Tenth-year survival and size of underplanted seedlings in the Oregon Coast Range

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Abstract: This study initiated a two-aged forest stand structure by underplanting 50-year-old stands, primarily of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*) and Douglas-fir – western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), thinned to 19–33 m^2/ha on interior and coastal sites in the Oregon Coast Range. Douglas-fir, grand fir (*Abies grandis* (Dougl. ex D. Don) Lindl.) (interior site only), western hemlock, and western redcedar (*Thuja plicata* Donn ex D. Don) were planted following thinning either uniformly or in gaps of 0.06 or 0.1 ha. Understory vegetation treatments included (*i*) a preharvest site preparation herbicide application and an untreated control at both sites and (*ii*) a postharvest herbicide release treatment at the interior site. Planting conditions and stock at the interior site were not ideal, so survival was adjusted for first-year mortality. Adjusted 10 year survival ranged from 27% to 56% for Douglas-fir, 47% to 65% for western hemlock, 61% to 80% for grand fir, and 78% to 96% for western redcedar. Tenth-year survival at the coastal site ranged from 79% to 92% for Douglas-fir, 61% to 75% for western hemlock, and 67% to 86% for western redcedar. All species grew moderately well beneath the lowest-density overstories, and size was better within gaps than matrices for most species. Understory site preparation improved size for most species. Browsing on Douglas-fir and western redcedar impacted size on both sites.

Résumé : Cette étude a amorcé l'établissement d'une structure bisétagée en effectuant une plantation sous le couvert de peuplements de 50 ans, composés principalement soit de douglas de Menzies typique (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*), soit d'un mélange de douglas et de pruche de l'Ouest (*Tsuga heterophylla* (Raf.) Sarg.). Ces peuplements, établis sur des stations intérieures et des stations côtières de la chaîne côtière de l'Oregon, ont été éclaircis à des densités résiduelles de 19 à 33 m^2/ha. À la suite des éclaircies, des semis de douglas, de sapin grandissime (*Abies grandis* (Dougl. ex D. Don) Lindl.) (stations intérieures seulement), de pruche de l'Ouest et de thuya géant (*Thuja plicata* Donn ex D. Don) ont été plantés uniformément ou dans des zones dégagées à l'intérieur de trouées de 0,06 à 0,1 ha. Des traitements de maîtrise de la végétation de sous-étage ont aussi été appliqués. Ils comprenaient une application d'herbicide avant la coupe et un témoin non traité dans les deux types de station, ainsi qu'un traitement de dégagement avec un herbicide après la coupe dans la station intérieure. La qualité des plants et les conditions de plantation dans la station intérieure n'étaient pas idéales. La survie a donc été ajustée en fonction de la mortalité survenue la première année. La survie ajustée pendant les 10 premières années variait de 27 % à 56 % pour le douglas, de 47 % à 65 % pour la pruche, de 61 % à 80 % pour le sapin grandissime et de 78 % à 96 % pour le thuya géant. La survie après 10 ans sur la station côtière variait de 79 % à 92 % pour le douglas, de 61 % à 75 % pour la pruche et de 67 % à 86 % pour le thuya. Toutes les espèces avaient une croissance modérément bonne aux endroits où l'étage dominant avait la plus faible densité résiduelle et la taille des plants situés dans les trouées était supérieure à celle des plants situés sous la matrice forestière chez la plupart des espèces. La préparation de terrain en sous-étage a amélioré la taille des plants chez la plupart des espèces. Le broutement des plants de douglas et de thuya a réduit leur taille sur les deux stations.

[Traduit par la Rédaction]

Introduction

In the Pacific Northwest, greater diversity and vertical complexity within stands have been associated with greater wildlife abundance (Hansen et al. 1991; Ruggiero et al. 1991; Carey 2001; Carey and Harrington 2001; Muir et al. 2002). Public agencies in the region are proposing two-aged stand management to encourage growth of larger trees and to recruit understory conifers to provide vertical structure (USDA Forest Service 1994; Oregon Board of Forestry 2003). Franklin and Van Pelt (2004) have listed conceptual elements when manipulating stands to generate late-seral features. They described two components of the complex spatial arrangement of structures: (1) vertical distribution of canopy, which is often manifested by continuous or multiple canopy layers, and (2) irregular, horizontal distribution of structures, as seen in areas with canopy gaps or forest openings and in dense patches of sapling and poles.

Many of the stands designated for late-successional or structure-based management are even-aged young-growth stands with a relatively narrow range of habitat features but with a high potential for producing sawtimber. Several authors (McComb et al. 1993; Hershey et al. 1998; O'Hara 1998; Carey and Harrington 2001; Franklin et al. 2002) have identified late-successional stand features and structural features toward which management might move sec-

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ond-growth Douglas-fir-dominated forests, and Hummel (2003) stressed the goal of providing benefits to nontimber resources while producing wood simultaneously. Tappeiner et al. (1997) indicated that heavy thinning in young stands in the central Oregon Coast Range could be used to promote large trees and other structures similar to that found in late-successional stands.

Underplanting is postulated as a means of ensuring understory conifer cover. In such endeavors it is assumed that understory regeneration would not only survive but would eventually grow to produce intermediate levels of crown structure and, in some instances, would potentially survive to provide replacement stands to perpetuate the Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*) forest type. Recently, there have been a few studies (Brandeis et al. 2001; Maas-Hebner et al. 2005; Chan et al. 2006; Harrington 2006) that evaluated combinations of thinning and underplanting to direct managed stands toward a late-seral structure.

In the Coast Range of Oregon, overstories are primarily Douglas-fir, but there are large areas where other species, such as western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), western redcedar (*Thuja plicata* Donn ex D. Don), or grand fir (*Abies grandis* (Dougl. ex D. Don) Lindl.), are present and tend to become more prominent as individual Douglas-fir trees mature, senesce, and eventually give way to shade-tolerant tree and understory species (Franklin and Dyrness 1973). Douglas-fir is regarded as shade intolerant to moderately tolerant (Harlow and Harrar 1950); hence, limits on survival in understory environments are presumably related to light intensity or overstory density (Del Rio and Berg 1979; Mason et al. 2004; Maas-Hebner et al. 2005; Chan et al. 2006). In structure-based management, late-successional features are encouraged but there is also incentive to encourage regeneration of Douglas-fir because of the high value of its wood (Garman et al. 2003). However, existing data suggest that many, perhaps most, old stands containing Douglas-fir were established not only with full sunlight but also with a relatively low stocking level of regeneration (Tappeiner et al. 1997; Poage and Tappeiner 2002; 2005).

Underplanting studies from Scotland (Mason et al. 2004) indicated that basal areas less than 31 m^2/ha are needed to maintain Douglas-fir planted under Sitka spruce (*Picea sitchensis* (Bong.) Carr.). Chan et al. (2006) and Maas-Hebner et al. (2005) found that 8 year survival rates for seedlings underplanted in western Oregon Douglas-fir stands that were thinned from 43 to 47 m^2/ha down to 7 to 23 m^2/ha averaged 88%, while survival in unthinned stands was very low. Tappeiner et al. (2007) provided density diagrams that relate natural regeneration in understories to overstory density. This provides insight into the stand densities that are required to maintain plantations in understories of stands in the 30 year age class, but little information is available for older stands, those previously thinned, or those with heavy shrub understories.

The pattern of residual overstory, especially related to canopy gaps, has an effect on the understory environment, and hence on regeneration. Gap size has been shown to affect the growth of planted seedlings (Wright et al. 1998; Coates 2000; York et al. 2004), especially shade-intolerant species. Underplanting in stands that include gaps emphasizes survival and growth of shade-intolerant as well as shade-tolerant species.

Maintenance of growth in underplanted seedlings is important for survival (Kobe and Coates 1997; Kneeshaw et al. 2006) and for development of multilayered canopies (Messier et al. 1999). Understory vegetation has been shown to decrease seedling performance in underplanting situations (Saunders and Puettmann 1999; Brandeis et al. 2001), but the positive or negative effects of vegetation control have varied based upon species and overstory density (Smidt and Puettmann 1998; Brandeis et al. 2001; Mitchell et al. 2003; Mitchell et al. 2004; Harrington 2006).

Our study describes the conditions influencing the survival and size of planted conifers in underplanting experiments in Douglas-fir stands thinned when 50 years old, after having been thinned previously. We planted conifers with an array of shade tolerances beneath residual overstories after thinning to a range of basal area levels based on percentages of “normal stocking” according to a standard reference (McArdle et al. 1961). This design aimed to create a range of densities that bracketed the tolerance of underplanted seedlings through cycles of overstory growth between rethinnings, perhaps triggering mortality at high densities but not low. Previous reports (Brandeis et al. 2001, 2002) have described early mortality as well as various sources of damage on small seedlings, and early seedling growth at one of the sites. Specific objectives addressed in this paper are

1. To determine the influences of residual overstory density and distribution following thinning of 50-year-old conifer stands on medium to good sites on survival and size of underplanted conifers.
2. To determine if treatment of understory vegetation influences survival and size of underplanted conifers.

Methods

Study sites

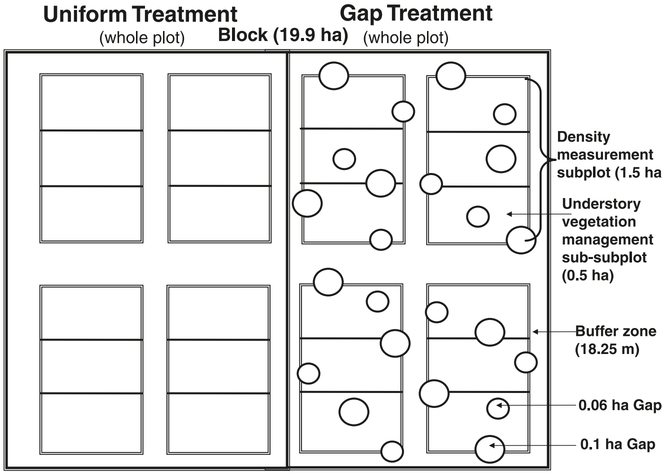
The two installations are a Willamette Valley foothill site, McDonald Forest, near Corvallis, Oregon (44.65°N, 123.27°W), and a coastal site, the Blodgett Forest (46.07°N, 123.35°W), approximately 50 km east of Astoria, Oregon, and about 3 km south of the Columbia river. These sites reflect interior and coastal climatic and vegetation regimes within the Oregon Coast Range and are located approximately 200 km from each other. Site attributes are listed in Table 1.

Stands at McDonald Forest were dominated by 50-year-old Douglas-fir with scattered grand fir and bigleaf maple (*Acer macrophyllum* Pursh). The stands had been thinned at least twice before, in 1964–1965 and 1980–1981. Information on those thinnings was not available. Understory vegetation was well developed prior to the thinning for this study and consisted of western swordfern (*Polystichum munitum* (Kaulf.) K. Presl.), hazel (*Corylus cornuta* Marsh.), ocean spray (*Holodiscus discolor* (Pursh) Maxim.), Pacific poison oak (*Toxicodendron diversilobum* (Torr. & Gray) Greene), western brackenfern (*Pteridium aquilinum* (L.) Kuhn), trailing and Himalaya blackberries (*Rubus ursinus* Cham. & Schlecht. and *Rubus discolor* Weihe and Nees, respectively), and other species in lesser amounts.

Table 1. Site attributes for McDonald and Blodgett forests installations.

	McDonald Forest	Blodgett Forest
Elevation	200–400 m	200–400 m
Aspect	West-northwest	East, west, south
Slope	10%–50%	10%–70%
Soils	Rittner–Price gravelly clay loam, medium depth; and Jory clay loam, moderate to deep; both derived from marine basalt	Scaponia-Braun and Tolke series, loamy and deep, derived from decomposed mudstone
Precipitation	1500 mm, 80%–85% October–April	1700–2000 mm, 80%–85% October–April
Prethinning basal area	34–46 m^2/ha	32–57 m^2/ha
"Normal" stocking and site $index_{50}$ (McArdle et al. 1961; Barnes 1962)	48–49 m^2/ha; sites II and III	49–51 m^2/ha Douglas-fir; 67 m^2/ha western hemlock; sites I and II

Fig. 1. Layout of a single block showing gap and uniform thinning regimes (whole plots), density treatments (subplots), and understory treatments (sub-subplots) with and without gaps for McDonald Forest.



At Blodgett Forest, stands were a mixture of 50- to 55-year-old Douglas-fir and western hemlock in a range of species mixtures from nearly pure Douglas-fir to mostly western hemlock. Most stands had been thinned one time 6–8 years prior to establishment of this study. Understory vegetation consisted of western swordfern, vine maple (*Acer circinatum* Pursh), salal (*Gaultheria shallon* Pursh), Oregon grape (*Mahonia nervosa* Pursh), naturally regenerated western hemlock, and other species in lesser amounts.

Design and treatments

The experimental design was a split–split plot with three replications (blocks) at each installation. The blocks reflected differences in slope, pretreatment overstory species, and aspect. The blocks were divided into two equal whole plots and randomly assigned to either a uniform or gap thinning regime. The gap thinning regime was thinned to the same basal area per hectare of total overstory growing stock as that of the corresponding uniform density, but was distributed to have three circular gaps of 0.06 ha and three gaps of 0.10 ha (Fig. 1). If not enough basal area was removed in the gaps, trees were thinned uniformly between gaps (matrix areas).

Each whole plot was divided into four (three at Blodgett Forest) overstory-density subplots. Subplots were 2.46 ha with a 1.46 ha measurement subplot inside 18 m buffers (Fig. 1). We refer to the lowest densities as LOW, the highest as HIGH, and the intermediate levels at McDonald Forest as MED and MHI (Table 2), and the intermediate at Blodgett Forest as MED (Table 3). Thinning occurred during fall of 1993 at McDonald Forest and fall–winter of 1995–1996 at Blodgett Forest, and it utilized ground and cable systems, depending upon slope. Single-tree selection was used for the thinning, with emphasis on the removal of intermediate and defective trees and the maintenance of spacing. Trees were limbed in place and utilizable tops were removed. Although all felling was completed by March 1996 at Blodgett Forest, yarding was not completed until fall 1996 on ground-yarded units because of saturated soils.

Measurement subplots were divided into three 0.49 ha (McDonald Forest) or two 0.73 ha (Blodgett Forest) sub-subplots and randomly assigned one of the following understory treatments.

1. Spray treatment — broadcast ground application of herbicides delivered by a backpack sprayer with a single nozzle at the following amounts of active ingredient: 1.6 kg/ha glyphosate plus 0.14 kg/ha imazapyr in water for total spray volume of 47 L/ha in McDonald Forest units applied late summer 1993; 1.6 kg/ha glyphosate, 0.2 kg/ha imazapyr, and 0.16 kg/ha sulfometuron in water at 28 L/ha on Blodgett Forest units applied late summer 1995 to control understory competition before thinning;
2. Release treatment (McDonald Forest only) — spot-directed foliage application of 3% triclopyr product (Garlon 4) in oil or 3% glyphosate product (Accord) in water around individual seedlings, depending on the competing species 2 years after planting;
3. Plant treatment — no understory treatment apart from the effects of logging.

Some plots at Blodgett Forest also included triclopyr ester at 3.3 kg/ha in the mixture applied for site preparation where evergreen shrubs were prevalent. The Blodgett Forest installation had to be resprayed owing to delayed completion of logging. The second application to the same plots entailed an October 1996 treatment with sulfometuron at 0.16 kg/ha plus 2,4-dichlorophenoxyacetic acid or with a mixture of 2,4-dichlorophenoxyacetic acid and diclorprop at 1.1 kg/ha total phenoxy acid equivalent, as the butoxyethanol esters in water for a total spray volume of 28 L/ha. Plots with remaining competitive levels of salal also received triclopyr in the spray mixture at 2.2 kg/ha. The release treatment was largely ineffective in controlling competitors in McDonald

Table 2. Stand conditions averaged over three blocks at McDonald Forest immediately, year 7, and year 10 after thinning.

	Year 0				Year 7		Year 10			
Stand density	BA (m^2/ha)	TPH	QMD (cm)	Relative density*	BA (m^2/ha)	Relative density	BA (m^2/ha)	TPH	QMD (cm)	Relative density
Gap thinning										
LOW	17.5	104	47.6	2.5	21.9	3.0	23.6	108	53.9	3.2
MED	23.5	137	47.5	3.4	28.2	3.9	23.9	103	55.2	3.2
MHI	27.7	160	47.4	4.0	33.1	4.6	28.8	121	55.3	3.9
HIGH	29.7	198	44.1	4.5	35.3	5.1	37.6	194	50.2	5.3
Uniform thinning										
LOW	18.6	98	49.4	2.6	23.3	3.1	25.4	101	57.1	3.4
MED	22.8	110	52.0	3.2	28.1	3.7	24.1	84	61.9	3.1
MHI	27.8	140	50.8	3.9	33.7	4.5	28.7	101	60.7	3.7
HIGH	30.9	211	43.3	4.7	37.4	5.4	40.2	202	50.4	5.7

Note: MED and MHI units were rethinned in year 8. BA, basal area; TPH, trees/ha; QMD, quadratic mean diameter.
*From Curtis (1982).

Table 3. Stand conditions averaged over three blocks at Blodgett Forest immediately and year 10 after thinning.

	Year 0				Year 10			
Stand density	BA (m^2/ha)	TPH	QMD (cm)	Relative density*	BA (m^2/ha)	TPH	QMD (cm)	Relative density
Gap thinning								
LOW	19.7	101	49.9	2.8	26.3	108	55.8	3.5
MED	26.4	141	49.0	3.8	34.1	146	52.7	4.6
HIGH	32.7	199	45.8	4.8	40.8	195	51.6	5.7
Uniform thinning								
LOW	20.5	129	45.1	3.1	26.8	127	51.8	3.7
MED	27.1	159	46.7	4.0	34.8	157	53.1	4.8
HIGH	32.4	211	44.5	4.9	41.4	211	50.1	5.8

Note: BA, basal area; TPH, trees/ha; QMD, quadratic mean diameter.
*From Curtis (1982).

Table 4. Mean seedling size at the time of planting for McDonald and Blodgett forests.

	Western redcedar		Douglas-fir		Grand fir		Western hemlock	
	Height (cm)	Basal diameter (mm)	Height (cm)	Basal diameter (mm)	Height (cm)	Basal diameter (mm)	Height (cm)	Basal diameter (mm)
McDonald	59	5.7	54	6.1	33	5.8	33	2.6
Blodgett	20	2.0	59	7.6	—	—	26	2.0

Forest and was not part of the treatments for Blodgett Forest; hence, the difference in sub-subplot numbers and dimensions.

Measurement subplots were underplanted at a 3 m × 3 m spacing in January 1994 (McDonald Forest) and at 3 m × 4 m in February 1997 (Blodgett Forest). In McDonald Forest, the plantations consisted of randomized double rows of each species, including western redcedar, grand fir, western hemlock, and Douglas-fir. Grand fir, not native at Blodgett Forest, was not planted there. All seedlings were transplants as Plug+1 or Plug+2 (western redcedar only in McDonald Forest) (Table 4). At Blodgett Forest, western redcedars were very small Plug+1 seedlings. In each sub-subplot, four randomly selected "grids" containing six seedlings of each species in McDonald Forest and 10 seedlings of each at Blodgett Forest were identified for periodic measurements. A total of 24 seedlings of each species were tagged in each sub-subplot in McDonald Forest (6912 total seedlings), and 40 per species in each sub-subplot for the Blodgett Forest (4320 total seedlings). Grids within sub-subplots were pooled for analyses. One-fourth of all planted seedlings were protected with Vexar tubes to protect against browsing by black-tailed deer (*Odocoileus hemionis columbiana*) (both sites) and Roosevelt elk (*Cervus elaphus*) (Blodgett Forest), and clipping by mountain beavers (*Aplodontia rufa*) (Blodgett Forest). Mountain beavers (Blodgett Forest) near seedling grids were trapped twice yearly to prevent loss of planted seedlings. Tubing was adequate to protect from mountain beaver clipping but did not protect against browsing above 45 cm.

The study was originally designed to include future thinnings. Eight years after planting in McDonald Forest, we ob-

Table 5. *F* and *P* values, and least-squared means and standard errors (SE) from analyses of variance for year 10 survival at McDonald Forest.

		Western redcedar		Douglas-fir		Grand fir		Western hemlock	
	df	Unadjusted	Adjusted	Unadjusted	Adjusted	Unadjusted	Adjusted	Unadjusted	Adjusted
		***F* value (*P* value)**							
G(T)	2, 4	5.72 (0.0671)	2.77 (0.1760)	30.90 (0.0037)	4.88 (0.0846)	1.19 (0.3938)	0.39 (0.7005)	36.68 (0.0027)	0.20 (0.8252)
D	3, 18	2.44 (0.0977)	3.64 (0.0328)	6.12 (0.0047)	5.90 (0.0055)	6.45 (0.0037)	3.67 (0.0318)	5.34 (0.0083)	0.77 (0.5275)
G(T) × D	3, 18	1.08 (0.4117)	0.37 (0.8883)	0.24 (0.9555)	1.00 (0.4526)	2.45 (0.0657)	1.16 (0.3704)	1.47 (0.2423)	0.42 (0.8543)
U	2, 31–43*	1.44 (0.2473)	0.91 (0.4100)	2.43 (0.1003)	3.69 (0.0350)	3.43 (0.0417)	3.16 (0.0525)	3.87 (0.0296)	2.39 (0.1081)
U × G(T)	4, 31–43*	0.94 (0.4506)	1.17 (0.3381)	0.23 (0.9183)	2.07 (0.1055)	0.37 (0.8296)	0.46 (0.7659)	0.30 (0.8775)	0.57 (0.6843)
U × D	6, 31–43*	0.43 (0.8559)	0.49 (0.8093)	2.08 (0.0760)	0.72 (0.6330)	1.01 (0.4326)	0.85 (0.5401)	2.13 (0.0719)	0.25 (0.9548)
U × D × G(T)	12, 31–43*	0.66 (0.7744)	0.81 (0.6391)	1.50 (0.1636)	1.25 (0.2898)	0.28 (0.9901)	0.66 (0.7793)	1.37 (0.2202)	1.57 (0.1516)
		Least-squared means (SE)							
Gap–gap		0.90 (0.041)	0.94 (0.032)	0.56 (0.040)	0.54 (0.056)	0.66 (0.040)	0.69 (0.040)	0.56 (0.038)	0.50 (0.068)
Gap–matrix		0.73 (0.036)	0.86 (0.028)	0.21 (0.033)	0.49 (0.047)	0.61 (0.035)	0.73 (0.035)	0.15 (0.031)	0.55 (0.056)
Uniform		0.74 (0.036)	0.84 (0.028)	0.18 (0.033)	0.33 (0.045)	0.58 (0.035)	0.69 (0.035)	0.25 (0.031)	0.55 (0.051)
HIGH		0.70 (0.047)	0.78 (0.037)	0.14 (0.045)	0.27 (0.064)	0.49 (0.045)	0.61 (0.045)	0.17 (0.039)	0.47 (0.066)
MHI		0.72 (0.045)	0.87 (0.035)	0.28 (0.042)	0.37 (0.059)	0.54 (0.043)	0.64 (0.044)	0.32 (0.040)	0.053 (0.071)
MED		0.77 (0.044)	0.87 (0.034)	0.32 (0.041)	0.51 (0.054)	0.64 (0.043)	0.74 (0.043)	0.33 (0.039)	0.54 (0.068)
LOW		0.90 (0.045)	0.96 (0.035)	0.39 (0.041)	0.56 (0.055)	0.76 (0.042)	0.80 (0.043)	0.38 (0.039)	0.61 (0.065)
Plant		0.76 (0.038)	0.88 (0.030)	0.26 (0.037)	0.38 (0.051)	0.59 (0.037)	0.70 (0.038)	0.25 (0.034)	0.50 (0.059)
Release		0.75 (0.040)	0.84 (0.031)	0.25 (0.037)	0.38 (0.051)	0.55 (0.038)	0.63 (0.038)	0.27 (0.034)	0.46 (0.058)
Spray		0.82 (0.039)	0.89 (0.031)	0.34 (0.036)	0.51 (0.048)	0.69 (0.037)	0.77 (0.038)	0.38 (0.035)	0.65 (0.059)

Note: G(T), Gap(treatment); D, density; U, understory. Unadjusted values are the means for year 10 survival. Adjusted values are year 10 means adjusted for first year mortality.

*Degrees of freedom varied by species.

served that seedlings planted beneath both intermediate (MED and MHI) overstory densities were showing signs of suppression; those beneath low densities were growing satisfactorily, and those beneath the highest overstory density were showing heavy mortality. At that time, we rethinned the two intermediate overstory densities to their original postthinning basal areas, as described in Newton and Cole (2006).

Measurements

Diameters at breast height (dbh, 137 cm above ground) on overstory trees greater than 5 cm in diameter were measured immediately after thinning, and after 2, 4, 7, and 10 years. Underplanted seedlings were evaluated for height and basal diameter (15 cm) annually for the first 5 years and at ages 7 and 10 (McDonald Forest) and annually for the first 3 years and at ages 5, 7, and 10 (Blodgett Forest). At each observation, damage to seedlings from biotic and abiotic injuries was noted. If a seedling was not found, it was recorded as dead if not found during the next measurement period.

Analyses

All statistical analyses were done using SAS (Statistical Analysis Systems, Cary, North Carolina) software PROC MIXED with block and the block error terms as random effects. Because of the differences in time of thinning and stock type, installations (sites) were analyzed separately. The study design allowed for species to be analyzed separately or together. For simplification of results, species were analyzed separately.

ANOVAs were performed on the most recent survival data, year 10. For Blodgett Forest, an arc-sine square-root transformation was used to achieve homogeneity of variance. At McDonald Forest, weather at the time of planting was dry and windy with temperatures below freezing that persisted for 10 days. This weather resulted in unexpectedly high mortality for Douglas-fir and western hemlock in the first year. Based on other plantings in the area with the same stock, there was some evidence of poor stock quality as well. An additional set of analyses was performed for all species at McDonald Forest with 10 year survival adjusted for first-year mortality. For this set of analyses, only those seedlings alive after the first growing season were included in survival data for year 10. Both sets of analyses are included, because the unadjusted survival estimates would tend to underestimate survival, while the adjusted survival estimates would tend to overestimate overall survival under average conditions.

Seedling height and diameter trends were examined through time, but the numbers of years of repeated measurements exceeded the number of replications. Therefore, year was included as a continuous variable within the framework of the original ANOVA design (Littell et al. 1996). This technique determines if various ANOVA effects change through time by testing for interactions of the effects and year. Included in this model were the ANOVA factors, year, year^2, and all of the interactions of the ANOVA effects with year and year^2. Interactions with year that were not significant ($P > 0.10$) were deleted from the analysis, and the data were re-analyzed with the reduced model. For all other determinations, a significance level of $P < 0.05$ was used. Slopes were then compared. Denominator degrees of freedom for year, year^2, and subsequent interactions were adjusted to the total number of subjects. Different covariance matrices for the repeated measures were selected based on Akaike's information criteria, residual distribution, and overall model fit. In most cases, the unstructured covariance matrix was used. A natural log transformation was used to improve homogeneity of variance. For all analyses, only seedlings that were alive in year 10 were included in the analyses. Seedlings that had been clipped by mountain beaver were eliminated from the sample. From initial populations of 1728 of each species, sample numbers at McDonald Forest were 1334 for western redcedar, 399 for Douglas-fir, 1040 for grand fir, and 409 for western hemlock. At Blodgett Forest, from initial populations of 1440 seedlings per species, sample numbers were 1104 for western redcedar, 1178 for Douglas-fir, and 1016 for western hemlock. All analyses were weighted by the number of seedlings in each "cell". For Douglas-fir at McDonald Forest, the HIGH density was not included in the analyses, because survival was too low for adequate sample numbers.

The second thinning to prolong survival of suppressed seedlings beneath the two intermediate densities at McDonald Forest resulted in mortality of seedlings damaged by felling and equipment. Details of those losses are given in Newton and Cole (2006). Survival and seedling sizes for the MED and MHI densities at McDonald Forest were not adjusted for logging damage in these analyses, and data had to be interpreted accordingly.

Results

Stand density effects

Unadjusted survival at McDonald Forest at age 10 for all species (Table 5) was poorest beneath overstories with postthinning basal areas greater that 31 m^2/ha, an overstory density about 65% of that of a "normal" stand for this site and age as defined by McArdle et al. (1961). When survival was adjusted for first-year mortality, western hemlock survival, being generally low, was no longer affected by overstory density, but the other species still showed decreased survival at the HIGH density. Mortality mostly occurred during the first year following planting and was highest with Douglas-fir and western hemlock. Patterns of mortality have not changed since that reported by Brandeis et al. (2001) for the McDonald Forest plots. Seedlings have continued to die, even seedlings of the more shade-tolerant grand fir and western redcedar (Fig. 2). The overall adjusted survival was 86% for western redcedar, 69% for grand fir, 54% for western hemlock, and 42% for Douglas-fir. Unlike McDonald Forest, survival at Blodgett Forest at age 10 was not affected by overstory density for any of the species (Table 6). The overall survival was 79% for western redcedar, 83% for Douglas-fir, and 72% for western hemlock.

At both installations, in general, the highest-density overstories led to the smallest seedlings and the lowest density the largest (Fig. 3; Tables 7–10). However, there were some exceptions to that. Browsing influenced western redcedar height at Blodgett Forest so that differences among the densities were minor, and the HIGH density did not differ from the MED density. In McDonald Forest, western redcedar,

Table 6. (A) *F* and *P* values and (B) least-squared means and standard errors from analyses of variance for year 10 survival at Blodgett Forest.

(A) *F* value (*P* value).

	df	Western redcedar	Douglas-fir	Western hemlock
G(T)	2, 4	3.04 (0.1574)	1.02 (0.4396)	1.11 (0.4148)
D	2, 12	1.13 (0.3559)	1.68 (0.2275)	1.17 (0.3439)
G(T) × D	4, 12	1.32 (0.3174)	0.73 (0.5900)	1.19 (0.3629)
U	1, 15–18*	0.66 (0.4259)	12.69 (0.0026)	1.57 (0.2283)
U × G(T)	2, 15–18*	1.18 (0.3308)	0.42 (0.6670)	0.33 (0.7266)
U × D	2, 15–18*	0.70 (0.5104)	0.36 (0.7022)	0.01 (0.9921)
U × D × G(T)	4, 15–18*	0.31 (0.8684)	0.91 (0.4804)	0.07 (0.9914)

(B) Least-squared means.

	LSMEAN (SE)	Mean†	LSMEAN (SE)	Mean†	LSMEAN (SE)	Mean†
Gap–gap	0.95 (0.067)	0.67	1.25 (0.052)	0.90	0.89 (0.081)	0.61
Gap–matrix	1.04 (0.067)	0.74	1.16 (0.048)	0.84	0.96 (0.068)	0.67
Uniform	1.18 (0.067)	0.86	1.16 (0.048)	0.84	1.05 (0.068)	0.75
HIGH	1.03 (0.071)	0.73	1.14 (0.051)	0.83	1.03 (0.078)	0.74
MED	1.08 (0.071)	0.78	1.23 (0.052)	0.89	0.92 (0.072)	0.63
LOW	1.16 (0.071)	0.84	1.17 (0.052)	0.85	1.01 (0.074)	0.72
Plant	1.05 (0.058)	0.75	1.09 (0.043)	0.79	0.94 (0.060)	0.66
Spray	1.13 (0.058)	0.82	1.28 (0.042)	0.92	1.04 (0.062)	0.74

Note: G(T), Gap(treatment); D, density; U, understory.

*Degrees of freedom varied by species.

†Mean is back-transformed from least-squared mean.

Fig. 2. Unadjusted (Unadj.) and adjusted (Adj.) survival of underplanted western redcedar and grand fir by overstory density through age 10 at McDonald Forest. Thinning regime and understory treatments have been pooled for simplification.

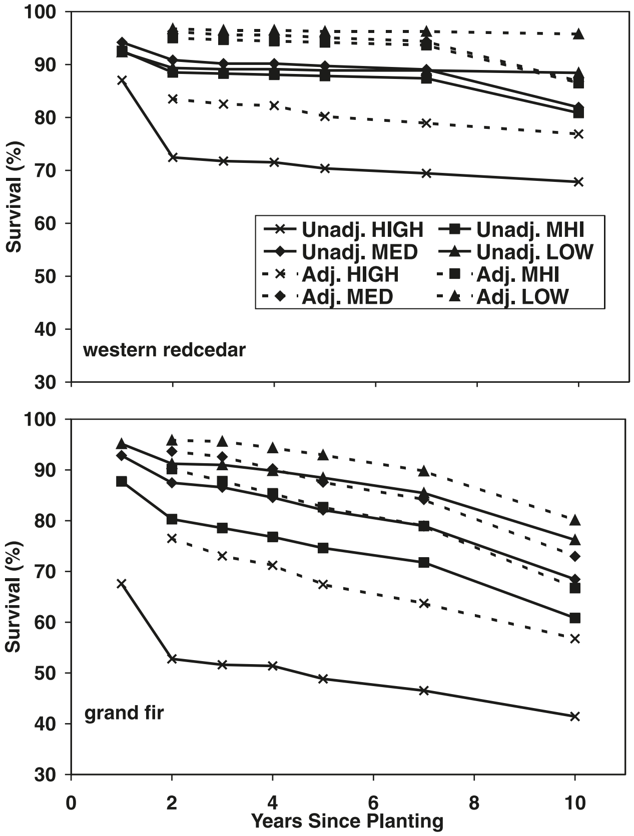


Fig. 3. Trend lines from analyses of variance for height and basal diameter for density effects and thinning pattern effects for western redcedar at McDonald Forest.

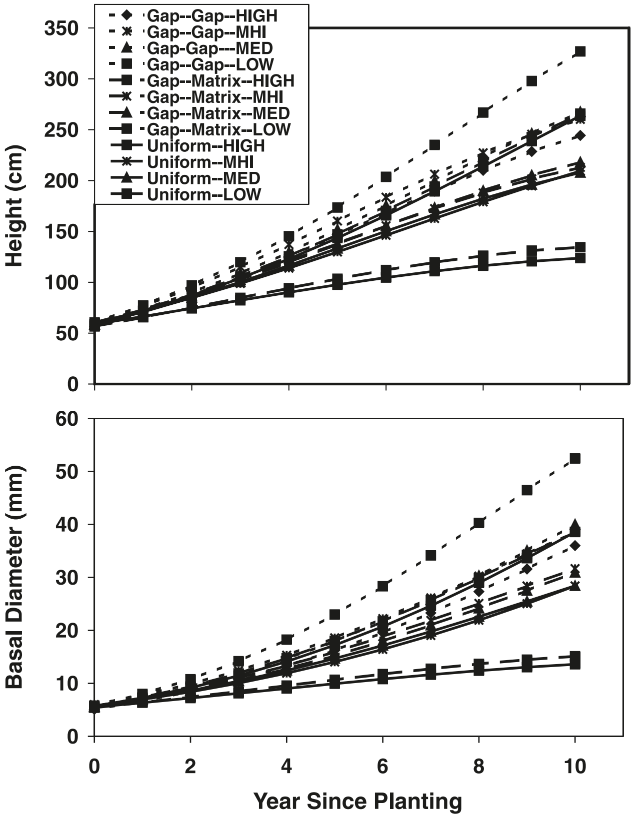
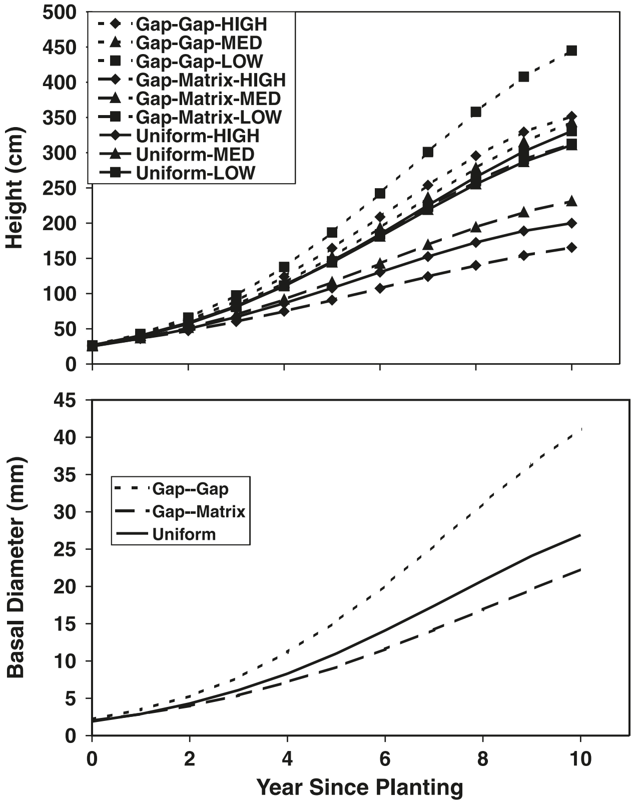


Table 7. Tenth-year height (HT10) and basal diameter (BD10) raw data (non-analysis of variance) means and standard errors for underplanted seedlings at McDonald Forest.

	Western redcedar				Douglas-fir				Grand fir				Western hemlock			
	HT10 (cm)	SE	BD10 (mm)	SE	HT10 (cm)	SE	BD10 (mm)	SE	HT10 (cm)	SE	BD10 (mm)	SE	HT10 (cm)	SE	BD10 (mm)	SE
Gap–gap	286	35.1	44.8	7.8	219	31.3	28.6	6.8	201	36.1	29.3	6.7	329	31.7	40.8	6.0
Gap–matrix	212	16.2	30.2	2.8	173	4.6	22.5	0.8	165	17.3	24.1	2.3	255	24.4	30.5	4.2
Uniform	216	23.7	30.2	3.6	141	12.4	17.8	1.5	178	6.5	25.2	1.2	254	5.8	31.0	0.9
LOW	283	36.3	43.0	6.2	209	16.3	27.2	3.2	209	30.4	29.2	4.6	307	9.9	36.7	1.6
MED	228	9.3	32.8	2.3	164	5.2	21.2	1.6	186	16.8	27.6	3.1	262	29.9	33.0	4.1
MHI	225	3.3	33.4	1.2	138	11.0	18.2	1.2	158	10.5	23.9	1.7	254	9.4	31.9	1.7
HIGH	150	4.5	18.4	0.4	156	32.8	17.3	2.3	134	12.7	18.0	1.9	192	7.5	22.2	1.7
Plant	217	2.0	29.6	0.5	167	10.0	20.6	2.6	163	3.7	21.7	0.3	246	11.5	29.1	2.4
Release	215	15.0	31.0	2.9	172	8.8	22.3	2.5	161	14.3	22.6	2.8	243	15.5	28.6	2.0
Spray	246	16.6	37.5	2.8	177	4.0	23.7	1.1	204	13.4	31.2	2.3	302	3.6	38.7	0.6

Fig. 4. Trend lines from analyses of variance for height and basal diameter for thinning pattern effects for western hemlock at Blodgett Forest.



grand fir, and western hemlock heights did not differ between the MHI and MED densities. This may have been an effect of the rethinning. After 10 years at McDonald Forest, overall height differences among the overstory densities ranged from 70 to 130 cm for all species. Height differences at Blodgett Forest after 10 years ranged from 20 to 130 cm. For all species at both installations, trends indicated that the HIGH-density seedlings were growing on a different (lower) trajectory than the LOW-density seedlings, and these differences were increasing at the time of the last measurement (Fig. 3).

Thinning pattern effects

At McDonald Forest, both western hemlock and Douglas-fir had greater unadjusted survival in gaps than in the matrix areas in the gap treatments (Table 5). However, once the survival estimates were adjusted for first-year mortality, the differences were no longer significant. At Blodgett Forest, thinning regime did not affect survival.

All species at both installations exhibited greater heights and diameters in the gaps than in the matrix or uniform areas. In some instances, differences in mean heights between gaps and matrix areas were not large (Tables 7 and 8), but growth trajectories were higher for seedlings in gaps (Figs. 3 and 4).

Spraying effects

Unadjusted survival of western hemlock at McDonald Forest was slightly higher after spray treatment than in other

Table 8. Tenth-year height (HT10) and basal diameter (BD10) raw data (non-analysis of variance) means and standard errors for underplanted seedlings at Blodgett Forest.

	Western redcedar				Douglas-fir				Western hemlock			
	HT10 (cm)	SE	BD10 (mm)	SE	HT10 (cm)	SE	BD10 (mm)	SE	HT10 (cm)	SE	BD10 (mm)	SE
Gap–gap	67	5.6	7.1	0.8	249	7.9	30.6	4.2	393	14.2	43.2	0.05
Gap–matrix	53	3.2	5.1	0.5	190	8.2	21.2	0.7	244	23.5	24.6	2.5
Uniform	60	3.1	6.1	0.3	191	6.6	21.6	1.3	282	29.2	28.6	3.8
LOW	71	2.8	7.4	0.5	231	9.9	28.3	1.5	347	26.9	36.6	2.9
MED	54	3.7	5.5	0.4	197	1.8	22.6	0.8	287	17.7	29.8	1.3
HIGH	49	5.1	4.7	0.4	173	4.1	18.8	0.5	214	14.7	20.9	1.6
Plant	57	2.8	5.5	0.4	188	13.1	20.1	1.9	236	17.6	22.3	1.7
Spray	60	3.5	6.2	0.5	212	4.8	25.9	1.4	322	25.7	34.8	2.7

understory treatments. For Douglas-fir, adjusted survival after spray treatment was greater than after the release and plant-only treatments (Table 5). At Blodgett Forest, survival after spray treatment was higher for Douglas-fir but not for the other species (Table 6).

Overall, spraying before the initial thinning increased the size of seedlings at the last observation (Fig. 5), but there were some exceptions. The heavily browsed western redcedar at Blodgett Forest exhibited no significant size increases with spraying, nor were there significant increases in Douglas-fir height at Blodgett Forest (also heavily browsed) with spraying. Although spraying tended to increase the size of seedlings, differences were small (<10 cm for height and <3 mm for diameter) in some instances.

Interactions

Significant three- and four-way interactions occurred with time for western redcedar, Douglas-fir, and grand fir at McDonald Forest, and for western redcedar and western hemlock at Blodgett Forest.

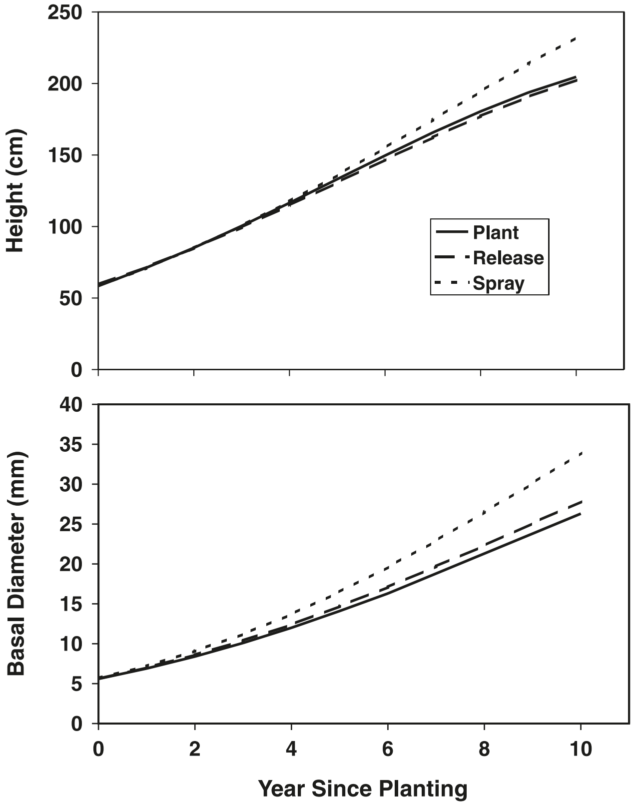
At McDonald Forest, the significant interaction for Douglas-fir basal diameter was difficult to interpret because of the impact of browsing (see Browsing effects). The trajectories indicted that in the matrix and uniform areas, both density and understory effects were important, but these effects were less important in the gap areas. The trajectories for Douglas-fir seedlings growing in gaps showed no trends for density or understory treatments.

Grand fir seedlings tended to be taller in gaps than under a canopy regardless of the overstory density. In the uniform and matrix areas, size of seedlings correlated with density. Spraying resulted in taller and larger grand fir seedlings in both gaps and matrices, but the effect was greater in gaps.

In uniform and matrix areas, the HIGH density resulted in much lower western redcedar heights and diameters than did the other densities (Fig. 3) at McDonald Forest. In the gaps, the separation among the densities was not as great.

At Blodgett Forest, for western hemlock height, differences in gaps among the densities were not great, but within the matrices there was a clear trend in decreasing size as overstory density increased (Fig. 4). Western redcedar height at Blodgett Forest was not affected by spraying in the gap plots, but was slightly higher in the sprayed areas in the uniform plots. However, the difference at year 10 was slight (6 cm), and this interaction was confounded by browsing.

Fig. 5. Trend lines from analyses of variance for height and basal diameter for understory treatment effects for western redcedar at McDonald Forest.



Browsing effects

Browsing had an influence on Douglas-fir and western redcedar survival and size at both installations, but it is not known to what degree browsing affected the treatment outcomes. At McDonald Forest, 56% of the western redcedar and 78% of the Douglas-fir were browsed at least once. Seventy-eight percent of western redcedar were browsed in the HIGH-density plots compared with approximately 50% in the other plot densities; HIGH plots also had the smallest seedlings. Browsing was 55% in matrices compared with 35% in gaps. Part of this difference between gaps and matrices occurred because western redcedars in gaps were able to grow out of reach of deer more quickly than in matrices. This is seen by the lower incidence of repeated browsing in

Table 9. *F* and *P* values from McDonald Forest analyses of variance for height (HT) and basal diameter (BD) with year as a continuous variable.

			F value (*P* value)							
			Western redcedar		Douglas-fir		Grand fir		Western hemlock	
Effect	dfn*	dfd†	HT	BD	HT	BD	HT	BD	HT	BD
G(T)	2	4	5.90 (0.0641)	7.66 (0.0429)	5.67 (0.0680)	8.98 (0.0332)	1.51 (0.3241)	1.76 (0.2831)	1.02 (0.4381)	0.15 (0.8669)
D	3 (2)	11–18	13.90 (<0.0001)	17.25 (<0.0001)	0.81 (0.4682)	2.21 (0.1556)	7.12 (0.0024)	9.79 (0.0005)	4.42 (0.0191)	3.26 (0.0490)
G(T) × D	6 (4)	11–18	0.39 (0.8787)	0.28 (0.9398)	3.47 (0.0456)	0.58 (0.6839)	0.91 (0.5102)	0.20 (0.9708)	0.70 (0.6505)	1.50 (0.2421)
U	2 (2)	21–41	1.04 (0.3617)	3.73 (0.0325)	2.40 (0.1144)	5.26 (0.0136)	0.88 (0.4210)	5.85 (0.0059)	4.56 (0.0226)	7.30 (0.0039)
G(T) × U	4 (4)	21–41	0.45 (0.7739)	0.57 (0.6855)	0.42 (0.7954)	0.63 (0.6491)	0.03 (0.9986)	0.28 (0.8876)	0.66 (0.6295)	0.54 (0.7093)
D × U	6 (4)	21–41	0.20 (0.9756)	0.16 (0.9861)	0.72 (0.5865)	0.37 (0.8255)	0.82 (0.5598)	0.22 (0.9673)	0.24 (0.9596)	0.72 (0.6375)
G(T) × D × U	12 (7)	21–41	0.60 (0.8272)	0.46 (0.9245)	3.10 (0.0197)	2.38 (0.0569)	1.40 (0.2070)	0.46 (0.9286)	1.04 (0.4521)	1.12 (0.3979)
Y	1	74–101	3529 (<0.0001)	4396 (<0.0001)	1055 (<0.0001)	1591 (<0.0001)	5309 (<0.0001)	2324 (<0.0001)	5678 (<0.0001)	7514 (<0.0001)
Y × G(T)	2	74–101	14.47 (<0.0001)	25.88 (<0.0001)	8.85 (0.0003)	11.55 (<0.0001)			6.10 (0.0035)	8.55 (0.0005)
Y × D	3 (2)	74–101	36.64 (<0.0001)	49.81 (<0.0001)	5.78 (0.0046)	3.36 (0.0400)	6.69 (0.0004)	5.38 (0.0018)	10.18 (<0.0001)	6.56 (0.0005)
Y × G(T) × D	6 (4)	74–101	1.83 (0.1006)	2.35 (0.0364)		2.50 (0.0495)				
Y × U	1	74–101	4.77 (0.0105)	9.14 (0.0002)			11.79 (<0.0001)	14.27 (<0.0001)	11.13 (0.0001)	17.00 (<0.0001)
Y × D × U	6	74–101								
Y × D × U × G(T)	22 (17)	74–101					1.50 (0.0908)			
Y^2	1	74–101	267 (<0.0001)	32.54 (<0.0001)		17.97 (<0.0001)	2820 (<0.0001)	147 (<0.0001)	457 (<0.0001)	388 (<0.0001)
Y^2 × G(T)	2	74–101					5.31 (0.0064)	4.72 (0.0110)		
Y^2 × D	3 (2)	74–101			7.17 (0.0003)		4.23 (0.0073)	11.87 (<0.0001)		2.38 (0.0764)
Y^2 × D × G(T)	6 (4)	74–101				1.96 (0.0633)	5.56 (<0.0001)			
Y^2 × U	1	74–101					6.86 (0.0016)	9.45 (<0.0001)		6.52 (0.0025)
Y^2 × D × U × G(T)	22 (17)	74–101				1.77 (0.0484)	1.88 (0.0186)			

Note: G(T), Gap(treatment); D, density; U, understory; Y, year; Y^2, year^2.

*Numerator degrees of freedom in parenthesis are for Douglas-fir.

†Denominator degrees of freedom varied by species.

Table 10. *F* and *P* values from Blodgett Forest analyses of variance for height (HT) and basal diameter (BD) with year as a continuous variable.

		Western redcedar			Douglas-fir			Western hemlock		
			F value (*P* value)			*F* value (*P* value)			*F* value (*P* value)	
Effect	dfn	dfd	HT	BD	dfd	HT	BD	dfd	HT	BD
G(T)	2	4	12.49 (0.0190)	8.56 (0.0359)	4	7.37 (0.0456)	10.30 (0.0265)	4	28.17 (0.0044)	13.36 (0.0169)
D	2	12	23.58 (<0.0001)	24.5 (<0.0001)	12	2.84 (0.0981)	14.12 (0.0007)	12	40.44 (<0.0001)	16.83 (0.0003)
G(T) × D	4	12	0.46 (0.7664)	0.55 (0.7060)	12	1.26 (0.3392)	3.29 (0.0488)	12	3.64 (0.0365)	1.60 (0.2369)
U	1	17	0.08 (0.7781)	1.88 (0.1877)	16	0.76 (0.3976)	11.95 (0.0032)	13	21.72 (0.0004)	23.19 (0.0003)
G(T) × U	2	17	1.06 (0.3692)	0.02 (0.9827)	16	1.39 (0.2774)	1.94 (0.1763)	13	0.97 (0.4037)	0.21 (0.8135)
D × U	2	17	0.36 (0.7056)	1.12 (0.3477)	16	1.05 (0.3730)	2.02 (0.1646)	13	0.36 (0.7056)	0.26 (0.7734)
G(T) × D × U	4	17	0.48 (0.7494)	2.03 (0.1358)	16	0.82 (0.5283)	1.15 (0.3702)	13	1.52 (0.2539)	1.28 (0.3269)
Y	1	53	2083 (<0.0001)	1766 (<0.0001)	52	4326 (<0.0001)	1809 (<0.0001)	49	8042 (<0.0001)	4577 (<0.0001)
Y × G(T)	2	53	3.06 (0.0553)	8.36 (0.0007)	52	8.17 (0.0008)	9.97 (0.0002)	49	23.29 (<0.0001)	9.92 (0.0002)
Y × D	2	53	18.91 (<0.0001)	22.49 (<0.0001)	52	21.04 (<0.0001)	20.83 (<0.0001)	49	45.48 (<0.0001)	19.45 (<0.0001)
Y × G(T) × D	4							49	2.88 (0.0321)	
Y × G(T) × U	3	53	3.97 (0.0206)							
Y × U	1			8.87 (0.0044)	52	5.00 (0.0297)	16.03 (0.0002)	49	28.50 (<0.0001)	25.15 (<0.0001)
Y^2	1	53	1136 (<0.0001)	354 (<0.0001)	52		49.38 (<0.0001)	49	995 (<0.0001)	370 (<0.0001)
Y^2 × G(T)	2	53	4.94 (0.0108)	8.11 (0.0008)				49		4.02 (0.0242)
Y^2 × D	3			5.40 (0.0073)	52	3.21 (0.0304)		49		3.77 (0.0300)
Y^2 × U	1				52	8.58 (0.0050)				

Note: G(T), Gap(treatment); D, density; U, understory; Y, year; Y^2, year^2.

the gaps. Thirty-one percent of western redcedars were browsed more than once in the matrices, but only 18% were browsed repeatedly in gaps.

At Blodgett Forest, western redcedar seedlings were small at the time of planting (Table 4), and damage from browsing was especially severe because of the high percentage of foliage removed. Through 10 years of observations, less than 7% of western redcedars escaped browsing and over 70% were browsed at least three times. Browsing was so severe that after 10 years, mean heights were less than 75 cm. Browsing was also heavy on Douglas-fir, with 89% of the Douglas-fir browsed at least once and 56% browsed at least three times.

Relative frequencies of seedlings taller than 3 m

Although we did not perform any statistical tests on these data, the relative frequency of seedlings taller than 3 m at year 10 gives an indication of the potential structure. Height frequency graphs were developed for each species comparing gaps, matrices, and uniform treatments (Figs. 6 and 7). For simplification, HIGH density and the release treatment at McDonald Forest were not included. None of the species within the matrices and in uniform plots of the HIGH density had more than 25% of seedlings taller than 3 m. Trends for the release treatment usually fell in between the plant and spray treatments. Frequency graphs from McDonald Forest indicated that very few Douglas-fir and grand fir had reached 3 m in 10 years. For all species, there were trends for greater frequencies of 3 m seedlings in gaps and with low overstory densities. At Blodgett Forest, only two western redcedars had reached 3 m; therefore, those data are not shown. Graphs of Douglas-fir and western hemlock indicated the greater frequency of 3 m seedlings in gaps, at lower densities, and with spraying.

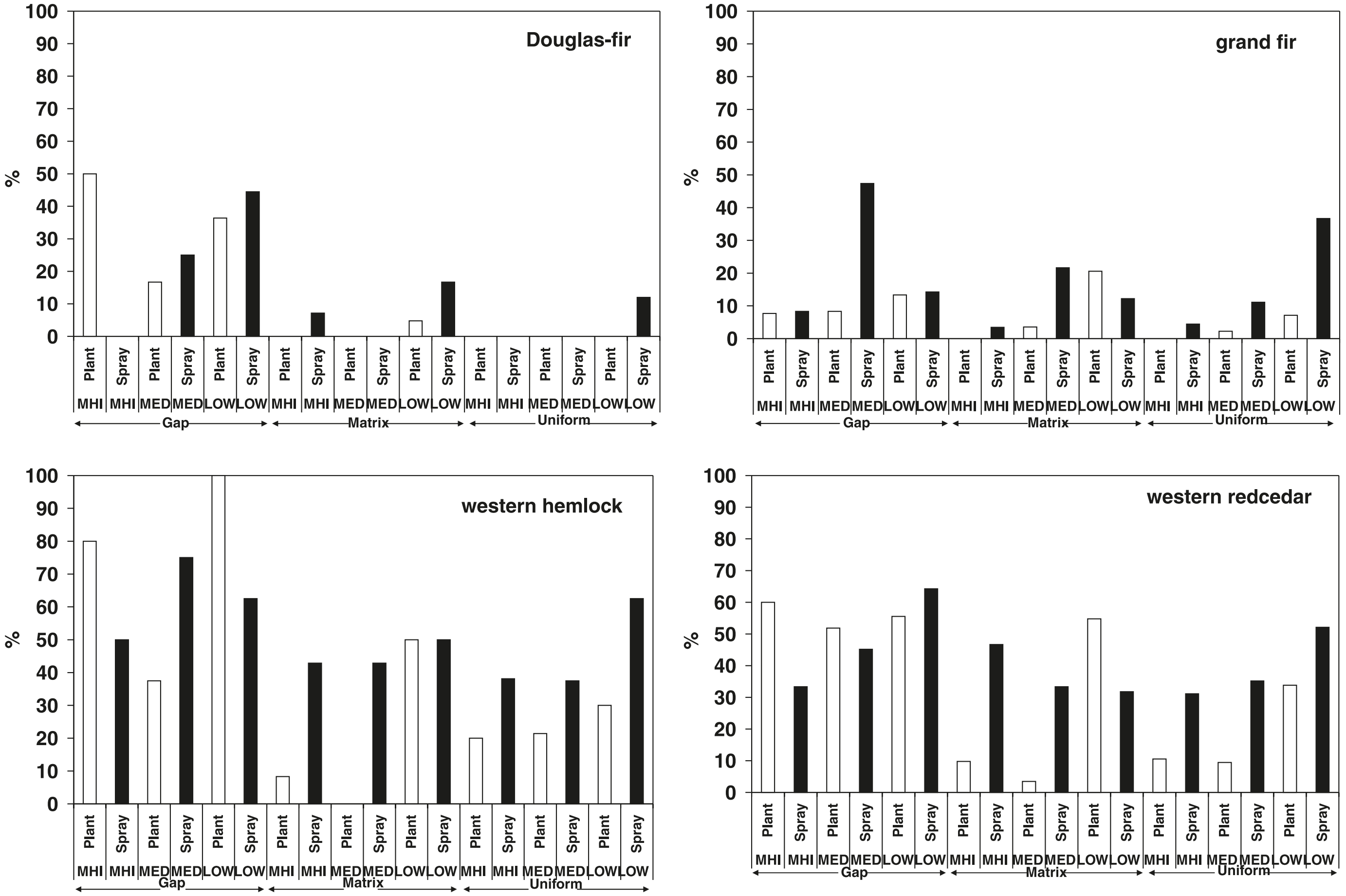
Discussion

Underplanting conifer seedlings after thinning has been identified as a potential means for increasing vertical complexity and diversity in even-aged forests in the Pacific Northwest (McComb et al. 1993; Cole 1996; Carey and Harrington 2001; Carey 2003). Although underplanting can be successful, numerous factors affect the ability of seedlings to survive, grow, and ultimately contribute to a multilayered canopy. Overstory cover and overtopping by understory vegetation affected survival and size of underplanted seedlings, but impacts varied between the sites and among species. The survival and size of underplanted seedlings decreased as residual overstory density increased (Figs. 2 and 3). Growth trends indicated different future projections among densities and for seedlings in gaps (Figs. 3 and 4). Aside from the seedling heights observed in gaps, relative height frequencies indicated that less than 60% of the seedlings had reached 3 m in 10 years (Figs. 6 and 7).

Stand density and thinning pattern effects

Although overstory density influenced survival at McDonald Forest, survival at Blodgett Forest was not affected by overstory density. Survival of Douglas-fir and western hemlock at Blodgett Forest was better than at McDonald Forest. Many seedlings did not recover from the apparent water-

Fig. 6. Relative height frequencies for seedlings taller than 3 m at year 10 for gap, matrix, and uniform areas at McDonald Forest. HIGH density and the release treatment are not shown.



stress problems associated with conditions during planting in McDonald Forest; whether those species might be expected to perform better most years, is conjectural. The failure of grand fir and western redcedar to show similar symptoms is the reason for assuming the condition of the seedlings on arrival was poor. Western redcedars survived as well at McDonald Forest as at Blodgett Forest.

The survival rates of underplanted seedlings at Blodgett Forest were similar to the rates from thinned stands in other studies in the Oregon Coast Range (Maas-Hebner et al. 2005; Chan et al. 2006), Washington (Harrington 2006), and Scotland (Mason et al. 2004). In these studies, survival was over 85% when stands were thinned to less than 26 m^2/ha, and 35% when residual densities were over 40 m^2/ha.

Seedling size at age 10 decreased with increasing overstory density. When compared with the seedling size expected in clearcuts (6–10 m height at age 10; Harrington et al. 1995; Stein 1997; Rose et al. 2006), even our lowest overstory density of roughly 20 m^2/ha slowed Douglas-fir height growth. Growth decreased rapidly once basal areas reached 27 m^2/ha, especially at McDonald Forest, and the LOW densities are now at that level of basal area. Similar decreases in Douglas-fir growth have been previously reported (Weise and Ehring 1993; Mason et al. 2004; Maas-Hebner et al. 2005; Chan et al. 2006; Harrington 2006). Shade-tolerant species continued to grow relatively well at somewhat higher densities. As the overstory grows, it is expected that growth of even shade-tolerant species will slow (Fig. 3) (Khan et al. 2000). Trajectories indicated that declines were occurring at the highest densities.

Overstory density and dynamics, along with seedling injury, appear to be the overwhelming variables that influence the long-term outlook for underplanted seedlings. Overstories may be thinned, but they will not remain static. Residual overstory stands grew in basal area at about the same rates at McDonald and Blodgett forests, ranging from 4 to 9 m^2/ha in 10 years, or averaging 2.8% growth per year, or 28% growth in a decade. In both installations, the amount of growth moved up with each density class to the next higher class in a pattern similar to that reported by Chan et al. (2006). In the process, the overstory cover increased proportionally more than basal area. The impact on western redcedar seedlings coincided with the trends, i.e., that growth had slowed (Fig. 3) as overstory basal area increased over time.

Even though the gap seedlings grew faster than those in matrices, the density of surrounding stands apparently influenced growth. Although Coates (2000) found that western hemlock and western redcedar displayed little increase in growth in gaps greater than 0.1 ha after 5 years, he did report that the best growth was in the centers of the gaps and that the difference was probably related to overstory effects. Malcolm et al. (2001) remarked that cutting small gaps in

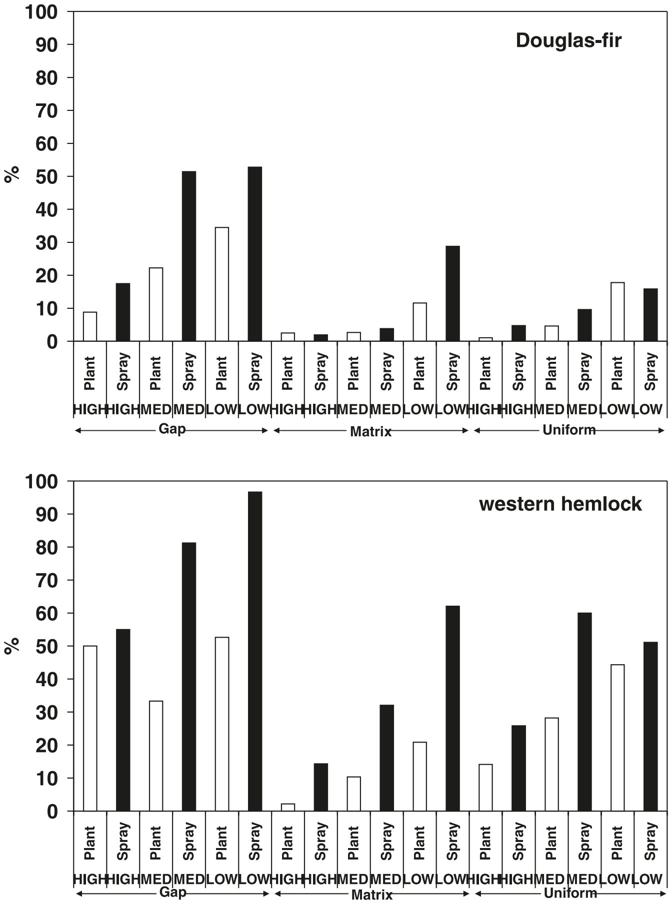


Fig. 7. Relative height frequencies for seedlings taller than 3 m at year 10 for gap, matrix, and uniform areas at Blodgett Forest. Western redcedar is not shown.

rapidly growing British conifer stands would be unsuccessful because of the growth rate of the overstory trees. They recommended gaps of 0.1–0.2 ha for Douglas-fir, whereas gaps of 0.05 ha or less would accommodate western hemlock and western redcedar for establishing a new cohort within stands. In a study in California (York et al. 2004), models developed for Douglas-fir indicated that the maximum predicted height occurred in their largest opening, 1 ha.

Spraying effects

The site preparation treatment increased adjusted survival for Douglas-fir at McDonald and Blodgett forests but did not increase survival for the other species. Site preparation had a minor influence on survival in relation to the effect of overstory density.

Understory site preparation by application of broad-spectrum mixtures of herbicides increased the size of most underplanted species, with the degree of growth dependent on overstory density and understory vegetation. Harrington (2006) reported that soil water availability from the vegetation control decreased as the overstory level increased. He observed that the effect of root competition could be similar for a wide range of overstory densities because of the confounding effect of overstory and understory vegetation. Mitchell et al. (2004) reported that western hemlock had a greater growth response to vegetation control in clearcuts where target vegetation was the only competition than under canopies. Not only does overstory density have a negative influence on underplanted seedlings, it also has a negative influence on many of the understory competitors of those underplanted seedlings. Higher overstory densities will affect understory vegetation development (Tappeiner and Zasada 1993; Bailey and Tappeiner 1998; Chan et al. 2006), which may impact seedling growth in unknown ways. We speculate that the greater the understory development prior to planting, the greater will be the growth benefits of an effective preplanting vegetation management treatment within any given overstory density.

Studies of seedlings growing in the open have shown that vegetation management positively influences seedling growth even in the presence of browsing (Gourley et al. 1990; O'Dea et al. 2000; Harrington 2006). Saunders and Puettmann (1999) found that an increased intensity and frequency of clipping (for simulated browsing on white pine) lessened the gains achieved by vegetation management in an understory situation. We believe that the lack of response by western redcedar to spraying at Blodgett Forest was related to the severity of browsing; very few seedlings grew at their potential. These factors operate within the general scheme of a generally negative growth response to increasing overstory density (Drever and Lertzman 2003), under which herbivory has an influence (Harrington 2006).

Overall, the release treatment at McDonald Forest was not generally effective at removing competing vegetation or enhancing growth, and the spot-directed foliage application injured some seedlings. In some instances, the release treatment was effective in removing competition, and this resulted in larger seedlings in those areas. Regression analyses (E. Cole and M. Newton, unpublished data, 2008) that examined the relationships between seedling volume and overstory cover, overtopping, and understory vegetation indicated that seedlings were responding to their environment. The significant interactions among density and understory treatments were in part a reflection of the presence of shrubs and the variability in the efficacy of the understory treatments.

Other effects

Of the species planted in our study, western redcedar is considered the most shade tolerant, followed by western hemlock, grand fir, and Douglas-fir (Carter and Klinka 1992; Kobe and Coates 1997). Although underplanting western redcedar is preferred because of its ability to survive (Kobe and Coates 1997) and grow (Carter and Klinka 1992; Coates and Burton 1999; Khan et al. 2000) in understory situations and the high value of its wood, the impact of browsing needs to be considered (Maas-Hebner et al. 2005). Likewise, Douglas-fir size in an underplanting situation can be severely limited by browsing. Douglas-fir also requires more light than western hemlock, western redcedar, or grand fir to maintain growth rates (Chan et al. 2006; Carter and Klinka 1992). Browsing was minimal on grand fir and western hemlock. The intense but erratic browsing pattern eliminated our ability for fine-resolution determination of some of the interactions.

Poor planting conditions and rethinning at McDonald Forest and browsing at both sites confounded our results. We were unsuccessful at quantifying these impacts at this time, and thus, they have unknown impact on the treatment results. In addition, our study was limited by having only two sites that could not be compared directly. Our sites differed in site quality, geology, climate, and vegetation; yet seedling growth trends with density were consistent between sites and were similar to those from other studies (Chan et al. 2006; Harrington 2006).

Implications for management

Operational guidelines for commercial thinning programmed to enhance tree size and quality while preserving stand growth will seldom reduce stand density enough to recruit and grow a shade-intolerant species such as Douglas-fir. Hayes et al. (1997) recommended that for wildlife diversity, stands should be thinned to a relative density (RD) (Curtis 1982) of 3.6 and allowed to grow until RD reaches 6.5. Harrington (2006) found that a RD of 3.8 in thinned stands limited growth of understory Douglas-fir as well as western hemlock and western redcedar. Chan et al. (2006) estimated that stands thinned moderately to a RD of 2.2–3.6 might offer opportunities to enhance structural diversity and timber production with thinning intervals at 15 years or longer. Our data indicate that some stands thinned to these moderate RDs (Tables 2 and 3) might require thinning earlier to maintain growth of underplanted conifers and that allowing stands to reach RDs of over 5.5 will severely limit growth and possibly survival of underplanted conifers. Although underplanted conifers may continue to survive at the higher densities, growth will be slowed to the point that it will be many decades, if ever, before they will contribute to structural diversity. At the LOW density, understory conifer growth is expected to decline as canopies close; however, survival and growth of tolerant species should be sufficient for a midlayer to develop. We hope to follow these plots for at least another decade so that this can be confirmed or refuted.

Managers will need to consider the desired species, overstory growth rates, understory vegetation, and special requirements in logging when manipulating stands to generate late-seral features. General comments about some of these considerations follow.

1. Survival in these underplanting situations varied based on species, planting conditions, stock conditions, overstory density, and understory vegetation.
2. In our study stands, shade-intolerant species, such as coastal Douglas-fir, did not tolerate overstory basal area levels much over 20 m^2/ha at any time after thinning to maintain growth rates. It appears likely that a considerable level of initial stand opening or rethinning will be necessary on these coastal-type sites for establishing and growing Douglas-fir. Very low overstory stocking may increase the risk of windthrow.
3. None of the shade-tolerant species grew well beneath overstories of 30 m^2/ha initial basal area, even though those plots did not exceed 215 trees/ha.
4. Rethinning will damage or kill a significant proportion of underplanted seedlings unless logging and planting patterns are designed to preserve regeneration (Newton and Cole 2006). It may prove feasible to establish gaps or areas with low overstory densities that benefit the survival and growth of seedlings and to fell or yard trees away from the regeneration.
5. To meet underplanting development objectives, vegetation control may be necessary in some stands. Stands that have already reached the stem-exclusion stage prior to thinning and underplanting may have shaded out understory vegetation to the point that vegetation control may not be necessary. Effective vegetation control is more likely to increase growth of underplanted seedlings in stands that have developed dense understory vegetation and in stands thinned to lower densities where understory vegetation is likely to increase after thinning. At Blodgett Forest, naturally regenerated western hemlock was abundant in some locations (Nabel 2008), was not seriously affected by the site preparation treatment, and is expected to impact other understory vegetation in the future.
6. Protection against herbivory may be needed to maintain planted seedlings, especially western redcedar (Maas-Hebner et al. 2005).

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