Overstory and understory development in thinned and underplanted Oregon Coast Range Douglas-fir stands

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Abstract: Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) forests managed for timber in western Oregon frequently lack structure and diversity associated with old-growth forests. We examined thinning effects on overstory and understory development for 8 years after treatment. Three 30- to 33-year-old Oregon Coast Range plantations were partitioned into four overstory treatments: unthinned (~550 trees/ha) and lightly (~250 trees/ha), moderately (~150 trees/ha), and heavily (~75 trees/ha) thinned. Within each overstory treatment, two understory treatments were established: underplanted with Douglas-fir and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) or not underplanted. Thinning increased overstory stem growth, crown expansion, and retained crown length. Thinned overstory canopies began to close rapidly the third year after thinning, decreasing % skylight by approximately 2%/year, whereas % skylight in unthinned stands increased slightly. All seedlings planted in unthinned stands died, whereas eighth year survival in thinned stands averaged 88%. Natural regeneration densities and distributions were highly variable. Understory shrub cover was reduced by harvesting disturbance but recovered by the fifth year. Thinning increased understory plant species diversity, and no shrub species were lost. Thinning to low densities and underplanting has the potential to accelerate development of multilayered stands characteristic of old-growth Douglas-fir forests.

Résumé : Les forêts de sapin de douglas de (*Pseudotsuga menziesii* (Mirb.) Franco) aménagées pour le bois d'œuvre dans l'ouest de l'Oregon souvent n'ont pas la structure ni la diversité caractéristiques des forêts anciennes. Nous avons étudié les effets de l'éclaircie sur le développement de l'étage dominant et du sous-étage de peuplements pendant huit ans après l'application du traitement. Trois plantations âgées de 30 à 33 ans de la chaîne côtière de l'Oregon ont été divisées en fonction de quatre traitements de l'étage dominant : témoin (~550 arbres/ha), éclaircie légère (~250 arbres/ha), éclaircie modérée (~150 arbres/ha) et éclaircie forte (~75 arbres/ha). Pour chaque traitement de l'étage dominant, deux traitements du sous-étage ont été appliqués : plantation de sapin de douglas et de pruche de l'Ouest (*Tsuga heterophylla* (Raf.) Sarg.) sous couvert ou aucune plantation. L'éclaircie a augmenté la croissance de la tige et l'expansion de la cime des arbres de l'étage dominant et a maintenu la longueur de leur cime. Les canopées éclaircies de l'étage dominant ont commencé à se refermer rapidement durant la troisième année après l'éclaircie, ce qui a diminué le pourcentage d'ouverture d'environ 2 % par année alors que le pourcentage d'ouverture des peuplements non éclaircis a légèrement augmenté. Tous les semis plantés sous les peuplements non éclaircis sont morts alors que les semis plantés sous les peuplements éclaircis avaient un taux moyen de survie après huit ans de 88 %. La densité et la distribution de la régénération naturelle étaient très variables. La perturbation associée à la récolte a diminué le pourcentage de couverture des arbustes du sous-étage, mais les valeurs initiales ont été atteintes de nouveau cinq ans après les traitements. L'éclaircie a augmenté la diversité en espèces des plantes du sous-étage et aucune espèce arbustive n'est disparue. Une éclaircie laissant de faibles densités résiduelles jumelée à une plantation en sous-étage peut potentiellement accélérer le développement de peuplements à étages multiples qui sont caractéristiques des forêts anciennes de sapin de douglas.

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Introduction

Over the last 50 years, intensive forest management to produce timber in the Oregon Coast Range has created large areas of young, even-aged Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) stands with high tree densities, simple vertical structure, little understory development, and low tree species diversity. These young stands do not sup-

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port the diversity and abundance of wildlife species that exist in older, unmanaged forests (Carey 1989; Lehmkuhl and Ruggiero 1991; Franklin et al. 2002). Tappeiner et al. (1997*a*) and Poage and Tappeiner (2002) suggest that many old-growth Douglas-fir forests in western Oregon developed over long time periods with low densities of dominant trees. This developmental pathway produced forests with multiaged, multistoried canopies with low overstory tree densities, features that are not common in most young Douglas-fir plantations managed for timber (Hayes et al. 1997).

Although thinning is frequently used for timber management, it can be used to enhance structural diversity and increase biological diversity in young stands (Carey 2000; Muir et al. 2002) and accelerate development of mature forest conditions (Carey and Johnson 1995; Carey and Curtis 1996; Tappeiner et al. 1997*a*). Thinning dense stands reduces tree density and opens the canopy, allowing additional light to reach the forest floor, thereby promoting development of understory vegetation and natural tree regeneration, which leads to more structurally complex stands (McComb et al. 1993; Tappeiner and Zasada 1993; Bailey and Tappeiner 1998). Accelerated development of large trees increases the potential for earlier recruitment of large snags and down wood, both of which are important components of late-seral stands (Franklin et al. 2002). Development of large live crowns provides habitat for small mammals, such as the red tree vole (*Phenacomys longicaudus*), and nest platforms for some bird species (Carey 1996; Hayes et al. 1997).

Thinning also aids survival and growth of underplanted seedlings (Mailly and Kimmins 1997; Coates and Burton 1999; Brandeis et al. 2001) and natural regeneration. Thinned stands have been found to have understory plant diversity more similar to old-growth stands compared with unthinned stands (Bailey and Tappeiner 1998; Bailey et al. 1998; Lindh and Muir 2004). Wender et al. (2004) reported that thinning increased the probability and abundance of flowering or fruiting of two native shrub species, *Mahonia nervosa* (Pursh) Maxim. and *Vaccinium ovatum* Pursh.

Recent studies in thinned western Oregon Douglas-fir stands indicate that thinning has either neutral or positive short-term effects for many species of songbirds (Hayes et al. 2003; Hagar et al. 2004), bats (Humes et al. 1999), and small mammals (Larson 2002; Suzuki and Hayes 2003). Additionally, Hagar et al. (1996) reported that thinning from below in densely stocked stands in the Oregon Coast Range increased the abundance of some bird species associated with old-growth forests. In the Pacific Northwest, thinning has become one of the most widely advocated silvicultural approaches for managing federal lands classified as either "late-successional reserves" or "matrix lands" (Forest Ecosystem Management Assessment Team 1993). Thinning is also central to state forests managed under the Oregon Department of Forestry's structure-based management plan (Bordelon et al. 2000).

Presently, there is a lack of quantitative information on how thinning intensity affects light availability and canopy development over time or how temporal changes in light availability are related to understory development and growth rates of underplanted conifer seedlings. Our objectives were to determine the effects of thinning intensity in Douglas-fir stands on (*i*) overstory canopy development, (*ii*) understory light availability, (*iii*) the establishment and growth of underplanted conifers seedlings and naturally regenerating conifers and hardwoods, and (*iv*) understory vegetation.

Methods

Study area

The study targeted 30- to 35-year-old Douglas-fir plantations on highly productive sites on the west slope of the Oregon Coast Range. Three plantations (Cataract, Wildcat, and Yachats) were selected on the Siuslaw National Forest covering a geographic range of 140 km and size range of 11–16 ha (Table 1). Each plantation originated from 22–52 ha clearcuts. The harvested units had been planted with Douglas-fir seedlings following clear-cut harvesting of old-growth stands and were site prepared in the early 1960s (prescribed fire and herbicide application) and precommercially thinned approximately 15 years after planting. The plantations are within the coastal fog zone and located on southwest to northwest aspects with slopes ranging from 17% to 51%. Soils are deep (>120 cm) and well-drained and were formed in weathered colluvium from sedimentary rock (Table 1). The plant associations represented in this study, despite differences in vegetation composition and cover, are similar in terms of temperature and moisture regimes (Emmingham 1982). Climate in this region is temperate with mean monthly temperatures ranging from 6 °C in January to 16 °C in July (Taylor and Hannan 1999). Precipitation averages 165–229 cm/year, falling predominately as rain during the dormant season while summers are often warm and dry (Taylor and Hannan 1999). Damaging or killing frosts are infrequent.

Study design and treatments

We used a randomized, complete-block, split-plot experimental design, with plantation serving as blocks and thinning treatments as the whole-plot factor. Each plantation (or block) was partitioned into four whole plots (or stands) and assigned to one of the following treatments: (*i*) unthinned (~550 trees/ha); (*ii*) light thinning (~250 trees/ha); (*iii*) moderate thinning (~150 trees/ha); and (*iv*) heavy thinning (~75 trees/ha). Whole plots were 2–5 ha in size, square or rectangular, and located in upslope forest areas avoiding areas of visible pockets of laminated root rot (*Phellinus weirii*), pretreatment windthrow, riparian areas, and headwater areas. Prior to thinning, all stands had similar mean basal areas (m^2/ha; P = 0.40) and mean trees per hectare (P = 0.13). Thinning treatments were randomly assigned to whole plots, but unthinned plots in each block were designated to facilitate harvesting efficiency and reduce potential edge effects from adjacent thinned stands. Within each whole plot, two 0.4 ha split plots or subplots were established and the following underplanting treatments were randomly assigned: (*i*) underplanting after thinning with two species of conifer (Douglas-fir and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.)); and (*ii*) no underplanting after thinning (Fig. 1). Buffers between subplots were equal to or greater than two crown widths (approximately 30 m). Buffers between the top edge of subplots oriented closest to logging roads or landings were approximately 20–46 m. Minimum plot number, size, and buffers were based on guidelines from Curtis

Table 1. Site characteristics of the three study locations on the western slope of the Oregon Coast Range.

Site	Area (ha)	Age at thinning (years)	Latitude, longitude	Site index (m, at 50 years)[a]	Elevation (m)	Slope (%)	Aspect	Soil	Plant association[b]
Cataract	11	30	44.09°N, 123.93°W	46	183	30–49	N	Preacher–Bohannon–Slickrock and Blachly silty clay loam series[c]	*Tsuga heterophylla* / *Acer circinatum* / *Gaultheria shallon* / *Polystichum munitum*
Yachats	16	33	44.28°N, 123.94°W	41	213	33–51	NW	Preacher–Bohannon–Slickrock and Astoria silt loam series[d]	*T. heterophylla* / *P. munitum* and *T. heterophylla* / *Rubus spectabilis* / *G. shallon*
Wildcat	14	33	45.32°N, 123.78°W	38	305	17–28	SW	Klootchie–Necanicum series[e]	*T. heterophylla* / *R. spectabilis*

[a]King (1966).
[b]McCain and Diaz (2002).
[c]Patching (1987).
[d]Shipman (1997).
[e]Bowlsby and Swanson (1964).

(1983) and Curtis and Marshall (2005). All overstory trees in each subplot were individually tagged before thinning.

Stands were thinned from below (or low thinned), a process by which trees in lower crown classes are removed and dominant and codominant trees are retained (Helms 1998). Logs were yarded from the sites by suspended cable systems along designated corridors. Understory vegetation was initially sparse and was not controlled before planting or during the study because shrub species that could overtop underplanted seedlings were mostly suppressed by the closed overstory canopy and reduced in height from the logging operation. The Cataract site was thinned in fall 1992. The Yachats and Wildcat sites were thinned during summer 1993. Therefore, all measurements were made at similar times since thinning rather than in a similar calendar year; hence, calendar year was subsumed in the block effect.

Prethinning measurements were taken the summer before thinning at each site. After thinning, seedlings (98 each of Douglas-fir and western hemlock) were planted late winter or early spring in an alternate fashion (the first species planted in the first row was chosen randomly) in each subplot designated for underplanting using a 4.6 m × 4.6 m spacing shortly after harvest. The number of planting rows and the length of each planting row varied by plot because of slight variations in plot dimensions, but spacing was kept constant. All seedlings were protected with 0.6 m tall plastic mesh tubing at the time of planting. Stock was genetically appropriate to the area and consisted of 1 + 1 Douglas-fir (1 year in a nursery bed then transferred to a more widely spaced transplant bed for 1 year) and plug + 1 western hemlock (1 year in a container then transferred to a bed for 1 year) seedlings. Smaller sampling plots were designated within each subplot to measure natural tree regeneration, understory vegetation, and % skylight.

Overstory tree sampling and measurements

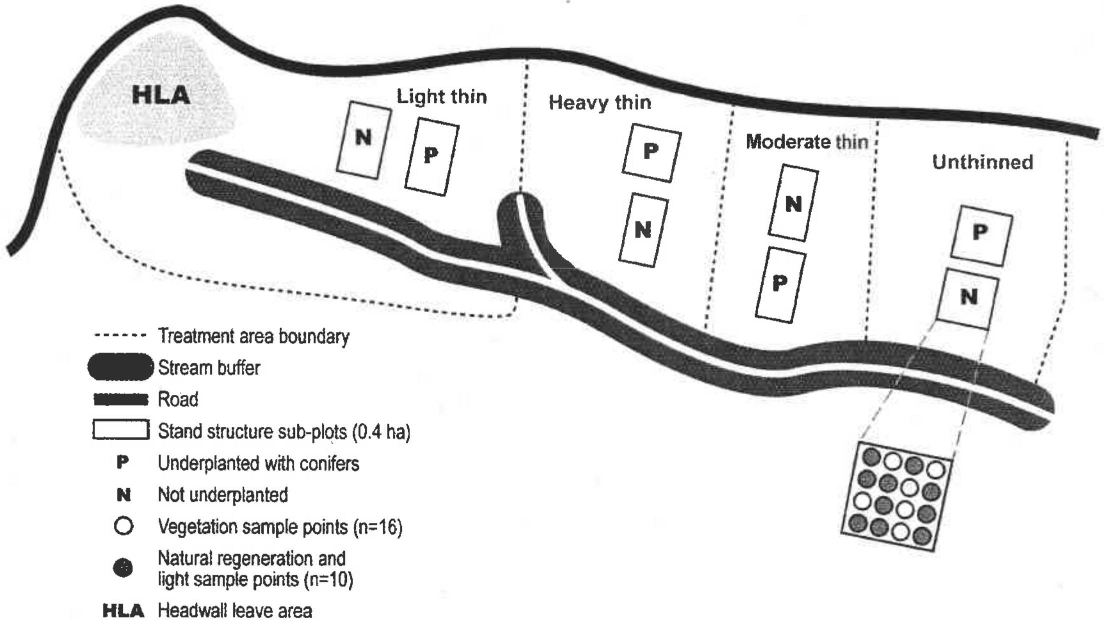
Within each 0.4 ha subplot, measurements of total tree height, height to live crown (height to the lowest whorl with at least three-quarters of its branches alive), and diameter at breast height (DBH) were made on a subset of 40 overstory trees in unthinned, lightly thinned, and moderately thinned stands and on all trees (approximately 30) in heavily thinned stands. The subset of overstory trees was chosen using stratified random sampling based on the frequency distribution of 5 cm diameter classes (Freese 1962) to achieve a proportional sample of overstory tree sizes within each subplot. The sampling scheme was done for both the prethinned stands and the postthinned stands because the diameter distributions were expected to change after thinning.

Measurements were taken before thinning (prethinning), immediately after thinning (postthinning), and 4 and 8 years after thinning. Descriptions of overstory conditions immediately after thinning were based on preharvest measurements of trees designated for retention after thinning. In addition to the subset of trees, the DBH of all living trees in the 0.4 ha subplots were measured before thinning (prethinning), immediately after thinning, and 8 years after thinning to accurately determine stand density and tree mortality.

Underplanted seedling measurements

All of the underplanted seedlings were monitored over the

Fig. 1. A graphical representation of the Cataract site showing the relationship of the whole plots (thinning treatments) to subplots (underplanted and not underplanted) and to sample points used for understory measurements and hemispherical photo points. The figure is not drawn to scale.



course of the study. Seedling stem diameter to the nearest 0.1 cm was measured at 15 cm above the ground, and total stem height to the nearest centimetre was measured to the highest live bud (hemlocks were measured to the highest point of leader droop). Survival and condition (e.g., browse, insect damage, disease, shaded, and overgrown) of each seedling was also assessed. Measurements and seedling conditions were recorded at time of planting and after the third, fifth, and eighth growing seasons.

Understory vegetation, natural regeneration, and available skylight sampling and measurements

Understory vegetation in each subplot was sampled using a grid of 16 vegetation sample plots at 12.2 m × 12.2 m spacing in each 0.4 ha subplot (Fig. 1). Nested 2.5 m^2 and 5 m^2 circular plots were established at each plot center. Percent cover of all shrubs combined and % cover and maximum height (to the nearest 0.01 m) of each shrub species was measured in each 5 m^2 plot. Percent cover of all herbaceous species (including sword fern, *Polystichum munitum* (Kaulfuss) K. Presl.)) combined and % cover and maximum height of the three dominant (most abundant in cover) herbs were estimated in each 2.5 m^2 plot. Vegetation measurements were made prethinning, immediately after thinning, and 3, 5, and 8 years after thinning.

Ten of the sixteen vegetation sample plots in each 0.4 ha subplot were randomly selected to sample hardwood and conifer natural regeneration and available skylight (Fig. 1). A 0.004 ha (40 m^2) circular plot was located at the vegetation sample plot center to count and measure all naturally regenerating conifer and hardwood seedlings taller than 15 cm during February and March 8 years after thinning. The average number of naturally regenerating seedlings per hectare taller than 15 cm was estimated based on these counts.

Hemispherical images were used in this study to provide an indirect but generally accurate method for estimating the skylight environment in the understory and changes in the skylight environment and canopy gaps over time (Pearcy 1989; Cannell and Grace 1993; Easter and Spies 1994; Comeau et al. 1998). Skylight and canopy gap estimates from hemispherical images encompass 180°, which may differ from visual estimates or radiation sensors based on narrower view angles. To estimate % available skylight (referred to as % skylight) through the canopies, the area of visible sky was calculated from hemispherical photographic images taken at each of the 10 randomly selected sample plots in each subplot. The images were taken with black and white (Kodak TMAX) 100 ASA negative film using a 35 mm Canon AE-1 single lens reflex camera with a 7.5 mm equal distance fisheye lens. The camera was leveled and images were taken approximately 1 m above the forest floor with the top of the image oriented toward magnetic north. Film was processed by the same technician throughout the study using standard development methods. Developed images were analyzed with CANOPY© integration software (Rich 1990). Images were taken prior to thinning, the year after thinning, and 3, 5, and 8 years after thinning.

Data analysis

Overstory tree growth

We did not detect differences in overstory tree height or DBH between underplanted and unplanted overstory split plots after 8 years within a given whole plot (ANOVA, $P >$ 0.30). Therefore, the overstory was characterized with the average of the two 0.4 ha subplots in each stand. We calculated live-tree crown ratios (LCR), whole plot basal area (BA, m^2/ha), and whole plot relative density (RD, $m^2 \cdot ha^{-1} \cdot cm^{-1}$; Curtis 1982) from the basic field measurements. RD is a means of describing the relative degree of intertree competition in stands of differing average tree size and stand density (Curtis 1982). BA and RD were calculated for plots immediately before thinning, immediately after thinning, and 4 and 8 years after thinning based on the diameters of all trees in the 0.4 ha. Measurements were taken repeatedly on the same overstory trees, so we used repeated measures in the MIXED procedure of SAS (SAS Institute Inc. 1999) to account for nonindependence of measurements. The first-order autoregressive covariance structure was selected by comparing test statistics generated by the maximum likelihood test and Akaike's information criteria (Burnham and Anderson 1998). Orthogonal contrasts were used to test three null hypotheses for each overstory variable in the eighth year of the study: (*i*) mean values were equal between thinned and unthinned stands; (*ii*) mean values were equal between lightly thinned stands and both moderately and heavily thinned stands; and (*iii*) mean values for moderately thinned stands were equal to heavily thinned stands.

Linear regression was used to examine the relationship of % skylight to overstory trees per hectare, BA, and RD. This was achieved by averaging % skylight over the 20 sample plots in each subplot to attain unique skylight values for each of the whole plots. We did not statistically examine differences in % skylight between treatments and years, but did generate means and 95% confidence intervals to descriptively display changes in % skylight over time.

Underplanted seedlings

For underplanted conifers, we analyzed height, stem diameter at 15 cm above the ground, and height-to-stem diameter ratios (H:D) among thinning treatments at the time of planting years 3, 5, and 8 years after planting. Height growth rates were calculated for three time intervals (0–2, 3–5, and 6–8 years) over the 8 year period. Unthinned stands were not included in this analysis because of the high seedling mortality rates during the first 2 years after planting. Since measurements were taken repeatedly on the same seedlings, we used repeated measures in the MIXED procedure of SAS (SAS Institute Inc. 1999) to account for nonindependence of measurements. Orthogonal contrasts were used to test two null hypotheses for each variable in the eighth year of the study: (*i*) mean values of each species were equal between lightly thinned stands and both moderately and heavily thinned stands; and (*ii*) mean values for each species in moderately thinned stands were equal to heavily thinned stands. We did not statistically test for differences between underplanted conifer species because the assumption of equal variance among species was not met.

Understory vegetation and natural regeneration

Based on analysis of variance, we did not detect differences in % cover of shrub or herbaceous vegetation or height of naturally regenerating conifers and hardwoods between underplanted and unplanted overstory subplots after 8 years ($P > 0.23$). Therefore, we used the average of the two 0.4 ha subplots in each stand when examining effects of thinning on understory vegetation and natural regeneration. We used least-squares means to generate % cover of shrubs and herbaceous plants and summary statistics to describe differences in individual species. We did not statistically test for differences among treatments for naturally regenerating seedlings because presence and abundance was highly variable among sample plots and sites. We used least-squares means to generate heights of seedlings among treatments.

Common analyses

In all statistical analyses, we examined variables for normality and constant variance using histograms and residual plots (Sabin and Stafford 1990; PROC UNIVARIATE, SAS Institute Inc. 1999) and transformed variables if these assumptions were not met. With the exception of naturally regenerating conifer and hardwood heights, no transformations were needed for variables examined in ANOVA. Confidence intervals were used to provide an estimate of the true size of treatment effects (Di Stefano 2004). Confidence intervals were not used to test for significant differences between treatment means.

Results

Overstory tree response to treatment

Prior to thinning, mean tree DBH and LCR were similar in all stands (Table 2; Figs. 2*a* and 2*b*). Immediately after thinning, mean DBH was larger in thinned stands than unthinned stands. Significant differences in mean DBH and LCR were seen between thinned and unthinned stands over the course of the study (Table 3; Figs. 2*a* and 2*b*). Eight years after thinning, mean DBH continued to be higher in moderately and heavily thinned stands compared with lightly thinned stands, but DBH was similar between moderately and heavily thinned stands (Table 2). Although there were no statistical differences in LCR among thinned stands (Table 3), a trend was apparent: mean LCR was maintained in moderately and heavily thinned stands, whereas LCR decreased in lightly thinned and unthinned stands (Fig. 2*b*). There was no significant difference in tree height among treatments over the 8 year period ($P = 0.19$). When averaged over all treatments, height was 24.8 ± 4.4 (mean ± SE) m immediately after thinning, and 29.5 ± 4.1 m 8 years after thinning.

Overstory tree density

Prior to thinning, overstory tree densities varied from 547 to 686 trees/ha, but BA (43–47 m^2/ha) and RD (7.7–8.6) were similar among stands (Table 2). Thinning reduced BA by 51%, 67%, and 84% in lightly, moderately, and heavily thinned stands, respectively (Table 2). Tree densities in thinned stands were slightly reduced by windthrow and stem breakage during severe winter storms in the first 4 years of the study (storm mortality in thinned plots ranged from 1% to 7%; overall mortality ranged from 2.8% to 7.2%); however, BA and RD still increased in the first 4 years. Mortality during years 4 through 8 was minimal (0.3%–2.9%) and causes were not readily determined. Tree density decreased the most in unthinned stands over the 8 year period because of mortality related to suppression.

Following thinning, increases in RD and BA were higher in thinned stands than in unthinned stands, with the largest percentage increase seen in heavily thinned stands. The rates of % increase were greater in the second 4 years of the study than in the first 4 years (Table 2). During the second 4 years,

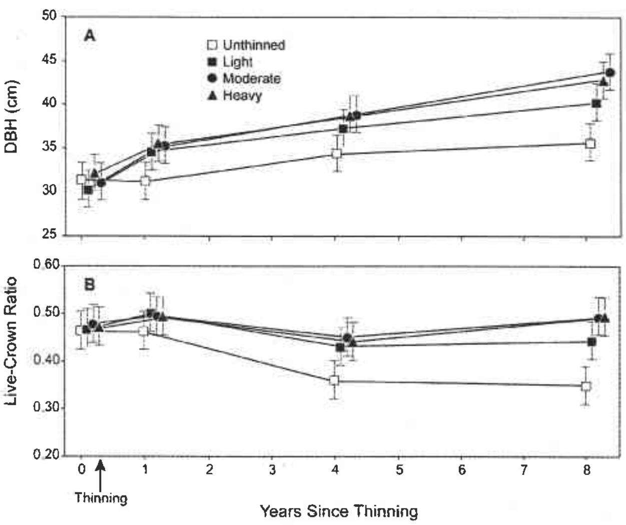
Table 2. Stand densities before thinning, immediately after thinning (year 1), and 4 and 8 years after thinning.

		Mean density (95% CI)				% Change	
Density measure	Treatment	Prethinning	Year 1	Year 4	Year 8	Years 1–4	Years 5–8
Trees/ha	Unthinned	547 (493–601)	547 (493–601)	510 (454–568)	496 (435–558)	–6.8	–0.3
	Light	686 (556–816)	252 (225–279)	244 (215–274)	242 (212–273)	–3.2	–0.8
	Moderate	598 (512–683)	138 (120–156)	128 (119–138)	126 (117–136)	–7.2	–1.6
	Heavy	671 (526–816)	72 (68–77)	70 (64–75)	68 (63–73)	–2.8	–2.9
Basal area (m^2/ha)	Unthinned	44 (40–47)	44 (40–47)	45 (40–51)	49 (44–54)	2.3	8.9
	Light	47 (43–50)	23 (21–26)	27 (23–31)	31 (27–35)	17.4	14.8
	Moderate	43 (39–46)	14 (11–16)	15 (13–18)	18 (16–21)	7.1	20.0
	Heavy	45 (40–50)	7 (6–8)	8 (7–9)	10 (8–13)	14.3	25.0
Relative density[a]	Unthinned	7.7 (7.2–8.2)	7.7 (7.2–8.2)	7.8 (6.9–8.7)	8.2 (7.4–9.0)	1.3	5.1
	Light	8.6 (7.7–9.4)	4.0 (3.6–4.3)	4.4 (3.8–5.0)	4.9 (4.3–5.5)	10.0	11.4
	Moderate	7.7 (7.0– 8.4)	2.3 (1.9–2.7)	2.4 (2.0–2.8)	2.8 (2.4–3.1)	4.3	16.7
	Heavy	8.3 (7.2–9.4)	1.2 (1.1–1.3)	1.3 (1.1–1.5)	1.6 (1.3–1.9)	8.3	23.1

Note: The percentage of change in density was calculated for the first 4 years (years 1–4) and the second 4 years (years 5–8) post-thinning.

[a]Relative density = $(BA/QMD)^{0.5}$, where BA is the basal area (m^2/ha) and QMD is the quadratic mean stand diameter (cm; Curtis 1982); RD (Imperial) = 6.945 28 × RD (metric).

Fig. 2. Changes over 8 years in DBH and LCRs of overstory trees by thinning treatment. Error bars are 95% confidence intervals. Data points are slightly offset for presentation.



mean net increase in BA was similar for all but the heavily thinned stand. The % increase in BA was greater in moderately and heavily thinned stands than in lightly thinned stands in the last 4 years of the study despite the early storm damage.

Percent skylight and canopy development

Hemispherical photographs taken just after thinning and 8 years after thinning illustrate how crown size and % skylight changed over time (Fig. 3). After thinning, % skylight through the canopy ranged from 2% in unthinned stands to 48% in heavily thinned stands (Fig. 4). Over 8 years, the percentage of skylight in thinned stands decreased as a result of increases in tree height (bole area), crown length, and crown width. Percent skylight in unthinned stands increased slightly. After 8 years, % skylight in lightly thinned stands was similar to levels in unthinned stands, and % skylight in moderately thinned stands had diminished to levels similar to those in lightly thinned stands just after thinning (Figs. 3 and 4). Increases in % skylight were not proportional to tree densities (trees/ha, BA, or RD) resulting from thinning. Percent skylight was not linearly related to changes in any of the stand density measures (trees/ha, RD, or BA) we examined. For example, reducing BA from approximately 20 to 10 m^2/ha increased % skylight from approximately 18% to 40%, whereas reducing BA from 40 to 20 m^2/ha increased % skylight from 2% to 17%. These relationships changed only slightly after 8 years, especially for BA and RD (Fig. 5).

Underplanted conifers

Seedlings in unthinned stands had very low survival rates; all Douglas-fir seedlings died within the first year, and only 13% of western hemlock seedlings survived the first 2 years. Eight years after planting, seedling survival in the thinned stands averaged 88%. Eight year survival for Douglas-fir was lowest in lightly thinned stands (64%) and increased with increasing thinning intensity to 90% and 96% survival in moderately and heavily thinned stands, respectively. Western hemlock survival also increased with increasing thinning intensity (92%, 94%, and 96% survival in lightly, moderately, and heavily thinned stands, respectively).

Initial seedling size was consistent among sites and treatment but varied by species because of stock differences. At the time of planting Douglas-fir mean size (47 cm height; 0.71 cm stem diameter) was larger than western hemlock (40 cm height; 0.36 cm stem diameter).

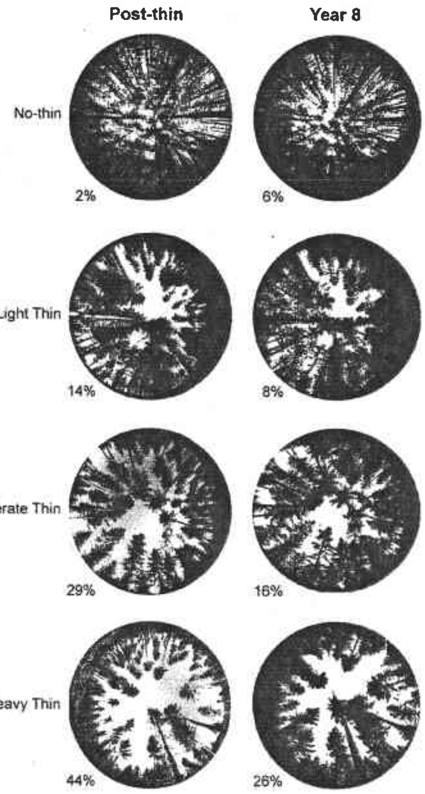
Differences in height and stem diameter among treatments became apparent 5 years after planting for each species (Figs. 6*a* and 6*b*). Treatment differences continued through year 8. Throughout the study period, H/D ratios of western hemlock decreased in all treatments and decreases were greatest in moderately and heavily thinned stands (Fig. 6*c*), whereas H/D ratios for Douglas-fir increased in each thinning treatment. Height growth rates for both species increased over the three time periods measured, and increases were positively related to thinning intensity (Fig. 7).

Table 3. Orthogonal contrasts for overstory diameter at breast height (DBH) and live-crown ratio (LCR) among unthinned and lightly, moderately, and heavily thinned stands 8 years after thinning.

Test	Contrasts	*P*	Result difference (90% CI)
DBH	Unthinned versus thinned	**0.0012**	6.6 (4.3, 8.8)
	Light versus moderate and heavy	**0.0490**	3.0 (0.6, 5.4)
	Moderate versus heavy	0.5246	1.4 (–1.8, 3.7)
LCR	Unthinned versus thinned	**0.0037**	12.8 (7.4, 18.3)
	Light versus moderate and heavy	0.1401	5.0 (–0.7, 10.8)
	Moderate versus heavy	0.9683	–0.1 (–6.6, 6.5)

Note: *P* values in bold indicate a significant difference between treatments and (or) contrast variables.

Fig. 3. An example of the % skylight through the canopy for 1 and 8 years after thinning within each stand. Each set of photographs in this figure is from a selected point in a stand to allow direct comparison of changes over time. Percent skylight for each photograph in year 8 are close to, but may not represent the mean % skylight in each treatment after 8 years. The year 8, heavily thinned value of 26% skylight approximates the average value for the heavily thinned treatment when the Wildcat site infected by Swiss needle cast is excluded.



Orthogonal contrasts show that Douglas-fir was consistently smaller, had higher H/D ratios, and had lower growth rates in the lightly thinned stands than in either the moderately and heavily thinned stands (Table 4). Seedlings in moderately thinned stands were smaller and had lower growth rates than seedlings in heavily thinned stands; however, there was no difference between mean H/D ratios. For western hemlock, contrasts were only significant for stem diameter, H/D ratio, and height growth rate when seedlings

Fig. 4. Changes over 8 years in % skylight through the canopy by thinning treatment. Error bars are 95% confidence intervals. Data points are slightly offset for presentation.

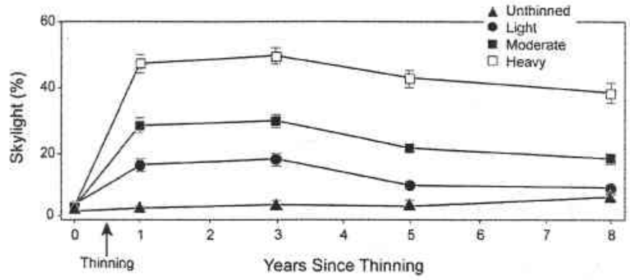


Fig. 5. Observed values and fitted regression lines of % skylight in relation to stand density measures (trees/ha, relative density (RD; see Table 3 for definition of RD), and basal area (BA)) of thinned stands postthinning (open squares and solid lines) and 8 years (solid squares and broken lines) after thinning. Postthinning results are from two sites (six stands) because of missing data from one site. Year 8 data is from three sites (nine stands). Arrows show the regression lines that correspond to to the regression equations. The postthinning and year 8 regression equations and lines for BA are nearly the same. Values are valid from 5.3% to 55.2% skylight.

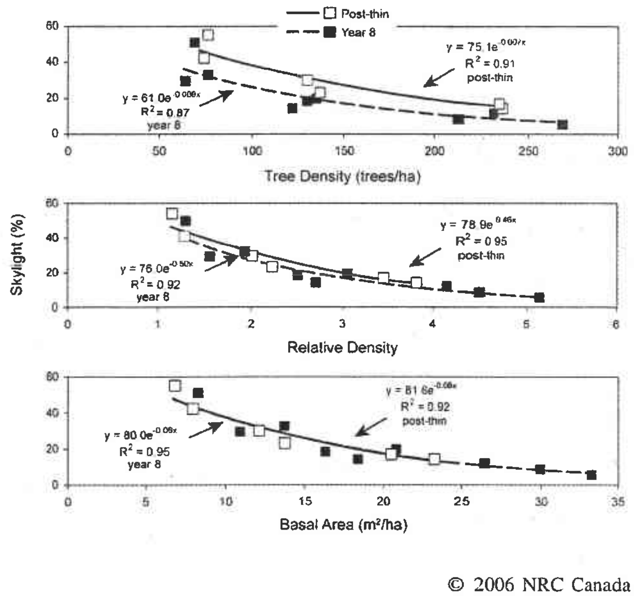


Table 4. Orthogonal contrasts for underplanted Douglas-fir and western hemlock seedlings 8 years after planting in lightly, moderately, and heavily thinned stands.

Contrast	Height	Stem diameter	H:D	Height growth rate
Douglas-fir				
Light versus moderate and heavy	**0.002**	**0.002**	**0.004**	**0.002**
Moderate versus heavy	**0.02**	**0.01**	**0.06**	**0.03**
Western hemlock				
Light versus moderate and heavy	**0.06**	**0.03**	**0.046**	**0.03**
Moderate versus heavy	0.35	0.23	0.81	0.32

Note: Boldface *P* values indicate a significant difference between treatments and (or) contrast variables.

Fig. 6. Changes over 8 years in (A and B) height, (C and D) stem diameter, and (E and F) height to diameter ratios (H:D) of underplanted conifers in lightly, moderately, and heavily thinned stands. Error bars are 95% confidence intervals. Data points are slightly offset for presentation.

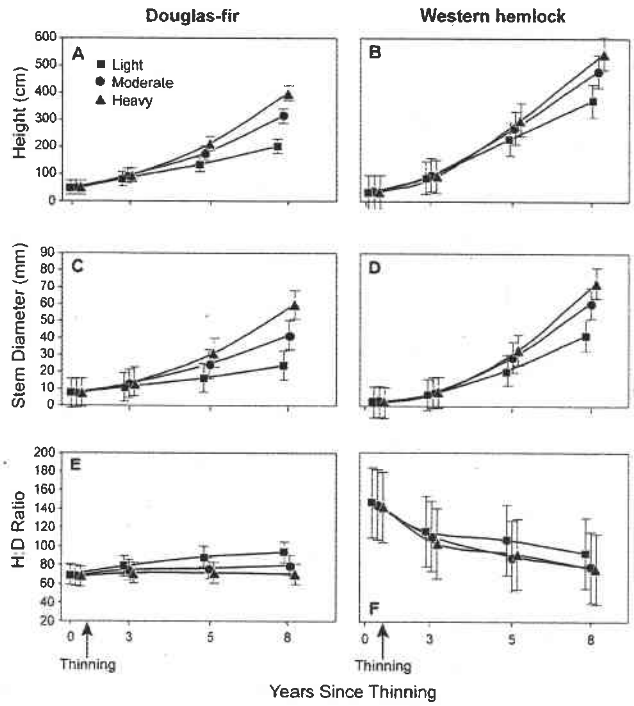
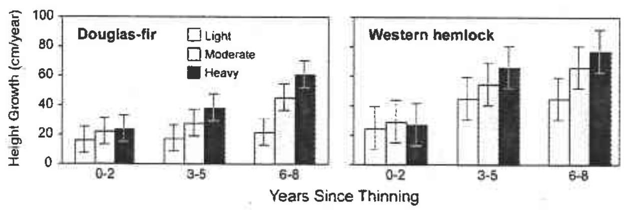


Fig. 7. Changes over 8 years in mean height growth rates of underplanted conifers in lightly, moderately, and heavily thinned stands. Error bars are 95% confidence intervals.



in lightly thinned stands were compared with moderately and heavily thinned stands.

Conifer and hardwood natural regeneration

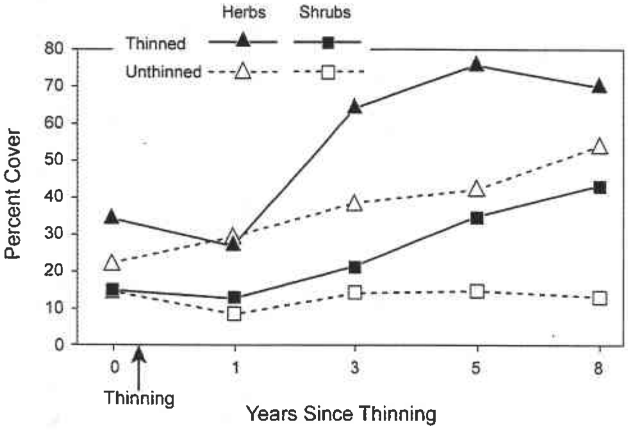
Natural regeneration varied by site 8 years after thinning. Douglas-fir, western hemlock, and red alder (*Alnus rubra* (Bong.)) were present at all three sites, but Sitka spruce (*Picea sitchensis* (Bong.) Carr.) was only present at the Wildcat and Yachats sites, so we focused our analysis on the first three species. Regeneration was absent or sparse in unthinned stands. Western hemlock was the only species found in two of the unthinned stands, and density was estimated to be 17 seedlings/ha. Natural regeneration was not uniformly distributed in the thinned stands. Estimated seedling densities within individual thinned stands ranged from 0 to 3650 seedlings/ha for Douglas-fir, 0 to 1150 seedlings/ha for western hemlock, and 38 to 3688 seedlings/ha for red alder. Mean densities across thinning treatments were 1101 ± 172 seedlings/ha for Douglas-fir, 495 ± 49 seedlings/ha for western hemlock, and 743 ± 240 seedlings/ha for red alder. Estimates for all species combined was 2340 ± 406 seedlings/ha. Mean height of Douglas-fir and western hemlock was similar over all thinning treatments averaging 57.8 ± 1.7 cm for Douglas-fir and 64.3 ± 3.9 cm for western hemlock. Red alder height increased with thinning intensity and was twice as tall in heavily thinned stands (519.5 ± 12.6 cm) compared with lightly thinned stands (252.2 ± 18.1 cm).

Understory vegetation

Overall, % cover and height of dominant shrubs and herbaceous species were similar among thinned treatments, so we only examined differences between thinned and unthinned stands over the life of the study. Physical damage caused by thinning operations tended to reduce both shrub and herb cover, but both responded positively to thinning: by year 8, cover increased two to three times that of prethinning conditions (Fig. 8). In unthinned stands, shrub cover remained stable, whereas herb cover increased from 21% to 53% over 8 years (Fig. 8). Prior to thinning, mean height of five dominant shrubs, salmonberry (*Rubus spectabilis* Pursh), thimbleberry (*Rubus parviflorus* Nutt.), salal (*Gaultheria shallon* Pursh), and two huckleberry species (*Vaccinium parviflorum* Sm. and *Vaccinium ovatum* Pursh), averaged 0.7 m over all treatments. Immediately after thinning, mean height in thinned stands decreased to 0.4 m and increased to 0.9 m after 8 years. Mean height of these shrubs declined to 0.4 m in unthinned stands after 8 years. Prior to thinning, mean height of tall shrubs (e.g., vine maple) averaged 4.9 m over all treatments. After thinning, mean height in thinned stands was reduced to 1.2 m and increased to 2.0 m after 8 years, but decreased to 1.9 m in unthinned stands.

Species richness of shrubs increased with thinning intensity and, after 8 years, ranged from 11 species in unthinned

Fig. 8. Changes over 8 years in % cover of shrubs and herbs in thinned and unthinned stands.



stands to 18 species in heavily thinned stands. Cover by species differed among treatments. Salmonberry cover was greatest in moderately and heavily thinned stands, salal cover was greatest in lightly thinned stands, and vine maple cover was greatest in unthinned stands. Himalayan blackberry (*Rubus discolor* Weihe & Nees), cutleaf blackberry (*Rubus laciniatus* Wild.), and English holly (*Ilex aquifolium* L.) were the only nonnative shrubs present in the stands before and after thinning; cover of each individual species was less than 2% for any treatment. Of the 21 shrub species found, nine were common to all three sites.

Sword fern was considered a dominant herbaceous species in 82% of the vegetation sample plots and distribution was similar in all treatments. Other dominant herbaceous species found in more than 25% of vegetation sample plots were Oregon oxalis (*Oxalis oregana* Nutt.), which was found primarily in unthinned, lightly, and moderately thinned stands; bracken fern (*Pteridium aquilinum* (L.) Kuhn), which was found primarily in thinned stands; and evergreen violet (*Viola sempervirens* Greene), which was found equally in all treatments.

Of the 31 most dominant herbaceous species found in the study, 13 were common to all three sites. The number of dominant herbaceous species found in the 32 vegetation sample plots in each stand was greatest in heavily thinned stands (24 species) and lowest in lightly thinned and unthinned stands (19 species). However, because only the dominant three species were recorded, it is unknown if any herbaceous species were absent from any stand after thinning

Several introduced herbaceous species were found in the stands after thinning and were considered dominant species. Smooth hawksbeard (*Crepis capillaris* (L.) Wallr.), purple foxglove (*Digitalis purpurea* L.), Australian fireweed (*Erechtites minima* (Poir.) DC.), sheep sorrel (*Rumex acetosella* L.), common dandelion (*Taraxacum officinale* G.H. Weber ex Wiggers), and several species of thistles (*Cirsium* spp.) and groundsels (*Senecio* spp.) were present only after thinning. Only purple foxglove was present in a few stands prior to thinning and at a low frequency.

Discussion

Our discussion focuses on the implications of thinning young Douglas-fir plantations to accelerate development of complex stand structure and species diversity. We found that treated stands exhibited positive responses to all three thinning intensities; increased overstory canopy development, moderate to good survival and growth of underplanted seedlings, and increased understory species richness and cover (Figs. 9 and 10). It is important to note that the 8 year period over which we collected data was crucial in the interpretation of the results of this study. There was little change in overstory or understory characteristics during the first 3 years after thinning. We saw the largest changes in vegetative response 5–8 years after thinning. How these stands will continue to change over time is yet to be determined, and we strongly recommend continued long-term monitoring (>20 years) of overstory and understory responses to thinning and rethinning.

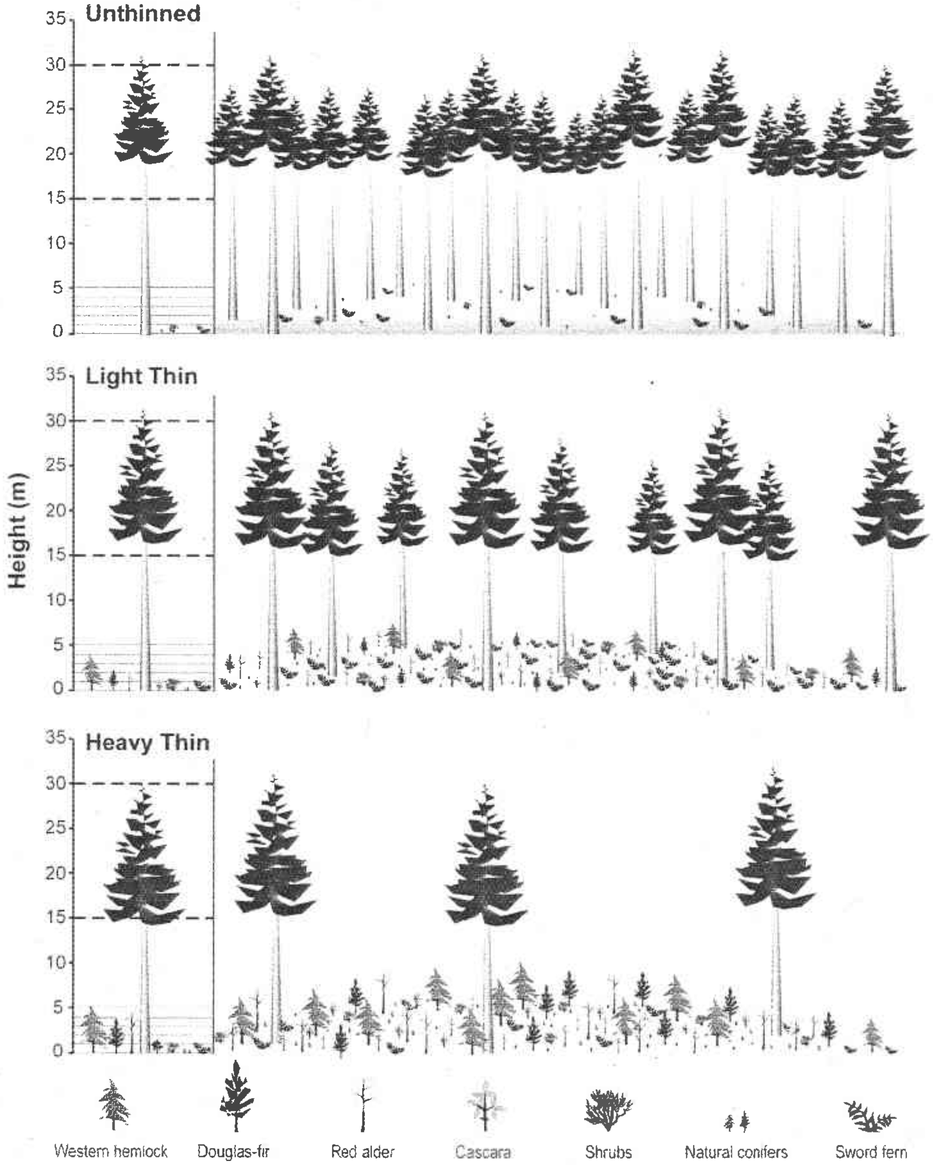
Overstory response to thinning

Despite the loss of some overstory trees from storm damage within thinned subplots, large increases in mean stand BA in moderately and heavily thinned stands indicate that individual trees have accelerated their diameter growth. Trees in both unthinned and lightly thinned stands decreased LCR after 8 years (Fig. 9) indicating crown recession, whereas trees in both moderately and heavily thinned stands maintained LCR. Marshall and Curtis (2002) found that thinning to different densities decreased the rate of crown recession compared with unthinned stands. Crown recession did not occur in our moderately and heavily thinned stands, suggesting increased longevity of lower branches compared with unthinned and lightly thinned stands. Franklin et al. (2002) attributed increased longevity of branches and increasing crown depth in old-growth forests to more open canopies and higher light conditions, which we find associated with our moderate and heavy thinning treatments. Retaining large original branches and the production of epicormic branches were found to enhance structural characteristics of crowns in old-growth Douglas-fir trees (Zenner 2000; Ishii and McDowell 2001, 2002; Franklin et al. 2002). Irrespective of the thinning treatment, most trees in our study plots did not develop epicormic branching in the 8 years after thinning.

Thinned overstory canopies began to close rapidly the third year after thinning. Our data indicates that % skylight through the canopy decreased by an average of 2%/year in all thinning treatments because of the rapid and dynamic live crown development in the stands. Over the 8 year postthinning period, % skylight reaching the understory in lightly thinned stands was reduced to levels that likely slowed growth rates of underplanted conifers compared with moderately and heavily thinned stands.

Strong relationships (r^2 = 0.87–0.95) between % skylight and stand density measures (trees/ha, RD, and BA) were evident after thinning. These relationships, especially for RD and BA, remained strong 8 years after thinning and may aid management decisions on how heavily to thin to achieve long-term stand development objectives. We thinned relatively homogeneous, 30- to 40-year-old Douglas-fir stands

Fig. 9. Stand development 8 years after thinning based on measured median heights of overstory trees and dominant understory vegetation in this study. Diagram on left illustrates the actual measured mean of tree height, overstory crown length, and height of dominant understory components 8 years after thinning in unthinned and lightly and heavily thinned stands.

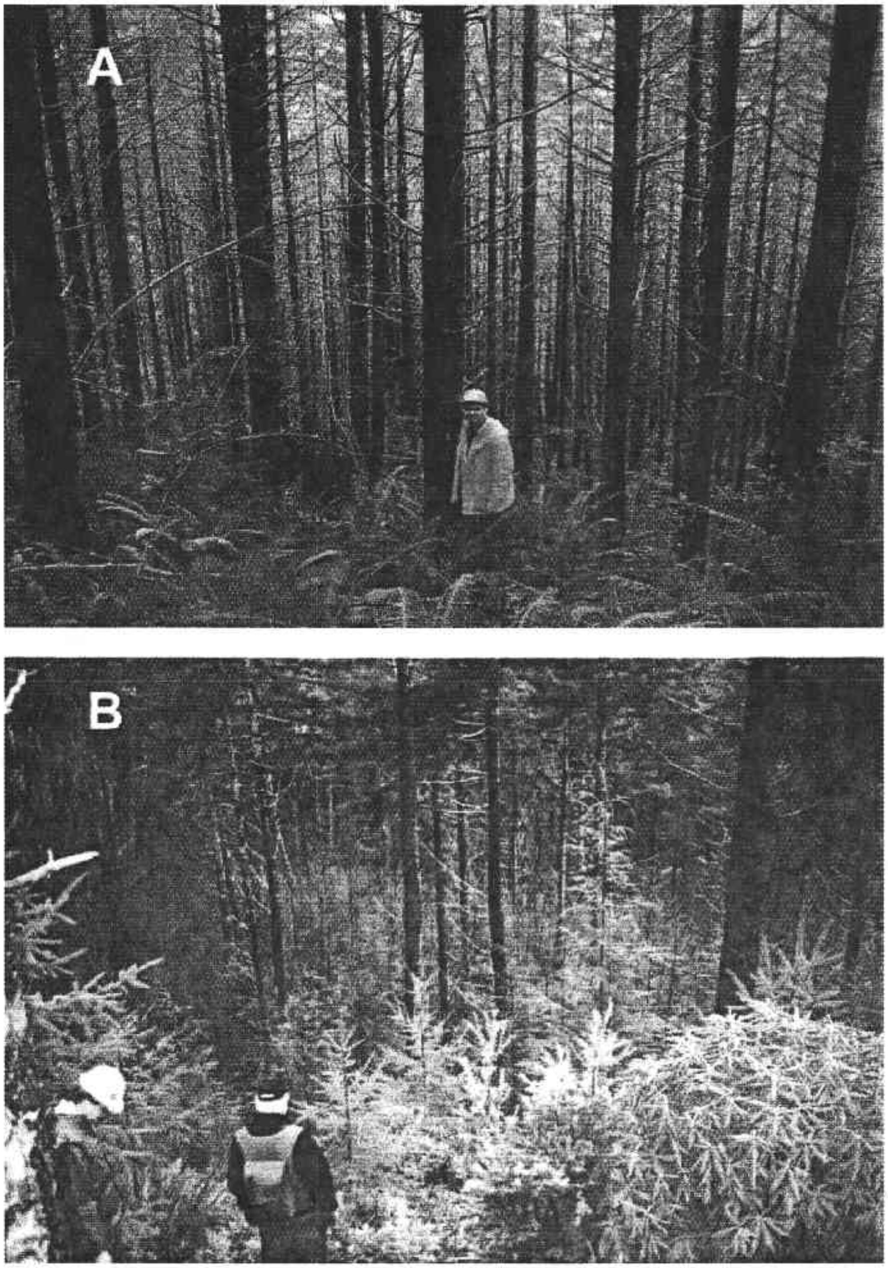


located on the coastal flank of the Oregon Coast Range. Researchers in British Columbia have reported different relationships of light availability to both stand density and BA in aspen stands (Comeau 2001) and Douglas-fir forests (Drever and Lertzman 2003). Therefore, use of these regressions should be restricted to forested stands of similar composition, age, and geographic location.

Underplanted seedling response to thinning

With the exception of Douglas-fir in lightly thinned stands, seedling survival after 8 years was very high. Western hemlock survival ranged from 92% to 96%, and Douglas-fir survival ranged from 64% to 96% in thinned stands. Douglas-fir survival in the lightly thinned stands was low (64%) because survival at the Cataract site was only 13%, and we attribute the high mortality rate to very low mean skylight levels (~5%) in that stand. Survival rates in our study were higher than those reported in other studies where the entire overstory was removed in clearcuts (Ketchum 1995; Stein 1995). Our survival rates were also higher than in a thinning study on the drier, eastern flank of the Oregon Coast Range, where competition by understory vegetation and herbivory affected seedling survival (Brandeis et al. 2001). After four growing seasons, they reported that Douglas-fir and western hemlock survival was 50%–60%. In a species trial conducted on our study sites, Maas-Hebner et al. (2005) reported 8 year survival rates of 87% for Douglas-fir in thinned stands and 94% for western

Fig. 10. Unthinned (A) and heavily (B) thinned treatments underplanted with Douglas-fir and western hemlock at the Cataract site showing differences in overstory tree density, understory vegetation response, and patterns between the overstory and understory 8 years after thinning. The photographs were taken in early spring. The red alder saplings in the background of B have not yet leafed out. All underplanted trees in the unthinned treatments (A) had died by the second year of the study.



hemlock. Additionally, they noted that all Douglas-fir seedlings in unthinned stands died within the first year, and 95% of western hemlock seedlings had died by year 4, which is similar to our plantings.

Both underplanted species exhibited the highest mean annual height and diameter growth rates in the heavily thinned stands. Mailly and Kimmins (1997) and Drever and Lertzman (2001) suggest that light environments lower than 40% will substantially reduce growth rates of conifer seedlings. In both studies, which took place in British Columbia, height growth rates were approximately 20–30 cm/year for Douglas-fir and western hemlock at 40% available skylight. Even though light levels in our study ranged from 8% to 40%, seedling height growth rates (20–80 cm/year between years 5 and 8) equaled or exceeded those reported by Mailly and Kimmins (1997) and Drever and Lertzman (2001). This suggests that moderately shade-intolerant conifer species, such as Douglas-fir, as well as shade-tolerant species, such as western hemlock, can have adequate seedling growth rates in lower light conditions (<40% skylight) to meet stand diversity objectives.

H/D ratios are a way to assess relative suppression of seedlings from surrounding vegetation (Cole and Newton 1987). For Douglas-fir, Cole and Newton (1987) reported that H/D ratios >70 resulted in decreased maximum height growth rates, and seedlings with H/D ratios nearing 100 exhibited little growth and poor vigor. In our study, Douglas-fir H/D ratios were 67–69 at the time of planting and steadily increased over time (ranging from 70 to 93), with the largest increase occurring in the lightly thinned stands indicating increasingly suppressive growing conditions for Douglas-fir in the thinned stands. A similar H:D index for western hemlock is not available. Because hemlock seedlings tend to be taller for a given diameter than Douglas-fir, using Cole and Newton's (1987) values for Douglas-fir is not appropriate, and the higher H/D ratios in western hemlock do not suggest that hemlock is experiencing more suppression than Douglas-fir. The decreases in western hemlock H/D ratios over the 8 year period suggest that the seedlings are not being adversely suppressed by the overstory canopy. At the time of planting, H/D ratios of western hemlock seedlings ranged from 141 to 146. Eight years later, ratios ranged from 76 to 93.

Better seedling growth and H/D ratios were associated with more intense thinning and higher % available skylight levels. However, seedling growth under existing canopies may be affected by other environmental factors (e.g., moisture and (or) nutrient availability). Drever and Lertzman (2001) hypothesized that neither site quality nor moisture levels were as important as light to height growth of Douglas-fir under low-light conditions (<43% available light through the canopy). Chan et al. (2003) found that moisture levels in low-light conditions did not affect aboveground growth of Douglas-fir. In our study, site quality was high, and soil moisture did not appear to be limiting in the temperate, maritime-influenced climate of the region. Therefore, we believe the levels of light produced by different thinning intensities are most likely responsible for the observed differences in growth among treatments of underplanted seedlings.

Natural regeneration in thinned stands

Natural regeneration of Douglas-fir, western hemlock, and red alder was present in our thinned stands, but densities and distributions were highly variable. Eight years after thinning we estimated that there was a similar number of conifer seedlings (1597 seedlings/ha) in our thinned stands, but considerably fewer in our unthinned stands (17 seedlings/ha). Bailey and Tappeiner (1998) found that 40- to 100-year-old thinned Douglas-fir stands had significantly more natural conifer regeneration (primarily Douglas-fir and western hemlock) than unthinned stands. Ten to twenty-four years after various stands were thinned, they found seedling density in thinned stands was 1433 seedlings/ha as compared with 233 seedlings/ha in unthinned stands. Bailey and Tappeiner (1998) also reported that the average seedling density found in their thinned stands was similar to old-growth stands (1010 seedlings/ha).

Natural regeneration is affected by several factors including seed availability, germination site availability, soil moisture regime and temperature, seed predation, herbivory on seedlings, and postemergence diseases such as damping off. We did not determine Douglas-fir seed availability nor did we observe any large cone crops during the course of the study. However, Maas-Hebner and Emmingham (1998) examined cone production in thinned Douglas-fir stands in the northern Oregon Coast Range 2 and 3 years after thinning and observed more cones (Douglas-fir, western hemlock, and red alder) in moderately thinned stands than in unthinned and heavily thinned stands.

Douglas-fir dominated the overstory in our study plots. The few overstory western hemlock trees present in prethinned stands were removed during thinning. However, a few overstory western hemlock trees remained in unthinned stands at two of the three sites. Based on our general observations, western hemlocks were also infrequent in the stands bordering the study sites. Overstory red alder was also removed from the thinned study plots, but some remained within the plot buffers and adjacent riparian areas.

Bailey and Tappeiner (1998) found that seedling density and frequency were positively related to the amount of overstory volume removed during thinning and suggested that more intense thinnings created more microsites for seedling establishment over longer periods of time than less intense thinnings. In our study, thinning and cable yarding logs through designated corridors did not scarify much soil for available seed beds. Immediately after thinning, exposed mineral soil accounted for only 7% of the forest floor in heavily thinned stands, compared with 2.5% in unthinned stands.

The density and growth of naturally regenerated red alder, a shade-intolerant species, in our study added to understory diversity in all thinning treatments. A companion study conducted on the same sites by Maas-Hebner et al. (2005) found that underplanted red alders outgrew all underplanted conifers including Douglas-fir and western hemlock. Eight years after planting, the mean height of the red alder was 7.7 m in the thinned stands (Maas-Hebner et al. 2005). Red alder, a nitrogen-fixing species, has the potential to contribute not just structural diversity in thinned Douglas-fir stands but to forest nutrient cycling and overall species diversity by supporting wildlife species (McComb 1994), insects, and rhizosphere organisms (Bormann et al. 1994) that may not be found in pure conifer forests.

Thinning and understory vegetation

Increased resource availability, including available light in thinned Douglas-fir stands can create conditions that contribute to emergence and accelerated growth of both low and tall shrubs (Tappeiner and Zasada 1993; Bailey and Tappeiner 1998) and herbaceous vegetation (Bailey et al. 1998). Thysell and Carey (2001) reported that variable-density thinning in Douglas-fir stands initially decreased understory vegetative cover but eventually increased the dominance of 20 native species, including 2 tree species. Similarly, Bailey et al. (1998) found that thinned Douglas-fir stands in western Oregon had higher understory diversity and cover of shrubs and herbaceous species than unthinned stands and old-growth stands. In our study, thinning also had positive effects on understory vegetation cover and diversity in all thinning intensities even though cover was initially reduced by thinning. In addition to increasing plant diversity and cover, thinning young Douglas-fir stands can increase the probability of increasing flower and fruit production of some species of understory shrubs (Wender et al. 2004) important for wildlife.

Invasive, exotic plant species in managed stands are a growing concern in the Pacific Northwest. Bailey et al. (1998) concluded that thinning can accelerate the formation of old-growth-type understory communities, but thinning can also increase the frequency of invasive species, which can impede the development of native old-growth forest communities. Only three exotic shrubs and one herbaceous plant species were present in our stands prior to thinning. After thinning, the number of exotic herbaceous species, including perennials such as *Cirsium arvense* (L.) Scop. and *Senecio jacobea* L., increased in number and cover. All of these species are common to the Oregon Coast Range and are present along roads and logging landings (personal observations of the authors). Thysell and Carey (2000) reported that conventional thinning of Douglas-fir in Washington state maintained 19 exotic species for >15 years after thinning. We expect many of the exotic species to remain in our stands until the overstory or understory canopies close to shade out early seral species. Thus, maintaining rapid growth in both the overstory and understory will likely decrease the persistence of early seral invasive species.

Management implications

Silvicultural systems designed to create stand structural complexity and species diversity while producing high yields of wood products are becoming increasingly important to managers (Tappeiner et al. 1997*b*). Thinning offers a way to foster development of naturally occurring old-growth stand structure in a much shorter time frame. Thinning young stands retains deep crowns and promótes understory development (Curtis et al. 1998). Unless otherwise disturbed (e.g., windthrow), heavily stocked young Douglas-fir plantations left unthinned are less likely to produce large trees with healthy crowns or provide satisfactory conditions to establish and maintain a vigorous understory that favors diverse wildlife populations.

Stands that are lightly thinned to RD 4.3–5.8 offer minimal opportunity to create diverse, multistoried stands. Underplanting may facilitate establishment of conifer and hardwood species, but the growth of these seedlings or saplings can be expected to diminish as the overstory canopy closes. Therefore, lightly thinned stands will need one or more additional thinnings on a fairly frequent basis (e.g., 10 year intervals) if management objectives are to maintain LCR, increase stem diameter of overstory trees, accelerate understory vegetation, and promote development of vigorous growth of underplanted and naturally regenerating conifers and hardwoods.

Stands heavily thinned to RD 1.2–1.4 offer an opportunity to develop a vigorous understory for several decades, but with marked reduction in stand volume growth. Computer simulations conducted for thinned Douglas-fir stands suggest that the overstory of such stands will eventually close (Barbour et al. 1997), but we believe that they will retain a significant midstory layer of pole-size, shade-tolerant trees, perhaps to the exclusion of understory vegetation.

Stands moderately thinned to RD 2.2–3.6 may offer a compromise between enhanced stand diversity and timber production, with thinning opportunities at approximately 15 year intervals or longer. The high net BA growth of moderately thinned stands in our study implies that relatively little loss in volume growth is possible at these densities on highly productive sites. Our data support the recommendation by Hayes et al. (1997) for a thinning regime in which stand densities are reduced to RD 3.6 and allowed to grow to RD 6.5. Maintaining a lower RD regime than what is recommended for timber production (RD 5–7.9) should be sufficient to maintain light levels, understory vegetation, and regeneration of merchantable tree species.

Swiss needle cast

Swiss needle cast disease (SNC; caused by the ascomycete *Phaeocryptopus gaeumannii*) has recently emerged as a serious problem in young Douglas-fir plantations in the northern Oregon Coast Range (Hansen et al. 2000). Symptoms of SNC can include loss of the previous year's foliage and a reduction in diameter and height growth (Maguire et al. 2002). In a retrospective study, Mainwaring et al. (2005) assessed the growth of SNC infected Douglas-fir stands thinned 4–10 years earlier. The authors found that BA growth declined with increasing severity of SNC; however, they observed a positive response to thinning, regardless of infection level, based on their analysis of annual trends in BA over the first 5 years after thinning.

SNC became evident in our northernmost study site (Wildcat) 3 years after thinning, where % skylight in the eighth year in the heavily thinned stand was approximately the same as postthinning conditions (about 50%). However, changes in % skylight over 8 years in lightly and moderately thinned stands (which did not exhibit obvious symptoms of SNC) at this site followed the same patterns of decreasing % skylight as sites with no SNC. In areas where SNC is prevalent, reduced overstory growth could delay canopy closure in heavily thinned stands and create favorable conditions for establishing a cohort of nonsusceptible trees. Underplanting hemlock or other tree species not affected by SNC could also increase species diversity.

Summary

The stands that we reported on in this study have changed significantly in 8 years (Figs. 9 and 10), and we expect these stands will continue to develop structurally at different rates depending on thinning intensity and underplanting. Our study supports the hypothesis that thinning can help accelerate development of old-growth structural characteristics in young Douglas-fir plantations (McComb et al. 1993; Tappeiner et al. 1997*a*). Findings from this study suggest that thinning and underplanting can be an effective management tool to accelerate the development of overstory and understory stand characteristics leading to structurally complex and diverse stands. Underplanting may be necessary to supplement sparse natural regeneration in thinned stands when tree species and structural diversity is a management goal. More research is needed on the interactions between thinning intensity and cone and seed production and how seasonal weather and precipitation patterns may influence seed availability. This information could aid managers in determining if artificial regeneration may be necessary to promote diversity in some stands.

Although shrub and herbaceous cover developed within the first 5 years after thinning, their presence did not appear to impede the successful establishment of underplanted trees. Additionally, both shrub and dominant herbaceous plant species increased in thinned stands, with heavy thinning providing the greatest opportunities for increasing plant species diversity (Fig. 9). Thus, thinning combined with underplanting has accelerated the development of a multilayered canopy structure by increasing light availability that enhanced overstory crown size and promoted understory development (Figs. 9 and 10).

In temperate, mesic environments such as the west slope of the central and northern Oregon Coast Range, we conclude that light availability is a principal driver in many of the processes that lead to increasing stand diversity and complexity. Our results indicate that a substantial number of trees must be thinned to increase light availability to the understory. Furthermore, the rapid reduction in light levels in the lightly thinned stands suggests that thinning to these levels will provide only a short-term benefit for diversity goals. Even with heavy thinning, the overstory canopy began to fill in rapidly after 3 years. The high rates of canopy closure attest to the rapid growth dynamics of tree canopies in mesic environments and point to the need for further thinning in moderately thinned stands in the near future.

Our study sites were in highly productive stands in a low-elevation, mesic environment. Inferences from this study can best be applied to managed forests where similar conditions exist. Under less favorable conditions, different responses and rates of overstory structural development, survival and growth of underplanted conifers, and understory vegetation development may occur. Our results on thinning and underplanting should generally apply to plant associations in which western hemlock is the climax tree species in the coastal mountain regions of the Pacific Northwest.

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