand development show inconsistent results. Some PCT studies found that decreasing stand density decreased
forest C stores (Skovsgaard et al. 2006, Jimenez et al. 2011), while others found that the increased growth rate of trees grown at lower densities can maintain or increase live tree C (Hoover and Stout 2007, Dwyer et al. 2011), especially in the case of longer-term responses to thinning (Horner et al. 2010). Short-term studies of the effects of PCT on aboveground C have shown consistent decreases in aboveground C with decreases in density (Campbell et al. 2009, De las Heras et al. 2012, Jimenez et al. 2011, Dwyer et al. 2010), indicating that low densities of small trees do not fully occupy the site (Turner et al. 2016). Given these conflicting results, it is still unclear whether precommercial thinning treatments are compatible with C storage goals (Jimenez et al. 2011).

The age that a stand is thinned at has a strong effect on aboveground C storage. Evidence from the few PCT studies that compared the timing of thinning have found that total stem volume, which is a large component of the aboveground C (Harmon et al. 2004), was greater in stands thinned early than stands that were thinned late (Varmola et al. 2004). This is consistent with stand dynamics theory that suggests volume growth rates recover more quickly from early thinnings than late thinnings (Oliver and Larson 1996, Long et al. 2004, Varmola et al. 2004).

Aboveground forest C stores are made up of more than just live overstory trees. Understory vegetation, woody detritus, and forest floor material are also important pools of aboveground C. Substantial C is also stored in mineral soil (Johnson and Curtis 2001, Page-Dumroese and Jurgensen 2006, Bisbing et al. 2010), however evidence suggests that these C stocks are not as responsive to management as aboveground C pools (Johnson and Curtis 2001, Nave et al. 2010, Zhao 2013, Hoover and Heath 2015). Understory vegetation—composed of shrubs, subcanopy trees, forbs, and grasses—can
be a major C pool, especially early in stand development or at lower stand densities (Campbell et al., 2009). Woody detritus, including snags, coarse woody debris (CWD; diameter ≥ 7.62 cm), and fine woody debris (FWD; diameter < 7.62 cm), can store large amounts of C, especially in temperate forests where trees may attain large sizes but decompose slowly (Harmon and Hua 1991). Forest floor C is composed of litter, duff, and soil wood. Forest floor C can store significant amounts of C especially as large logs decay and become part of the forest floor (Page-Dumroese and Jurgensen 2006). In second growth forests where large woody structures from the previous stand were left onsite both the woody debris and forest floor pools can be largely composed of biomass produced by the pre-disturbance, old-growth stand (Franklin et al. 2002). These C stores, referred to here as legacy C, can make up a substantial proportion of the C stored in a second growth forest (Spies et al. 1988, Sturtevant et al. 1996, Franklin et al. 2002), however we would not expect these C stores to be strongly affected by early density management with PCT.

Questions remain about how early thinning affects long-term total aboveground C because many studies (1) focused on controlling the “level of growing stock” with repeated thinning entries throughout the tenure of the study (e.g. Skovsgaard et al. 2006, D’Amato 2011); (2) involved treatments applied relatively later in stand development (30 + years), after tree canopy closure and the onset of intense competition and crown recession, a scenario in which we would only expect a negative C impact from thinning (e.g. Finkral and Evans 2008, North et al. 2009, D’Amato et al. 2011); (3) collapsed many different types of thinning treatments into one catch all category (e.g., Powers et al. 2012); (4) only examined a short-term post-treatment response (e.g. Campbell et al. 2009,

We overcame these limitations by measuring all aboveground C pools in a well replicated, long-term (54-year-old) western larch (Larix occidentalis) precommercial thinning experiment that included nine different thinning treatments. Our objectives were to determine whether and how different precommercial thinning treatments affect total aboveground C storage, and C distribution among different aboveground pools. We tested four predictions for the effect of tree density management with PCT on aboveground C pools.

1. *Live overstory conifer C will increase with stand density.* Forest structural development theory suggests that overstory tree carbon increases with increased density (Turner et al. 2004, Kashian et al. 2013, Turner et al. 2016); at high densities mean C per tree is smaller but the greater number of trees compensates for the small mean tree size.

2. *Live non-conifer C (understory and subcanopy trees, shrubs, forbs, and grasses) will decrease with increasing stand density.* Forest structural development theory predicts that as canopies close and light becomes limited below the main canopy, a majority of understory plants and subcanopy trees will die (Peet and Christensen 1987, Oliver and Larson 1996, Franklin et al. 2002). This occurs earlier and more completely at high stand densities, resulting in less mass of understory vegetation (Campbell et al. 2009).
3. **Non-legacy deadwood C**—dead woody material produced since initiation of the current stand—will increase with stand density. Self-thinning theory predicts that as a stand nears a maximum size-density relationship, mortality will increase (Reineke 1933, Yoda et al. 1963, Peet and Christensen 1987) shifting carbon from live pools to the deadwood pools (snags and woody detritus).

4. **Total aboveground non-legacy C will increase with density.** Past studies of carbon storage in temperate forests suggest that the overstory tree pool and the deadwood pool generally drive carbon dynamics, even in second growth forests (Harmon et al. 2004, Bisbing et al. 2010, Powers et al., 2012).

We also expected that the proportion of the aboveground carbon in dead biomass will increase with stand density due to self-thinning mortality. In order to fully quantify aboveground C stocks we sampled legacy deadwood and the forest floor above the surface of mineral soil, though we did not expect these pools to respond to the experimental treatments given their dominance by legacy inputs from the previous old-growth stands.

**Methods**

**Study sites**

Our study is superimposed the Western Larch Density Management Study (WLDMS), a western larch precommercial thinning study located in northwestern Montana, USA and established in 1961 by USDA Forest Service researchers (Schmidt 1964). The WLDMS is replicated at four sites (i.e., blocks), which were chosen for their uniform stocking and to capture the productivity gradient of western larch forests in the western Montana (Table 1). WLDMS replicates were located in areas of old-growth
forest harvested using even-aged methods between 1951 and 1953 (Table 1) and that regenerated naturally in the good western larch seed years of 1952 and 1954. Those conditions resulted in high initial (pre-treatment) densities (25,000 to 63,000 trees per hectare) of primarily western larch (*Larix occidentalis*) and included lesser amounts of Engelmann spruce (*Picea engelmannii*), Douglas-fir (*Pseudotsuga menziesii* v. *glauca*), subalpine fir (*Abies lasiocarpa*) and paper birch (*Betula papyrifera*) (Schmidt 1964). Additional details are provided in the study establishment report (Schmidt 1964).

The WLDMS has a nested 2-way factorial design with two factors: target density and number of thinning entries (hereafter referred to as entries). There are three levels of target density (494 trees ha\(^{-1}\), 890 trees ha\(^{-1}\), and 1640 trees ha\(^{-1}\)) which were originally chosen to determine the ideal spacing for western larch growth (Schmidt and Shearer 1961). Nested within each level of the target density are three different numbers of thinning entries (one entry, two entries, and four entries) that were used to achieve the target density (Table 2). The one entry treatments meet the target density in one thinning in 1961; the two entries treatments thinned to a prescribed intermediate density in 1961 then met the target density with a second thinning in 1981; the four entries treatments thinned to prescribed intermediate densities in 1961, 1971, and 1981 then met the target density in 1991 (Table 2). There are also unthinned plots at each site. This results in nine unique thinning treatments and one unthinned plot per site (i.e., treatments are not replicated within blocks). When the study was established, unthinned plots were only established at two of the sites (Coram 1 and Coram 2) so prior to the 2015 measurement unthinned plots were established at the remaining two replicates in areas within the
original harvest units in which the WLDMS experimental plots are located, and of similar
topography and habitat type as the thinned plots.

At each site, experimental plots and thinning treatments were established in the
winter of 1961/62 before the growing season. All snags were felled and residual seed
trees remove prior to the establishment of the plots (Schmidt 1964). Treatment plots (the
experimental unit) are 0.04 ha in size and all trees that were present at study initiation
within the plots were tagged. To minimize edge effects each plot was surrounded by a 10
m to 20 m wide buffer that was thinned with the same treatment (Figure 1). Plots were
installed in uniformly stocked areas of similar aspect, habitat type, and soil conditions
then treatments were randomly assigned to each plot.

Initial thinning in 1961 sought to establish a relatively uniform spacing of leave
trees, but since the primary variable of interest was stand density, not spacing, the
individual tree quality took precedence over uniform spacing in all thinnings (Schmidt
1964). All shrubs were cut in all plots at the time of initial thinning because of the
difficulty of not cutting some shrubs while thinning, though no shrubs were cut after the
initial thinning. Subsequent entries were thinned from below, removing trees with
damage or from subordinate crown classes (J. Schmidt, 2015, personal communication).
All plots were initially weeded of conifer in-growth to maintain the target densities as
well as a composition of pure larch, but no weeding occurred after 1966.

Field Methods

We aggregated C in different plant life forms and organic detritus types into four
pools, reflecting our predictions (Introduction). We separated overstory conifers from
other non-conifer trees, which were exclusively paper birch (Betula papyrifera), and refer
to this C pool as live conifer C. This separation is due to the goal of the original study to examine western larch growth. The live conifer pool was composed entirely of the western larch (*Larix occidentalis*) in the thinned experimental treatments but included a few individual trees of other conifer species in unthinned plots. Live conifer C includes all aboveground tissues, including stem wood, bark, branches, and foliage. The live non-conifer pool includes mid-story paper birch, shrubs, herbs, and graminoids. We divided the woody debris pool into legacy woody debris (defined as woody debris produced by the previously harvested old-growth stand) and non-legacy woody debris (defined as woody debris produced by the current second-growth stand). The non-legacy deadwood pool includes snags, coarse woody debris (CWD; >7.62 cm) and fine woody debris (FWD; <7.62 cm), but excludes woody structures that were not produced by the current stand (legacy C). The forest floor refers to all dead organic material that is above the mineral soil and includes litter, duff, humus, and soil wood (defined as decay class 5+ logs whose central axis has sunk beneath the forest floor surface; Page-Dumroese and Jurgensen 2006). Total non-legacy C is the sum of live conifer C, live non-conifer C, and non-legacy woody debris C. Total C with legacy includes the legacy deadwood C as well as the forest floor C. The forest floor was considered a legacy pool for the purpose of testing our predictions because it was dominated by large amounts of soil wood originating from highly decomposed old-growth logs, although the forest floor obviously includes some C produced by the current stand.

*Live conifer sampling*

Overstory sampling was done in accordance with the original thinning study. All of the larch trees in each 0.04 ha experimental treatment plots are tagged. For each tree
the following measurements were recorded: diameter at breast height (DBH), total height, height to the base of the live crown, height to the widest point in the live crown, and crown width.

*Large hardwood, shrub and herbaceous vegetation sampling*

Inside the 0.04 ha treatment plots the species, DBH, status (live or dead), and total height of every hardwood tree was measured and recorded. For all shrubs larger than 2.54 cm at root collar in the treatment plot diameter at root collar (DRC) and species were recorded. Shrubs smaller than 2.54 cm at root collar were clipped in three randomly located 1 m² quadrates per treatment plot. Herbaceous vegetation (herbs, graminoids, sedges, etc.) was clipped in three 0.25 m² quadrats per treatment plot. Clipped vegetation was bagged and taken to the lab to be dried and weighed.

*Woody detritus*

All snags in the treatment plots were measured and recorded variables included: species, DBH, DRC, top diameter, total height, and decay class (Keane et al. 2006). We measured every piece of CWD inside the treatment plots. Variables recorded for each CWD particle included species (if identifiable), decay class, total length as well as the major and minor axis diameters at the small, middle, and large ends of the log. Each snag and CWD particle was classified in the field as legacy or non-legacy based on assessment of size, decay class, and type (e.g., large diameter old-growth stumps were always classified as legacy CWD). Fine wood debris (diameter < 7.62 cm) was collected in four randomly located 1 m² quadrates inside each treatment plot and taken back to a lab to be dried and weighed. All FWD was assumed to have been produced by the current stand and classified as non-legacy.
Forest floor

Forest floor subsamples were collected at the center of three of the FWD quadrats per treatment plot. All organic material (litter, duff, humus, and soil wood) was collected inside a 30 cm diameter ring down to the mineral soil surface. Forest floor depth was measured at five locations per subsample (the center of the ring and the four corners of the 1 m² FWD sampling quadrat).

Laboratory analysis

FWD was sorted by size class: > 0.64 cm (1-hour), 0.64-2.54 cm (10-hour), and 2.54-7.62 cm (100-hour), then a subsample of each size class from each site was oven dried to a constant mass at 105° C, as were clipped shrub biomass samples. Site-level and size class specific average moisture contents were calculated for both FWD and shrubs then were used to calculate the dry mass for un-dried samples. All forest floor and herbaceous samples were oven-dried to a constant mass at 60° C. Forest floor and herbaceous vegetation were then ground and analyzed for carbon content on a Leco TruSpec CN dry combustion analyzer (St. Joseph, MI, USA).

Carbon calculations

Biomass of each component was calculated on a per treatment plot basis and expanded to Mg ha⁻¹. Biomass to C ratios were derived from laboratory analysis for the herbaceous vegetation and forest floor pools. Other biomass to C ratios used were 0.5 for live tree C and shrub C (Sollings et al. 1987, Harmon et al. 1990, Harmon et al. 2004), and decay-class specific ratios for woody debris (Harmon et al. 2008 and Bisbing et al., 2010).
Live conifer aboveground dry biomass was estimated by calculating the sum of three aboveground components: stem wood, stem bark, and crown (branches and foliage). Total stem cubic volume and bark volume were calculated from ground level to the tip of the tree with species specific taper profile equations using diameter and height (Flewelling and Raynes 1993) provided by the Inland Northwest Growth and Yield Cooperative. Stem wood volume was converted to dry biomass using species-specific wood density values (Harmon et al. 2008; Jenkins et al. 2003). Bark volume was multiplied by a species-specific bark density (Miles and Smith 2009) to calculate dry bark biomass. Tree crown volume was calculated by modeling tree crowns as two cones, one upright and one upside-down cone, using measurements of total tree height, crown base height, height to the widest point of the crown, and crown width (Burkhart and Tome 2012). Crown volume was then multiplied by a species-specific crown bulk density for the upper portion of the crown as well as the lower portion of the crown (Brown 1978) to derive a mass for the crown (foliage plus live and dead branches) of each tree. Total tree biomass was calculated as the sum of these three components. Biomass was then converted to C by multiplying biomass by generic ratio of 0.5 (Sollins et al. 1987, Harmon et al. 1990, Harmon et al. 2004).

Hardwoods and large shrubs (≥2.54 cm DRC) consisted Betula papyrifera, Acer glabrum, Alnus sinuata, Sorbus scopulina, Salix scouleriana, and Amelanchier alnifolia. Allometric equations were used to estimate dry biomass from DBH and height for Betula papyrifera (Ker, 1984) and DCR for the other five species (Brown 1976). The mass of large shrubs estimated from allometric equations and the oven dry mass of small shrubs (≥2.54 cm DRC) from the three clipped 1 m² quadrats were converted to C using the
generic ratio of 0.5 (Sollins et al. 1987, Harmon et al. 1990, Harmon et al. 2004).

Herbaceous samples from the three 0.25 m² quadrats per treatment plot were oven dried to a constant biomass. Herb samples were then analyzed for proportion C content, averaged over the three subsamples per plot then expanded to Mg ha⁻¹.

Volume of each CWD particle was calculated using Newton’s formula:

\[ V = \frac{L(A_b + 4A_m + A_t)}{6} \]

Where \( V \) is the volume, \( L \) is the length, and \( A_b, A_m \) and \( A_t \) are the areas of the base (large end), middle and top (small end), respectively (Harmon and Sexton 1996). The volume was then converted to biomass using species and decay class specific wood densities and biomass to C ratios (Harmon et al. 2008, Bisbing et al. 2010). FWD biomass was calculated by averaging the four 1 m² subsamples per treatment. The generic wood C to biomass ratio of 0.5 was then applied to calculate FWD C (Sollins et al. 1987, Harmon et al. 1990, Harmon et al. 2004).

To calculate forest floor C we first calculated the sample volume using the diameter of the sample ring (30 cm) and the measured sample depth at the center of the ring. Forest floor bulk density was calculated by dividing the oven-dried mass by the subsample volume, then averaged subsamples within each treatment plot. To expand to mean forest floor biomass per treatment plot we calculate the mean forest floor volume per treatment plot using the five sample depths per subplot (15 total depth measurements per treatment plot) and multiplied mean volume by the mean bulk density. To calculate mean C per treatment plot we multiplied the mean forest floor biomass per plot by the corresponding mean C content.

*Statistical Analysis*
Due to the nested design of the two factors (entries nested within target density) 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. The resulting explanatory variable was a factor with 10 levels (3 entries × 3 target densities plus the control). Several of the carbon pools exhibited variance heteroscedasticity, so different variance structures were modeled for each level of target density by fitting the model with generalized least square regression using gls function in the nlme package in R (R Development Core Team, 2016) then specifying the weights argument. Residual plots were checked to see that modeling different variances improved the model fit over a linear model.

We used a priori mutually orthogonal contrasts to test our predictions. We first used three contrasts to test our predictions for stand density effects on C storage: (1) the unthinned treatment against all of the thinned treatments, (2) the 1680 trees ha\(^{-1}\) treatment against the 890 trees ha\(^{-1}\) and 494 trees ha\(^{-1}\) treatments combined; and (3) the 890 trees ha\(^{-1}\) against the 494 trees ha\(^{-1}\) treatment (Table 3). To evaluate the effect of the number of entries within each of the three thinned target densities we compared (at each density) the 1 entry treatment against the 2 and 4 entry treatments combined, and the two entry treatment against the four entry treatment (Table 3). P-values were adjusted using the Bonferroni method to ensure a family-wise type I error rate of \(\alpha=0.05\). All statistical analyses were conducted using R 3.2.4 (R Development Core Team 2016).

The reported results are for C values in 2015, 54 years after precommercial thinning treatments began (mean stand age of 62 years). Unless otherwise noted, the
means reported are the main effect of the density treatment, which is the mean of all of the three different number of entry treatments within a given density level.

**Results**

*Prediction 1: live conifer carbon*

Live conifer C was not significantly affected by thinning treatment or stand density ($P > 0.10$; Table 3), contrary to our expectation. The unthinned plots had the highest average C (80.52 Mg ha$^{-1}$) but only by 3.49 Mg ha$^{-1}$ more than the average of the thinned plots, a non-significant difference. There were no significant differences between the three thinned densities (Table 3). As an experiment-wide average, live tree C made up 90% of the non-legacy aboveground C but that value ranged from a low of 80% in the unthinned treatment to 90-91% in the thinned treatments. Variability generally increased with density (Appendix: Table A1). The effect of the number of entries was not significant for the live conifer C pool at any of the target densities ($P > 0.10$; Table 3).

The average C per tree was inversely related to stand density (Figure 3). Average C per tree was more than twice as much in the 494 trees ha$^{-1}$ treatment than the 1680 trees ha$^{-1}$ treatments and more than 8 times greater than the unthinned treatments. The average C per tree was 159.0 kg, 93.0 kg, 56.5 kg, and 18.1 kg across the 494 trees ha$^{-1}$, 890 trees ha$^{-1}$, 1680 trees ha$^{-1}$, and unthinned treatments respectively. Within each level of target density, per tree C was higher in treatments with fewer entries, with the exception of the 494 trees ha$^{-1}$ treatments where the two entry treatment had an average of 2.1 kg more C per tree than the one thinning treatment (Figure 3).

*Prediction 2: live non-conifer carbon*
Live non-conifer C stores differed among treatments due to density ($P = 0.006$, global test) and increased as density decreased (Figure 2 b), in agreement with our prediction for this pool. The greatest differences were between the 494 trees ha$^{-1}$ treatment (5.52 Mg ha$^{-1}$) and the unthinned treatments (3.14 Mg ha$^{-1}$). Live non-conifer C made up a small proportion of the total non-legacy C ranging from a low of 3.1% for the unthinned treatment and increasing inversely with density to 3.7%, 5.0% and 6.6% for the 1680, 890 and 494 trees ha$^{-1}$ treatments, respectively. Variability of the understory C tended to decrease as density increased (Appendix: Table A1). Number of entries did not significantly affect the live non-conifer C pool within any target density ($P > 0.10$; Table 3).

*Prediction 3: non-legacy deadwood*

Non-legacy deadwood C pools varied among treatment densities (global test; $P = 0.031$), consistent with our prediction. However, the individual contrasts showed no significant effect of density ($P > 0.10$), likely due to the high level of variability in the non-legacy deadwood pool. The unthinned treatment had the highest level of C (13.43 Mg ha$^{-1}$) and was more than twice as large as the 1680 trees ha$^{-1}$, 890 trees ha$^{-1}$, or 494 trees ha$^{-1}$ treatments (Fig. 2c). The proportion of total non-legacy C was the highest in the unthinned treatment at 17.3% and decreased with density to 7.4%, 4.7% and 4.0% for the 1680, 890 and 494 trees ha$^{-1}$ treatments, respectively. Variability in deadwood C stocks increased with density (Figure 2c; Appendix: Table A1) and variability was very high in the unthinned treatments with standard errors more than twice as large as the other treatments. The effect of the number of entries was not significant for the non-legacy deadwood C pool for any of the target density levels ($P > 0.10$).
**Prediction 4: total aboveground non-legacy carbon**

Contrary to our expectation, total aboveground non-legacy C was not significantly affected by density ($P > 0.10$; Figure 2 d). Aboveground non-legacy C storages, which excluded both legacy woody debris C and forest floor C, ranged 76.15 Mg ha$^{-1}$ to 100.49 Mg ha$^{-1}$ (Appendix: Table A1). Carbon stocks generally increased with density and unthinned plots had the largest C stores (100.49 Mg ha$^{-1}$), but were not statistically different from thinned stands ($P > 0.10$; Table 3). Total aboveground non-legacy C values differed by less than 3 Mg ha$^{-1}$ between the 494 trees ha$^{-1}$ (84.20 Mg ha$^{-1}$), 890 trees ha$^{-1}$ (84.78 Mg ha$^{-1}$), and 1680 trees ha$^{-1}$ (86.31 Mg ha$^{-1}$) treatments (Figure 2, d). There was high variability in most treatments and variability in stores generally increased with density. The effect of the number of entries was not significant for the total aboveground C pool ($P > 0.10$; Table 3).

**Legacy C pools**

There was no significant effect of either target density or number of entries on legacy CWD or forest floor C ($P > 0.10$). These pools contained C residues originating primarily from the harvested old-growth stands and were unlikely to be strongly affected by the treatments. However, they did contain substantial amounts of C (Appendix: Table A1). The experiment-wide mean legacy CWD C load was 4.7 Mg ha$^{-1}$, and it ranged from 2.29 Mg ha$^{-1}$ to 8.09 Mg ha$^{-1}$ (Fig. 4a). Legacy CWD made up an average of 4.1% of the total aboveground C with legacy pools included. The experiment-wide mean of the forest floor pool was 22.74 Mg ha$^{-1}$ and ranged from 14.64 Mg ha$^{-1}$ to 34.46 Mg ha$^{-1}$ (Fig. 4b). Forest floor C made up an average of 20.0% of the total aboveground C with legacy pools included and together with the legacy CWD made up 24.1% of total C. The
relatively high forest floor C values are due to substantial amounts of partially
decomposed soil wood, especially in the sites where harvest residues broadcast burned
and not dozer piled and burned (Table 1).

*C distribution among live and dead pools*

Stands with higher target densities had a larger proportion of total C in non-legacy
dead pools (Figure 5 a), consistent with our expectation. The unthinned treatment had
largest proportion of C in dead pools (17.3%); the proportion of C in dead pools declined
with target thinning density, with 7.4 %, 4.7% and 4.0% of C in dead pools for the 1680,
890 and 494 trees ha$^{-1}$ treatments, respectively. As expected, when legacy pools are
included the clear effect of treatment on the proportion of C in live and dead pools was
masked. The unthinned plots still had the largest proportion in dead pools at 34.6%
(Figure 5 b), which may in part be due to the effect of the non-legacy deadwood pools.
However, by chance, there were multiple very large legacy logs in two of the unthinned
plots, which also contributed to this pattern.

**Discussion**

Our results indicate that regulation of stand density with early precommercial
thinning does not decrease total aboveground C stores 54 years after treatment in western
larch forests. These findings have numerous implications for managing second growth
forests to meet both C storage (climate change mitigation) and other management
objectives, such as development of complex stand structures and provision of wildlife
habitat. A key implication of our results is that regulating stand density to increase
individual tree growth does not necessarily result in a trade-off of reduced stand-level
aboveground C (Horner et al. 2010, Dwyer et al. 2010). This is an important finding
because current understanding (D’Amato et al. 2011, Bradford and D’Amato 2012) emphasizes that there is a tradeoff between management for climate mitigation (i.e., maximizing C storage) and management for climate adaptation (development of structurally and compositionally complex stands): stands thinned to low densities store less C but are more structurally complex. Our results indicate that no such tradeoff exists a half-century after precommercial thinning in western larch forests. Low density stands had much larger trees (Fig. 3) and more understory and midstory vegetation (Fig 2b)—hallmarks of structural and compositional complexity—yet low density stands stored as much aboveground C as unthinned stands and stands thinned to high densities (Fig 2).

These contrasting results arise from the very different thinning regimes studied here compared to those investigated by D’Amato et al. (2011). Here, precommercial thinning treatments were implemented at an average stand age of eight years, prior to the onset of canopy closure and intense intertree competition leading to crown recession. In contrast, thinning treatments were implemented at stand age 85 years in the red pine (Pinus resinosa) forests studied by D’Amato et al. (2011), with thinnings then repeated every 5 to 10 years in a levels-of-growing-stock (LOGS) style experiment. The results of both studies are consistent with foundational stand dynamics theory (Oliver and Larson 1996) and should not be interpreted as contradictory. The key implication for management and policy is that not all forest thinning treatments are equal in their design or effects. This nuance needs to be captured and communicated to policy makers and managers involved in efforts to devise forest management strategies for climate change adaptation and mitigation.

_Mechanisms causing C storage convergence across stand densities_
The fact that total non-legacy aboveground C does not vary by treatment is largely driven by strong effect of stand density on mean overstory tree size. In a companion analysis, target density strongly affected mean tree diameter, height, and crown volume (Schaedel et al. in preparation), the three variables that have the greatest effect on individual tree biomass, and therefore tree C. These results agree with density management theory (Drew and Flewelling 1979, Harrington and Harrington 2009). Estimating mean total tree C as the sum of the stem wood, bark and crown allows us to account for the known effects of density on mean height and crown volume (Schmidt and Seidel 1988, Harrington and Harrington 2009). Mean crown volume per conifer tree follows similar trends seen in the mean tree C; tree volumes are inversely related to both density and number of entries. However, the effect of the crown C in western larch is less than it may be for other species as western larch have crowns with comparatively low bulk densities (Brown 1978). Trees growing in lower density stands have deeper and wider crowns as they have grown under more open conditions than trees in higher density stands, resulting in less crown abrasion and crown recession. Using the sum of the components approach allows us to detect these effects of target stand density on mean tree C in ways that are more congruent with our understanding of how density affects tree attributes than if we used allometric equations based on diameter alone (e.g. Jenkins et al. 2003).

Live non-conifer C was affected by target density as we had anticipated: higher stand densities had lower amounts of C in this pool. This is consistent with the findings of other studies on the effect of thinning on understory C (Campbell et al. 2009, Powers et al. 2012, Zhou et al. 2013) as well as stand dynamics theory (Oliver and Larson 1996).
As stand density decreases more growing space and resources are available for understory vegetation. The result is a greater amount of shrub and mid-story hardwood C in low density stands. Non-conifer live C pool makes a greater contribution to total C than found in other studies (Campbell et al. 2009, Bisbing et al. 2010, Powers et al. 2012, Jang et al. 2015) in part because we have grouped mid-story hardwoods (primarily *Betula papyrifera*) with shrubs and herbs. Even including these mid-story hardwoods, which were nearly absent at two of the experiment sites, this pool makes a relatively small contribution to total aboveground C at this point in stand development at an experiment wide average of 5% of the total aboveground C and ranging from 6.6% in the 494 trees ha\(^{-1}\) to 3.1% in the unthinned treatment. This low proportion of total aboveground C is likely due to all densities being closed canopy stands, which reduces understory vegetation until density-independent mortality events create canopy gaps leading to the re-initiation of the understory (Oliver and Larson 1996).

Non-legacy deadwood showed strong increases with increased stand density, with unthinned plot having more than twice the C than the 1680 trees ha\(^{-1}\) treatment and more than 5 times the C as the 494 trees ha\(^{-1}\) treatment. This substantial increase in deadwood C is important from a carbon storage perspective but the patterns of variability in this pool are also noteworthy (Table 3 and Appendix: Table A1). Early precommercial thinning increases average tree size as well as decreases the variability between stands; in contrast, the unthinned stands tend to be more variable (Fig 2c and Appendix Table A1). Our results show that for the non-legacy deadwood C pool variability generally decreases with decreases in stand density. This is likely due to mortality in stands experiencing self-thinning tending to be both episodic as well as spatially aggregated, with mortality
concentrated in locally crowded areas within unthinned plots (Kenkel 1988, Larson et al. 2015). Since low density stands are experiencing less competition and, subsequently less density-dependent mortality, this would suggest that there would be lower mortality and lower inputs to the woody debris pool, as well as lower variability to deadwood inputs. It has also been shown that larger trees are more resilient to the stressors that lead to mortality, such as drought (Horner et al. 2010), or wind and snow damage (Wonn and O’Hara, 2001), suggesting that density-independent mortality is also less frequent at lower densities.

We emphasize that our finding of constant yield of total aboveground C across a wide range of densities was achieved with the application of the early low thinning common to PCT; thinning treatments were implemented at an average stand age of eight years. We expect that similar results may eventually be found from long-term studies of stands initiated (planted) at different initial spacing (e.g., Harrington et al. 2009). This is because early PCT is functionally similar to initial spacing—the manipulation of stand density occurs before the trees have experienced major effects of competition, such as canopy closure and crown recession. We would not expect to see similar results from studies other thinning methods, such as thinning across the diameter range or crop tree thinning, especially when treatments are implemented at later stand ages and after canopy closure and crown recession (Hoover and Stout 2007, D’Amato et al. 2011). In fact, there is a substantial amount of evidence from LOGS and other commercial thinning studies, which employ thinning across the diameter range and crop tree thinning, showing a consistent decrease in total aboveground C with decreases in growing stock or density (Skovsgaard et al. 2006, Chattergee et al. 2009, D’Amato et al. 2011, Zhou et al. 2013).
We also stress that the multiple thinning entries in this study (Table 2) are distinctly different from the multiple thinning entries of LOGS studies; in this study the multiple thinning entries removed the smallest trees to achieve a target density over multiple thinnings, while LOGS thinnings seek to maintain a constant level of growing stock through time, defined by basal area, bole surface area, or total cubic volume (Marshall and Curtis 2002). The removal of larger trees in LOGS experiments results in significant loss of live tree C and reduces future inputs to woody detritus pools by reducing competition. The removal of large trees in LOGS studies also leaves gaps in the canopy which residual trees are slow to fill, especially in older stands, reducing rates of stand-level biomass accumulation (Long et al. 2004). In contrast, low thinning removes the least productive trees from a stand which results in little loss in stand-level growth (Smith et al. 1997). If thinning is done early, before individual tree growth is reduced by inter-tree competition, the residual trees are able to reoccupy the site more quickly than stands thinned after completion has caused self-pruning and crown recession (Long et al. 2004).

Even 62 years after harvest, legacy pools, primarily large CWD and soil wood in the forest floor, stored a substantial amount of C, making up an experiment-wide average of 24% of total aboveground C. Large CWD pieces have a long residence time (Harmon et al. 1986) especially in the relatively cold and dry forests of the Northern Rockies (Bisbing et al. 2010, Mobley et al. 2013). There is little evidence that the experimental thinning treatments would have significantly affected these pools—changes in decay rate due to the stand density caused changes in light and temperature are likely to be small, especially since the stands are all in closed canopy conditions (Harmon et al. 1986). The relatively slow growth rates of many western larch sites indicate that producing trees of
large enough diameter to produce large snags and CWD may take 200 years or more (Bisbing et al. 2010). This underscores the importance of retaining large woody debris on site following harvest to promote long-term C storage as well as the other important ecological functions of large CWD (Duvall and Grigal 1999, Franklin et al. 2002). In second growth stands this also suggests that, despite an initial reduction of the amount of C in the dead wood pools due to thinning (Fig 2c), promoting the rapid growth of large trees may be the fastest way to ultimately recover large deadwood structures (Sturtevant et al. 1997).

For timber production objectives, it is rarely economically viable to enter a stand more than once before removing a merchantable product. From our results we conclude that for C storage objectives there is also no significant benefit of achieving a target stand density through multiple light thinnings. Number of entries did not significant affect any aboveground C pool, although it did subtly influence mean conifer tree C at the individual tree scale (Figure 3). The only potential benefit to multiple light thinnings is to allow for the replacement of damaged trees, or trees lost mortality. Our results suggest that such potential benefits are marginal at best.

Conclusions, management implications, and future work

Three main conclusions follow from our examination of the effects on early thinning on total aboveground C.

- Fifty-four years after treatment the total aboveground C of stands precommercially thinned to a wide range of densities is similar, due primarily to the increase in mean tree C of trees grown at lower stand densities.
• Sixty-two years after stand replacing disturbance deadwood legacies from the pre-disturbance old-growth forest still play an important role in long-term C storage, accounting for approximately 20-25% of aboveground C stores.

• Given enough time since early thinning, there is no trade-off between managing stands to promote rapid individual tree growth and development of understory vegetation, and maximizing stand level accumulation of aboveground C.

*From these results we infer that there is potential to use early precommercial thinning to simultaneously achieve climate change mitigation and adaptation objectives,* provided treatments are implemented early in stand development before the onset of intense intertree competition. We expect that there is a lower limit of stand density that will achieve these simultaneous outcomes, due to natural limitations of maximum tree size and the importance of full site occupancy to achieving high rates of C accumulation (Newton 1997, Kashian et al. 2013).

There is great potential to use long-term silvicultural experiments to test novel ecological hypotheses and answer contemporary management questions that were not envisioned at study initiation (D’Amato et al. 2011, Bradford and D’Amato 2012). Continuing to monitor carbon stocks and other attributes of stands experimentally manipulated to different target densities can provide insight to the future effects of management actions, as well as the mechanisms that govern dynamics of natural forests. For example, because large diameter, full crowned trees continuously increase C accumulation rates with increasing tree size (Stephenson et al. 2014), are more resilient to perturbations such as fire (Agee and Skinner 2005), and are more resistant to uprooting and stem breakage (Wonn and O’Hara 2001), stands thinned to initial low density may
ultimately have greater long-term C storage potential than unthinned stands, or stands thinned to higher densities (Oliver and Larson 1996). Continued measurement of the WLDMS and other long-term thinning studies for the next several decades will permit testing of this prediction.
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USDA, Forest Service, Northern Research Station, Newtown Square, Pennsylvania, USA.


### Figures and Tables

Table 1. Characteristics of the four study sites where the larch thinning study was installed. The aspect and slope are the average of all of the treatment plots.

<table>
<thead>
<tr>
<th>Study site</th>
<th>Harvest Date</th>
<th>Harvest Method</th>
<th>Site preparation</th>
<th>Habitat type[^a]</th>
<th>SI[^b] (m)</th>
<th>Elevation (m)</th>
<th>Aspect</th>
<th>Slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coram 1</td>
<td>1951</td>
<td>Clearcut/Seed-tree</td>
<td>Dozer piled, Broadcast burn</td>
<td>Abies lasiocarpa/Clintonia uniflora, Aralia nudicaulis phase</td>
<td>24</td>
<td>1200</td>
<td>350°</td>
<td>21%</td>
</tr>
<tr>
<td>Coram 2</td>
<td>1951</td>
<td>Shelterwood</td>
<td>Broadcast burn</td>
<td>Abies lasiocarpa/Clintonia uniflora, Aralia nudicaulis phase</td>
<td>23</td>
<td>1200</td>
<td>300°</td>
<td>25%</td>
</tr>
<tr>
<td>Cottonwood Lakes</td>
<td>1953</td>
<td>Clearcut</td>
<td>Dozer piled, scarified, piles burned</td>
<td>Abies lasiocarpa/Clintonia uniflora, Vaccinium caespitosum phase</td>
<td>19</td>
<td>1450</td>
<td>355°</td>
<td>20%</td>
</tr>
<tr>
<td>Pinkham Creek</td>
<td>1953</td>
<td>Clearcut</td>
<td>Dozer piled, scarified, piles burned</td>
<td>Abies lasiocarpa/Clintonia uniflora, Clintonia uniflora phase</td>
<td>24</td>
<td>1475</td>
<td>65°</td>
<td>20%</td>
</tr>
</tbody>
</table>

[^a]: Pfister et al 1977

[^b]: Site index (SI) was calculated with the equations of Milner et al., 1992.
Table 2. The experimental design of the larch spacing study. The target densities indicate the desired density of a treatment after its final thinning. Actual density is the density recorded the summer of 2015.

| Target density (Trees ha\(^{-1}\)) | Number of entries | Year(s) thinned: | Intermediate thinned densities | Actual 2015 density (Trees ha\(^{-1}\)):
|-----------------------------------|-------------------|-----------------|-------------------------------|---------------------------------
| Unthinned                         | 0                 |                 |                               | 4474                            |
| 494                               | 1                 | 1961            | 494                           | 463                             |
| 4.56 x 4.56                       | 2                 | 1961            | 890                           | 488                             |
|                                   |                   | 1981            | 494                           |                                 |
| 890                               | 1                 | 1961            | 890                           | 828                             |
| 3.35 x 3.35                       | 2                 | 1961            | 2199                          | 815                             |
|                                   |                   | 1981            | 890                           |                                 |
| 1680                              | 1                 | 1961            | 1680                          | 1334                            |
| 2.44 x 2.44                       | 2                 | 1961            | 4260                          | 1415                            |
|                                   |                   | 1981            | 1680                          |                                 |
Table 3. Results of linear contrasts (standard error of the mean shown in parentheses) for aboveground C pools sensitive to treatment. Global density test p-values represent the significance of all three contrasts simultaneously.

<table>
<thead>
<tr>
<th>Contrast</th>
<th>Carbon pool</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Live conifer</td>
<td>Other live</td>
<td>Non-legacy</td>
<td>Total non-legacy</td>
</tr>
<tr>
<td></td>
<td>(Mg ha(^{-1}))</td>
<td>(Mg ha(^{-1}))</td>
<td>deadwood (Mg ha(^{-1}))</td>
<td>(Mg ha(^{-1}))</td>
</tr>
<tr>
<td><strong>Density</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Global density test p-value</td>
<td>0.993</td>
<td>0.0062**</td>
<td>0.0314*</td>
<td>0.622</td>
</tr>
<tr>
<td>Unthinned vs Thinned</td>
<td>3.49 (18.22)</td>
<td>-1.21 (0.37)**</td>
<td>12.82 (6.72)</td>
<td>15.39 (11.93)</td>
</tr>
<tr>
<td>1680 vs 890 and 494</td>
<td>0.55 (5.00)</td>
<td>-1.64 (0.77)</td>
<td>2.68 (1.22)</td>
<td>1.82 (4.821)</td>
</tr>
<tr>
<td>890 vs 494</td>
<td>1.21 (5.88)</td>
<td>-1.26 (0.92)</td>
<td>0.59 (0.47)</td>
<td>0.58 (5.83)</td>
</tr>
<tr>
<td><strong>Number of entries</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1680: 1 entry vs 2 and 4 entries</td>
<td>8.93 (8.59)</td>
<td>1.37 (1.31)</td>
<td>1.20 (2.54)</td>
<td>11.07 (8.11)</td>
</tr>
<tr>
<td>1680: 2 entries vs 4 entries</td>
<td>12.72 (9.92)</td>
<td>1.24 (1.52)</td>
<td>-0.95 (2.94)</td>
<td>12.95 (9.37)</td>
</tr>
<tr>
<td>890: 1 entry vs 2 and 4 entries</td>
<td>15.85 (8.30)</td>
<td>1.20 (1.29)</td>
<td>-0.74 (0.63)</td>
<td>16.67 (7.71)</td>
</tr>
<tr>
<td>890: 2 entries vs 4 entries</td>
<td>0.55 (9.59)</td>
<td>-0.22 (1.49)</td>
<td>0.17 (0.73)</td>
<td>0.73 (8.90)</td>
</tr>
<tr>
<td>494: 1 entry vs 2 and 4 entries</td>
<td>-2.96 (9.32)</td>
<td>0.73 (1.46)</td>
<td>-0.24 (0.78)</td>
<td>-2.56 (9.78)</td>
</tr>
<tr>
<td>494: 2 entries vs 4 entries</td>
<td>4.05 (10.76)</td>
<td>2.11 (1.69)</td>
<td>-1.48 (0.90)</td>
<td>0.53 (11.29)</td>
</tr>
</tbody>
</table>

*Significance codes (p-value): 0 < *** < 0.001 < ** < 0.01 < * < 0.05*
Figure 1.A. Locations of the four study sites (i.e. blocks) in the northwest Montana, USA.

B. An example layout of the plots within a site. Gray squares are the 0.04 ha treatment plots (i.e., experimental units) and the white polygons demarcated by the dashed lines are buffer zones thinned with the same treatment.
Figure 2. Effects of thinning treatment on the three C pools predicted to be affected by treatment. A. live conifers, B live non-conifers, C non-legacy deadwood. The final panel (D) is the sum of the three previous three pools. The bars are grouped by target density, shown on the x-axis. Within each density level three different thinning regimes (1, 2 or 4 entries) were used to achieve the target density (Table 2). The dashed lines across the three grouped bars are the average of all number of entry treatments within a density and
represent the main effect of density on C stores. Error bars represent one standard error of the mean.
Figure 3. The relationship between treatment and mean C per tree. Error bars represent one standard error. On the x-axis the target density (trees ha$^{-1}$) is listed first and the number of thinning entries is listed after the period.
Figure 4. The mean C content by treatment for legacy pools. Error bars represent one standard error. The dashed lines across the three grouped bars are the average of all number of entry treatments within a density and represent the main effect of density on C stores. The apparent increase in legacy deadwood in the unthinned treatment is due to the chance presence of several very large logs in two unthinned plots. Forest floor was considered a legacy pool due to a dominance of highly decayed soil wood.
Figure 5. The effect of treatment on the partitioning of C between dead and live pools.

When only non-legacy pools are compared (A) there is a clear increase in C in dead pools as density increases. When legacy C pools (legacy deadwood and forest floor) are included (B), the proportion on carbon in dead pools increases by an average of 20% and the treatment effect is masked.
Appendix A

Table A1. Mean aboveground C stores (standard error) by component pool for each thinning treatment.

<table>
<thead>
<tr>
<th>Target Density</th>
<th>Thinning entries</th>
<th>Live conifer&lt;sup&gt;a&lt;/sup&gt; (Mg ha&lt;sup&gt;-1&lt;/sup&gt;)</th>
<th>Other live&lt;sup&gt;b&lt;/sup&gt; (Mg ha&lt;sup&gt;-1&lt;/sup&gt;)</th>
<th>Non-legacy deadwood&lt;sup&gt;c&lt;/sup&gt; (Mg ha&lt;sup&gt;-1&lt;/sup&gt;)</th>
<th>Total non-legacy&lt;sup&gt;d&lt;/sup&gt; (Mg ha&lt;sup&gt;-1&lt;/sup&gt;)</th>
<th>Legacy deadwood&lt;sup&gt;e&lt;/sup&gt; (Mg ha&lt;sup&gt;-1&lt;/sup&gt;)</th>
<th>Forest Floor&lt;sup&gt;f&lt;/sup&gt; (Mg ha&lt;sup&gt;-1&lt;/sup&gt;)</th>
<th>Total aboveground&lt;sup&gt;g&lt;/sup&gt; (Mg ha&lt;sup&gt;-1&lt;/sup&gt;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>494</td>
<td>1</td>
<td>74.29 (11.01)</td>
<td>6.01 (2.57)</td>
<td>3.17 (0.58)</td>
<td>82.49 (11.71)</td>
<td>2.92 (1.49)</td>
<td>23.24 (5.28)</td>
<td>108.66 (16.94)</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>79.27 (12.77)</td>
<td>4.22 (1.99)</td>
<td>2.67 (0.20)</td>
<td>85.32 (12.96)</td>
<td>3.15 (2.34)</td>
<td>23.61 (7.72)</td>
<td>112.08 (19.19)</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>75.22 (11.95)</td>
<td>6.33 (3.09)</td>
<td>4.15 (0.76)</td>
<td>84.79 (13.07)</td>
<td>4.42 (3.28)</td>
<td>34.46 (14.79)</td>
<td>123.67 (24.44)</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>76.26 (6.26)</td>
<td>5.52 (1.38)</td>
<td>3.33 (0.35)</td>
<td>84.20 (6.59)</td>
<td>3.50 (1.13)</td>
<td>27.11 (5.55)</td>
<td>114.80 (10.89)</td>
</tr>
<tr>
<td>890</td>
<td>1</td>
<td>88.03 (15.91)</td>
<td>5.06 (2.57)</td>
<td>3.43 (0.68)</td>
<td>95.90 (16.23)</td>
<td>6.91 (1.15)</td>
<td>20.38 (3.71)</td>
<td>123.18 (18.18)</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>72.45 (11.85)</td>
<td>3.75 (1.24)</td>
<td>4.25 (0.43)</td>
<td>79.59 (11.54)</td>
<td>4.81 (2.51)</td>
<td>18.11 (3.87)</td>
<td>102.51 (14.14)</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>71.90 (16.03)</td>
<td>3.97 (1.94)</td>
<td>4.09 (0.46)</td>
<td>78.86 (16.43)</td>
<td>2.97 (1.35)</td>
<td>20.53 (5.54)</td>
<td>102.36 (20.14)</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>77.46 (8.01)</td>
<td>4.26 (1.05)</td>
<td>3.92 (0.30)</td>
<td>84.78 (8.14)</td>
<td>4.90 (1.05)</td>
<td>19.67 (2.35)</td>
<td>109.35 (9.81)</td>
</tr>
<tr>
<td>1680</td>
<td>1</td>
<td>83.36 (17.42)</td>
<td>4.17 (1.67)</td>
<td>7.11 (2.11)</td>
<td>93.69 (19.17)</td>
<td>6.50 (4.17)</td>
<td>14.64 (2.64)</td>
<td>114.83 (20.11)</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>80.79 (19.87)</td>
<td>3.41 (0.91)</td>
<td>5.43 (2.03)</td>
<td>89.10 (20.58)</td>
<td>3.51 (1.61)</td>
<td>20.60 (6.00)</td>
<td>113.21 (27.27)</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>68.07 (11.32)</td>
<td>2.18 (0.72)</td>
<td>6.38 (2.71)</td>
<td>76.15 (12.82)</td>
<td>3.75 (1.68)</td>
<td>25.17 (6.22)</td>
<td>105.06 (20.20)</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>77.41 (8.90)</td>
<td>3.25 (0.66)</td>
<td>6.31 (1.22)</td>
<td>86.31 (9.58)</td>
<td>4.59 (1.50)</td>
<td>20.14 (3.02)</td>
<td>111.03 (12.12)</td>
</tr>
<tr>
<td>Unthinned</td>
<td>0</td>
<td>80.53 (17.95)</td>
<td>3.14 (1.59)</td>
<td>17.34 (6.71)</td>
<td>100.49 (14.00)</td>
<td>8.09 (4.03)</td>
<td>26.65 (5.54)</td>
<td>135.23 (18.13)</td>
</tr>
</tbody>
</table>

* p<0.05
** p<0.01
*** p<0.001

<sup>a</sup> Live conifer includes all C in conifers but is composed only of larch in all thinned stands.
<sup>b</sup> Other live includes C in overstory hardwoods, shrubs, and herbaceous vegetation.
<sup>c</sup> Non-legacy deadwood includes all C in snags and wood debris produced by the current second-growth stands.
<sup>d</sup> Total non-legacy is the sum of all of the aboveground C pools most affected by treatment; the previous three columns.
<sup>e</sup> Legacy deadwood includes all C in woody debris that was produced by the logged old-growth stands.
<sup>f</sup> Forest floor includes all C in the O horizons (litter, duff, and humus) as well as soil wood (woody debris < decay class 5).
<sup>g</sup> Total Aboveground C is the sum of all other pools and represents both legacy and non-legacy pools.
Thesis Conclusion

Trees are among the longest living organisms on the planet and change occurs on a large temporal scale. Subsequently, the results of most forest manipulation experiments can be viewed as relatively short-term results. There is great potential to use long-term silvicultural experiments to test novel ecological hypotheses and answer contemporary management questions that were not envisioned at study initiation (D’Amato et al. 2011, Bradford and D’Amato 2012). These experiments allow researchers to gain a greater understanding of forest change through time than simulation studies as no human assumptions need to be made for the tree and stands to continue to develop. Continuing to monitor the tree growth, stand dynamics, and carbon stocks of stands experimentally manipulated to different target densities can provide insight to the future effects of management actions, as well as the mechanisms that govern dynamics of natural forests. For example, because large diameter, full crowned trees continuously increase C accumulation rates with increasing tree size (Stephenson et al. 2014), are more resilient to perturbations such as fire (Agee and Skinner 2005), and are more resistant to uprooting and stem breakage (Wonn and O’Hara 2001), stands thinned to initial low density may ultimately have greater long-term stand yield and C storage potential than unthinned stands, or stands thinned to higher densities (Oliver and Larson 1996). Continued measurement of the WLDMS and other long-term thinning studies for the next several decades will permit testing of such predictions.
Supplemental material:

Methods:

The goal of this supplemental material is to document the field and laboratory methods in greater detail than in the body of the thesis. Some of the material may be redundant but it is included so that the experimental design and methodology can be found in one place.

Supplement 1: Tree measurement field methods

Supplement 1a. Spacing Study Experimental Design and Remeasurement:

The experimental design of the historic larch spacing study had a core 3x3 factorial design that included three target densities (680, 360, and 200 trees per acre (TPA)) that were achieved through three different thinning intervals (4 thinnings (10 year intervals: 1961, 1971, 1981, 1991), 2 thinnings 20 year intervals: 1961, 1981), and 1 thinnings (40 year intervals: 1961)). See Figure 1.

<table>
<thead>
<tr>
<th>Target Density TPA (TPH)</th>
<th>200 TPA (494 TPH)</th>
<th>360 TPA (890 TPH)</th>
<th>680 TPA (1640 TPH)</th>
<th>110 TPA (272 TPH)</th>
<th>Control (no thinning)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thinned on 20 year interval (Thinned 2 times to reach target density: 1961, 1981)</td>
<td>200 TPA, reached in 2 thinnings</td>
<td>360 TPA, reached in 2 thinnings</td>
<td>680 TPA, reached in 2 thinnings</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thinned on 40 year interval (Thinned one time to reach target density: 1961) (Shrubs not treated)</td>
<td>200 TPA, reached in 1 thinning (no shrub treatment)</td>
<td>360 TPA, reached in 1 thinning (no shrub treatment)</td>
<td>680 TPA, reached in 1 thinning (no shrub treatment)</td>
<td>110 TPA, reached in 1 thinning (only Coram 1 &amp; 2)</td>
<td>Control</td>
</tr>
<tr>
<td>Thinning on 40 year interval (Thinned one time to reach target density: 1961) (Shrubs Treated)</td>
<td>200 TPA, reached in 1 thinning (shrubs treated)</td>
<td>360 TPA, reached in 1 thinning (shrubs treated)</td>
<td>680 TPA, reached in 1 thinning (shrubs treated)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 1. The original 3x3 factorial design, including the low density 110 TPA treatment (only at Coram 1&2), unthinned plots (originally only at Coram 1&2) and the shrub removal treatments.
Plot design and description:

Each treatment plot is 66 ft x 66 ft (20 m x 20 m). There is a 33-66 ft buffer around each plot which is thinned with the same density and interval treatment as the plot.

White angle irons: White angle irons designate the buffer zone for each treatment plot. This is an area 33 to 66 feet beyond the edge of the treatment plot that was thinned with the same treatment (target density and number of entries) as the plot in order to minimize for treatment edge effects.

Red angle irons: Red angle irons designate each individual 66ft x 66 ft or 0.1 acre (0.04 ha) treatment plot. The plots are oriented so that the sides are generally running up and down hill while the top and bottom generally stay on the same contour around the slope. If you are standing on the downhill side of the treatment plot, looking uphill, the upper right corner is on the uphill side of the plot to your right. There is a metal tag indicating the respective plot code on the bottom right corner angle iron of each plot. The plot code is a unique four digit code. See the descriptions below and Figure 2:

- The first number indicates the final target density:
  - 1 = 680 TPA
  - 2 = 360 TPA
  - 3 = 200 TPA

- The second number indicates the thinning interval to achieve the final target density:
  - 2 = 2 thinnings (every 20 years: 1961, 1981)
  - 3 = 1 thinnings (every 40 years: 1961)

- The third number indicates whether the shrubs were treated with chemicals or not. All shrubs were cut in every treatment plot because of the inability not to cut some of the shrubs in the initial thinning in 1961:
  - 1 = shrubs cut at initial thinning but no chemical treatment
  - 2 = shrubs cut at initial thinning and stumps chemically treated

- The fourth number indicates the replicate (the site).
  - 1 = Coram 1
  - 2 = Coram 2
  - 3 = Cottonwood Lakes
  - 4 = Pinkham Creek
Figure 2. A description of the plot code

Identifying Plots in the Field

Navigate to each plot location using the maps of the four replicates below. To positively identify you are on the correct plot there is the tag on the RED angle iron at the lower right corner of the plot with the plots 4 digit plot code (see figure 2). On this same corner there may also be a second tag that describes the initial treatment done to the plot, for example: “4 x4 spacing, 2722 TPA, thinned every ten years, shrubs treated.” These tags may be helpful in confirming which plot you are on but also may give confusing information. Rely on the plot code to correctly identify the plot. Plot codes are already recorded on the data sheets.

Tree Tag Numbers:

All trees in each 20 m x 20 m treatment plot are tagged with a unique number at breast height. Control plots have a different sampling scheme discussed later. Each tree was assigned a unique number when the plots were first thinned in 1961. The tree numbers were given starting from the upper right corner of the plot and working counter-clockwise in a sinuous pattern to the lower right corner of the plot (Figure 3). Since all the plots were thinned after the numbers were assigned, with the exception of the plots only thinned once, many of the numbered trees have been removed. DO NOT worry if many of the tree numbers are missing. They were likely thinned or died and fell over before 2001.
Figure 3. A diagram of the order of the tree tag numbers

To sample the plot start at the upper right hand corner, which should contain the tree with the lowest number (it may not be number 1). Take all of the required measurement on that tree (described below) then move to the next highest number tree.

**Live tree with a tag:**
If you come to a live tree with a tag, simply take the 9 live tree measurements (described below) and record them on the data sheet.

**Dead tree, fallen, with a tag:**
If you come to a tagged tree and it is dead and fallen, record on the main data sheet vigor class as 4 and the damage codes (probable cause of death/description of the tree, see below). Write D.O.G. (Dead On Ground) in the DBH column.

**Dead tree, standing (snag), with a tag:**
If you come to a snag with a tag, record on the main data sheet the vigor class as 4 and the damage codes (probable cause of death/description of the tree, see below). On the snag data sheet, record the necessary measurements.

**Cannot find tree:**
If a tree was present on the data sheet in 2001 and you cannot find it. Look on the ground around you, as it may have died. If you find a log on the ground with a tree tag on it, follow the dead tree procedures above. If you do not initially find it after a thorough search, make a note on the back of the data sheet. Continue to sample the plot following the sinuous pattern in figure 3. You may come across the missing tree later in
the plot or you may find one tree with a missing tag and be able to deduce that it is the missing tree if the measurements make sense with the 2001 data. If you still cannot find the tree and you have exhaustively searched, record the dead, (10) damage code.

**Tree tag is missing:**
If you come to a tree that appears to be in the plot (check trees on the edge to the plot carefully by sighting from one red angle iron corner marker to the next) and the tree does not have a tag look carefully in the duff and underbrush on the ground to find the tag. If you cannot find the tag flag the tree, write missing tag on the flagging, and continue to measure the plot. By the end of the plot you may be able to deduce which tree it is if there is one unmeasured tree remaining on the data sheet. Confirm the tree’s identity by measuring it and seeing if the new measurements make sense with the old ones on the data sheet. If they do, record the data, put an x in the “see back of data sheet box, and make a note that tree ###, in plot code #### is missing a tag. Nail a temporarily tag to the tree at 4.5’ with the tree number scratched on the tag. The crew should carry extra tags nails and a small hammer in their cruise vests.

**Control plot sampling scheme**
At the establishment of the study in 1961, each control plot had 20 trees tagged. These twenty trees should have the same 9 measurements recorded on the main data sheet. In addition to the twenty tagged trees, there are 10 circular milacre plots (3.72 ft radius) where all trees are measured (see Figure 3 for milacre plot layout). The data for these trees should be recorded on the separate milacre plot data sheet. The trees in the milacre plots are not tagged. The same 9 measurements should be taken for the milacre trees that are taken for the tagged trees.

![Figure 4 The layout of the milacre plots in the control treatments.](image_url)
Supplement 1b. Overstory Tree Measurements

**Live tree Measurements**
Each live tree in the treatment plots requires 9 measurements:
1. Diameter at breast height
2. Total height
3. Crown base height
4. Crown width height
5. Crown diameter (two measurements)
6. Vigor
7. Crown class
8. Crown density
9. Damage code

**Dead Tree Measurements**

For all dead trees within a plot record the following on the main data sheet: if a tree is a snag (as opposed to already fallen) there are additional measures to be taken on the separate snag data sheet:
1. Vigor class 4 (dead tree)
2. Damage code (description of the tree/probable cause of death). These codes will be between the numbers of 10 and 19.
3. If the tree is dead on the ground, note that with the letters “DOG” in the DBH column.

**If the tree is a snag (standing dead)**

If a tree is a snag (standing dead) on the separate snag data sheet record the following:
1. Diameter at breast height
2. Diameter at ground level
3. Top diameter (if the tree has a broken top, use 0.1” if the tree is not broken topped)
4. Total height
5. Snag decay class
6. Damage code describing the probable cause of death. These codes will be between the numbers of 10 and 19.

1. **Diameter at Breast Height (DBH)** - Bole diameter is to be measured at 4.5 ft above tree base to the nearest 0.1 inch. All of the tree tag nails are at exactly 4.5 feet above where the tree base was in 1961. Measurement location is directly above the tree tag nail using an ENGLISH loggers DBH tape (Figure 5).
Figure 5. The location of the DBH measurement, 4.5 feet (1.37 m) above the uphill side of the tree, directly above the tree tag nail, if present (image adapted from the USFS Timber cruising manual).

2. **Total Tree Height** - Total tree height will be measured from the ground to the topmost reach of the tree with a laser hypsometer (Figure 6). Directions for use of the laser hypsometer are detailed below:

Figure 6. Where to measure total tree height (image adapted from the USFS Timber cruising manual).
Direction for use of the laser hypsometers:

**Laser Ace**

*Note:* for more details and for troubleshooting the user manual is in the box on a cd

- Turn on the instrument by holding the top red button
- When using it the first time, in MENU scroll to SETUP using the arrow button and select with the red button
  - Select UNITS with the red button and make sure it is in meters by using the arrow to toggle through and select with the red button
  - Next select CONFIGURATION and scroll to COMPASS and set the declination to 14°E
  - Select RANGING in CONFIGURATION and select FRST HIT
    - This selection tells the laser to measure the object first hit by the laser and returned. **REMEMBER:** you need to have a clear view of the tree of interest in order to get an accurate reading!
  - Press the button with the circle inside to go back to SETUP then MENU
- In MENU select 3. LENGTH/LEAN/VOL
  - Leave it in STADIA NIL mode (shown at the bottom of the screen)
  - Ignore the TAPERING% by pushing the red button
  - Scroll to select 3. THREE POINT
  - It will first ask a diameter, ignore by pushing the red button
  - Next is SHOOT MIDDLE, aim the scope from eye level to the tree of interest and push the red button, it will beep if the measurement is taken otherwise a buzzing sound is made and the target cannot be acquired and needs to be taken again
  - Then SHOOT BOTTOM, aim for the base of the tree at ground level
  - Last is SHOOT TOP, aim for the top most branch
  - Tree height and HD (horizontal distance will be shown on the screen)
- To turn off the instrument hold the circle and square buttons simultaneously and it will count down from 5 and then shutdown.

**Laser Tech Impulse Laser**

*Note:* for more details and for troubleshooting a copy of the user manual is in the datasheets binder behind the manuals tab

- Mount the impulse laser on a monopod to increase the accuracy of the measurements.
- Turn the instrument on by holding the button closest to the viewing scope on the right hand side.
- Set to HT by pressing the button farthest from the viewing scope on the right side.
- To activate the laser in the scope, press the closest button to the viewing scope. When active, HD will be flashing in the top right of the screen.
  - First, shoot the middle of the tree of interest at a level and press the button closest to the viewing scope. It will beep when the measurement is taken.
  - Next, shoot the base of the tree at ground level again pressing the button closest to the viewing scope. Make sure to physically move the laser to
point the viewing scope down, otherwise it will not properly measure the tree. It will beep when the measurement is taken.

- Lastly, shoot the top of the crown where the tree ends by pressing the button closest to the viewing scope. It will beep when the measurement is taken.
- The height of the tree will appear on the screen. Numbers displayed in meters will be indicated by an M on the right most part of the viewing screen.
  - If numbers are not displayed, press the middle button on the right side.
- To turn off, hold the middle and farthest button on the left side down simultaneously. Screen should read OFF before going blank.

Laser Tech TruPulse 200

**Height Routine**

Height Measurements involve a simple routine that prompts you to take 3 shots to the target: HD, INC base (or top), and INC top (or base). The TruPulse uses these results to calculate the height of the target. Figure #17 shows the three shots required for the height routine.
1. Select your target and look through the eyepiece, using the crosshair to aim to your target. The HT indicator displays steady and the HD indicator flashes, prompting you to measure the Horizontal Distance to the “face” of the target.

2. Press-and-hold \( \text{Laser} \). The LASER status indicator is displayed while the laser is active. The laser will remain active for a maximum of 10 seconds while acquiring data about the target. The measured horizontal distance appears briefly in the Main Display and then \( \text{Ang}_1 \) and the INC indicator flashes; prompting you to measure the inclination to base (or top) of the target.

3. Press-and-hold \( \text{Laser} \) and aim to the base (or top) of the target. The measured inclination appears in the Main Display and is updated as long as you continue to hold \( \text{Laser} \). The measured inclination is “locked” when you release \( \text{Laser} \). The measured inclination appears briefly in the Main Display and then \( \text{Ang}_2 \) appears and the INC indicator flashes, prompting you to measure the inclination to the top (or base) of the target.

4. Press-and-hold \( \text{Laser} \) and aim to the top (or base) of the target. The measured inclination appears in the Main Display and is updated as long as you continue to hold \( \text{Laser} \). The measured inclination is “locked” when you release \( \text{Laser} \). The measured inclination appears briefly in the Main Display and then the calculated Height is displayed. The measurement flashes one time and then displays steady until you press any button or the unit powers OFF.

*Figure #18*

During the height routine:

- Press \( \text{Laser} \) to re-shoot the previous point.
- Press \( \text{Laser} \) to exit the height routine.
- The laser is not active while measuring the \( \text{ANG1} \) and \( \text{ANG2} \) values. As long as you hold \( \text{Laser} \), the inclination reading is displayed and updated as your aiming point changes. The measured inclination is based upon your aiming point when you release \( \text{Laser} \).
- When the height result is displayed, just press \( \text{Laser} \) to start the routine and repeat the steps.
If these directions are insufficient, consult the manuals found in the carrying case of each instrument.

3. **Crown width height** – This is the height from the base of the tree to the widest point of the crown (Figure 10). This will be measured with a laser hypsometer as outlined in the tree height section above.

![Figure 7. Where to measure crown width height (image adapted from the USFS Timber cruising manual)](image)

4. **Crown Base Height** - The height from the ground to the base of the lowest full live whorl. The height should be record to the nearest foot. Ignore single branches or small isolated epicormic branch sprays. If there are two live branches on half of the trunk at 16 feet and to on the opposite side at 20 feet, that taken together would account for a complete live whorl take the average of the two heights as the base of the live crown: \( \frac{16+20}{2} = 18 \text{ feet} \). Measure this height with a laser hypsometer using the same procedures outlined in the tree height section above.
5. **Crown width** – This is the diameter at widest part of crown to nearest tenth of a foot. Two diameters will be taken: (1) across the slope of the hillside and (2) straight up and down the slope. Take the diameter to the furthest out branch of the crown that is overhead. These measurements will be obtained with a measuring tape and a densitometer or clinometer, and is best done with two people.

Two people: Standing under the crown of the tree 180° degrees from each other, identify the edge of the crown with a densitometer or clinometer. To do this stand at the edge of the tree crown drip line and look through the densitometer. Make sure the bubble from the level is in the center of the circle and move closer or further from the pith of the tree until you have identified the edge of the canopy. Use a tape to measure the distance between the two edges. Take two perpendicular measurements. They will be averaged later.
6. Vigor- Roe's preliminary vigor classification for larch (Northern Rocky Mountain Forest and Range Experiment Station Research Note 66, November 1948).

Vigor is a relative measure and should be made by comparing the individual tree to other trees in the treatment plot. Vigor class ranges from 1-4. If the tree needles have good green color, a high density, and no visible defoliation it is considered a 1 (a good vigor tree) if the needles are slightly yellower than the good vigor trees, foliage density is lower but still has a moderate density, and/or there are some signs of defoliation the tree is a 2 (Fair vigor). If the needles are very yellow, the foliage is sparse, and/or there is a large amount of defoliation the tree is a 3 (poor vigor tree). Vigor class 4 is a dead tree.

- **Vigor codes:** the easiest way to classify vigor is to see if a tree meets the criteria for vigor class 1 or 3. Trees that qualify for neither of these classes are assigned to class 2 (Figure 4) A majority of trees will meet the criteria for vigor class 1.
  - **Class 1: vigorous;** uncompacted live crown ratio of at least 35 percent and < 5 percent dieback. (Note that damage caused by browsing mammals is classified as missing foliage, and not as dieback, and that twigs and branches that have died as a result of normal shading are not included in dieback). Also, 80 percent or more of the leaves present must be undamaged. Damaged foliage is defined as leaves with more than 50
percent of their original surface area chewed, discolored, missing, or otherwise damaged.

- **Class 2: moderately vigorous**; do not meet class 1 or 3 criteria. They may have any uncompacted live crown ratio, may or may not have dieback, and 21 to 100 percent of their foliage is classified as normal.

- **Class 3: poor vigor**; may have any uncompacted live crown ratio. Less than 20 percent of their leaves are undamaged. Leaves of twigs and branches that have died as a result of normal shading are not considered missing or damaged.

- **Class 4**: Dead, include a damage code.

---

**Figure 10**: Diagram of western larch vigor classifications. Reproduced from Van Pelt 2008

7. **Crown class** – Codes shown below:
   1. Dominant
   2. Codominant
   3. Intermediate
   4. Suppressed
Figure 11. A diagram of the Kraft crown class system.

1—**Dominant**: the crown receives light from at least three to four directions. These are trees that rise above the main canopy of the forest. They are taller, have wider crowns and tend to have larger live crown ratios than lower crown classes. They could also be called “emergent” trees.

2—**Codominant**: the crown receives light from at least one to two directions. These are the trees that make up the bulk of the main canopy layer. They have smaller crowns that the dominant trees but not by much.

3—**Intermediate**: the crown only receives light from the top. These trees are shorter than the dominant and codominant trees. They may only get direct sunlight from straight above. They typically have small live crown ratios.

4—**Suppressed**: the crown is entirely over-topped (no direct light) and underneath the stand canopy. They have very low vigor and small live crown ratios. Since larch is a very shade intolerant species these trees tend to appear as if they are going to die soon.

NOTE: It is important to compare this classification with that from the last measurement. Larch that are suppressed (4) or intermediate (3) are unlikely to become codominant (2) or dominant (1) but codominant trees may become intermediate.

8. **Crown density** – This is a relative measure compared to all other trees in that replicate:

1 - Below average crown density
2 - Average crown density
3 - Above average crown density
9. Damage Code

The damage codes are a numerical description of the general tree condition. All trees will receive at least the first damage code. Up to four codes may be given to describe a host conditions a tree is affected by. The codes are listed from most serious to least serious. Healthy well-formed trees with no defects are given the code 00. Trees that have died since the last measurement will have a first code that is between 10 and 19.

<table>
<thead>
<tr>
<th>General codes</th>
<th>Mortality Causes</th>
</tr>
</thead>
<tbody>
<tr>
<td>00 Healthy, well-formed tree</td>
<td>10 Dead</td>
</tr>
<tr>
<td>01 Forked</td>
<td>11 Dead, removed</td>
</tr>
<tr>
<td>02 Leaning, snow-bent, or crooked</td>
<td>12 Dead, uprooted by wind and/or snow</td>
</tr>
<tr>
<td>03 Injury (fire, animal, mechanical, etc.)</td>
<td>13 Dead, fire</td>
</tr>
<tr>
<td>04 Abnormally large branches</td>
<td>14 Dead, suppression</td>
</tr>
<tr>
<td>05 Unhealthy (poor color or density of foliage)</td>
<td>15 Dead, disease</td>
</tr>
<tr>
<td>06 Attacked by insects</td>
<td>16 Dead, insects</td>
</tr>
<tr>
<td>07 Prostrate</td>
<td>17 Dead, cut and left</td>
</tr>
<tr>
<td>08 Top dead or broken off animal</td>
<td>18 Dead, broken top</td>
</tr>
<tr>
<td>09 Visible conks, punk knots, or rotten face</td>
<td>19 Dead, from miscellaneous injuries, i.e., mechanical, or smelter</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Physical Damage</th>
<th>Disease</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 Snowbend severe, and tree unlikely to recover</td>
<td>40 Defoliating diseases/needle cast</td>
</tr>
<tr>
<td>21 Bear severe &gt; 50% girdled crown</td>
<td>41 Root rots</td>
</tr>
<tr>
<td>22 Bear moderate &lt; 50% girdled</td>
<td>42 Rust cankers on branches or other limiting diseases</td>
</tr>
<tr>
<td>29 Bear damage</td>
<td>43 Rust cankers on stem</td>
</tr>
<tr>
<td></td>
<td>44 Mistletoe</td>
</tr>
<tr>
<td></td>
<td>45 Unknown</td>
</tr>
<tr>
<td></td>
<td>48 Disease-killed top</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Insect Damage</th>
<th>General Damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 Defoliators</td>
<td>72 * Big game (deer, elk, moose)</td>
</tr>
<tr>
<td>51 Leader-damaging insects</td>
<td>74 * Porcupine</td>
</tr>
<tr>
<td>53 Bark beetles of the lower bole</td>
<td>76 * Rabbits or hares</td>
</tr>
<tr>
<td>54 *Western Spruce Budworm</td>
<td>77 * Tree squirrels</td>
</tr>
<tr>
<td>55 * Larch Casebearer</td>
<td>79 * Man (other than logging)</td>
</tr>
<tr>
<td>58 Bark beetles of the upper bole</td>
<td>80 * Weather (Unknown or other)</td>
</tr>
<tr>
<td></td>
<td>81 * Wind</td>
</tr>
<tr>
<td></td>
<td>83 * Frost damage to shoots</td>
</tr>
<tr>
<td></td>
<td>85 * Winter desiccation (Red Belt)</td>
</tr>
<tr>
<td></td>
<td>88 * Lightening</td>
</tr>
<tr>
<td></td>
<td>91 * Logging or Thinning</td>
</tr>
<tr>
<td></td>
<td>98 * Crooks and or sweep</td>
</tr>
</tbody>
</table>
Control milacre plots:
The 20 tagged crop trees and those falling in the milacre plots (Figure 3—see above) located in control units are to be measured following the methods given above (Remeasurements 1-9). Tree species also needs to be recorded for each tree in the milacre plots

10. Species – Only use in the no thinning control plots since all other tagged trees are western larch. Codes are as shown below:

1. western white pine       6. western red cedar
2. western larch            7. lodgepole pine
4. grand fir                9. subalpine fir
5. western hemlock          0. ponderosa pine

Supplement 2: Carbon pool field data collection protocols:
Live-tree C will be estimated using stem volumes and crown volumes calculated from the tree measurements so no additional field measurements are required. The other C pools (CWD, snags, FWD, forest floor, small shrubs, and large shrubs) will be measure using the methods listed below.

To clarify terms:
- “Treatment plot” will always indicate the 20 m x 20 m plots within which all trees are tagged
- “Quadrat” will always refer to the smaller subsample plots.

Supplement 2a: Coarse woody debris procedures:
CWD will be defined as any piece of dead wood on the forest floor having a minimum diameter of 7.6 cm (3 inches). CWD will be sampled using the fixed area plot methodology described in Harmon and Sexton 1996, where the 20m x20m treatment plot from the larch spacing study is the fixed area. All CWD in each plot will be measured down to 7.6 cm, below that it will be sampled in the FWD protocols. Logs which start larger than 7.6 cm but taper down to < 7.6 cm will stop being counted as CWD when their diameter is less than 7.6 cm, so as not to double count the < 7.6 size class (figure 12).
Figure 12. The dotted lines indicate the locations of CWD field measurements.

CWD Field Methods:

1. Wrap a 100 m fiberglass measuring tape around the four corner angle irons of the treatment plot to clearly delineate the perimeter of the plot. Only measure the portion of the logs that are within the plot perimeter (figure 12).
2. Use a fuel gauge (go-no-go gauge) or calipers set at 7.6 cm to determine if each piece of woody debris fits in the CWD category.
3. If the log is larger than 7.6 cm its entire length: measure the length, then take 2 diameters (one parallel to the ground surface and the other perpendicular to the ground surface) at each end of the log and two diameters in the middle. Only measure the portion of the log that is in the plot. If the log extends beyond the edge of the plot measure the log as if the edge of the plot was the end of the log. If the log tapers below 7.6 cm, measure the log as if the point it drops below 7.6 cm diameter is the end of the log (figure 12).
4. Record the decay class of the log. Decay classes are described in table 1 below.
5. Record whether the log appears to be legacy CWD, which is defined as wood produced by the pre-harvest old-growth stand (circa 1953). Legacy will generally have a diameter much larger than the trees currently in the stand as well as an advanced decay class. See below for decay class descriptions.
6. Record species if it is identifiable, otherwise western larch will be assumed as the species.
7. Stumps: Stumps will also be sampled as CWD. For each stump record the average height (on the side of the stump, not the uphill or downhill faces), diameter on top (use a diameter tape), diameter at ground surface, decay class, and species (if identifiable).

8. Up-rooted stumps, trunk fragments, and unusual chunks of wood: For pieces of CWD that are not easily measured cylinders of wood try to imagine folding protrusions into gaps and visualize a cylinder of wood, which may be longer or shorter than the actual piece of wood to account for protrusions and gaps. Take the measurements (length and diameters) of the visualized piece of wood.

Table 1: Use these descriptions to determine the decay class of logs in the plot (Modified from Keane et al 2006).

<table>
<thead>
<tr>
<th>Decay class</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>All bark is intact. All but the smallest twigs are present. Old needles probably still present. Hard when kicked.</td>
</tr>
<tr>
<td>2</td>
<td>Some bark is missing, as are many of the smaller branches. No old needles still on branches. Hard when kicked.</td>
</tr>
<tr>
<td>3</td>
<td>Most of the bark is missing, and most of the branches less than 1 inch in diameter also missing. Still hard when kicked.</td>
</tr>
<tr>
<td>4</td>
<td>Looks like a class 3 log but the sapwood is rotten. Sounds hollow when kicked, and you can probably remove wood from the outside with your boot. Pronounced sagging if suspended for even moderate distances.</td>
</tr>
<tr>
<td>5</td>
<td>Entire log is in contact with the ground. Easy to kick apart but most of the piece is above the general level of the adjacent ground. <strong>If the central axis of the piece lies in or below the duff layer then it should not be included in the CWD sampling</strong>, as these pieces act more like duff than wood when burned. These logs will be counted as forest floor.</td>
</tr>
</tbody>
</table>

Supplement 2b: Snags field method:

Standing snags will be recorded on the live-tree data sheet with a vigor class of 4 and a damage code describing the probable cause of death. On the separate snag data sheet the following measurements will be recorded: diameter at breast height, diameter at ground height, diameter at snag top (if broken, if not broken record 0.1”), height, species (unthinned plots only), and decay class. Snag decay class characteristics are described in figure 13 and table 2 below.
Figure 13. Visual representation of snag decay classes. See tables 1 and 2 for associated descriptions.

Table 2. Snag decay class descriptions (reproduced from Keane et al 2006)

<table>
<thead>
<tr>
<th>Snag decay class</th>
<th>Limbs</th>
<th>Top of bole</th>
<th>Bark</th>
<th>Sapwood</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>All present</td>
<td>Pointed</td>
<td>100% remains</td>
<td>Intact</td>
<td>Height intact</td>
</tr>
<tr>
<td>2</td>
<td>Few limbs</td>
<td>May be broken</td>
<td>Some loss, variable</td>
<td>Some decay</td>
<td>Some loss in height</td>
</tr>
<tr>
<td>3</td>
<td>Limb stubs only</td>
<td>Usually broken</td>
<td>Start of sloughing</td>
<td>Some sloughing</td>
<td>Broken top</td>
</tr>
<tr>
<td>4</td>
<td>Few or no limb stubs</td>
<td>Always broken</td>
<td>50% or more loss of bark</td>
<td>Sloughing evident</td>
<td>Always loss in height</td>
</tr>
<tr>
<td>5</td>
<td>No limbs or limb stubs</td>
<td>Broken and usually rotten</td>
<td>&gt;20% bark remaining</td>
<td>Sapwood gone</td>
<td>Decreasing height with rot</td>
</tr>
</tbody>
</table>
Supplement 2c. FWD Field Protocols

Fine woody debris (FWD) is defined as woody material having a maximum diameter < 7.6 cm at the large end. These size classes equate to 1, 10, and 100 hour fuels classes. FWD will be sampled with four 1 m² quadrats randomly located in each 20 x 20m treatment plot (Harmon and Sexton 1996, Harmon et al. 2004, Keane 2012).

Random quadrat location selection will be done by dividing the treatment plot into 20 blocks 1 m in length on the uphill edge (running with the contour) and 20 blocks 1 m in length on the side of the plot (running up and down the slope). A sheet with 4 sets of 2 random distances per plot (one x and one y coordinate), between 0 and 19, will be provided. Starting at the uphill right (as viewed looking uphill through the plot) corner marker, walk x meters across the plot and y meters down the plot (figure 14). The sampler will be in the upper right corner of where the quadrat should be placed (figure 14). Distances can be measured or paced.

Figure 14. A visual representation of how to locate a random FWD sampling quadrat. The example x and y coordinates are 10 m and 12 m respectively. Place the 1 m² quadrat (red box in the image above) downhill and to the left of the random point.

Four 1 m² samples will be taken per treatment plot. Locate the four, 1 m² quadrats to sample FWD using the provided random plot location protocol described above. Set out a 1 m² quadrat frame so the edges are parallel to the edges of the treatment plot. Collect all FWD within the quadrat. Break or cut (with loppers or saw) the sticks at the inside edge of the quadrat. Cut the pieces to a small enough size that they can to fit into the sample bag. Bag all size classes in paper shopping bags (use plastic construction grade trash bags if it is raining). Label the bags with the following information: sample type (FWD), plot code, sample number (1-4), bag # of #, and date.
collected. Put the same information on a write-in-the-rain tag and place in the bag. Take the samples back to the laboratory for analysis.

Supplement 2d: Forest floor: litter, duff, and soil wood field methods

Three samples will be taken per plot. Using the first three out of four FWD 1 m\(^2\) quadrats, measure the depth of the forest floor by inserting a metal ruler down to the mineral soil at the four corners of the FWD quadrats and at the center. Record the depth to 0.1 cm. Take a sample of the forest floor by placing a 30 cm diameter metal ring in the center of the quadrat, remove the herbaceous vegetation with hand pruners or loppers, then use a soil knife to cut along the inside edge of the ring. Remove all of the organic material down to the mineral soil, including litter, duff, and highly decomposed wood (soil wood). Bag the sample then label it with the following information: sample type (FF), plot code, sample number (1-4), bag # of #, and date collected. Put the same information on a write-in-the-rain tag and place in the bag. Take the samples back to the laboratory for analysis.

Supplement 2e: Small understory plant field methods: woody shrubs <2.54 cm diameter at root collar (DRC), saplings, & herbs

Three 1 m\(^2\) quadrats will be randomly located in the buffer zone just outside of the 20m x 20m treatment plots using the random quadrat location sheets provided. The procedure of finding the random plots will be similar to that of the FWD quadrats with two exceptions: (1) the x distance will follow along the edge of the treatment plot and the y distance will travel away from the plot into the buffer zone, and (2) the first sample will occur along the top edge of the treatment plot, the second sample will occur along the left edge of the treatment plot, and the third sample along the bottom edge of the treatment plot. All material will be harvested within 9 m of the treatment plot edge. Do not harvest shrubs and herbs within the treatment plots. Clip and bag all woody shrubs < 2.54 cm DRC and all saplings in the vertical space above the 1 m\(^2\) quadrat. This means cut and bag only the portion of a plant that crosses within the vertical planes above the quadrat, which may mean only a portion of an individual plant is harvested. Bag the sample in a plastic construction grade trash bag, tape the top shut with masking tape, then label the tape with the following information: sample type (shrubs), plot code, sample number (1-4), bag # of #, and date collected. Put the same information on a write-in-the-rain tag and place in the bag. Take the samples back to the laboratory for analysis.

Shrubs ≥ 2.54 cm will be measured with the protocols described below. In the downhill right corner of the 1 m\(^2\) quadrat (0.25 m\(^2\)) all non-woody vegetation (herbs, forbs, and graminoids) in the vertical space above the quarter quadrat will be clipped and bagged for laboratory analysis. Bag the sample in a plastic Zip-lock bag then label it with the following information: sample type (herbs), plot code, sample number (1-4), bag # of #, and date collected. Put the same information on a write-in-the-rain tag and place in the bag. Take the samples back to the laboratory for analysis.

Supplement 2f. Large understory/mid-story plant field methods: woody shrubs ≥2.54 cm diameter at root collar (DRC)
To sample the biomass of large woody shrubs in a treatment plot wrap cloth tapes around the metal plot corner markers, as done to sample CWD, to clearly define the treatment plot boundaries. Several attributes will be recorded for each individual shrub stem ≥ 2.54 cm DRC. These attributes differ by species. If the shrub is a paper birch (*Betula papyrifera*) record the following: species, status (live or dead), DBH, total height, and decay class (only if it is dead). For any other species record the following: species, status (live or dead), DRC, and decay class (only if it is dead.)

**Supplement 3: Laboratory methods**

**Supplement 3a: FWD Sorting Protocols**

FWD sorting will be done in the Forest Ecology lab (Clapp 432). Sort one replicate at a time. Before sorting the contents of individual bags make sure that all of the samples from a replicate are accounted for. Completely sort all samples from a replicate before taking them to the fire lab to be dried.

**Sort one sample from a plot at a time. Do not mix all samples from one plot or site. In other words, sort the FWD from only one paper bag on the table at a time!!!).**

1. Label the bags that the woody debris is going to be sorted into. The information to include is:
   - FWD
   - Four digit plot code (ex. 1213)
   - Sample # (1,2,3,4)
   - Fuel class (1 hour, 10 hour, 100 hour)
   - Bag 1 of __

2. Dump bag of FWD pieces onto clean table.
   - Leave forest floor, duff and litter samples (contained in plastic zip lock bags) inside original paper bag.

3. Using fuel gauges, divide FWD pieces into groups by time lag class of 1, 10 or 100 hour fuels.
   Time lag class breaks are as follows:

   **1 hour:** <1 cm (<0.25 inches)

   **10 hour:** 1 - 2.5 cm (0.25-1.0 inches)

   **100 hour:** 2.5 – 7.6 cm (1-3 inches)

   **1000 hour:** >7.6 cm (> 3 inches)
• 1000 hour fuels should not have been collected, so remove any of this size woody debris from the sample.
• If a piece of fuel tappers from one time lag class to another, break piece and separate into appropriate category.
• Treat lichen and other matter attached to piece as a part of FWD piece, do not remove.

4. Place FWD into bags by time lag class.
• Dispose of any non-FWD material (i.e. deciduous leaves, forest floor, loose bark).  Non-FWD is captured in other protocols.

5. Label paper bag with plot code, sample number and time lag class (1, 10 or 100 hour).
• If sample does not contain a size class, make note on label (i.e. no 100 hour fuels).

6. Shelve bags. Organize by site using plot code.

7. Clean table of debris from bag before moving on to the next sample.

**Drying procedures and schedule**

**Goal:** The goal of drying the FWD samples is to get total dry mass. This is more ideal than non-dried (wet) mass as moisture content is highly variable, especially in larger time lag classes.

We will use a sub-sampling protocol to establish an average moisture content for each time lag class and each site (Coram1, Coram 2, Cottonwood, and Pinkham). This will allow us to systematically establish moisture content for all samples from a single replicate and single time lag class. The sub sample that we will dry is all time lag classes of sample # 1 and all 100 hour fuels for samples #1 to #4.

**Sub-sampling protocols:**

Replicate:  
Cottonwood Creek

Treatment Plots:  
1113, 1213, 1313, 2113, 2213, 2313, 3113, 3213, 3313, unthinned

Sample #:  
# 1  # 2  # 3  # 4
Fuel class: 1 HR 10 HR 100 HR

Figure 1. All of the different layers of a sample and the term associated with each layer.
1. Sort all of the samples from a replicate as described above.
2. For one replicate take all time lag classes for sample # 1 and all 100 hour fuels for all sample numbers to the Fire Lab. Transport them in labeled paper bags.
3. Dry all FWD samples in the oven at 105°C.
4. Once at the fire lab, bring in all samples from the 1 hour fuel class.
5. Weigh each sample before drying. Tare the scale with an empty aluminum metal baking tray. Put the sample into the tray and weigh the sample. Record the wet (pre-dried) biomass in grams. This will give us a pre-dried weight to establish the average moisture content.
6. Weigh all of the samples and put them into the oven by time lag class, 1 hour fuels with 1 hour fuels.
7. Allow the sample to dry to a constant mass. This will require returning to the fire lab several times to reweigh and record the weights of the samples to make sure the samples are not continuing to lose weight, which would indicate that they are still losing moisture. Once they have stopped losing weight, two consecutive measurements are nearly identical, they are completely dry. 1 hour fuels should obviously take much less time to dry than 100 hour fuels.
8. Take dry samples out of the oven and weigh them immediately. Record the dry biomass in grams.
9. Calculate the moisture content as a proportion with the following equation:

\[
\text{moisture content proportion} = \frac{\text{wet mass} - \text{dry mass}}{\text{dry mass}}
\]
10. Average the moisture content by time lag class and replicate.
11. Repeat this procedure for each size class in from each replicate.

**Applying average moisture contents to non-dried samples to calculate dry mass:**
1. Due to the fact that FWD samples have equilibrated to indoor ambient humidity for at least 3 months following field collection not all samples will be oven-dried.

2. Weight all of the un-dried samples (samples 2-4 for 1 and 10 hour time lag classes) in metal trays and record the weight.

3. The dry mass for un-dried samples (samples 2-4 for 1 and 10 hour time lag classes) will be calculated by multiplying the wet (un-dried) mass of the sample by one minus the average moisture content proportion for the associated time lag class and replicate. Use the following equation:

\[
\text{dry mass} = \text{wet mass} \times (1 - \text{moisture content proportion})
\]

4. If unusually damp samples are discovered while getting the un-dried weights these samples should be dried using the previously discussed protocols.

**Supplement 3b: Forest Floor sample processing protocols**

The objective of the forest floor sample processing protocols is to capture the dry mass of the samples as well as what proportion of the sample is composed of carbon (C). There is no sorting phase as all parts of the forest floor will be dried together. All 3 samples from each treatment plot must be dried (not sub-sampling like the FWD protocol), as moisture content is likely to be highly variable due to differing amounts of soil wood in each sample and because a subsample of all samples will be ground and tested for C content with a LECO TruSpec CN analyzer. Soil wood (mostly highly decayed coarse woody debris (CWD) past definition of decay class 5) will be measured together with the rest of the forest floor (needles and duff) due to the difficulty in separating the two pools in the field.

**Drying protocols**

Process one replicate at a time!

1. Label a paper tag to be put in the tray the forest floor will be dried in. The information to include is:
   a. Forest floor
   b. Four digit plot code (ex. 1213)
   c. Sample # (1,2,3)
   d. Tray 1 of __
2. Dump bag into tray.
   a. Many of the forest floor samples will be large so it is likely that they will fill multiple trays.
b. Include the paper tag which describes the sample. Make sure there is a tag in each tray.
c. Remove any non-forest floor material such as live herbs. It is likely that there will be small fine woody debris (FWD) embedded in the forest floor sample. DO NOT remove FWD from the sample. If it is imbedded in the forest floor it should be counted as part of that pool.
d. Soil wood (highly decayed woody debris past definition of decay class 5) will be included in the forest floor samples due to difficulty separating the two pools in the field.

3. Weigh each sample before drying. Tare the scale with an empty aluminum baking tray. Put the sample tray onto the scale and weigh the sample. Record the pre-dried biomass in grams. This will give us a pre-dried weight to establish average moisture content or check for irregularities.

4. Clean table of debris before moving to the next sample.

5. Weigh all of the samples and put them into the oven.

6. Dry forest floor at 60°C.

7. Allow the samples to dry to a constant mass. This will require returning to the fire lab several times to reweight and record the weights of the samples to make sure the samples are not continuing to lose weight, which would indicate that they are still losing moisture. Once they have stopped losing weight (i.e. two consecutive measurements are nearly identical) they are completely dry.

8. Take dry samples out of the oven and weigh them immediately. Record the dry biomass in grams with 2 significant digits (0.01g).

9. Repeat this procedure for each replicate.

**Grinding the forest floor samples:**

In order to calculate the C content of the forest floor C pool the sample needs to be ground to a fine powder. Only a small amount of the ground sample will actually be analyzed (between 0.1500 g and 0.1599 g) but grind at least 5 g so that additional samples can be made if some of the ground material is lost. There are many ways to grind the sample, Wiley mills are commonly used but can be labor intensive to clean between samples. Three easier and faster methods that accomplish the same results will be used: (1) grinding the sample in a coffee grinder, (2) pulverizing the sample inside a 20 mL scintillation vial full of 1/4” - 3/8” ball bearings shaken by a paint shaker, and (3) pulverizing the sample inside a 20 mL scintillation vial full of 1/4” - 3/8” ball bearings.
shaken by a reciprocating saw (saws-all). The sample should be pulverized enough that it resembles refined white flour, or at least corn meal.

**Coffee Grinder**

5. Pour the forest floor sample onto the lab table.
6. Homogenize the material by hand; breaking up the soil wood and mixing with the needles and duff until a relatively homogenous mixture is achieved.
7. As you homogenize the sample remove any rocks that you find. Set the rocks aside and weigh them. Subtract this weight from the dry weight of the sample as rocks are not part of the forest floor C pool.

8. If the sample is small enough (about a fist full; not common), put the entire sample into the coffee grinder. If the sample is not small enough, a representative sub sample will have to be randomly selected. There are many ways of doing this. A common method (described by Joanna Tirocke of RMRS, Moscow) is as follows:
   a. Divide the sample into four equal piles.
   b. Randomly select one of the piles by looking at the second hand of a watch and choosing the pile in the quadrant the second had is pointing to.
   c. If it is small enough grind it all. If not divide it into four equal piles and select the pile to using the previous method.
   d. Continue these steps until the entirety of the sub sample can be ground.
   e. Note: other methods besides the direction of the second hand can be used to make a random selection.

9. Run the coffee grinder until the sample is completely pulverized. Commonly the litter, duff, and highly decomposed soil wood will be pulverized but the harder portions of the soil wood may not be. If the coffee grinder cannot get the entire sample pulverized the paint shaker and/or the reciprocating saw methods will have to be used.

10. Fill a 20 mL scintillation vial ~1/2 full with a representative portion of the ground sample (regardless of whether it is fully pulverized or not). Pour the remainder of the ground sample into a paper coin envelope or a zip lock bag. The coin envelope avoids the static electricity problems associated with zip lock bags and may be useful if the sample is small in size.

11. Label the scintillation vial and zip-lock bag containing the extra ground sample with the carbon analysis code (a combination of the plot code, sample number, and the type of sample in this case herbaceous material). A sample C analysis code may look like this: 2213#1F. This indicates that it is from plot 2213, is sample #1, and is a forest floor (F) sample. Scintillation vials should be labeled
with a fine tipped sharpie on the lid as well as with a label on the side. Cover the label with clear packing tape so the code is not accidentally rubbed off.

12. If the sample was completely pulverized put the scintillation vial into the tray of samples to be C analyzed. If it is not pulverized continue to the paint shaker step described below.

13. Clean the coffee grinder and lid with Kim wipes and ethanol between samples.

**Paint Shaker**

1. Open the scintillation vial containing the partially pulverized sample and place 5-10, 1/4” - 3/8” steel ball bearings into the vial.
2. Tighten the lid on snugly and tape it in place.
3. Repeat this process with all partially pulverized samples.
4. Fill a clean, 1 gallon paint can with all of the samples to be ground. Then tightly pack the remainder of the paint can with empty scintillation vials and vial lids. The goal is to pack it so tight that when you start shaking the can in the paint shaker only the ball bearings inside the vials will move and not the vials themselves. The vials should not move at all within the paint can.
5. Pound the lid onto the paint can with a rubber mallet, then mount the paint can into the paint shaker.
6. Allow the paint shaker to run for 4-24 hours. Check a sample every 4 hours. Repack the can with more empty vials as needed.
7. Shake until all samples are pulverized.
8. Check all samples as they are removed from the can. If there are any samples that were not completely pulverized they will have to be completely pulverized using the reciprocating saw procedures described below.
9. Place pulverized samples in the tray to be analyzed.
10. Remove the lid of each scintillation vial and insert a magnet to pull out the ball bearings. Clean the magnet with Kim wipes and ethanol between samples.

**Reciprocating Saw (Saws-all)**

1. This is the final step on how to pulverize a sample. Most samples should be finely pulverized by now.
2. Make sure the vial has 5-10, 1/4” - 3/8” steel ball bearings inside it.
3. Tighten the lid of the sample very tightly and tape it down with clear masking tape or black electric tape. **Shaking the vials with a reciprocating saw can cause the lid of a scintillation vial to shake off or break! You must check the lid of the vial frequently while using this method.**
4. Tape one scintillation vial to the blade of a reciprocating saw.
5. Mount the blade in the saw. Cover the cutting portion of the blade with tape to reduce the risk of being cut.

6. Put on ear plugs and gloves.

7. Start the saw. This will cause the ball bearings to shake back and forth violently in the scintillation vial. Samples should take about one minute to be completely pulverized. Play with how fast the saw is moving back and forth. The faster it goes the faster the sample will be pulverized but the higher the likelihood that the lid will crack or come off. Be particularly cautious with samples that are small in size, where you cannot afford to lose any of the sample.

8. Remove the vial from the saw blade and check to see if the sample is pulverized. Continue to shake on the saw as needed. If this method does not work then the sample will have to be ground on a Wiley mill.

9. When the sample is pulverized remove the lid and insert a magnet to pull out the ball bearings. Clean the magnet with Kim wipes and ethanol between samples.

10. Place pulverized samples in the tray to be analyzed.

**LecoTruSpec CN analyzer**

These procedures are from Joanne Tirocke at the USFS Rocky Mountain Research Lab, Moscow Forest Sciences Lab.

**TruSpec CN Sample Prep School**

The carbon/nitrogen analyzer determines the total carbon and nitrogen in a sample by burning it, collecting the resulting gasses and analyzing them. The final percentages of carbon and nitrogen are based on the reported weight of the sample, so it is very important to properly prepare the samples. This document will help you to correctly weigh samples for analysis with the TruSpec analyzer.

We distinguish between two kinds of samples – organic and mineral. Each runs with a different burn profile to optimize combustion, requires a specific sample weight and special reference standard (Table 1).

**Table 1.** Differences in sample type, size, and standards.

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Sample Weight (g)</th>
<th>Calibration Standard</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Organic (FF, wood, etc.)</td>
<td>0.1500 – 0.1599</td>
<td>EDTA</td>
<td>Pine Needles (1575a)</td>
</tr>
<tr>
<td>Mineral (soil, sediment, etc.)</td>
<td>0.2000 – 0.2099</td>
<td>EDTA</td>
<td>Soil Reference</td>
</tr>
</tbody>
</table>
Procedure for preparing samples for analysis

1. If sample id codes are more than 8 characters long check with the lab manager for alternate sample ids which will require less typing by the analyst running the samples.

2. Know which sample type (organic or mineral) you will be working with. Do not mix sample types within a run (plate/box).

3. Gather materials: CN Analysis sheet, pencil, spatulas, forceps, samples, standards, foils, and a plate/box to organize and store your samples. Fill out the top left portion (date, initials, sample description) of the Analysis Worksheet (see attached).

4. A sample plate contains 48 wells for samples and standards, labeled alphabetically for rows and numerically for columns. The letter-number codes are the coordinates for the cells (e.g. A1, B5, E6). There are 6-7 labeled plates (Box 1, Box 2, etc.). Please note which plate you are filling on your Analysis sheet (Plate ID) and orient the plate correctly so your first Pine Ref goes in A2.

5. Turn on the scale (0/1). At the back right rear corner of the balance is a level. Make sure the bubble is centered within the middle circle. If you need assistance adjusting the balance, ask for help.

6. Things to remember before you start:

   Sample weight is very important, so make sure the sample is in the foil and not on the balance pan. Ensure that the balance pan is clean before taring a new foil and before the final weighing of the wrapped sample. If the pan has any material on it, the recorded weight is no longer correct but is still used in the calculation of the reported C and N values, thus creating an erroneous result.

7. Foils are pre-shaped and are easily misshapened when dropped or handled. Empty foils are best moved with forceps. Place an empty foil on the scale, close the door, and tare it (T). Foil weight should be about 0.11xx grams. If the weight before taring is 0.2xxx grams or more, then you probably have more than one foil on the balance. Since the instrument is blanked for a single foil, it is important to make sure each sample is only wrapped in one foil, otherwise the results will not be correct.

8. Using a clean spatula, fill the tip with sample from its envelope/container. Open the balance door and incline the spatula above the foil, allowing the sample to slide into the foil. Check the weight and add or remove sample so that the weight falls within the designated range for that sample type.
9. Carefully remove the filled foil from the balance and hold it with the fingertips of one hand. Use the other hand to gently fold the foil together at the top and to lightly wind the sample while the bottom hand is lightly compressing the sample in the foil. The objective is to remove as much air as possible from the foil, retain as much sample as possible, and to form a teardrop shaped sample that doesn’t leak. If you twist/wind the foil too much, it will split and the sample should be remade with a new foil (it is okay to use whatever sample is still in the first foil).

10. Return the wrapped sample to the balance, close the door, and allow the reading to stabilize (usually just a couple of seconds). Record the sample id and weight on the Analysis worksheet.

11. Place the wrapped sample into the corresponding well on the plate.

12. The first two spaces on the Analysis sheet are pre-labeled. Leave all the spaces labeled EDTA blank. EDTAs will be weighed out on the day of analysis.

13. Weigh out the reference standard specific to your sample type (pine needles or soil reference), circling the correct one on the analysis sheet, and recording its weight. You will need 3 of these per run (cells A2, C7, and F7).

14. Line 17 on the worksheet indicates I Rep. This stands for Inside Replicate and serves as a quality control measure for the run. You will weigh out two foils containing this sample. Place the second finished foil somewhere in the second column (any position 26-47, except 30). Record the sample id and weights in the appropriate spaces.

15. Line 30 indicates O. Rep. This stands for Outside Replicate and checks the analyzer’s precision between sample days. For a large sample set (>41 samples), you will repeat a sample here that would be weighed out in the next sample plate. Record sample id and weight. Leave the last O. Rep of the last plate in a set blank to be filled in by the analyst.

16. Weigh out the rest your samples and record their weights. If you encounter two samples with the same sample id, check with the lab supervisor to see how to proceed.

**Supplement 3c: Herb sample processing protocols**

The objective of the herb sample processing protocols is to capture the dry mass of the samples as well as what proportion of the sample is composed of carbon (C). There is no sorting phase as all parts of the herb sample will be dried together. All 3 samples from each treatment plot must be dried (not sub-sampling like the FWD
protocol), as moisture content is likely to be highly variable due to differing herb composition in each sample and because a subsample of all samples will be ground and tested for C content with a LECO TruSpec CN analyzer. The procedures for the LECO TruSpec CN analyzer are the same as listed in the forest floor carbon analyzing section above so they will not be listed here.

Drying protocols

Process one replicate at a time!

1. Label a paper tag to be put in the tray the herb sample will be dried in. The information to include is:
   a. Herb
   b. Four digit plot code (ex. 1213)
   c. Sample # (1,2,3)
   d. Tray 1 of __

2. Dump bag into tray.
   a. Remove any non-herb material such as fine woody debris (FWD).
   b. Include the paper tag which describes the sample.

3. Weigh each sample before drying. Tare the scale with an empty aluminum baking tray. Put the sample tray onto the scale and weigh the sample. Record the pre-dried biomass in grams. This will give us a pre-dried weight to establish average moisture content or check for irregularities.

4. Clean table of debris before moving to the next sample.

5. Weigh all of the samples and put them into the oven.

6. Dry herb at 60°C.

7. Allow the samples to dry to a constant mass. This will require returning to the fire lab several times to reweight and record the weights of the samples to make sure the samples are not continuing to lose weight, which would indicate that they are still losing moisture. Once they have stopped losing weight (i.e. two consecutive measurements are nearly identical) they are completely dry.

8. Take dry samples out of the oven and weigh them immediately. Record the dry biomass in grams with 2 significant digits (0.01g).

9. Repeat this procedure for each replicate.
Grinding the herb samples:

In order to calculate the C content of the herb C pool the sample needs to be ground to a fine powder. Only a small amount of the ground sample will actually be analyzed (between 0.1500 g and 0.1599 g) but grind at least 5 g so that additional samples can be made if some of the ground material is lost. There are many ways to grind the sample, Wiley mills are commonly used but can be labor intensive to clean between samples. Three easier and faster methods that accomplish the same results will be used: (1) grinding the sample in a coffee grinder, (2) pulverizing the sample inside a 20 mL scintillation vial full of 1/4” - 3/8” ball bearings shaken by a paint shaker, and (3) pulverizing the sample inside a 20 mL scintillation vial full of 1/4” - 3/8” ball bearings shaken by a reciprocating saw (saws-all). The sample should be pulverized enough that it resembles refined white flour, or at least corn meal.

Coffee Grinder

1. Pour the herb sample onto the lab table.
2. Homogenize the material by hand; breaking up the leaves and stems until a relatively homogenous mixture is achieved.
3. As you homogenize the sample remove any rocks or FWD that you find. Set the rocks or FWD aside and weigh them. Subtract this weight from the dry weight of the sample as rocks and FWD are not part of the herb C pool.
4. If the sample is small enough (about a fist full), put the entire sample into the coffee grinder. If the sample is not small enough, a representative sub sample will have to be randomly selected. There are many ways of doing this. A common method (described by Joanna Tirocke of RMRS, Moscow) is as follows:
   a. Divide the sample into four equal piles.
   b. Randomly select one of the piles by looking at the second hand of a watch and choosing the pile in the quadrant the second hand is pointing to.
   c. If it is small enough grind it all. If not divide it into four equal piles and select the pile to using the previous method.
   d. Continue these steps until the entirety of the sub sample can be ground.
   e. Note: other methods besides the direction of the second hand can be used to make a random selection.
5. Run the coffee grinder until the sample is completely pulverized. Commonly the leaves will be pulverized but the harder portions of the stem may not be. If the coffee grinder cannot get the entire sample pulverized the paint shaker and/or the reciprocating saw methods will have to be used.
6. Fill a 20 mL scintillation vial ~1/2 full with a representative portion of the ground sample (regardless of whether it is fully pulverized or not). Pour the remainder of the ground sample into a paper coin envelope or a zip lock bag. The coin envelope avoids the static electricity problems associated with zip lock bags and may be useful if the sample is small in size.

7. Label the scintillation vial and zip-lock bag containing the extra ground sample with the carbon analysis code (a combination of the plot code, sample number, and the type of sample in this case herbaceous material). A sample C analysis code may look like this: 2213#1H. This indicates that it is from plot 2213, is sample #1, and is an herb (H) sample. Scintillation vials should be labeled with a fine tipped sharpie on the lid as well as with a label on the side. Cover the label with clear packing tape so the code is not accidentally rubbed off.

8. If the sample was completely pulverized put the scintillation vial into the tray of samples to be C analyzed. If it is not pulverized continue to the paint shaker step described below.

9. Clean the coffee grinder and lid with Kim wipes and ethanol between samples.

**Paint Shaker**

1. Open the scintillation vial containing the partially pulverized sample and place 5-10, 1/4” - 3/8” steel ball bearings into the vial.
2. Tighten the lid on snugly and tape it in place.
3. Repeat this process with all partially pulverized samples.
4. Fill a clean, 1 gallon paint can with all of the samples to be ground. Then **tightly** pack the remainder of the paint can with empty scintillation vials and vial lids. The goal is to pack it so tight that when you start shaking the can in the paint shaker only the ball bearings inside the vials will move and not the vials themselves. The vials should not move at all within the paint can.
5. Pound the lid onto the paint can with a rubber mallet, then mount the paint can into the paint shaker.
6. Allow the paint shaker to run for 4-24 hours. Check a sample every 4 hours. Repack the can with more empty vials as needed.
7. Shake until all samples are pulverized.
8. Check all samples as they are removed from the can. If there are any samples that were not completely pulverized they will have to be completely pulverized using the reciprocating saw procedures described below.
9. Place pulverized samples in the tray to be analyzed.
10. Remove the lid of each scintillation vial and insert a magnet to pull out the ball bearings. Clean the magnet with Kim wipes and ethanol between samples.

**Reciprocating Saw (Saws-all)**
1. This is the final step on how to pulverize a sample. Most samples should be finely pulverized by now.
2. Make sure the vial has 5-10, 1/4” - 3/8” steel ball bearings inside it.
3. Tighten the lid of the sample very tightly and tape it down with clear masking tape or black electric tape. **Shaking the vials with a reciprocating saw can cause the lid of a scintillation vial to shake off or break! You must check the lid of the vial frequently while using this method.**
4. Tape one scintillation vial to the blade of a reciprocating saw.
5. Mount the blade in the saw. Cover the cutting portion of the blade with tape to reduce the risk of being cut.
6. Put on ear plugs and gloves.
7. Start the saw. This will cause the ball bearings to shake back and forth violently in the scintillation vial. Samples should take about one minute to be completely pulverized. Play with how fast the saw is moving back and forth. The faster it goes the faster the sample will be pulverized but the higher the likelihood that the lid will crack of come off. Be particularly cautious with samples that are small in size, where you cannot afford to lose any of the sample.
8. Remove the vial from the saw blade and check to see if the sample is pulverized. Continue to shake on the saw as needed. If this method does not work then the sample will have to be ground on a Wiley mill.
9. When the sample is pulverized remove the lid and insert a magnet to pull out the ball bearings. Clean the magnet with Kim wipes and ethanol between samples.
10. Place pulverized samples in the tray to be analyzed.

**LecoTruSpec CN analyzer**

The procedures for the LECO TruSpec CN analyzer are the same as listed in the forest floor carbon analyzing section above so they will not be listed here. See procedures listed above for herb C content analysis.

**Supplement 3d: Shrubs sample processing protocols**

The objective of the shrubs sample processing protocols is to capture the dry mass of the samples. Similar to the FWD processing protocols there will be a sorting phase, where leaves will be separated from woody stems, and a drying phase. To cut down on the labor and because the samples have been equilibrating in an indoor space for at least 3 month, a sub sample of the 3 samples per plot will be dried (all sample # 1 from each treatment plot).
Sub-sampling protocols:

Sub-sampling protocols:
Replicate: Cottonwood Creek

Treatment Plots: 1113, 1213, 1313, 2113, 2213, 2313, 3113, 3213, 3313, unthinned

Sample #: # 1 # 2 # 3

Shrub component: Wood Leaves

Figure 1. All of the different layers of a shrub sample and the term associated with each layer.

Sorting and drying protocols

Process one replicate at a time. Sorting of the leaves from the woody material will be done at the fire lab just before drying. Sort one sample at a time. Before sorting the contents of individual bags make sure that all of the samples from a replicate are accounted for.

Sort one sample from a plot at a time. Do not mix all samples from one plot or site. In other words, sort the shrubs from only one bag on the table at a time!!.

1. Label the trays that the shrubs going to be sorted into. The information to include is:
   a. Wood or leaves
   b. Four digit plot code (ex. 1213)
   c. Sample # (1,2,3)
   d. Tray 1 of __
2. Dump bag onto clean table.
a. Separate leaves from the woody material and place in the separate labeled trays. Cut the woody material with loppers or hand pruners so that the material fits in the tray.

b. Remove any non-shrub material such as FWD or herbs. These carbon pools are captured in other protocols.

3. Clean table of debris from bag before moving to the next sample.

4. Dry woody portion of shrub samples in the oven at 105°C and the leaf portion at 60°C.

5. Weigh each sample before drying. Tare the scale with an empty aluminum metal baking tray. Put the sample into the tray and weigh the sample. Record the pre-dried biomass in grams. This will give us a pre-dried weight to establish the average moisture content to apply to the un-dried portion of the samples.

6. Weigh all of the samples and put them into the oven by shrub component, wood with wood and leaves with leaves.

7. Allow the samples to dry to a constant mass. This will require returning to the fire lab several times to reweight and record the weights of the samples to make sure the samples are not continuing to lose weight, which would indicate that they are still losing moisture. Once they have stopped losing weight, two consecutive measurements are nearly identical, they are completely dry. Leaves should obviously take much less time to dry than the woody portions of the shrub.

8. Take dry samples out of the oven and weigh them immediately. Record the dry biomass in grams.

9. Calculate the moisture content as a proportion with the following equation:

\[
\text{moisture content proportion} = \frac{\text{wet mass} - \text{dry mass}}{\text{dry mass}}
\]

10. Average the moisture content by shrub component and replicate.

11. Repeat this procedure for each replicate.
Applying average moisture contents to non-dried samples to calculate dry mass:

1. Due to the fact that shrub samples have equilibrated to indoor ambient humidity for at least 3 months following field collection not all samples will be oven-dried.
2. Sort the undried sample by woody and leaf component and weight all of the undried samples (samples 2 and 3) in metal trays and record the weight.
3. The dry mass for un-dried samples (samples 2 and 3) will be calculated by multiplying the wet (un-dried) mass of the sample by one minus the average moisture content proportion for the associated time lag class and replicate. Use the following equation:

\[
\text{dry mass} = \text{wet mass} \times (1 - \text{moisture content proportion})
\]

4. If unusually damp samples are discovered while getting the un-dried weights these samples should be dried using the previously discussed protocols.

Supplement 4: Carbon percentage tables.

The tables presented below contain the average carbon percentage from three sub-samples per treatment plot. They are included in this document for completeness and to provide values for other studies to use. This is particularly useful because there is a lack of information about carbon percentages of forest floor material and herbaceous plant matter in forest ecology literature.
Table 1. Average carbon percentages of forest floor samples from second-growth western larch forests in northwest Montana at stand age 62.

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<th>Stand density</th>
<th>Number of entries</th>
<th>Replicate&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Percent carbon</th>
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<sup>a</sup>Replicate 1 is Coram 1, replicate 2 is Coram 2, replicate 3 is Cottonwood Lakes, and replicate 4 is Pinkham Creek. See chapter 1, table 1 for site information.

<sup>b</sup>Low carbon percentages may be due to the unintentional inclusion of some mineral soil in the forest floor sample.
Table 2. Average carbon percentages of herbaceous plant samples from second-growth western larch forests in northwest Montana at stand age 62.

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<sup>a</sup>Replicate 1 is Coram 1, replicate 2 is Coram 2, replicate 3 is Cottonwood Lakes, and replicate 4 is Pinkham Creek. See chapter 1, table 1 for site information.