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Establishment and growth of native hardwood and conifer seedlings underplanted in thinned Douglas-fir stands

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Abstract

Five conifers and two hardwoods native to the Pacific Northwest were planted under four overstory densities of 30-year-old plantations of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) in the Oregon Coast Range, USA. Stand treatments were unthinned (547 trees ha^{-1}), narrow thin (252 trees ha^{-1}), wide thin (138 trees ha^{-1}), and very wide thin (72 trees ha^{-1}). Conditions in the unthinned stands were lethal to both hardwoods and conifers. Eighth-year survival in thinned stands ranged from 87 to 94% for conifer species and 61 to 94% for hardwood species. Eighth-year mean heights of conifer species ranged from 2.6 to 5.4 m. On the basis of size and damage incurred during the study, we ranked conifer species in decreasing order of suitability for underplanting as western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), Sitka spruce (*Picea sitchensis* (Bong.) Carr.), Douglas-fir, grand fir (*Abies grandis* (Dougl. ex D. Don) Lindl.), and western redcedar (*Thuja plicata* Donn ex D. Don). Eighth-year mean height of red alder (*Alnus rubra* (Bong.)) was 7.7 m in thinned stands. Heavy and repeated browse (mostly from elk, *Cervus elaphus*) on bigleaf maple (*Acer macrophyllum* Pursh) and to a lesser degree on western redcedar led us to conclude that these species may be unsuitable for underplanting unless they can be adequately protected. The other five conifer species and red alder suffered little damage during the study and are all viable choices for underplanting where diversity enhancement is an objective. Major findings from this study are (1) underplanting was successful (good survival and size) when the overstory canopy was thinned to wide or very wide spacings and available light was markedly increased; (2) fast growth of planted seedlings such as red alder, western hemlock, and Sitka spruce can enhance stand structure early in the development of thinned stands; (3) the level of thinning intensity affects light availability in the understory and will determine the vitality and longevity of underplanted seedlings; and (4) animal damage, mostly from elk browse and antler rubbing, varied by species and by size of seedlings but can be so serious as to limit the choice of seedlings.

Keywords: Oregon; Regeneration; Species diversity; Structural diversity; Thinning; Underplanting

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1. Introduction

Previous logging, catastrophic fires, and regeneration practices in the Oregon Coast Range, USA, have favored high-density, second-growth stands of Douglas-fir (*Pseudotsuga menziesii* (Mirb. Franco)), developing with uniform density from a single cohort. Tappeiner et al. (1997) found that most young plantations were nearly pure Douglas-fir and varied little in tree size and age. Mature or old-growth forests that developed without management were often multi-aged and had several species present, including Douglas-fir, western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), and western redcedar (*Thuja plicata* Donn ex D. Don). Bailey and Tappeiner (1998) found that densities of seedlings and saplings in thinned Douglas-fir stands were similar to those in old-growth forests; however, seedling density and frequency in thinned stands were strongly related to the volume removed and the stand density index just after thinning.

In the Douglas-fir region of the Pacific Northwest, federal and state agencies adopted guidelines to increase stand structural complexity and species diversity of plants and wildlife (USDA and USDI, 1994; Oregon Department of Forestry, 1998). The recent wide-scale spread of Swiss needle cast disease (*Phaeocryptopus gaeumannii*) in young Douglas-fir stands has also prompted managers to examine the possibilities of increasing species diversity by under-planting non-susceptible species in thinned stands (Kanaskie et al., 1996). Thinning plantations to encourage understory development is one tool being used to diversify stands (Curtis et al., 2004). The interest in performance of regeneration in understories for a variety of silviculture systems appears to be widespread (Turnbull, 1991; Wright et al., 2000; Ammer, 2002; Diaci, 2002; Nilsson et al., 2002), and several large-scale management studies have been initiated in the Pacific Northwest region of North America (Monserud, 2002).

Commercial thinning, followed closely by under-planting, presents an opportunity to increase stand structural diversity and plant and wildlife species diversity by establishing an understory of one or more native tree species. A mixture of hardwood and conifer species will increase species diversity, and growth rate differences among species will promote multiple canopy layers.

Natural regeneration and planted nursery stock are two options for establishing conifers and hardwoods in thinned stands. Natural regeneration is viewed favorably as a low cost, "natural" way to add diversity or reduce management costs in central and northern Europe (Mantel, 1990; Ammer, 2002). Natural regeneration may occur when seed sources are present at the time of disturbance, but it may not provide the desired species composition, distribution or density in a timely manner. Natural regeneration may not occur early enough after thinning to allow intermediate or shade-intolerant species to become established in the understory before canopy closure. If the overstory is allowed to grow to high densities again, even established regeneration can become suppressed or die.

Previous planting trials have examined how some native species, particularly Douglas-fir, grow in open conditions following a clearcut, at various planting densities, or in competition with shrubs (e.g. Howard and Newton, 1984; Chan and Walstad, 1987; Newton et al., 1993), but few have evaluated a variety of species performances under an existing Douglas-fir canopy. Ketchum (1995) and Brandeis et al. (2001) examined only a few underplanted species over a short period (4 years or less).

The objectives of this study were (1) to determine if Douglas-fir, western hemlock, western redcedar, Sitka spruce (*Picea sitchensis* (Bong.) Carr.), grand fir (*Abies grandis* (Dougl. ex D. Don) Lindl.), bigleaf maple (*Acer macrophyllum* Pursh), red alder (*Alnus rubra* (Bong.)), and Pacific yew (*Taxus brevifolia* Nott.) can be established within thinned and unthinned Douglas-fir stands in the Oregon Coast Range, (2) to quantify the survival and growth of each species and determine the effects of three thinning intensities, and (3) to describe the amount and type of damage sustained by seedlings growing in the understory. Growth, survival, and condition or damage for the main tree species of the Oregon Coast Range are presented for the first 8 years after planting.

2. Methods

2.1. Treatments

Treatments were replicated across three sites (referred to as plantations). Three 30-year-old

Douglas-fir plantations on the west flank of the Oregon Coast Range were commercially thinned: Cataract (lat 44°E07′N, long 123°E95′W), Yachats (lat 44°E28′N, long 123°E94′W), and Wildcat (lat 45°E2′N, long 123°E78′W). The plantations are in the western hemlock/sword-fern (*T. heterophylla/Polystichum*) plant association (Franklin and Dyrness, 1988). Although the plantations are on the coastal flank of the Coast Range, they are not within the coastal fog zone. Mean monthly temperatures range from 6 °C in January to 16 °C in July (Taylor and Bartlett, 1993). Precipitation averaging 165–229 cm per year falls predominately as rain during the dormant season; summers are often warm and dry (Taylor and Bartlett, 1993). Damaging or killing frosts are infrequent.

In the early 1960s, these plantations were established artificially with Douglas-fir seedlings after clear-cut harvesting and site preparation with fire and herbicides. The plantations were pre-commercially thinned approximately 15 years after planting. At age 30, stand densities averaged 625 trees ha^{-1}. Each plantation (replicate) was partitioned into four overstory density treatments: (1) unthinned control (C), averaging 547 trees ha^{-1}; (2) narrow thin (NT), averaging 252 trees ha^{-1}; (3) wide thin (WT), averaging 138 trees ha^{-1}; and (4) very wide thin (VWT), averaging 72 trees ha^{-1}. Stand metrics of overstory treatments are shown in Table 1. The Cataract site was thinned in fall 1992. The Yachats and Wildcat sites were thinned during summer 1993. Logs were yarded from the sites by suspended cable systems along designated corridors. Understory vegetation was not controlled before planting or during the study. During the first year after thinning, average vegetation cover ranged from 33 to 37%. The thinning operations decreased height and cover of many shrub and herbaceous species. Conifer and hardwood species were planted in two separate plots to account for the potential influence of inherent differences in height, form, and periodicity of growth between conifers and hardwoods. Stock age and type did vary by species and availability (Douglas-fir and grand fir were 1 + 1; Sitka spruce was plug + 1 at Wildcat and 1 + 1 at the other sites; western redcedar and western hemlock were plug + 1; red alder and bigleaf maple were 1 + 0). Stock was from seed sources appropriate to the planting locations. Proper on-site storage and handling techniques were used. All seedlings were planted with planting shovels or hoes and protected with 0.6-m tall plastic mesh tubing.

Six species of conifers were underplanted at 1.5 m × 1.5 m spacing in each of the four treatments during the winter after thinning: Douglas-fir, grand fir, western redcedar, western hemlock, Sitka spruce, and Pacific yew. Each species was planted in 13 four-seedling clusters arranged as a 6 × 13 grid of randomly selected clusters, for a total of 52 seedlings of each species. The study followed a total of 624 seedlings of each conifer species. Rooted cuttings of Pacific yew were not available when the other species were planted and did not experience the same early growing conditions as the other species; therefore, data for yew are not included in this paper.

Seedlings were planted at Cataract in winter 1993 and at Wildcat and Yachats in winter 1994. At Cataract, all but the NT treatment were planted on a north-facing slope; the NT treatment was planted on a south-facing slope. All seedlings at Wildcat were on a southwest-facing slope, and at Yachats they were on a northwest-facing slope.

Red alder and bigleaf maple were planted in each of the four overstory treatments in the winter of 1994 at all three sites. Each planting plot consisted of six rows of 16 seedlings spaced 2.4 m × 2.4 m apart; red alder and bigleaf maple were planted in alternate rows. A total of 48 seedlings/species/treatment were planted on each site. The study followed a total of 576 seedlings of each hardwood species.

Table 1
Douglas-fir overstory stand characteristics during the first year after thinning

Thinning treatment	Density (trees ha^{-1})	Mean diameter at breast height (cm)	Mean basal area (m^2 ha^{-1})	Relative density[a]	Canopy opening (%)
No thin	547	32.8	44.1	54	2
Narrow thin (NT)	252	34.3	23.7	28	15
Wide thin (WT)	138	35.9	14.2	16	27
Very wide thin (VWT)	72	35.4	7.2	8	48

[a] Relative density = $(G/Dg)^{1/2}$, where G = basal area and Dg = quadratic mean stand diameter (Curtis, 1982).

2.2. Species

The coastal variety of Douglas-fir is intermediate in shade tolerance and is considered a seral species that may be replaced by western hemlock, western redcedar, and Sitka spruce over long successional sequences (Hermann and Lavender, 1990). Western hemlock is very shade tolerant and is a climax species, either alone or with its shade-tolerant associates, western redcedar and Sitka spruce (Packee, 1990). Western redcedar is often present in all stages of succession and is usually considered a climax or near-climax species. It is rarely found in pure stands (Minore, 1990). Sitka spruce is a seral to climax species, usually growing in mixed stands. Its natural range is restricted to maritime climates with mild wet winters, but may extend inland along riparian corridors (Harris, 1990). Grand fir is shade tolerant and usually grows in mixed stands. It is considered a climax species, especially in forests on the eastern edge of the Coast Range (Foiles et al., 1990).

Bigleaf maple is shade tolerant and often seeds into undisturbed stands during intermediate and late succession. It occurs as dominant, codominant, or intermediate trees in even or uneven-aged stands (Minore and Zasada, 1990). Red alder is a shade-intolerant pioneer species that rapidly colonizes heavily disturbed areas. With rapid juvenile growth it can outgrow most northwestern conifers (Harrington, 1990).

2.3. Measurements

Seedlings were measured (stem diameter 15 cm above ground and total stem height to highest live bud) after planting and after the fourth and eighth growing seasons. Height to diameter (H:D) ratios were calculated to assess relative suppression of seedlings from surrounding vegetation (Cole and Newton, 1987). Seedling survival and condition were also assessed. Conditions monitored included browse, stem tissue dieback, antler rubbing, insect damage, disease, broken main stems, and stem deformities such as multiple leaders and multiple stems. To better reflect operational management practices, we minimized seedling care by not untangling seedlings from tubes, replacing missing tubes, or removing overstory debris that fell on seedlings.

Because conifer and hardwood plots were small (<0.08 ha), blowdown of one or more overstory trees near or within the plots or placement of plots near stand edges, logging roads, or landings may have affected the light available to underplanted seedlings. Therefore, the percent of available light (PAL) to some plots may have been greater than average values for light in the larger treatment area, potentially confounding analysis and interpretation. To test this effect, eight hemispherical photographic images were taken around the perimeter of each conifer species trial plot after the eighth growing season (ninth growing season for Cataract). Photographic images were taken approximately 1 m above the forest floor with 100 ASA 35-mm black-and-white slide film and a single-lens reflex camera with a 7.5-mm equal-distance fisheye lens. Developed images were analyzed with the CANOPY hemispherical analysis software (Rich, 1989) to determine the average PAL for each species trial plot.

2.4. Data analysis

We used a randomized complete-block design with sites as replicates to compare differences among treatments in height, stem diameter 15 cm above the ground, and H:D ratios of the five conifer and two hardwood species. To reflect treatment effects accurately in the analysis, we included only seedlings not experiencing growth-limiting damage (browsing of terminal leaders, leader death caused by insect damage, antler rubbing of stem, stem breakage, and tubing damage) severe enough to have caused heights to be less than the previous measurement. Because early mortality was extreme in unthinned stands, seedlings in those stands were not included in the analyses.

We assessed the influence of thinning over time on planted seedling size and survival by analysis of variance for year 0 and analysis of covariance (PROC MIXED; SAS Institute, 1999) for years 4 and 8 because all seedlings were uniquely marked at time of planting. All years were analyzed separately. We used Fisher's protected LSD (Ramsey and Schafer, 1997) when analyzing eighth-year data to separate means for significant main effects ($P < 0.1$ for thinning treatment, species, or treatment-species interactions). Because the number of replications was small

($n = 3$), we considered $P < 0.1$ to be statistically significant to reduce the chances of committing type II errors.

Linear regression analysis (PROC GLM; SAS Institute, 1999) was used to model stem diameter as a function of PAL at each conifer plot to determine if differences in light availability may have influenced underplanted seedling growth more than treatment effects. However, because each stand was treated as a unique stand regardless of site or treatment, these results should be considered experimental. In all statistical analyses, we examined response variables for normality and constant variance, using histograms and residual plots (Sabin and Stafford, 1990; PROC UNIVARIATE; SAS Institute, 1999). For ANOVA and ANCOVA, all response variables met these assumptions, and no transformations were needed. In the linear regression, we used 1/PAL as a variance stabilizing transformation for analysis of stem diameter as a function of light.

3. Results

3.1. Survival of underplanted conifers

In unthinned stands, all Douglas-fir and grand fir had died within the first year. All Sitka spruce seedlings had died within the first 2 years, and 95% of western hemlock and 65% of western redcedar had died within the first 4 years. In thinned stands, survival of underplanted conifer species 4 years after planting was high, averaging 95% and ranging from 91% for Douglas-fir to 98% for Sitka spruce. Most early mortality appeared to be related to condition before planting (for example, some redcedars experienced freezing temperatures during storage at the nursery), with most seedlings dying in the first year. Falling overstory limbs and uprooted trees during winter rainstorms in the third and fourth years killed a few seedlings.

Eight years after planting, survival of underplanted conifer species in thinned stands continued to be high, ranging from 87% for Douglas-fir to 94% for grand fir and western hemlock and averaging 91%. Survival of seedlings did not differ significantly among thinning treatments ($P = 0.56$) or species ($P = 0.51$), and there was no significant interaction between thinning treatment and species ($P = 0.19$). Most mortality of western hemlock and Sitka spruce between years 4 and 8 was caused by elk (*Cervus elaphus*) antler rubbing that scraped the cambium layer on one or more sides of the seedlings. Douglas-fir mortality tended to be higher in NT stands.

3.2. Conifer seedling size

Initial seedling size was consistent among sites and treatments, but varied among species. Planting heights ranged from 0.3 to 0.6 m, with western redcedar taller and grand fir shorter than the other species. After eight growing seasons, there was a significant height difference between species, but no treatment effect or interaction between treatment and species (Table 2). All species differed significantly from one another except for grand fir and Douglas-fir, which were similar in height (Fig. 1a). On average, western hemlock was 3.6 times taller than the shortest species, western redcedar.

Stem diameters at planting ranged from 0.3 to 0.6 cm, with Douglas-fir having the largest mean diameter and western hemlock the smallest. After eight growing seasons, there was a significant diameter difference between species, but no thinning treatment effect or interaction between treatment and species (Table 2). All species differed significantly from one another except for grand fir and Douglas-fir, which were similar (Fig. 1b).

At the time of planting, mean seedling H:D ratios ranged from 62 to 177, with western hemlock having the highest ratio (Fig. 1c). After eight growing seasons, treatment significantly affected H:D ratio, but no species effect or interaction between treatment and species was apparent (Table 2). Mean H:D ratio

Table 2
Summary of ANOVAs for seedling survival, seedling height, stem diameter 15 cm above the ground, and height:diameter (H:D) ratio 8 years after planting in thinned stands

Source of variation	d.f.	Probability > F			
		Survival	Height	Diameter	H:D ratio
Species	4	0.51	**0.0001**	**0.0001**	0.14
Thinning treatment	2	0.56	0.20	0.11	**0.08**
Species × treatment	8	0.19	0.42	0.42	0.80

Unthinned stands are not included. Numbers in bold indicate effects significant at $P \leq 0.1$.

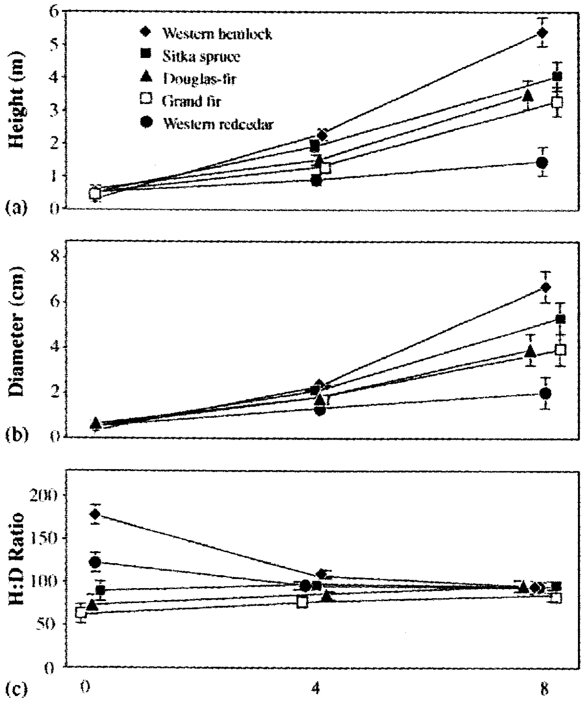

Fig. 1. Differences in height, diameter, and H:D ratios of five species of conifer seedlings underplanted in narrow (NT), wide (WT), and very wide thinned (VWT) stands. Measurements were taken at time of planting (year 0), 4 years, and 8 years after planting. Error bars are standard errors. Points at years 4 and 8 are offset for clarity.

was significantly higher in NT (H:D = 92) stands than in VWT stands (H:D = 79). The mean H:D ratio in WT stands (H:D = 87) was similar to the other two treatments. Over the 8 years, mean H:D ratios of all species converged (Fig. 1c).

3.3. Available light in conifer plots

PAL passing through the canopy to the individual planting plots was highly variable and did not always correspond well to thinning intensity when compared with PAL measured over a larger area of the thinned plantations (Table 3). Linear regression that modeled stem diameter after 8 years (9 years at Cataract) as a function of PAL proved to be a better indicator than analysis of variance. Goodness-of-fit (R^2) of the regression of an inverse function of light against diameter growth ranged from 0.64 to 0.89 (Fig. 2). With the exception of western redcedar, shapes of regression lines were similar among species, with the greatest increase in growth rates occurring between 10 and 20% available light. At light levels greater than 20%, increases in growth rates slowed but had not reached an upper asymptote at the upper range of light found in these stands. In all species, diameter growth at 20% available light was greater than 50% of total growth seen at 40% available light.

3.4. Survival of underplanted hardwoods

In unthinned stands, all red alder had died within 2 years after planting, and <1% of bigleaf maples had survived 4 years after planting. In thinned stands, 4 and 8 years after planting, there was no thinning treatment effect ($P = 0.66$ and 0.61, respectively) on

Table 3
Percent of available light [mean (range)] through the canopy from eight fish-eye photographs taken around conifer species trial plots, compared with mean percent of available light from 20 fish-eye photographs taken in larger thinned stands adjacent to the species trial plots

Thinning treatment	Site	Available light in	
		Species trial plots (%)	Adjacent stands (%)[a]
Narrow (NT)	Cataract	9 (6–12)	5 (2–10)
	Wildcat	20 (14–30)	12 (5–22)
	Yachats	14 (7–28)	9 (5–15)
Wide (WT)	Cataract	12 (10–16)	20 (9–34)
	Wildcat	27 (22–35)	18 (12–27)
	Yachats	35 (22–55)	14 (7–21)
Very wide (VWT)	Cataract	27 (22–30)	29 (13–37)
	Wildcat	42 (39–60)	51 (39–61)
	Yachats	28 (23–34)	33 (19–51)

[a] Values for percent available light in adjacent thinned stands from Chan et al. (Forest Science Laboratory, Corvallis, OR; in preparation).

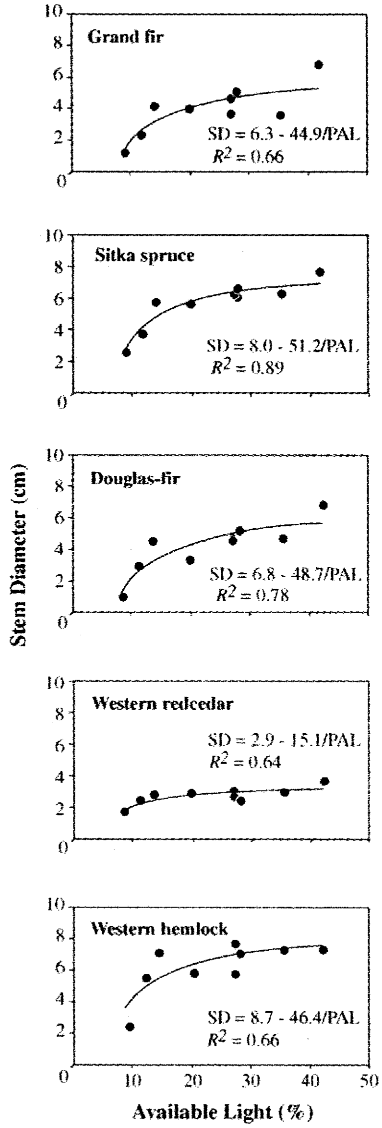

Fig. 2. Observed and fitted values for the relationship of conifer seedling stem diameter (SD) at 15 cm above ground to percent available light (PAL) in nine trial plots 8–9 years after thinning.

hardwood survival, but there was a species effect ($P = 0.007$ and 0.0008, respectively). There was no interaction between treatment and species in either year 4 or 8 ($P = 0.99$ and 0.58, respectively). After 4 years, survival was higher in red alder than in bigleaf maple across all thinning treatments (96% versus 90%, respectively). Half of the early mortality occurred before the end of the second growing season and may have been due in part to poor stock quality, handling during planting, or planting shock. After 8 years, red alder survival (94%) remained higher than that of bigleaf maple (64%) across all thinning treatments.

3.5. Hardwood seedling size

Seedling sizes at time of planting were consistent within each species across all treatments and sites. Bigleaf maple seedlings (0.6 m height, 0.6 cm diameter) were larger when planted than red alder (0.4 m height, 0.4 cm diameter). Because of severe browsing by elk on bigleaf maple during all eight growing seasons, we were not able to determine thinning treatment effects on bigleaf maple growth; seedling size reflected frequent browse damage more than it did growing conditions. Therefore, we did not test for treatment differences in bigleaf maple. Eight years after planting, maples averaged 1.3 m (S.E. = 0.7) in height and 1.2 cm (S.E. = 0.6) in diameter, with an average H:D ratio of 117 (S.E. = 35).

Eight years after planting, thinning treatment did not affect red alder height ($P = 0.18$), but did affect diameter ($P = 0.04$) and H:D ratio ($P = 0.08$). Mean seedling height was 7.6 m (S.E. = 2.7) across all treatments. Mean diameter was significantly larger in WT and VWT treatments than in NT treatments (Fig. 3). Mean H:D ratio was significantly lower in VWT than in NT, while mean H:D ratio in WT was similar to the other two treatments (Fig. 3).

3.6. Condition and damage of underplanted seedlings

The amount and type of damage to conifer and hardwood seedlings differed by species but in general did not appear to consistently differ in relation to the thinning densities, so data were pooled across thinning treatments. Most conifers and hardwood seedlings (90–97%, range by species) were in good condition at planting. Seedlings not starting in good condition had multiple stems or tops when they came from the nursery. Multiple leaders, but not multiple stems, increased in later years as a resulted of on-site animal browsing or insect damage to apical buds.

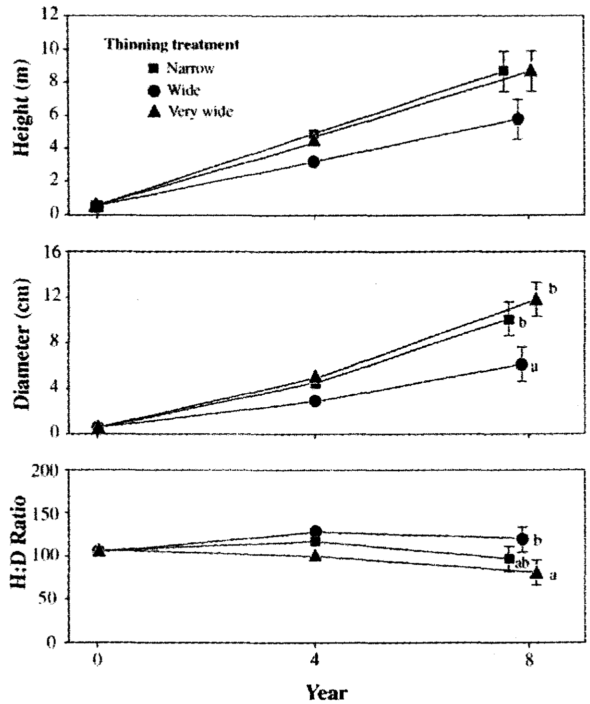

Fig. 3. Temporal trends in height, diameter, and H:D ratios of red alder seedlings underplanted in narrow (NT), wide (WT), and very wide (VWT) thinning treatments. Measurements were taken at time of planting (year 0), 4 years, and 8 years after planting. Error bars are standard errors. Letters indicate significant difference among treatments 8 years after planting ($P < 0.1$). Points at years 4 and 8 are offset for clarity.

Early on-site damage to seedlings was related to wildlife browse, leader entanglement in the mesh tubes (referred to as tubing damage), and pinning or stem breakage from windthrown overstory trees or fallen branches. Later, conditions affecting form and growth included browse, antler rubbing, insects, and foliar disease. Broken, leaning, or pinned stems were infrequent (<2.5%) and usually resulted from falling overstory branches, windthrow, high wind (wind-whipped), elk activity, or mesh tubes overgrown and entangled by understory vegetation. Most damage from windthrown overstory trees occurred during the second and third years.

Browse on Douglas-fir, Sitka spruce, grand fir, and western hemlock was usually <10% each measurement period, whereas >60% of western redcedar seedlings were browsed (Table 4). Redcedars with repeated browse were considerably shorter than those with no or limited browsing. Mean 8-year height of unbrowsed redcedars was 2.4 m. Redcedars occasionally browsed (browse reported for either year 4 or year 8) had a mean height of 2.0 m. Seedlings that were frequently browsed (browse reported for both years 4 and 8) averaged 1.5-m height. Bigleaf maple typically sustained more damage than red alder from elk browse and associated die-back of stem tissue. After 4 years, 76% of bigleaf maple seedlings were heavily and repeatedly browsed by elk, and after 8 years 93% of all seedlings had been browsed (Table 4).

Bull elk antler rubbing damage was reported in years 4 and 8. In year 4, antler damage was low for most species, and increased between years 4 and 8, especially Sitka spruce. Mean diameter of conifer seedlings rubbed during the study was 2.5 cm (S.E. = 0.2); mean height was 2.1 m (S.E. = 0.2). Antler rubbing killed 23 conifer seedlings; in addition, 95 seedlings survived damage. The larger size of red alder in years 4 and 8 also placed them at risk of elk rubbing (Table 4). Mean diameter of red alder seedlings rubbed during years 4 and 8 was 5.5 cm

Table 4
General condition and selected damage (%) to living conifer and hardwood seedlings underplanted in thinned Douglas-fir stands after the fourth and eighth growing seasons

Species	Survival		Good condition		Multi-top/ multi-stem		Browsed		Tubing damage		Antler damage	
	4th	8th	4th	8th	4th	8th	4th	8th	4th	8th	4th	8th
Western hemlock	96	93	76	84	9	6	<1	0	11	<1	1	1
Sitka spruce	98	90	68	46	9	12	<1	0	15	<1	8	12
Douglas-fir	91	87	64	75	17	9	<1	0	7	<1	<1	<1
Grand fir[a]	97	94	83	19	4	4	0	0	6	1.0	<1	4
Western redcedar	91	91	28	16	2	3	63	69	3	<1	2	5
Red alder	96	94	78	88	6	6	<1	0	5	<1	6	<1
Bigleaf maple	89	61	19	4	1	0	76	93	1	<1	0	0

[a] By year 8, the majority of grand fir exhibited signs of chlorotic foliage and therefore were not considered to have good condition.

(S.E. = 0.2), and mean height was 4.8 m (S.E. = 0.2). As seedlings grew, they appeared to be less susceptible or less favored by elk.

Insect damage to seedlings (generally to terminal or lateral buds) was infrequent during the first during the studies except for Sitka spruce (data not shown). By year 8, white pine weevils (*Pissoides strobi*) had damaged and killed the leader in 28% of Sitka spruce.

Significant chlorosis of foliage occurred during year 1 on western redcedar when 21% of redcedar seedlings had symptoms. Chlorotic foliage on redcedar resulted from partial freezing during preplanting storage of seedlings planted at Cataract. In year 4, no chlorotic foliage was noted. By year 8, 59% of grand fir had chlorotic spotting on needles, but this did not appear to affect growth.

4. Discussion

4.1. Survival

After 8 years, six of the seven underplanted species had been successfully established with survival >80% in thinned stands, whereas all plantings in the unthinned stands failed within the first 2 years. Bigleaf maple was the exception, with only 64% survival and poor growth in thinned stands. Causes for increased mortality of bigleaf maple between years 4 and 8 are uncertain, but we suspect a combination of long-term severe browsing and overtopping by competing shrubs and other vegetation.

Survival of underplanted conifers and hardwoods was equal to or greater than that reported in several studies for open-grown seedlings planted after coastal region clearcuts (Omule, 1988; Radwan et al., 1992; Ketchum, 1995; Hardwood Silviculture Cooperative, 1997). Brandeis et al. (2001) reported lower overall early survival of conifers planted in thinned Douglas-fir stands at the drier, eastern edge of the Oregon Coast Range than we observed. At lower overstory densities (16.0–18.3 and 18.4–20.6 m^2 ha^{-1}basal area retention), 4-year survival rates for western redcedar (>90%) and grand fir (89–98%) were similar to ours. Survival of Douglas-fir (40%) and western hemlock (50–60%), however, was much lower, perhaps because of greater competition for moisture on the drier sites. In Oregon Coast Range locations similar to those studied by Brandeis et al. (2001), Ketchum (1995) also reported 4-year survival rates in 0.2-ha gaps and shelterwood density Douglas-fir stands for Douglas-fir (85.3 and 80.3%, respectively) and grand fir (88.4 and 77.8%, respectively) planted at 24–30 trees ha^{-1}. We know of no studies that report survival for planted seedlings of red alder or bigleaf maple under existing canopies.

4.2. Seedling size

Mean heights of western hemlock and Sitka spruce in our study were similar to those reported for open-grown seedlings (Smith and DeBell, 1973; Omule, 1988; Mayhead and Jenkins, 1992).

Mean height of underplanted Douglas-fir in the two wider thinning treatments appeared similar to that found in other studies reporting values for open-grown seedlings, but mean heights in the NT tended to be lower than reported values (Smith and DeBell, 1973;

Omule, 1988; Minore and Weatherly, 1990). Douglas-fir is considered intolerant to intermediate in shade tolerance. We expect growth in the NT and WT treatments to decrease as the overstory canopies close. Douglas-fir would benefit from repeated thinnings of the overstory. Based on their study on Vancouver Island, British Columbia, Drever and Lertzman (2001) suggested that light environments >40% of full sun are needed for good growth of Douglas-fir seedlings. Our data show it growing well at approximately 30–40% of full sun.

Grand fir growth has not been widely studied in the Coast Range. In general, grand fir seedlings are thought to grow well under moderate shade, whereas growth under full sun is less than that of faster growing, shade-intolerant species (Foiles et al., 1990). Seedling size in our study appeared similar to values reported from provenance trials in western British Columbia (Xie and Ying, 1993). Understory vegetation management significantly increased grand fir growth and size in thinned stands on the Willamette Valley/Coast Range margin (Brandeis, 1999). We did not control understory vegetation in our study, and our grand fir seedlings may have benefited from some level of vegetation management.

At 4 and 8 years after planting in thinned stands, red alder grew better than any of the conifers, but less than that reported by Harrington and Curtis (1986) and Harrington et al. (1994) for open-grown alders. They reported maximum height growth of >3 m annually under open conditions for 2- to 5-year-old red alder. DeBell and Giordano (1994) reported that alder planted on a good site at moderate density averaged 13 m tall and 11 cm diameter at 8 years of age; values similar to those we report for alder in VWT. Our study showed that VWT provided good growth conditions for the first 8 years and the alder may grow into a midstory position within the canopy. We do not, however, expect this to happen in the NT and WT treatments, where canopy closure will be more rapid.

Seedling/sapling H:D ratios provide a means of evaluating the degree of overstory shading or competition. Comparing H:D ratios of the different conifer species directly is not meaningful because their early growth patterns differ. Grand fir, Douglas-fir, and Sitka spruce seedlings typically have larger stem diameters for a given height than do western redcedar and western hemlock. Therefore, observed differences among H:D ratios do not necessarily reflect one species being more suppressed. Each species had different mean H:D ratios at the time of planting; over the eight growing seasons, however, the mean H:D ratios converged. All conifer species had lower H:D ratios in the VWT treatment than in the NT, suggesting that suppression was less in the VWT because more light reached the understory. We expect all the underplanted species in the NT treatment to increase H:D ratios as the overstory canopy closes and trees become more suppressed.

Unexpected differences in overstory tree densities within and surrounding species trial plots may have prevented us from detecting more distinct differences among thinning treatments. By looking at actual PAL in years 8 and 9 in conifer species trial plots, we were able to show expected, positive growth response of understory trees to higher light levels. A more detailed analysis of light levels by treatment within the study sites showed that 8 years after thinning, canopies in the NT stands had closed to the point where the available light was as low as that in unthinned stands before treatment (Chan et al, in preparation). Therefore, we caution that favorable early survival and good seedling size will not guarantee continued long-term success of any of the species studied under the overstory canopy in NT stands.

Overstory canopies were dynamic and began to close soon after thinning. Early growth and survival of intermediate shade-tolerant (Douglas-fir) and shade-intolerant (red alder) species under the thinned Douglas-fir canopies suggest that strict classification of shade tolerance according to low light levels (5–10% of full sun) may be misleading for comparisons at intermediate light levels. Coates and Burton (1999) reported variability in shade tolerance of conifers at intermediate light levels 30–70% of full light. Shade tolerance may consist of a gradient response to light conditions. Shade tolerance varies inter- and intraspecifically (Chen, 1997; Wright et al., 1998; St.Clair and Sniezko, 1999), by tree age (i.e., seedling versus mature tree; Hermann and Lavender, 1990), and by soil moisture (Carter and Klinka, 1992). Chen (1997) suggested that persistent survival without high growth rates is common in shade-tolerant species growing at low light levels in forest understories, whereas shade-intolerant species die faster with higher growth rates. Absolute growth rates at low light levels may not be a good indicator of overall shade tolerance; several researchers suggest that the probability of survival at a given growth rate may be a better characteristic to use (Kobe et al., 1995; Kobe and Coates, 1997; Coates and Burton, 1999). Ability to respond to increased light levels after suppression is another important species characteristic that has been correlated with general tolerance ratings of some Pacific Northwest tree species (Wright et al., 2000). We believe that further studies of shade tolerance are necessary. In the meantime, judgments about species suitability for management under widely thinned canopies should be based on species performance at intermediate light levels rather than dated rankings of shade tolerance at low light levels.

4.3. Damage to seedlings

The most serious growth-limiting damage that occurred in our studies was due to elk and insects. Severe animal damage to young conifers and hardwoods can lead to reduced growth rates, deformed trees, or death.

Growth of western redcedar was hindered severely by browse, as is common with redcedar (Omule, 1988; Minore, 1990; Stein, 1997; Brandeis et al., 2002). Most studies report deer (*Odocoileus hemionus*) as the main browser, but elk browse was more prevalent on our sites. Brandeis et al. (2002) reported that black-tailed deer browsed over 36% of western redcedar during the first 4 years after planting in thinned stands. Browsing on those seedlings may have been considerably less than we observed because they planted western redcedar on the eastern edge of the Oregon Coast Range, out of its normal range. Browse kept redcedar in our study shorter than the seedlings studied by Smith and DeBell (1973), but similar in height to, or taller than the severely browsed seedlings reported by Omule (1988).

Browse can be detrimental to Douglas-fir, but our seedlings were relatively browse free (<1%). In contrast, Brandeis et al. (2002) reported that >74% of 4-year-old Douglas-fir seedlings were browsed by black-tailed deer in thinned stands on the eastern flank of the Oregon Coast Range.

Bigleaf maple seedlings did not achieve their full growth potential because of persistent heavy browse, which is consistent with other observations (Fried et al., 1988; Minore and Zasada, 1990). Browsing severely limited height and diameter growth of maple in all thinning treatments, and mortality appeared to increase as a result of repeated browsing or of being overgrown by shrubs and other competing vegetation. Open grown bigleaf maple seedlings are generally thought to be capable of growing as much as 1–2 m year^{-1}, but this rate is rarely achieved under normal conditions of moisture and light, competition, and animal damage (Minore and Zasada, 1990). As a shade-tolerant species, bigleaf maple may survive in the understory and begin to grow if browsing decreases as the understory develops. We associated the stem die-back in our study with browsing wounds, whereas stem die-back reported in larger Coast Range plantings was attributed to frost or other unspecified environmental conditions (Hardwood Silviculture Cooperative, 1997).

As Sitka spruce, western hemlock, and red alder grew to sapling size, damage from elk antler rubbing became more prevalent and sometimes killed otherwise healthy saplings, especially of Sitka spruce. Even though western hemlock was, on average, larger than spruce, the elk seemed to prefer spruce. Red alder experienced some antler damage but its ability to quickly grow through the desired rubbing post size may have decreased its vulnerability to damage which is consistent with Newton and Cole (1994), who attribute the low occurrence of animal damage to red alder to its early rapid growth. Antler rubbing damage varied by site and was most severe at Cataract (twice that at Wildcat and 13 times that at Yachats), which was regularly visited by a resident elk herd. Girdling associated with rubbing was more likely to kill the young trees than browse or insect damage.

Damage to Sitka spruce by the white pine weevil concerns forest managers in the Pacific Northwest because it affects leader development, hence stem form and height growth (Mitchell et al., 1990). Damage is often most severe when plantations are 9–15 years old and may decline sharply in plantations >21 years old (Mitchell et al., 1990). Temperature is significant factor in weevil attacks and cooler coastal sites are less affected than inland sites (McMullen, 1976). Shading may also lower stand temperatures, making the understory environment unfavorable for weevil larvae development (Wallace and Sullivan, 1985) and decrease the incidence of weevil attacks

(Taylor et al., 1996). In our study, we had no weevil damage during the first four growing seasons, but it was prevalent by the end of the eighth growing season. Weevil damage was heaviest in VWT stands and limited height, but not diameter growth. At the Wildcat site, where weevil damage was highest, needle loss caused by Swiss needle cast in overstory Douglas-fir may have created more open and therefore more favorable conditions for weevils. More studies are needed to better quantify weevil damage in thinned stands.

4.4. Management implications

All of the species in this study appear to have the biological potential to survive and grow well when underplanted in stands thinned to low densities similar to ours with relatively low understory vegetation competition during the first 4 years of growth. Bigleaf maple and western redcedar may, however, require special protection in many Coast Range locations because of their susceptibility to heavy browsing. Based on survival, seedling size, and damage incurred over eight growing seasons, we ranked conifer performance in decreasing order of suitability for underplanting as western hemlock, Sitka spruce, Douglas-fir, grand fir, and western redcedar. On Vancouver Island, Omule (1988) ranked open-grown seedlings (6 years after planting) in decreasing order as Sitka spruce, Douglas-fir, western hemlock, and western redcedar. Western redcedar was the lowest ranked species in both trials because of frequent browse damage.

For hardwoods, we ranked red alder above bigleaf maple. Red alder did surprisingly well despite its shade-intolerant ranking (Harrington, 1990), and as a hardwood species, it may be superior to planted conifers for enhancing diversity, earlier, in widely thinned stands. Its rapid growth and unpalatability to browsers appeared to help it avoid browse damage. Hagar et al. (1996) and Hayes et al. (1997) noted that thinned conifer stands with hardwoods can support more diverse bird populations than pure conifer stands.

While NT stands may create conditions favorable for early survival and growth of underplanted trees, we believe that thinning to wide or very wide densities will be necessary to create favorable conditions for continued vitality and growth. In NT stands more suppressive conditions developed within a decade as the canopy closed. In order to maintain vigorous understory trees in timber-oriented management scenarios, repeated thinning entries will be needed to reduce the overstory densities. However, frequent re-entries pose a threat to understory trees during felling and yarding, and care must be taken to avoid severe damage to seedlings.

Growth-limiting animal damage needs to be assessed by site and preventative steps may need to be taken. On sites with high elk or deer populations, seedlings may need protection, however, protecting western hemlock, Sitka spruce, grand fir or red alder with mesh tubing is unnecessary in most locations. Where establishing browse-susceptible species such as western redcedar and bigleaf maple is a high priority or populations of deer or elk are large, protection may be necessary. Options include installing protective mesh tubing or tree shelters, seeding more palatable forage species, leaving more down logging debris to limit animal access, and increasing hunting opportunities (Black, 1994).

Taller mesh tubes may offer additional protection, but may also increase problems with seedling entanglement. Tree shelters (solid plastic tubes) may allow leaders to grow above the typical browse line for deer (about 1.3 m) and elk (up to 2.0 m). Height and diameter growth, however, are affected by microclimates in tree shelters. Trees grown in shelters may not develop adequate stem taper. The lack of taper weakens stems temporarily and make them susceptible to breakage or bending, which requires leaving the tube in place after browsing is no longer a threat (Potter, 1988; Applegate and Bragg, 1989).

The three most successful species, western hemlock, Sitka spruce, and red alder in our study, are immune to Swiss needle cast and are good candidates for underplanting in Douglas-fir stands infected by Swiss needle cast (Filip et al., 2000). However, Sitka spruce is best planted within the coastal fog belt in order to minimize damage from white pine weevils.

In a companion study, Chan et al. (in preparation) found high numbers of naturally regenerated conifers in the initial years after thinning, however, the number of successfully established natural seedlings declined over time. Also, natural seedlings were much shorter than planted seedlings 8 years after thinning. Thus, our studies do not support reliance on natural regeneration of conifers to provide either stand structure or lower cost regeneration. This seems to be in contrast to trends in central and northern Europe (e.g. Mantel, 1990) where a much greater reliance on natural regeneration exists. The difference may be related to our summer-dry climate which puts regeneration under more intense competition for moisture than in Europe where summer rains are more common.

We agree with Drever and Lertzman (2001) who suggested that the more shade-tolerant species will provide more flexibility to land managers in meeting varied management objectives. However, where timber values are high in management objectives, species considered to be of intermediate shade tolerance (e.g. Douglas-fir) may be acceptable because relative tolerance ratings at intermediate light levels do not match those at low light levels. In the case where diversity is a primary objective, even intolerant species such as red alder may be viable in the understories of very widely thinned stands. Thinning to very wide spacings on sites of moderate productivity may provide light levels high enough to allow seedlings to continue to grow and to develop a more diverse stand structure for two decades without further thinnings. Only very widely spaced thinnings will provide extended periods of understory development on highly productive sites. Repeated thinning of narrow or wide thinned stand will be necessary to maintain a vigorous understory component, especially on more productive sites.

5. Conclusions

Major findings from this study were (1) underplanting was successful (good survival and size) when the overstory canopy was thinned to wide or very wide spacings and available light is increased; (2) fast growth of planted seedlings such as red alder, western hemlock, and Sitka spruce provided early stand structure in thinned stands; (3) the level of thinning intensity will determine the long-term vigor and survival of underplanted seedlings; and (4) damage from a variety of causes (browse, antler rubbing, weevils, chlorosis) varied by species and by size of seedlings.

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