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forest management

Structural and Compositional Responses to Thinning over 50 Years in Moist Forest of the Northern Rocky Mountains

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A thinning study was established in 1967 in moist mixed forests on the Priest River Experimental Forest in northern Idaho, USA. The study design included three thinning intensities: low, moderate, and high intensity (1,976, 988, and 494 trees ha^{-1}). This study examined short-term (11 years) and long-term (50 years) thinning effects on residual stand characteristics, growth, and yield. Since regeneration may occur after thinning, understory change was also addressed. Thinning decreased stand density immediately but improved the growth of residual trees. Shade-tolerant species were favored in all the thinnings and dominated 50 years after thinning. Unthinned stands had higher total and merchantable volume than all thinned stands both 11 years and 50 years post treatment. Regeneration and nontree vegetation richness increased shortly after thinning, whereas nontree vegetation cover decreased sharply 50 years after treatment. The stands developed into multistrata forests with shade-tolerant species in both the overstory and understory. This is contrary to current thinning practice favoring shade-intolerant species, but demonstrates the resilience of moist Northern Rockies forests to partial overstory disturbances. In this study, thinning favoring shade-tolerant species in these mixed forests has a more significant effect on forest structure dynamics than timber production.

Keywords: Priest River Experimental Forests, forest growth and yield, thinning intensity, long-term effects, shade-tolerant species

Thinning removes trees and subsequently changes environmental conditions, which is applied to meet various forest-management objectives. Common objectives include improving timber quality and yields of residual overstory trees (Zeide 2004), lessening the vulnerability to disturbance by reducing ladder fuels to avoid damage from wildfires, increasing tree vigor to curtail beetle infestations (Sorensen et al. 2011, Hood et al. 2016), and promoting resilience to drought (D'Amato et al. 2013). Thinning has also been employed to enhance ecosystem processes, such as decreasing soil respiration at a given temperature (Tang et al. 2005), enhancing surface flux transfer (Vesala et al. 2005), modifying water quantity (Molina and del Campo 2012), or favoring wildlife habitat (Verschuyla et al. 2011, Neill and Puettmann 2013). Depending on the thinning prescription, thinning can adjust the species compositions and potentially diversify forest structure by increasing horizontal and vertical heterogeneity (Franklin et al. 2002, Zenner 2004, Ares et al. 2009, Dodson et al. 2011, Verschuyla et al. 2011).

Globally, numerous studies have examined the effects of thinning on forest growth and yield of residual trees (Cochran and Barrett 1993, Zeide 2001, Pothier 2002, Skovsgaard 2009, Sorg et al. 2016). In general, different spacing treatments affect residual tree size, growth, and merchantable volume (Sullivan et al. 2006, Dodson et al. 2011, Ferguson et al. 2011, Harrington and Devine 2011). In coniferous forests, thinning effects on residual overstory growth have been shown to persist for decades, as observed in Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) stands (Binkley and Reid 1984, Curtis and Marshall 2009) and mixed forests of Douglas-fir and western hemlock (*Tsuga heterophylla* [Raf.] Sarg.) (King et al. 2002) in the Northwestern United States. However, the longevity associated with thinning depends on the initial thinning intensity, stand structure and composition, and site quality

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(Pothier 2002, Pretzsch 2005). Thinning rarely produces greater total biomass when compared to allowing a stand to grow without intervention, but growing space left by thinning decreases the competition and provides more availability of essential resources to grow larger trees over time. However, the difference between thinned and unthinned stands is highly variable and depends on stand age, stand productivity, species composition, thinning intensity, and the type of thinning treatment (Pretzsch 2005).

Although regeneration is not the goal of thinning treatment, canopy gaps created by thinning often stimulate tree seedling establishment and undestory vegetation, because of the changes in the understory environment, available resources, and competition (Tappeiner and Zasada 1993, Sakai et al. 2005, Kuehne and Puettmann 2008). Regeneration of shade-tolerant tree species shortly after thinning was found in temperate forests (Olson et al. 2013), but long-term studies are required to determine whether trees that regenerate survive and grow to larger sizes (Spies and Franklin 1989, Zhu et al. 2003, Zald et al. 2008). The diversity and cover of nontree understory vegetation also change after thinning (Thomas et al. 1999). Even though excessive tree regeneration could reduce understory vegetative diversity and cover (Alaback and Herman 1988, Thomas et al. 1999), past studies have shown that three different types of understory vegetation occur (Ares et al. 2010): (1) decrease in abundance and richness shortly after thinning (Davis and Puettman 2009), (2) increase in abundance and richness (Lindgren et al. 2006), and (3) no significant change (Wilson et al. 2009). In many cases, these are short-term studies, and little information is available on the persistence of patterns through time (Larsen and Nielsen 2007, Ares et al. 2009).

Moist forests of the northern Rocky Mountains can support high conifer species diversity across a wide-range of shade tolerance (Hann et al. 1997). Depending on the overstory species favored with thinning, thinning intensity, and the type of thinning, a wide range of responses are possible. The goal of this study was to investigate the long-term effects from a thinning experiment installed in 1967. At that time, researchers implemented three thinning intensities in a 26-year-old mixed conifer forest located on the Priest River Experimental Forest in northern Idaho. The specific objectives were to: (1) examine forest structure, composition, and growth and yield 11 and 50 years after thinning and (2) examine the temporal changes in tree regeneration and the richness and cover of understory vegetation after thinning in these different thinning intensities.

Materials and Methods

Study Area

The study area is located at the Priest River Experimental Forest (PREF) in moist mixed conifer forests in northern Idaho, USA. PREF can experience both maritime and continental climates and is intermediate between mild climates west of the Cascade Mountains and more extreme conditions east of the Rocky Mountains. The mean monthly temperature ranges from –4.2 to 18.1° C (in January and July), whereas the mean annual precipitation is 798 mm, with 40–60 percent of precipitation occurring as snow (Tinkham et al. 2015). Aeolian loess and volcanic ash constitute the primary materials of soil surface in this area. The loams and fine-textured soils are characterized by high soil moisture and proper soil temperature, which result in high fertility and timber production (McConnell 1965). Forest types within PREF are typical in the northern Rocky Mountains. Common species include grand fir (*Abies grandis* [Douglas ex D. Don] Lindl.), western redcedar (*Thuja plicata* Donn ex D. Don), western hemlock (*Tsuga heterophylla* [Raf.] Sarg.), interior Douglas-fir (*Pseudotsuga menziesii* var. *glauca*), western larch (*Larix occidentalis* Nutt.), and western white pine (*Pinus monticola* Douglas ex D. Don).

Western white pine once dominated these forests since naturally regenerated following fires back to 1860 (Haig et al. 1941, Jurgensen et al. 1997), but the introduction of white pine blister rust (*Cronartium ribicola*) in the early 1900s and the insect outbreaks that peaked in the 1950s significantly reduced the abundance of this species (Fins et al. 2002). Afterwards, the forest was generally dominated by almost pure Doughlas-fir or mixed western larch and Douglas-fir (Wellner 1976). In recently decades, two shade-tolerant species, western redcedar and western hemlock, contributed approximately 50 percent basal area of the forest and gradually dominated the forest, because these two species could easily establish under the canopies (Tinkham et al. 2015).

The thinning study was installed in 1967 within a transect that was a strip clearcut in 1941 and 1942, which went from the north to the south ridge of Benton Creek (Gisborne 1935, Deitschman 1965). The study was implemented across approximately 9 hectares (width = 98 m, length = 927 m) on the north facing aspect of this transect with a mean slope of 33 percent. The central geographic location is 116°47′20″W, 48°20′56″N. Elevation of treatment units ranged from 1,019 to 1,257 m above sea level.

Experimental Design and Treatment History

The study was implemented in 17 plots: seven plots were thinned to 1,976 trees ha^{-1} (low intensity; 2.1–2.4 m mean spacing); seven plots were thinned to 988 trees ha^{-1} (moderate intensity; 3.0–3.4 m mean spacing); and three plots were left as unthinned controls. Each thinned plot was a 0.66-ha rectangle, whereas the controls were approximately 0.42-ha rectangles. The treatment was a thin from below where residual trees had good physical form, good health and vigor, and were generally in the dominant or codominant

Management and Policy Implications

This research examined early thinning effects on overstory and understory growth after 11 years and 50 years in moist forest of northern Rocky Mountains. In contrast to thinning practice favoring shade-intolerant species, this study provided a different perspective on the impact of thinning favoring shade-tolerant species. Although thinning favoring shade-tolerant species under three intensities had minimal effects in increasing stand and merchantable wood yield after 50 years, thinning still had significant effects on growth of residual trees and forest structure. The mixed coniferous forests showed resilience from partial overstory disturbances. Low-intensity thinning could be employed by forest managers or landowners because it produces more large size residual trees without much yield compromise compared to unthinned within 50 years. Moderate and high-intensity thinnings could play significant roles in species composition and structure adjustments regarding to specific management goals. If thinning treatments are introduced by forest managers or landowners in this mixed forest region, species selection should be made considering original species composition, species shade tolerance, and short-term and long-term timber production needs.

crown class. Shade-tolerant species were favored by these thinning treatments. Species were preferentially selected in a decreasing order: western redcedar, grand fir, Douglas-fir, western hemlock, and lastly western larch. Hardwoods were killed with a hypohatchet and Silvisar-510 Tree Killer (active ingredient cacodylic acid) in 1968. In 1970, within each of the seven low-intensity plots, half the area was thinned to 494 trees ha^{-1} (high intensity; 4.3–4.6 m mean spacing), and these seven high-intensity plots were added as the third study intensity using the same guidelines for residual tree selection as in the low- and moderate-intensity treatments.

Stand Inventory

In 1965, a prethinning survey was conducted 2 years before thinning treatments, where the number of trees by species and height class was measured within fourteen 0.54-ha units, each with eight or nine 0.002-ha plots. Trees were tallied by species for five conifer species (western hemlock, western redcedar, grand fir, Douglas-fir, and western larch), whereas all other conifer and hardwood trees were lumped into a single group. Trees were placed into one of four height classes: 0.1–1.5 m, 1.6–3.0 m, 3.1–4.6 m, and >4.6 m.

In 1978 (11 years after thinning), a 0.02-ha sample plot was established in the center of each thinned plot. Measurements included diameter at breast height (dbh; 1.37 m), tree height, crown ratio, and crown class (suppressed, intermediate, codominant, dominant, emergent; detailed description in Keane 2006) for all trees with dbh ≥ 11.5 cm. In addition, six 0.001-ha subplots were installed in each plot to measure understory vegetation, seedlings (dbh ≤ 2.5 cm), and saplings (2.6 cm ≤ dbh ≤ 11.4 cm). Nontree vegetation measurements included cover by individual species and life forms: shrubs, fern, grasses, mosses, and forbs. Dbh and height of seedlings and saplings were measured for two trees per species. Trees selected were those considered most likely to become future crop trees. The remaining trees for each species within 2.5-cm-diameter classes were tallied, and their height was estimated to the nearest 0.3 m by diameter class.

Plot coordinates were not recorded in 1978, and plot corner monuments had disappeared by the time these plots were revisited in 2017 (50 years after thinning). Thus, we installed a 0.04-ha circular plot near the center of each established 1978 thinned plot. We used a larger plot size to account for the change in tree size and number of trees as stand development progressed. Measurements of all trees ≥11.5 cm dbh included species, dbh, and crown class. We randomly selected two trees for each species within the suppressed, intermediate, codominant, and dominant crown classes, and measured tree height and crown length. A 0.004-ha circular subplot was located in the center of the 0.04-ha plot. All trees <11.5 cm dbh were counted and measured as seedlings (dbh ≤ 2.5 cm) and saplings (2.6 cm ≤ dbh ≤ 11.4 cm) by species, and nontree understory vegetation cover by life forms (shrubs, forbs, grass, and fern) were also measured.

Data Analysis

Since the prethinning inventory only counted the number of trees by species and height class, we could only calculate stem density per hectare. We used the data on trees ≥11.5 cm dbh collected 11 and 50 years after thinning to examine the effects of thinning on stand structure, tree species composition, and growth and yield over time. To quantify stand structure, we developed diameter distributions by 11 diameter classes: dbh ≤ 2.5 cm, 2.6 cm ≤ dbh ≤ 11.4 cm, eight 5-cm dbh classes for trees 11.5–51.5 cm, and a final class for trees >51.5 cm. We calculated overstory species composition as the percentage of basal area for a given species within a sample plot. Growth and yield calculation required estimates of the total tree height for all trees. Based on the available measurements of tree heights, unmeasured tree heights were estimated using species-specific height–diameter models in the Inland Empire variant of the Forest Vegetation Simulator (FVS) (Wykoff et al. 1982, FVS 2015). We calculated net stand total volume, net merchantable volume (for trees dbh ≥ 17.8 cm with commercial values, FVS 2015) and sapling volume by species using volume equations for northern Idaho (Woodall et al. 2011). Total aboveground biomass for each thinning intensity, merchantable trees, and saplings was estimated using generalized logarithmic regression equations developed by Jenkins et al. (2003). Mean annual increment of volume or biomass refers to the mean gain per year the stands have experienced from the regeneration year (1942) to a specific age (1978 and 2017 in this study). The periodic annual increment between 1978 and 2017 was calculated via the gain change divided by the number of years in between.

We used a repeated mixed-effects analysis of variance (ANOVA) (Pinheiro and Bates 2000) to quantify the temporal effects of different thinning intensities on stand structure, species composition, and growth and yield. The independent variables were year since thinning and thinning intensity ($\alpha = 0.05$), with plot as a random effect. We used the "nlme" package in R platform (Pinheiro et al. 2017, R Core Team 2017) to conduct the statistical analysis.

Results

Thinning Effects on Stand Structure and Composition

Prior to thinning, the plots were dominated by shade-tolerant western redcedar and western hemlock (39 percent and 33 percent of total stem density, respectively) (Table 1). Moderately

Table 1. Trees per hectare by species and height class in 1965, 2 years prior to thinning: means ± standard error and percentage of total density by species and height class.

Height class	Western hemlock	Western redcedar	Grand fir	Douglas-fir	Western larch	Other	Total	Percentage of total by height class
0.1–1.5 m	749 ± 548	1,168 ± 889	586 ± 1,152	183 ± 252	10 ± 27	49 ± 56	2,745 ± 1,766	27 percent
1.6–3.0 m	1,651 ± 983	1,530 ± 769	605 ± 820	273 ± 334	25 ± 51	48 ± 65	4,132 ± 1,399	42 percent
3.1–4.6 m	792 ± 624	790 ± 455	180 ± 170	86 ± 132	78 ± 66	74 ± 86	2,000 ± 834	20 percent
>4.6 m	102 ± 164	406 ± 334	14 ± 37	60 ± 126	385 ± 412	178 ± 289	1,145 ± 807	11 percent
Species total	3,294 ± 1,768	3,894 ± 1,659	1,385 ± 1,927	602 ± 749	498 ± 408	349 ± 429	10,022 ± 2,421	
Percentage of total by species	33 percent	39 percent	14 percent	6 percent	5 percent	3 percent		

shade-tolerant Douglas-fir accounted for 6 percent of the stem density, whereas shade-intolerant western larch comprised 5 percent of the stem density. The greatest proportion of trees was in the 1.6–3.0 m height class (42 percent), followed by the 0.1–1.6 m height class (27 percent) and the 3.1–4.6 m height class (20 percent). Trees taller than 4.6 m accounted for 11 percent of the total stem density and were primarily western larch.

Eleven Years after Treatment

The total stem density of thinned plots recovered to levels similar to those of the control plots 11 years after thinning (Table 2). All thinning treatments had a lower stem density of trees ≥11.5 cm dbh than the control (Table 2). However, the total basal area in the thinned stands had not recovered to the similar level of the control, suggesting that an influx of seedlings and saplings contributed to their higher tree densities in the thinned stands 11 years after treatment. The mean dbh of trees ≥11.5 cm increased 11 years after thinning, where the mean dbh ranged from 16.2 cm in the control to 17.9 cm in the moderate-intensity treatment (Table 3). Including trees of the new regenerated layer, the mean tree heights in the thinning treatments (6.2–6.5 m) were lower than that in the control (8.8 m) 11 years post thinning. This significant disparity may also result from thinning preference against western larch, which had the greatest pretreatment density in the >4.6 m class.

Thinning treatments also influenced the crown class and diameter distributions. The control treatments had high densities of dominant and codominant trees, with a few intermediate trees, and no suppressed trees (Figure 1). Comparatively, the low-intensity and moderate-intensity treatments favored codominant trees, likely because thinning favored western redcedar and grand fir that dominated the smaller height classes prior to thinning. Dominant and codominant trees dominated the high-intensity treatments with 209 and 174 trees ha^{-1}. All treatments showed a reverse-J diameter distribution 11 years after treatment (Figure 2). The high density of smaller stems in the thinning treatments was mainly contributed by the regeneration layer, especially shade-tolerant tree species. Compared to other treatments, the high-intensity treatment had the lowest proportion of trees from the diameter classes larger than 11.5 cm.

Western hemlock and western redcedar comprised a high proportion of the basal area 11 years after treatment across all unthinned and thinned stands (Figure 3). In addition, the composition in the high-intensity treatment was the most similar to the unthinned control, where western larch occupied ~20 percent and ~33 percent separately, whereas Douglas-fir occupied ~14 percent in the unthinned control and ~6 percent in the high-intensity treatment. In contrast, the low- and moderate-intensity treatments had very small components of western larch and Douglas-fir, besides the dominated western hemlock, western redcedar, and grand fir.

Fifty Years after Treatment

Stem density decreased, but basal area increased 50 years after treatment compared to 11 years after treatment for all trees (Table 2). Still, total stem density did not differ significantly among the treatments, whereas the density of trees ≥11.5 cm dbh remained between 625 (moderate intensity) and 650 (high intensity) trees ha^{-1} while 1,267 trees ha^{-1} in the control. A gradient of total basal area was found from the high-intensity treatment to the control, ranging

Table 2. Tree density and basal area 11 and 50 years after treatment.

Treatment	Total density (stem ha^{-1})	Density of trees ≥11.5 cm (stem ha^{-1})	Total basal area (m^2 ha^{-1})	Basal area of trees ≥11.5 cm (m^2 ha^{-1})
11 years after treatment				
Control	6,997 ± 540 a	988 ± 46 b	31.1 ± 1.4 b	21.3 ± 1.5 b
Low intensity	6,943 ± 290 a	505 ± 59 a	14.2 ± 2.4 a	11.7 ± 2.3 a
Moderate intensity	6,688 ± 350 a	427 ± 39 a	15.4 ± 3.4 a	13.7 ± 3.5 a
High intensity	6,829 ± 305 a	427 ± 35 a	11.3 ± 0.1 a	10.4 ± 0.8 a
50 years after treatment				
Control	2,300 ± 405 a	1,267 ± 137 c	69.17 ± 7.4 b	65.6 ± 8.2 b
Low intensity	2,479 ± 398 a	857 ± 84 b	56.05 ± 4.1 a	53.0 ± 4.9 a
Moderate intensity	1,954 ± 262 a	625 ± 42 a	48.20 ± 2.0 a	46.3 ± 1.8 a
High intensity	2,418 ± 321 a	650 ± 75 a	44.58 ± 3.1 a	41.5 ± 2.6 a

Note: Total metrics include large trees, saplings, and seedlings. For each treatment and metric, different letters indicate differences among treatments within a time period ($\alpha = 0.05$). Shown are means ± standard error.

Table 3. Mean dbh, height, and crown ratio for all trees and trees ≥11.5 cm dbh, 11 and 50 years after treatment.

Treatment	All trees mean dbh (cm)	Trees ≥11.5 cm mean dbh (cm)	All trees mean height (m)	Trees ≥11.5 cm mean height (m)	Trees ≥11.5 cm live crown ratio
11 years after treatment					
Control	9.6 ± 0.4 a	16.2 ± 0.8 a	8.8 ± 0.3 b	13.9 ± 0.6 a	0.6 ± 0.1 a
Low intensity	8.7 ± 0.3 a	16.3 ± 0.7 a	6.2 ± 0.2 a	11.3 ± 0.5 a	0.8 ± 0.1 a
Moderate intensity	9.4 ± 0.7 a	17.9 ± 1.4 a	6.4 ± 0.3 a	11.7 ± 0.7 a	0.8 ± 0.1 a
High intensity	9.1 ± 0.5 a	17.5 ± 1.1 a	6.5 ± 0.3 a	12.1 ± 0.6 a	0.8 ± 0.1 a
50 years after treatment					
Control	15.5 ± 1.1 a	24.7 ± 2.4 a	12.9 ± 0.5 ab	20.5 ± 1.1 a	0.4 ± 0.1 a
Low intensity	16.1 ± 0.8 a	27.8 ± 1.7 a	12.9 ± 0.6 ab	21.5 ± 1.0 a	0.5 ± 0.1 a
Moderate intensity	17.0 ± 0.6 a	29.8 ± 1.0 a	13.6 ± 0.5 b	23.1 ± 0.7 a	0.5 ± 0.1 a
High intensity	15.5 ± 0.5 a	26.9 ± 1.1 a	12.1 ± 0.3 a	20.7 ± 0.7 a	0.5 ± 0.1 a

Note: All trees include large trees, saplings, and seedlings. Different letters indicate differences among treatments within a time period ($\alpha = 0.05$). Shown are means ± standard error.

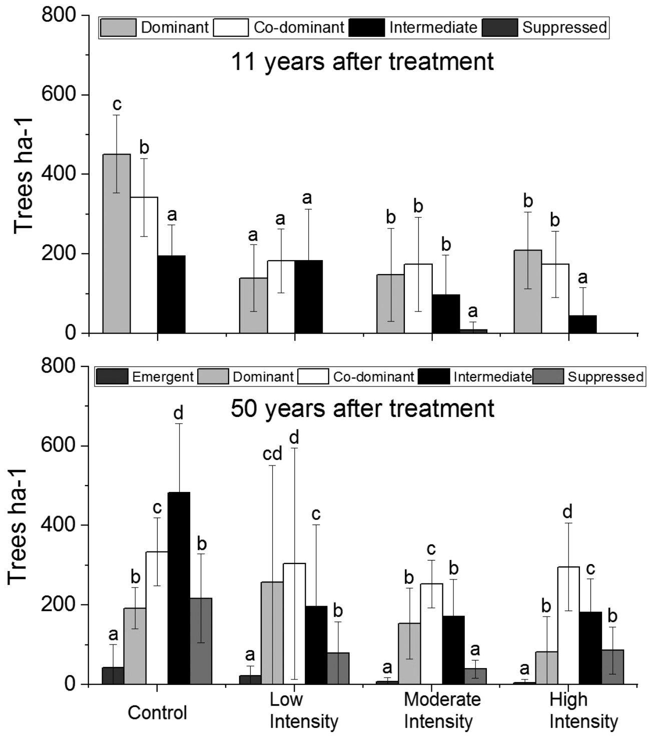

Figure 1. Stand crown class variation statistics of trees dbh ≥ 11.5 cm by 11 and 50 years after treatment. For each group, different letters indicate significant differences (α = 0.05).

from 44.58 to 69.17 m² ha⁻¹. Trees ≥11.5 cm dbh occupied the majority of the basal area 50 years after treatment. The mean dbh of trees ≥11.5 cm in the thinned stands exceeded that in the control with insignificant difference 50 years after thinning (Table 3). The initial gains in the height in the unthinned control with less regeneration at 11 years after treatment had diminished by 50 years after treatment. Instead, the moderate-intensity treatment had the greatest mean height (13.6 m).

Crown classes 50 years after treatment shifted upwards to include emergent trees, but there was also an influx of trees in the intermediate and suppressed crown classes across all treatments (Figure 1). The thinning treatments still maintained a significantly greater number of trees in the codominant crown class, whereas the unthinned control was dominated (on a stem per hectare basis) by intermediate trees. Diameter distributions also moved to the right, with the number of trees in diameter classes of trees larger than 11.5 cm increasing, and the number of trees in the smaller-diameter classes stayed constant or increased (Figure 2). After the initial peak in the density of the smaller-diameter trees, all treatments had a greater number of trees between 25 and 35 cm dbh.

Shade-tolerant western hemlock and western redcedar still dominated all treatments by 50 years after thinning (Figure 3). Specifically, these species occupied over 60 percent of the basal area in the control, and between 69 percent and 76 percent in the thinning treatments. Douglas-fir became a small contributor to total basal area, as did western larch in the high-intensity treatment. All thinning intensities had the effect of shifting composition over the long term to shade-tolerant late successional tree species, although shade-tolerant species were favored by thinning. This trend was likely the natural course of development, as evident by the similar trend in the unthinned control.

Stand Growth and Yield

Similar to total basal area, total volume and aboveground biomass were the greatest in the unthinned control, whereas merchantable volume (trees ≥ 17.8 cm dbh) in the moderate-intensity treatment recovered more, which was insignificantly different from that in the control 11 years after treatments. Merchantable volume was 25 and 35 m³ ha⁻¹ lower in the low-intensity and high-intensity treatments than that in the control. Saplings had a high contribution to the total biomass of the unthinned control (27 percent), whereas the thinning treatments selectively removed from below resulting in not only less total biomass than the control, but also smaller proportions from saplings (between 5 percent and 13 percent in the thinned stands). The net merchantable mean annual increment of volume (MAI) was similar among the treatments at 1978 (11 years after treatment), whereas the net total volume MAI was greater for the control than for the thinning treatments (Figure 4). This difference could result from the greater density of smaller trees after thinning.

Volume and biomass were still greatest in the unthinned control 50 years after treatment (Table 4). The merchantable volume in the control was 177, 111, and 101 m³ ha⁻¹ greater than that in the high-, moderate-, and low-intensity treatments, respectively. Interestingly, since the mean dbh of trees ≥11.5 cm dbh was not different among the treatments but tree density was, this suggested a high carrying capacity of trees larger than saplings for this forest type. The high carrying capacity of the forest was further supported by the increase in MAI and the high periodic annual increment at 2017 (50 years after treatment), indicating that biological maturity has not been reached.

Regeneration and Understory Vegetation after Thinning

Early thinning disturbance allows stands to develop into understory reinitiation stage can be developed immediately after early thinning disturbance without stem exclusion stage. Canopy gaps or growing space left by thinning were covered by more seedlings 11 years after treatment and also increased understory vegetation cover compared to the unthinned control (Table 5). Seedling density was 2,187 trees ha⁻¹ greater in the high-intensity treatment than in the control, whereas the greatest gain in understory cover was in the low-intensity treatment, which was 67 percent greater than the control. Western hemlock, western redcedar, and grand fir represented the highest percentage of seedling density in all stands 11 years post thinning (Figure 5), and the canopy gaps created by thinning resulted in a greater proportion of Douglas-fir and other conifer species (including shade-tolerant species: Engelmann spruce, subalpine fir, and western white pine and shade-intolerant species: western larch, lodgepole pine, and ponderosa pine).

Even following crown closure, the thinning treatments still had significantly greater seedling densities 50 years after treatment than the unthinned control (Table 5). Many of these seedlings must have grown into sapling-sized trees, as the high-intensity treatment had a mean of 1,143 saplings ha⁻¹, significantly higher than 966 saplings ha⁻¹ in the unthinned control. The initial flush of understory vegetation following thinning disappeared 50 years after thinning, where understory cover was 2–3 percent among all treatments. The diversity of seedling species also strongly diminished 50 years after

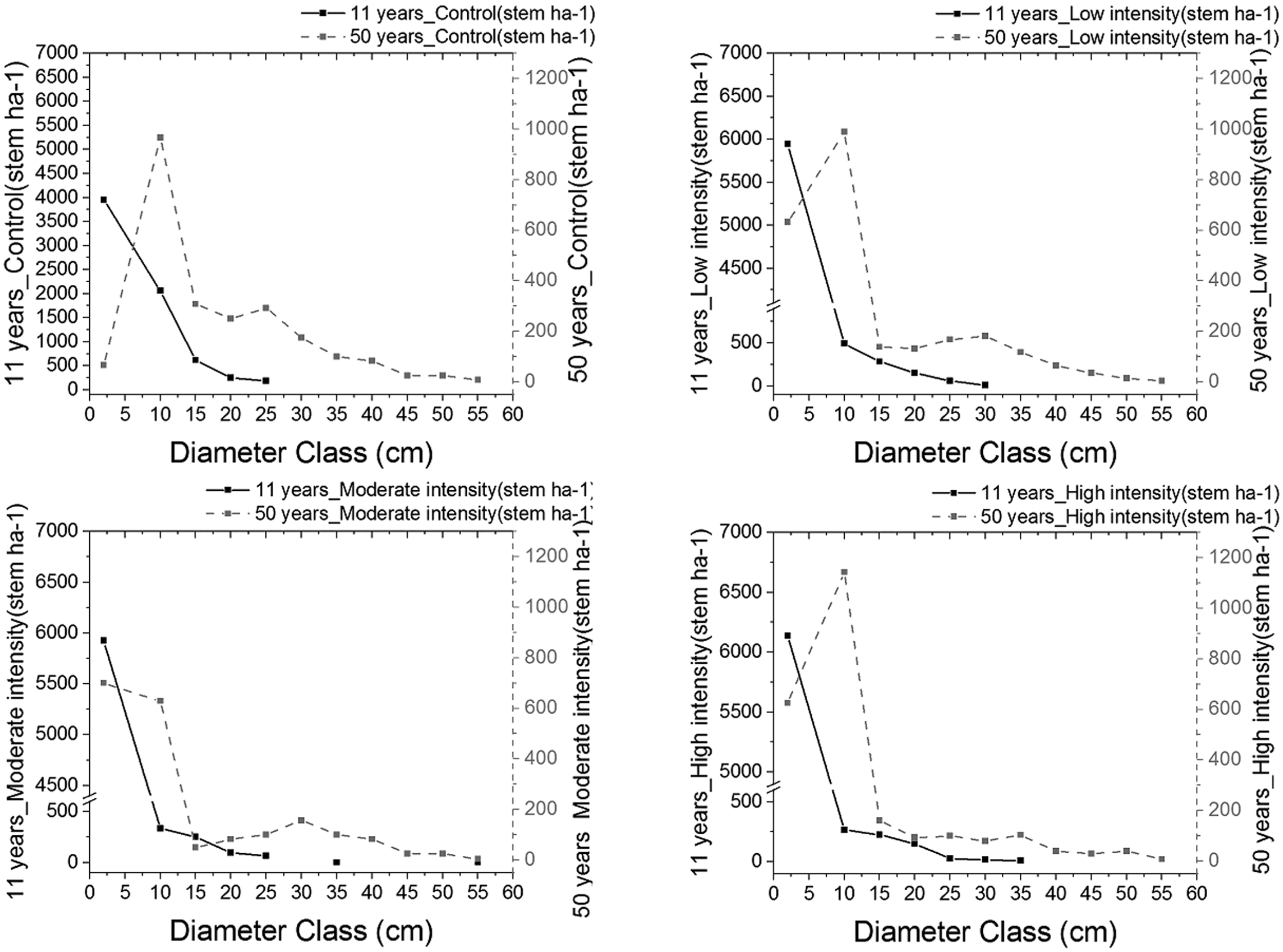

Figure 2. Diameter distributions 11 and 50 years after treatment for the control and thinning treatments. 11/50 years_Treatment stands for treatments of different intensities by 11/50 years after treatment (dark line/light dashed line and values on the left/right secondary axis). 2 cm stands for seedling diameter; 10 cm stands for sapling diameter; 15 cm: 11.5–16.5 cm; 20 cm: 16.6–21.5 cm; 25 cm: 21.6–26.5 cm; 30 cm: 26.6–31.5 cm; 35 cm: 31.6–36.5 cm; 40 cm: 36.6–41.5 cm; 45 cm: 41.6–46.5 cm; 50 cm: 46.6–51.5 cm. 55 cm stands for all diameter >51.5 cm.

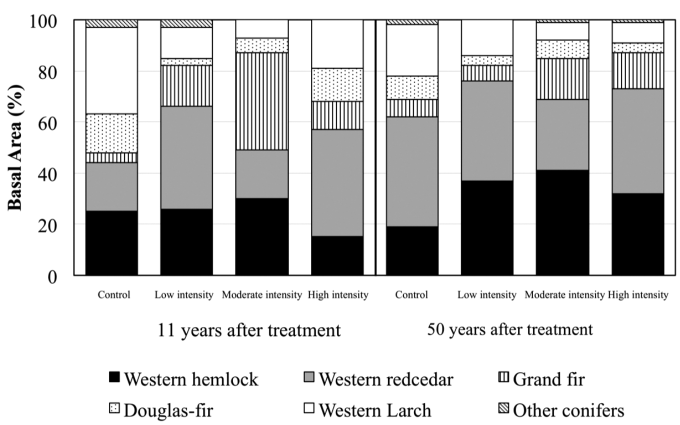

Figure 3. Species composition of different treatments 11 years and 50 years after thinning. Species are presented in order of shade tolerance with western hemlock as the most shade-tolerant and western larch the least shade-tolerant. Other conifers could include Engelmann spruce, subalpine fir, and western white pine, lodgepole pine, or ponderosa pine.

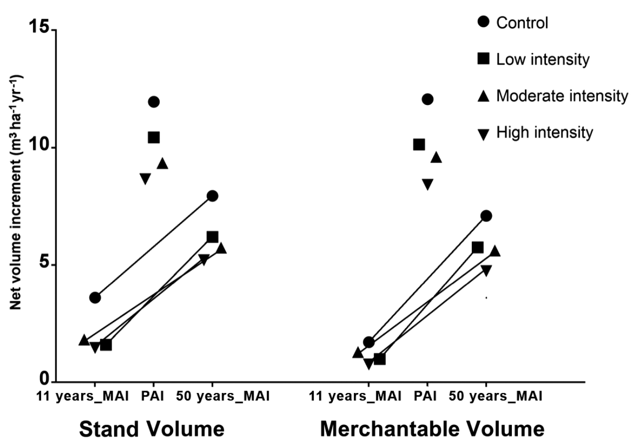

Figure 4. Mean annual increment (MAI) of stand volume and merchantable volume 11 years and 50 years after treatment and the periodic annual increment (PAI) for the time span in between.

Table 4. Short-term and long-term growth and yield statistics of stands under different thinning intensities.

Treatment	Total volume (m^3 ha^{-1})	Merchantable volume (m^3 ha^{-1})	Total aboveground biomass (Mg ha^{-1})	Aboveground biomass of merchantable trees (Mg ha^{-1})	Sapling biomass (Mg ha^{-1})
11 years after treatment					
Control	130 ± 14 b	62 ± 15 b	108.3 ± 5.3 b	45.7 ± 7.8 b	28.9 ± 1.7 c
Low intensity	57 ± 12 a	36 ± 12 a	50.4 ± 8.9 a	27.3 ± 8.6 a	6.6 ± 1.8 b
Moderate intensity	65 ± 18 a	46 ± 19 ab	72.7 ± 24.5 a	53.7 ± 26.1 b	3.9 ± 0.6 b
High intensity	53 ± 5 a	27 ± 7 a	42.5 ± 4.4 a	22.9 ± 5.9 a	2.1 ± 1.4 a
50 years after treatment					
Control	596 ± 87 c	532 ± 97 b	310.7 ± 47.5 b	279.5 ± 53.1 b	10.0 ± 2.9 b
Low intensity	464 ± 46 b	431 ± 54 a	254.9 ± 22.7 a	236.6 ± 26.9 b	8.0 ± 2.4 b
Moderate intensity	430 ± 25 ab	421 ± 28 a	240.7 ± 12.6 a	232.0 ± 13.9 b	4.1 ± 1.5 a
High intensity	390 ± 26 a	355 ± 24 a	210.9 ± 10.7 a	154.5 ± 19.6 a	8.0 ± 2.7 b

Note: For each structural metric, different letters indicate differences among treatments within a time period (α = 0.05). Shown are means ± standard error.

Table 5. Regeneration and understory nontree vegetation cover and life form richness for 11 years and 50 years after treatment for different thinning intensities.

Treatment	Seedling density (stems ha^{-1})	Sapling density (stems ha^{-1})	Total understory nontree vegetation cover (percent)/vegetation life form richness
11 years after treatment			
Control	3,951 ± 420 a	2,058 ± 121 b	77/3 a
Low intensity	5,944 ± 376 b	494 ± 86 a	144/4 b
Moderate intensity	5,926 ± 366 b	335 ± 48 a	127/4 b
High intensity	6,138 ± 300 b	265 ± 77 a	122/4 b
50 years after treatment			
Control	67 ± 45 a	966 ± 290 b	3/3 a
Low intensity	632 ± 116 b	989 ± 301 b	2/2 a
Moderate intensity	700 ± 169 b	629 ± 201 a	3/2 a
High intensity	625 ± 235 b	1,143 ± 264 c	3/3 a

Note: For each characteristic, different letters indicate differences among treatments within a time period (α = 0.05). Shown are means ± standard error. Nontree vegetation life form: shrubs, forbs, grass, fern. The numbers represent the number of nontree vegetation life forms observed.

thinning, where the seedling composition was purely dominated by these shade-tolerant species: western hemlock, western redcedar, and grand fir (Figure 5).

Discussions

The moist forests of northern Idaho are unique in terms of their diverse species composition and high productivity compared to many other conifer forests across the western United States. Early thinning is a common management treatment across the region, but there is a lack of information on the long-term response of early thinning. Our results demonstrate that in these forests dominated by shade-tolerant tree species, each thinning favoring shade-tolerant species had a minimal effect in increasing stand growth and yield over a 50-year period. Stand structure and species composition changed over time, but shade-tolerant species still dominated all unthinned and thinned stands. A flush of understory growth occurred shortly after early thinning, which maintained a high density for tree seedlings but declined for nontree vegetation. The resilience of moist coniferous forests to partial canopy disturbance, and their high carrying capacity when left unthinned, resulted in greater overall growth and yield 50 years after treatment. Still, thinning can be a viable option to reduce fuel loads and create structural heterogeneity according to specific management objectives.

Short- and Long-Term Changes in Stand Structure and Composition

Thinning, regardless of the type or intensity, removes trees and reduces stand basal area shortly after treatment, whereas the residual mean tree diameter can increase, decrease, or remain unchanged (Skovsgaard 2009, Horner et al. 2010). Although prethinning or immediate post-thinning inventories that included dbh measurements were not available, the lack of difference in mean dbh of trees larger than 11.5 cm dbh suggests that thinning favoring shade-tolerant species had a minimal effect on mean dbh by 11 years after treatment in this study, but did substantially reduce density and stand basal area. Possible differences of diameter among treatments might occur after 11 years as delayed response, which was not observed in this study. The prescription was a thinning from below, which presumably would increase the mean diameter, yet the lack of difference was likely because of the release of regeneration and small trees and growth into larger diameter classes. Similar to previous studies (Pothier 2002, Homyack et al. 2004, Horner et al. 2010), thinning stimulated growth of residual trees into larger sizes, and the establishment of new seedlings occurred. Harrington and Devine (2011) found that growth following thinning in western redcedar stands increased substantially starting 10 years after thinning, which was almost equal between the thinned and unthinned plots. A similar response was found in spruce–fir stands after thinning in Maine, where high-intensity thinning promoted the growth of larger-diameter regeneration 10 years after thinning (Olson et al. 2013). Thinning altered available resources and allocated growing space and essential resources to growth (Binkley et al. 2013, Hawthorne et al. 2013).

Very few investigations have examined changes in stand structure 50 years after thinning. One of the few studies available to compare is the Green River precommercial thinning study in New Brunswick (Pitt et al. 2013). The study included balsam fir-red

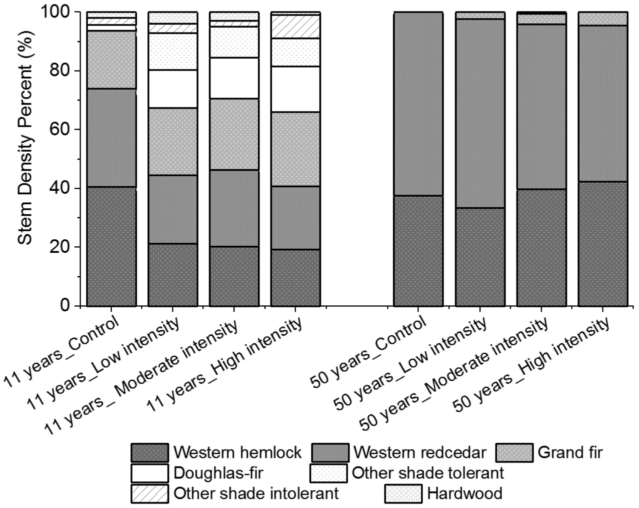

Figure 5. Seedling species composition short-term and long-term post thinning in the control and each thinning regime. Other shade-tolerant: Engelmann spruce, subalpine fir, and western white pine; Other shade-intolerant: western larch, lodgepole pine, and ponderosa pine; Hardwood: hardwood species.

spruce stands thinned to three different residual spacings at age 16. Similar to our results, the total stem density remained high 15 years after thinning, but then declined substantially by 44 years after thinning (Pitt and Lanteigne 2008). Fifty years after thinning, the basal area of trees ≥11.5 cm dbh in our thinned plots remained lower than that in the unthinned control by as much as 24.1 m^3 ha^{-1}. Comparatively, Pitt and Lanteigne (2008) found that the basal area of trees >9 cm dbh in all thinned stands exceeded the control after 50 years. The discrepancies between the two studies could result from the different thinning intensities. Our lowest-intensity thinning of 2.2 m spacing was mostly similar to their highest thinning intensity of 2.4 m spacing. The older age of our stand when thinned (26 years old) compared to the vigorous 16-year-old trees might have delayed crown closure following thinning that allowed understory regeneration to burst and develop into larger size classes. This advanced regeneration eventually became suppressed but persisted through 50 years after thinning because of high shade tolerance. The diameter distributions half a century after thinning at Green River produced a classic bell-shaped distribution that shifted to the right with greater thinning intensity (Pitt and Lanteigne 2008), whereas the diameter distributions in our study continued to follow a reverse-J shape, because of the high number of saplings. The structure suggests a persistent two-strata forest with shade-tolerant western hemlock and western redcedar growing beneath an overstory dominated by similar species.

In the Inland Northwest, western redcedar, western larch, western hemlock, and Douglas-fir are commonly associated tree species. Overall, all thinning treatments altered species composition by retaining the shade-tolerant species western redcedar and western hemlock, and these species dominated all treatments 50 years later. These species can survive and grow in a variety of light conditions and thus maintain high densities over a long time through continuous growth and regeneration (Harrington and Devine 2011). Preferences in species composition across the region have shifted toward favoring shade-intolerant and moderately tolerant species since the time of thinning (Witt et al. 2012). Current management efforts across federal, state, and private lands are made to increase the abundance and dominance of western white pine, western larch, and ponderosa pine across the moist forests of the region (Bollenbacher et al. 2014). In this study, we now have a forest dominated by shade-tolerant species pre- and post-thinning. The results indicated that thinning favoring shade-tolerant species allows shade-tolerant species to increase and dominate the forests over time.

Forest Growth and Yield

Studies have shown that thinning could reduce standing volume and biomass, which may persist throughout a rotation (e.g., Pitt and Lanteigne 2008, Harrington and Devine 2011). Similar trends were found in this study where merchantable volume was lower 50 years after thinning than in the unthinned control. The mean dbh of trees larger than 11.5 cm did not differ significantly among the treatments, but the overall stems per hectare were greater in the unthinned plots, suggesting that these moist forests of the Northern Rockies have the ability to maintain high stocking similar to other moderately productive forested regions (Miller et al. 2016).

Among the thinning treatments, the low-intensity treatment had the greatest merchantable volume, since this treatment maintained a higher stocking but also opened the canopy to stimulate growth of the residual trees, similar to other studies (Jozsa and Middleton 1994, Marshall and Curtis 2002, Sullivan et al. 2006). In this study, the low-intensity thinning seemed to provide an adequate tradeoff of stimulating growth and produce a high proportion of merchantable wood yield. Although the control treatment maximized both total and merchantable yield, thinning provides the opportunity to capture some value from the stand in the middle of the rotation (Curtis et al. 1997). Mortality was not tracked in the current study, so it is difficult to state how much volume was lost in the control because of mortality, but Harrington and Devine (2011) found negligible decline in stem density of western redcedar stands 25 years after other plots had been thinned. Initial cohort tree density remained constant across treatments, but even in the unthinned control the growth density increased substantially (Harrington and Devine 2011).

Regeneration and Understory Vegetation Changes

Regeneration increased with growing space and reducing competition left by thinning despite early thinning not having been applied to stimulate regeneration (Sakai et al. 2005). Regeneration richness, including seedling abundance and species diversity, declined after 50 years as dominance by more shade-tolerant species and species composition became more homogenous, as has been found in other forest types (Jobidon et al. 2004). Deal and Farr (1994) found that thinned young stands in southeast Alaska maintained dominance by shade-tolerant species, and advance regeneration occurred. Waiting until stands reach an older age before new shade-tolerant conifer regeneration is released defeats the purpose of increasing understory species diversity (Deal and Farr 1994). Our stands were also thinned at a young age, and trees that grew into larger size classes were likely present as advance regeneration. Once the canopy closed from the development of multiple strata, nontree understory vegetation was excluded.

Understory vegetation cover and composition diversity may increase with more shade-intolerant vegetation shortly after thinning

(Harrington and Edwards 1999, Dodson et al. 2008), which was shown by the significant increase in understory vegetation in this study. Shrub cover showed a notable increase 11 years post thinning. Similar to the dramatic decrease in vegetation by thinning in previous studies in the Northwestern United States (e.g., Alaback and Herman 1988), understory vegetation cover and diversity decreased significantly 50 years post thinning in both thinned and unthinned stands in this study. The effects of thinning on understory vegetation in mixed moist forests debilitated a long time span post thinning.

Conclusion

Our results demonstrate that different thinning intensities within the first 30 years of establishment result in a variety of stand structures 50 years after thinning in the moist forests of the Northern Rockies. Favoring shade-tolerant species, thinning had minimal effect in increasing growth and yield over time. Our results overwhelmingly indicate that shade-tolerant species can grow into larger size classes beneath similar species in the overstory. Furthermore, these shade-tolerant species are still expected to develop into a lower stratum beneath a shade-intolerant overstory. Changes in species composition across the region tend toward favoring more shade-intolerant species, which may need thinning, favor those shade-intolerant species as reserve trees. If prescribed fire is a widely available tool to help manage the growth, the structure might be considerably different, but currently it may be that periodic thinning entries are required to reduce fuel loads while maintaining productivity and resilience to future disturbances.

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