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Understory vegetation dynamics 15 years post-thinning in 50-year-old Douglas-fir and Douglas-fir/western hemlock stands in western Oregon, USA

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ABSTRACT

Recent trends in forest management practices designed to restore or enhance late-successional structure for habitat values typically include provisions for the creation and maintenance of structural and compositional diversity within and among stands. The Pacific Northwest in particular has expanses of young, structurally simple forests that range from high stocking (unthinned and little understory development) to relatively lower stocking having been previously thinned or initially regenerated at low densities. We have remeasured two long-term study sites in Oregon, USA, for 15 years to examine structural development and understory persistence at a range of overstory canopy cover, spatial arrangement, and understory treatments (spraying and planting). Understory responses to thinning varied primarily by site and species group, given the range of pre-existing plant communities, and through time. In general, shrub cover increased after thinning, while forb cover increased initially after thinning and then declined. Though spraying effects were still visible 15 years after treatment driven by reductions in one dominant understory species, it had little effect on the long-term development of structure at these overstory densities. Indeed, the range of overstory densities and spatial arrangements in this study did not have any large effects because all of the thinning treatments resulted in increased light availability to the understory at least through fifteen years after thinning. Combining more extensive overstory removal and understory treatments likely can be used to stimulate heterogeneous structure and composition development in these forests, including the possible stimulation of persistent early-seral vegetation within older stands.

1. Introduction

Forest managers are increasingly interested in management practices that include provisions for creation and maintenance of structural and compositional diversity within and among stands. In the Pacific Northwest specifically, interest focuses on the management of second-growth Douglas-fir (*Pseudotsuga menziesii* var. *menziesii* (Mirb.) Franco) forests for structural diversity (Carey and Curtis, 1996; Harrington and Nicholas, 2007; Franklin and Johnson, 2012). The Oregon Coast Range has a large land base of 50–80-year-old forests that range in stocking from high-density stands, which have not been thinned and have little understory development, to relatively open-grown stands that have been previously thinned or initially regenerated at low densities (Tappeiner et al., 1997; Bailey and Tappeiner, 1998).

Mid-rotation, or even early, thinning, whether the primary purpose is for enhancing timber production or structural diversity, impacts the composition and abundance of understories (Bailey et al., 1998; Wilson and Puettmann, 2007), and such understory development can contribute substantially to wildlife habitat and diversity (Hagar, 2007). Many authors (e.g. Alaback and Herman, 1988; McComb et al., 1993) have indicated that thinning dense stands can lead to increased structural diversity and/or a shortening of time to develop such diversity. Stand response is based on the fundamental linkage between overstory and understory development as they compete for limited site resources (Nemati and Goetz, 1995; Riegel et al., 1995; Puettmann and Berger, 2006; Sabo et al., 2008). However, thinning has also been shown to decrease the abundance of some wildlife species (Manning et al., 2012). Understanding the changes in post-thinning understory vegetation can help predict the impacts of thinning on wildlife.

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Changes in understory development after thinning may be quite temporary, depending upon treatment intensity, stand age and productivity of the site (Uresk and Severson, 1989; Thysell and Carey, 2001; Sullivan et al., 2009), or it may last for extended periods (Duffy and Meier, 1992). As the overstory grows/deepens and tree crowns expand, understory vegetation may lack adequate solar radiation for survival. Tracking and understanding such changes through time is needed to (1) determine how long shrubs and herbaceous species may persist in the understory and (2) help guide thinning regimes designed to improve stand diversity and wildlife habitat. In this way, habitat analyses can be adjusted to needed scales as forest management activities progress through landscapes.

Inclusion of gaps in overstory stands provides increased heterogeneity in thinned stands (Cissel et al., 2006; Gray et al., 2012), adding structural diversity over time, and maintaining shade-intolerant species in the under- and mid-story canopy (Coates and Burton, 1997; Schnitzer and Carson, 2001; Schumann et al., 2003). In addition to enhancing light penetration within stands, gaps can concentrate ground disturbance in order to promote germination of forbs and conifers.

Our objectives were to examine trends of understory vegetative abundance and persistence in 15 years following thinning to four residual densities, each with and without gaps of 0.06 and 0.10 ha following overstory thinning in Douglas-fir stands and Douglas-fir/western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) stands 50–55 years old. Specific objectives were to determine: (1) if development patterns of understory vegetation and associated shrub/forb species were related to thinning intensity and the inclusion of gaps, (2) if understory development patterns were related to previous understory pre-thinning herbicide treatments that altered pre-existing communities, and (3) if there were interactions between overstory density and understory vegetation treatment related to understory vegetation development.

2. Methods

2.1. Study sites

Two sites on Oregon State University Research Forests were selected for this study. The first was a Willamette Valley foothill site 200–400 m elevation near Corvallis, OR ("McDonald," Lat. 44.65°N. Long. 123.27°W) on which the study was established in 1993. Stands were dominated by 50–55-year-old planted Douglas-fir with scattered grand fir (*Abies grandis* Lindl.) and bigleaf maple (*Acer macrophyllum* Pursh). Understory vegetation was well developed prior to thinning due to previous thinning treatments in 1964–1965 and 1980–1981. Vegetation consisted of western swordfern (*Polystichum munitum* (Kaulf.) C. Presl.), hazel (*Corylus cornuta* Marshall), ocean spray (*Holodiscus discolor* (Pursh) Maxim.), Pacific poison oak (*Toxicodendron diversilobum* (Torr. & A. Gray) Greene), western brackenfern (*Pteridium aquilinum* (L.) Kuhn), trailing and Himalayan blackberries (*Rubus ursinus* Cham. & Schltdl. and *Rubus armeniacus* Focke, respectively), with other species in lesser amounts. This McDonald site had a dry-summer climate with moderate temperatures, and about 1500 mm of precipitation distributed primarily (85%) in October to May as rain. Soils were clay loams derived from basalts with good drainage, moderate to deep; sites were mostly facing west to northwest at slopes 10–50 percent.

The second site was established in 1995 ("Blodgett," Lat. 46.07°N, Long 123.35°W,) and was in the Coast Range about 185 km north of McDonald and about 50 km east-south-east of Astoria, OR. Blodgett stands were entirely of natural origin, also 50–55-years-old, and varied in the percentage of western hemlock and Douglas-fir. Western hemlock ranged from 4% to 81% of post-harvest basal area, making it nearly as abundant as Douglas-fir overall. Some areas contained small amounts of western redcedar (*Thuja plicata* [D.] Don.) and red alder (*Alnus rubra* Bong.). Most stands had been thinned 6–8 years prior to establishment of our study, with a mixture of cable and ground systems that provided disturbance of surface soil. Understory vegetation consisted of western swordfern, vine maple (*Acer circinatum* Pursh), salal (*Gaultheria shallon* Pursh), Oregon grape (*Mahonia nervosa* (Pursh) Nutt.), naturally regenerated western hemlock seedlings/saplings, and other species in lesser amounts. Rainfall distribution was similar to McDonald, but temperatures were cooler in summer, and precipitation was greater, (1700–2000 mm). Soils were silt loams, very deep, fertile, well drained and derived from highly weathered sedimentary parent material.

2.2. Design and treatments

The experimental design was a split-split plot with three replications (blocks) at each site (Cole and Newton, 2009). Blocks were divided into two whole plots randomly assigned to either a uniform or gap thinning regime. The gap thinning regime was thinned to the same basal area per hectare as the uniform regime, but with most of the cut removed in three 0.06 ha and three 0.10 ha circular "gaps". If insufficient basal area was removed in the gaps, then the matrix area between gaps was thinned uniformly.

Each whole plot was subdivided into four (McDonald) or three (Blodgett) density subplots. Subplots were 2.46 ha with an interior 1.46 ha measurement area that was to be planted and an 18 m area of the same density around each measurement area that would remain unplanted (Cole and Newton, 2009). Each subplot was randomly assigned to a density (Table 1), which ranged from 33 to 60 percent "normal stocking" (McArdle et al., 1961). Thinning occurred during the fall of 1993 at McDonald and the fall-winter of 1995–1996 at Blodgett using a mixture of cable and ground equipment depending upon the slope and proximity to roads.

Measurement areas were divided into three 0.49 ha (McDonald) or two 0.73 ha (Blodgett) sub-subplots and randomly assigned an understory vegetation treatment (Table 2). In addition to these treatments within the subplot, vegetation around the measurement area was sampled as a "No Plant" treatment. The "Spray" treatment was a broadcast-herbicide site preparation applied prior to logging (Table 2). The "Release" treatment (McDonald only) was a directed herbicide application that was applied around approximately 20–25% of the seedlings. The Blodgett spray treatment had to be re-applied because of a delay in removal of logs after thinning; the second application was in October 1996.

Measurement areas were underplanted at 3 m × 3 m spacing in January 1994 (McDonald) and at 3 m × 4 m in February 1997 (Blodgett). In McDonald, the plantings consisted of double rows of western redcedar, grand fir, western hemlock, and Douglas-fir. All seedlings were transplant plug+1 or plug+2 (western redcedar). At Blodgett, grand fir was not planted, and the western redcedar were smaller plug+1 seedlings.

This study was designed to have multiple thinning treatments. A second entry at McDonald was eight years later at stand age approximately 58–63 years, made when the overstory began suppressing underplanted seedlings in the intermediate densities (MED and MHI). These subplots were re-thinned back to the original thinning basal areas (Newton and Cole, 2006); Blodgett has not been re-thinned.

2.3. Measurements

Understory vegetation was inventoried on a series of permanent nested sample points, positioned systematically after a

Table 1
Basal area (BA) and trees per hectare (TPH) immediately after overstory thinning at the McDonald and Blodgett sites, western Oregon.

	McDonald		Blodgett	
	BA (m^2/ha)	TPH	BA (m^2/ha)	TPH
Gap thinning				
LOW	17.5	104	19.7	101
MEDIUM (MED)	23.5	137	26.4	141
MEDIUM-HIGH (MHI)	27.7	160		
HIGH	29.7	198	32.7	199
Uniform thinning				
LOW	18.6	98	20.5	129
MEDIUM (MED)	22.8	110	27.1	159
MEDIUM-HIGH (MHI)	27.8	140		
HIGH	30.9	211	32.4	211

Table 2
Herbicide application schedule for the McDonald and Blodgett Forest sites.

	Application method	McDonald	Blodgett
Spray	Broadcast application by backpack sprayer with a single nozzle	1.6 kg/ha glyphosate plus 0.14 kg/ha imazapyr in water for a total volume of 47 L/ha applied late summer 1993	1.6 kg/ha glyphosate, 0.2 kg/ha imazapyr, 0.16 kg/ha sulfometuron, and 3.3 kg/ha triclopyr ester[a] in water for a total volume of 28 L/ha applied late summer 1995 0.16 kg/ha sulfometuron, 2,4-dichlorophenoxyacetic acid or 2,4-dichlorophenoxyacetic acid plus dichlorprop[b], and 2.2 kg/ha triclopyr ester[a] at 1.1 kg/ha in water for a total volume of 28 L/ha October 1996
Release	Directed foliage application around individual seedlings	3% triclopyr ester in oil or 3% glyphosate in water summer 1995	
Plant	No treatment	No treatment	No treatment

[a] Triclopyr ester included only for plots with high percentage of evergreen shrubs.
[b] Dichlorprop is not currently registered for forestry use.

random start within a specified area. Ten (McDonald) or 15 (Blodgett) sample points were established prior to thinning in each subsubplot. In addition, 10 points were established in the no-plant portion around each measurement area. Although these points were not within the measurement area, the same overstory treatment had been applied to this area. Points for the no-plant treatment were randomly established within zones specified to minimize edge effects from adjacent subplots or unthinned areas. Prior to spraying and thinning, and growing seasons 1, 3, 5, 7, 10, and 15 years after thinning, understory cover was visually rated in 1- and 5-m radius nested plots. Cover estimates collected in the 1-m plots included percent shrubs, trailing blackberry, swordfern, brackenfern, other ferns, grass, forb, sedge and rushes, planted conifers, and natural conifers. Planted and natural conifers were segregated by species after year 3. Every forb species within 1-m radius of the point was recorded (Table A1). In the 5-m plots, cover estimates were made individually for every shrub and fern (excluding arboreal ferns) species (Table A2) in 3 layers: 0–1.49 m (low), 1.5–5 m (mid), >5–15 m (tall), and > 15 m (overstory). Height of maximum leaf area by species in each layer was also estimated.

2.4. Data analyses

Cover estimates were analyzed using ANOVA (PROC MIXED or GLIMMIX in SAS® software, SAS Institute, 2002–2012) to determine overstory density and vegetation management effects on species groups: forbs, swordfern, low deciduous shrubs (McDonald only), low + mid evergreen and deciduous shrubs (Blodgett only), mid-layer deciduous shrubs (McDonald only), overstory tree cover, and planted and natural understory conifers. Tall shrubs and small trees were a minor component of the vegetation and were not analyzed for cover. Data were examined through time using year 0 conditions as covariates and year as a continuous variable within the ANOVA (Littell et al., 1996). Both linear and quadratic terms for year were tested, non-significant interactions were removed, and data re-analyzed.

To determine similarity among overstory density and vegetation management treatments, non-metric multidimensional scaling (PC-ORD) was used to group plots. Cover of individual shrubs (low and mid-layers combined) or forb species frequency was used for measurement years 0 (pre-thinning), 1, 7, and 15. PC-ORD was also used to calculate Shannon and Simpson diversity indices for each measurement period (McCune and Grace, 2002). These were analyzed for density and vegetation management treatment effects utilizing PROC MIXED or PROC GLIMMIX (SAS® software) with year 0 as a covariate and year as a continuous variable (Littell et al., 1996). For ANOVAs, PROC GLIMMIX was used when results from PROC MIXED indicated that data were not normally distributed.

In addition to the above analyses, we examined the prevalence of late seral and exotic forb species. The average number of species per point for both late seral and exotic species was analyzed using PROC MIXED with year 0 as a covariate and using year as a continuous variable. Late seral species were based on their FEMAT classification (FEMAT, 1993), and exotic species were based on the USDA Plants database (plants.usda.gov). Many of the shrubs listed as late seral were common in early seral communities, so late seral shrubs were not analyzed. Distribution of exotic shrubs was sporadic and resulted in too many instances of zero means with zero variance to allow for ANOVAs.

Structural diversity was assessed by using "layers" as a substitute for species in both the Simpson's and Shannon-Weiner diversity equations. Layers included: (1) ground layer, which consisted of forbs, grasses, and sedge species; (2) fern layer, which consisted of all species of ferns; (3) low shrub; (4) mid-shrub layer; (5) tall shrubs; (6) low overstory, trees 15–25 m in height; and (7) overstory layer, trees > 25 m in height. Layers 3–7 were further divided into conifer, deciduous, and non-conifer evergreen species.

Structural diversity was analyzed through time in the same manner as other diversity measures using PROC GLIMMIX or MIXED as appropriate with year 0 as a covariate and year as a continuous variable.

PROC CORR in SAS® software was used to determine correlations among understory and overstory variables. This procedure was utilized as an initial screening tool to examine relationships among the variables. Variables with high correlations with each other were then analyzed using PROC REG and PROC MIXED. Cover was generally similar among the release, no plant areas and unsprayed areas; results will be discussed primarily between sprayed and unsprayed planted sub-subplots.

3. Results

Initial understory cover was highly significant as a covariate at both the McDonald Forest and Blodgett Forest sites and for all analyzed variables. With the exception of the Shannon Index for forb diversity at Blodgett ($P = 0.0840$), initial diversity indices were significant ($P < 0.05$) indicating the importance of initial species composition at the time of spraying and overstory thinning. Even though initial conditions influenced vegetation development, there were significant trends related to overstory density and vegetation management treatments over the first 15 years.

3.1. McDonald Forest – Willamette Valley Fringe

Analyses consistently indicated that the amount of vegetative cover changed over 15 years among residual overstory densities, spatial arrangement, and understory treatments (Figs. 1–3). Spraying had the largest single effect on near-surface and mid-layer vegetative cover, particularly swordfern (Fig. 3) which continues to have decreased cover 15 years after spraying. Spraying reduced total cover of shrubs initially but, by year 15, cover in the low vegetation layer was similar among sprayed and unsprayed sub-subplots (Fig. 1b) while, in the mid layer, cover was still lower than in unsprayed sub-subplots (Fig. 2b) for both uniform and gap overstory conditions. Number of exotic species increased after thinning, with the greatest increases in the sprayed plots. By year 15, numbers of exotics were declining across all densities and understory treatments, but the sprayed sub-subplots still had greater numbers (Table A3). Although we could not analyze the data statistically, overall mean cover of the most abundant exotic shrub, Himalayan blackberry, increased from 0.4% to 7% from year 0 to year 15, with some sub-subplots averaging >50% cover in year 15.

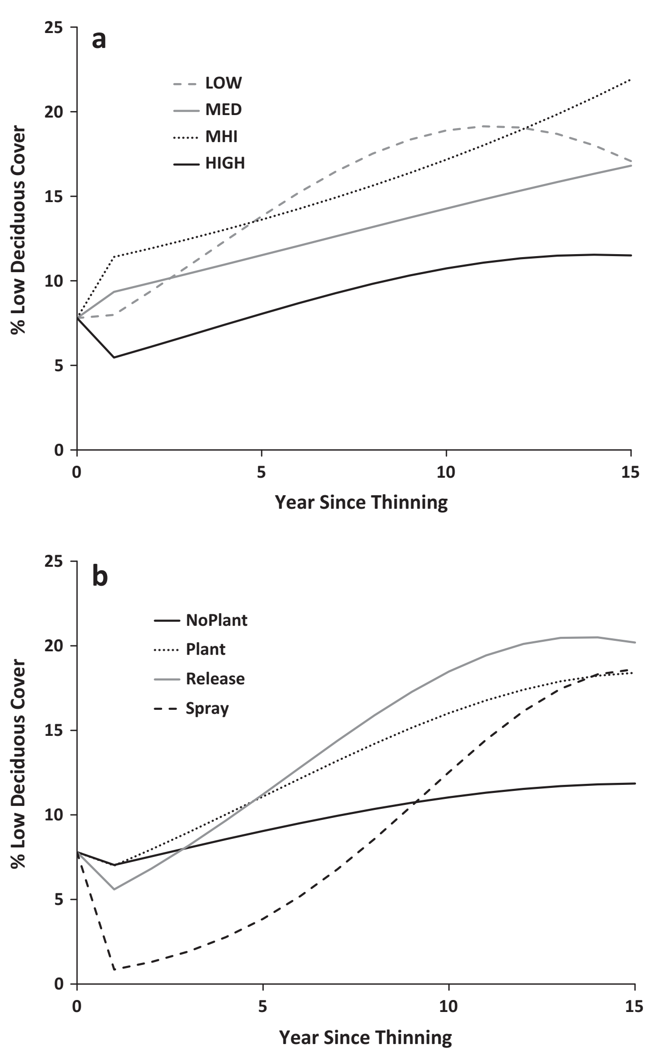

Fig. 1. Least-squared means comparisons for near-surface (low < 1.5 m) deciduous vegetation cover in McDonald Forest treatment units over 15 years across: (a) overstory density (low, medium, medium-high, and high) and (b) understory treatments.

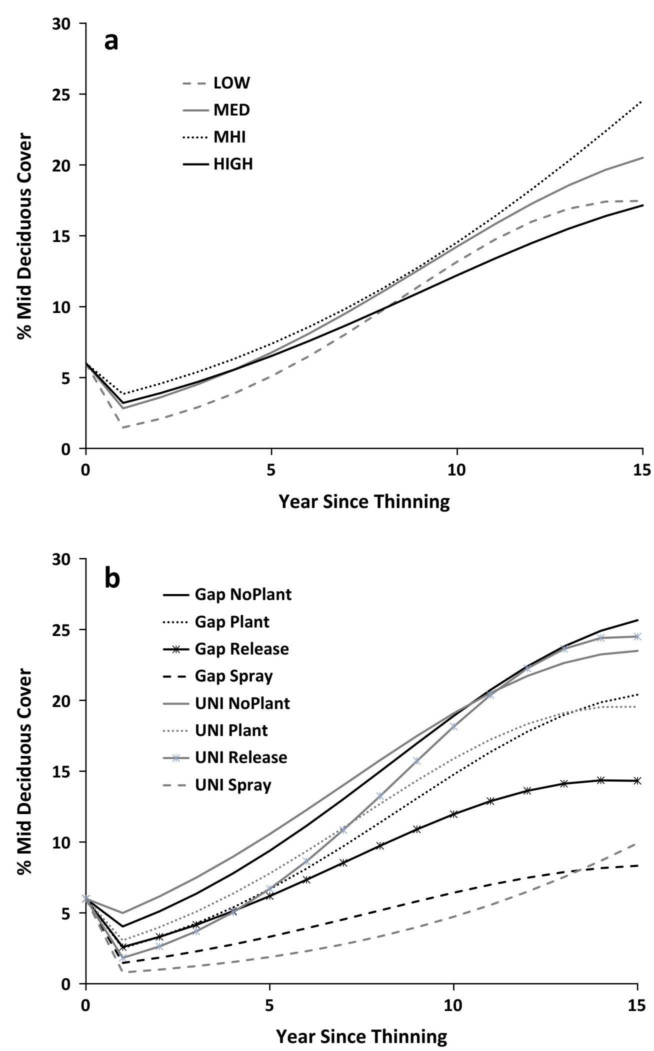

Fig. 2. Least-squared means comparisons for mid-layer deciduous vegetation cover in McDonald Forest treatment units over 15 years across: (a) overstory density (low, medium, medium-high, and high) and (b) understory treatments, separated by gap vs. uniform overstory arrangement.

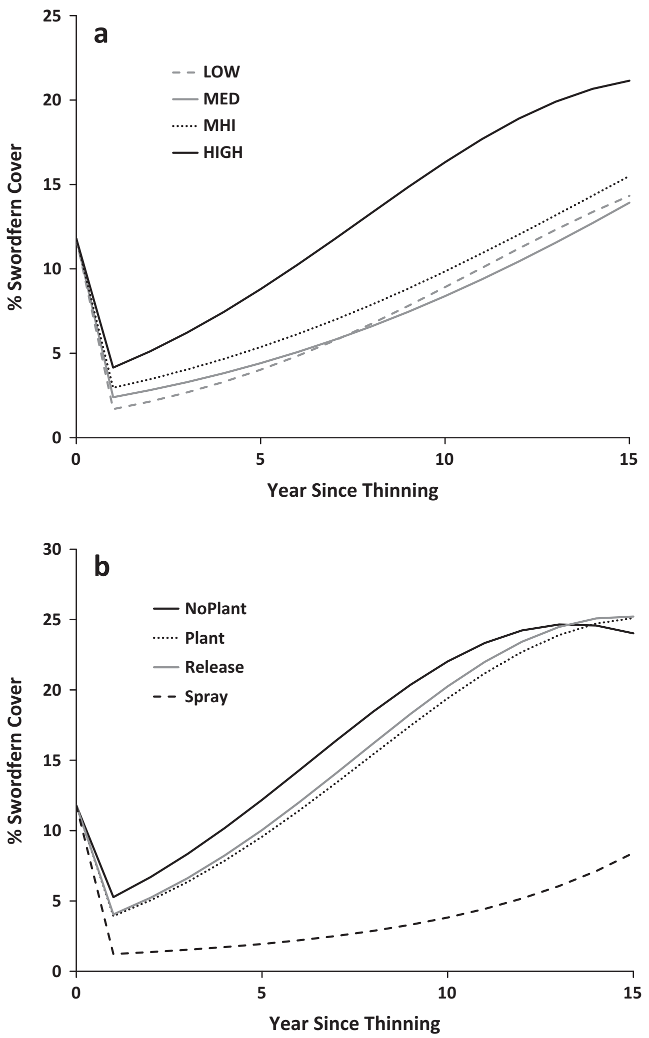

Fig. 3. Least-squared means comparisons for swordfern cover in McDonald Forest treatment units over 15 years across: (a) overstory density (low, medium, medium-high, and high) and (b) understory treatments.

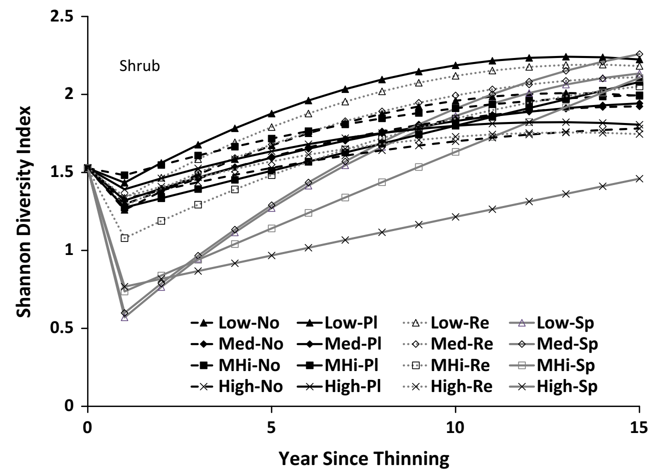

Fig. 4. Least-squared means comparisons for Shannon Diversity Index calculated for total shrub cover in McDonald Forest treatment units over 15 years across overstory density (low, medium, medium-high, and high) and understory treatments (no plant (No), plant (Pl), release (Re) treatment, and initial broadcast spray before planting (Sp)).

Overstory tree density further affected understory vegetation layers and their recovery over 15 years. Interactions with density were not significant, indicating that cover in the different understory treatments was responding similarly among the densities. In the low layer, shrub cover was least in the HIGH density plots (Fig. 1a). Although cover in the mid layer had the greatest reduction initially in the LOW density presumably related to greater disturbance from logging, by year 15, the HIGH and LOW densities had similar cover (Fig. 2a). Swordfern cover was greatest in the HIGH density, with the other densities having similar cover by year 15 (Fig. 3a).

Mean swordfern cover in sprayed sub-subplots on the Willamette Valley Fringe site was best predicted by total overstory canopy cover and low + mid understory cover, with r^2 values of 0.59–0.75 for all years except 15, when the r^2 value decreased to 0.39.

In unsprayed sub-subplots, mean swordfern cover was also best predicted by total overstory cover and low + mid understory cover (r^2 = 0.37–0.67); years 7 and 10 had the lowest correlations. For individual sample points (rather than means) in sprayed sub-subplots, however, r^2 values were only 0.08–0.47, with only years 0 and 1 having r^2 values > 0.4. For unsprayed sub-subplots, r^2 values ranged from 0.17 to 0.44, with the earlier years having the higher correlations.

The greatest influence on shrub diversity was initially the spraying treatment, though overstory density also affected Shannon Diversity Index with the HIGH density resulting in lower diversity, maintained over 15 years (Fig. 4). Number of late seral forbs was decreased by spraying initially, but by year 15, there were no effects of understory treatment (Table 3); forb diversity was not affected by spraying, even though forb cover initially increased after spraying. Both the Shannon and Simpson indices indicated that structural diversity was initially decreased by spraying (Table 3); however, after 15 years, there were no significant differences due to spraying. Trends in diversity varied across overstory density as well (Table 3) with the HIGH density showing the least but measurable increase over time after thinning. The degree of change created initially by spraying was greater than that created by the experimental range of overstory densities and spatial arrangement.

Ordination results varied by the spatial scale of the sampling and whether shrubs or forbs were analyzed (Figs. 5 and 6). For both 1-m and 5-m-radius samples, understory vegetation was similar among treatments prior to thinning; groupings were associated only with blocks. Fifteen years after thinning for the 1-m radius samples, sprayed sub-subplots tended to group together along two of the three primary axes (Fig. 5b). Swordfern was the primary species driving this relationship (r = −0.901 on axis 1), as swordfern cover was reduced in the sprayed sub-subplots initially and remained reduced throughout the 15 years. There was also a greater increase in trailing blackberry cover in the sprayed sub-subplots, changing from 2% in year 1 to 17% by year 15. For the 5-m-radius samples, groupings occurred with sprayed versus unsprayed sub-subplots primarily based on shrub species (Fig. 6b). Forb species frequency did not exhibit any patterns based on the ordination before or after thinning and/or with spraying.

3.2. Blodgett Forest – Coast Range mountains

As with the Willamette Valley Fringe site, the most consistent understory vegetation treatment response was to spraying and association with decreased swordfern cover (Fig. 7), which remained reduced for all 15 years. For swordfern cover, forb cover, and deciduous + evergreen cover (low + mid layers), spraying decreased cover compared to the plant and no plant

Table 3
ANOVA means for number of late seral forbs/point and forb and structural diversity for McDonald Forest, years 1 and 15.

	Late seral		Forb diversity				Structural diversity			
			Shannon		Simpson		Shannon		Simpson	
Year	1	15	1	15	1	15	1	15	1	15
Spacing										
Gap	0.32	0.59	2.46	2.51	0.89	0.90	1.45	1.75	0.71	0.80
Uniform	0.42	0.58	2.53	2.48	0.90	0.90	1.38	1.76	0.68	0.80
Density										
LOW	0.38	0.40	2.59	2.49	0.90	0.90	1.41	1.83	0.66	0.80
MED	0.37	0.61	2.49	2.59	0.89	0.91	1.41	1.76	0.65	0.79
MHI	0.45	0.79	2.48	2.54	0.89	0.90	1.42	1.79	0.66	0.80
HIGH	0.28	0.59	2.41	2.36	0.88	0.89	1.42	1.64	0.64	0.74
Understory										
No Plant	0.56	0.56	2.59	2.53	0.90	0.90	1.45	1.69	0.70	0.79
Plant	0.38	0.51	2.47	2.44	0.89	0.89	1.44	1.80	0.71	0.80
Release	0.32	0.66	2.46	2.51	0.89	0.90	1.41	1.78	0.70	0.79
Spray	0.26	0.61	2.47	2.51	0.89	0.90	1.14	1.81	0.61	0.79

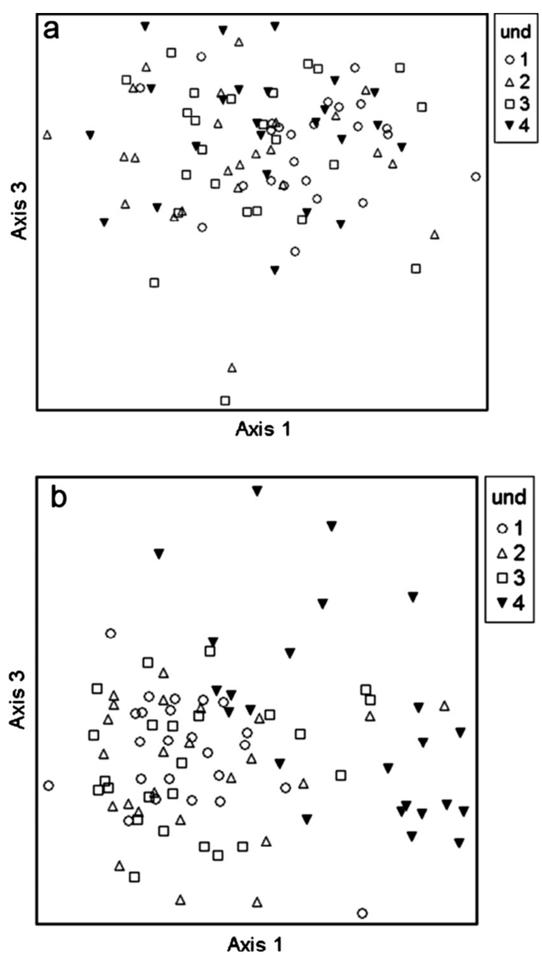

Fig. 5. Change over time in understory vegetation community ordination in McDonald Forest treatment units over 15 years at the 1-m-radius scale: (a) year zero (pretreatment), and (b) year 15. Understory vegetation treatments are 1 No Plant, 2 Plant, 3 Release, and 4 Spray.

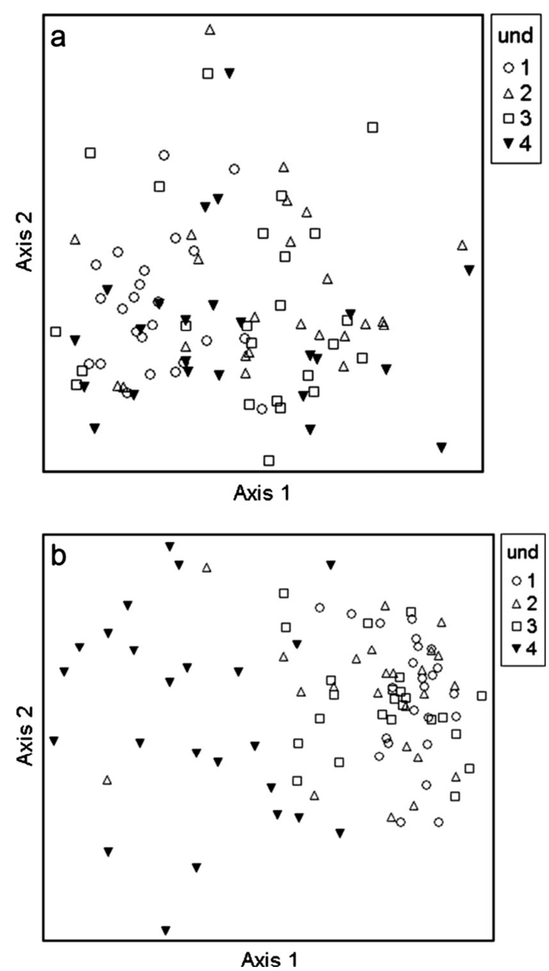

Fig. 6. Change over time in understory vegetation community ordination in McDonald Forest treatment units over 15 years at the 5-m-radius scale: (a) year zero (pretreatment), and (b) year 15. Understory vegetation treatments are 1 No Plant, 2 Plant, 3 Release, and 4 Spray.

sub-subplots, regardless of overstory density and spatial arrangement. For deciduous + evergreen cover, it appeared that spraying may have had a lasting effect in the gap treatment, but the effect was less apparent in the uniform treatment after 15 years (Table 4). Within the gap treatment, the lasting effect of spraying was more noticeable where overstories were densest.

Understory vegetation response at Blodgett was also highly influenced by abundant natural hemlock regeneration, which was greater with lower overstory densities and gap treatments (Fig. 8a) and with spraying (Fig. 8b) after 15 years. This hemlock cover weakened many of the understory vegetation response patterns seen on the Willamette Valley Fringe site; for example, there were

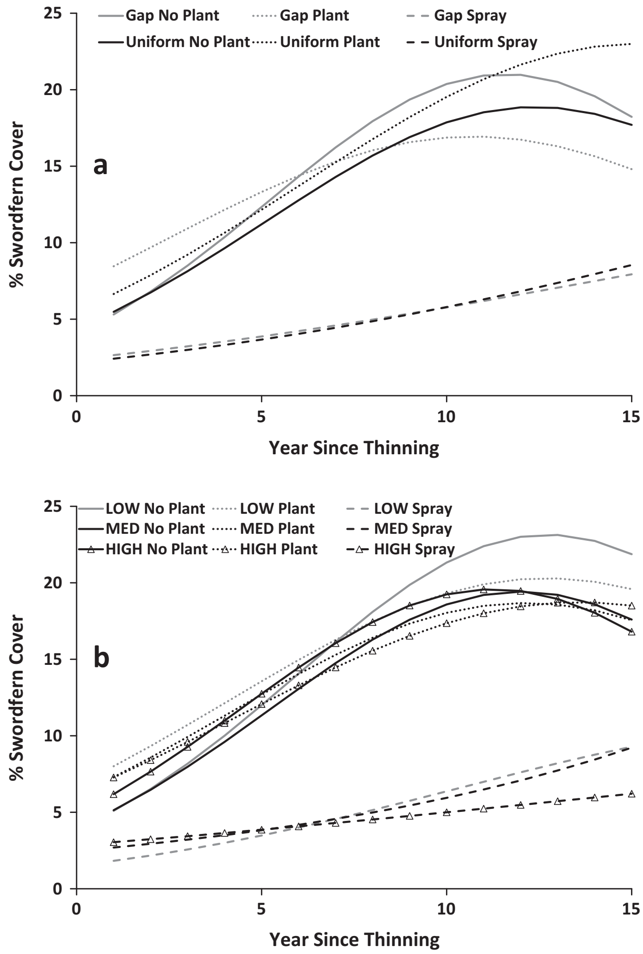

Fig. 7. Least-squared means for swordfern cover comparisons in Blodgett treatment units over 15 years across: a. thinning treatment and understory treatments and b. overstory density and understory treatments.

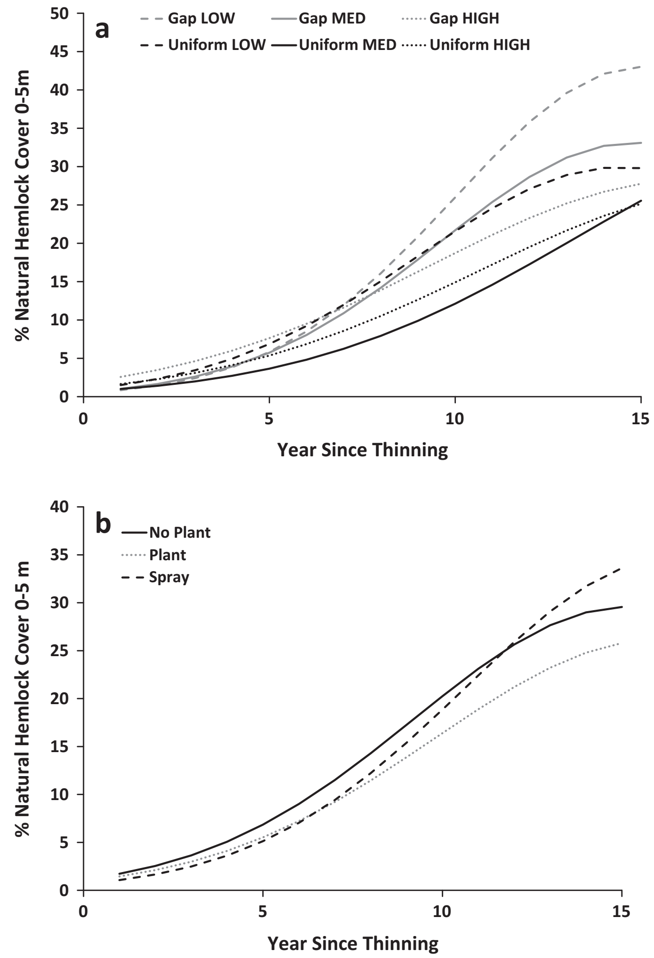

Fig. 8. Least-squared means for natural hemlock cover comparisons in Blodgett treatment units over 15 years across: (a) thinning treatment and density treatments and (b) understory treatments.

no clear patterns in low deciduous shrub cover over time, which was less than 5 percent at year 15.

As with the Willamette Valley Fringe site, late seral forbs were decreased initially by spraying but, by year 15, that difference was no longer significant. Exotic species were a minor component of the forb species initially (less than 0.1/point), but spraying increased their richness (0.2/point in the sprayed subplots compared to 0.05 in the other treatments). The Shannon Diversity Index indicated a slight difference in exotics among overstory densities, with the HIGH density having lower diversity than the other two densities.

Community composition shifted slightly with spraying, particularly at the 5-m sample scale (Figs. 9 and 10); shrub diversity was slightly lower in the sprayed sub-subplots. For 5-m radius plots (Fig. 10), clustering was by block and associated with the presence of salal. There were some trends based on spraying, but those trends were not as prominent as the influence of salal. Forb species also clustered both with blocks and spraying.

Many understory variables were correlated (r > 0.6) with each other in year 15, but there were few correlations between overstory and understory variables. Year 15 evergreen shrub cover sub-subplot means (both sprayed and unsprayed) were correlated with overstory Douglas-fir cover (r > 0.7). Negative correlations (<−0.7) were found between natural hemlock cover and all non-conifer cover, evergreen + deciduous cover, and shrub cover. Brackenfern cover and trailing blackberry cover were positively correlated with evergreen shrub cover. Regression analyses further indicated that non-conifer cover in the mid + low layers was

Table 4
ANOVA means for combined deciduous and evergreen cover (%) by thinning treatment for Blodgett Forest, years 1 and 15.

	LOW		MEDIUM		HIGH	
Year	1	15	1	15	1	15
Gap no plant	4.2	24	4.0	25	9.9	31
Gap plant	8.6	42	5.6	31	8.8	24
Gap spray	1.4	24	2.1	9	3.0	11
Uniform no plant	2.9	18	6.9	29	5.0	20
Uniform plant	3.5	26	6.0	31	4.0	18
Uniform spray	1.2	17	0.8	15	2.2	18

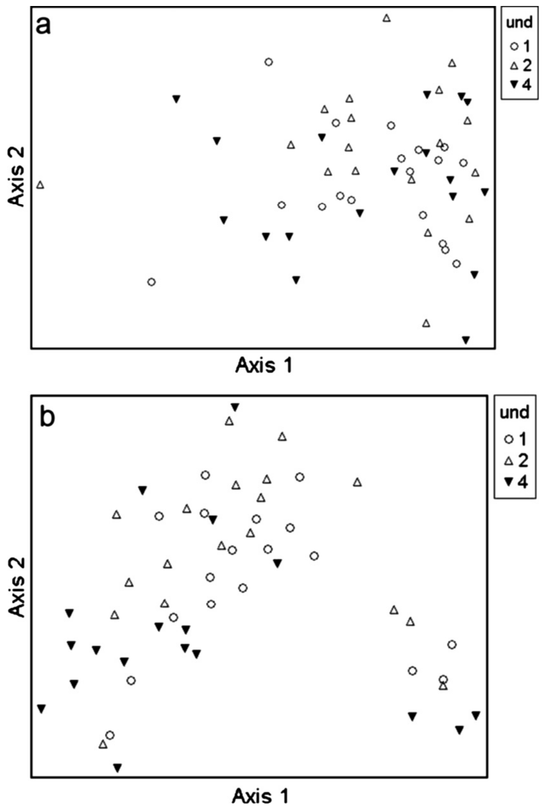

Fig. 9. Change over time in understory vegetation community ordination in Blodgett Forest treatment units over 15 years at the 1-m-radius scale: (a) year zero (pretreatment), and (b) year 15. Understory vegetation treatments are 1 No Plant, 2 Plant, and 4 Spray.

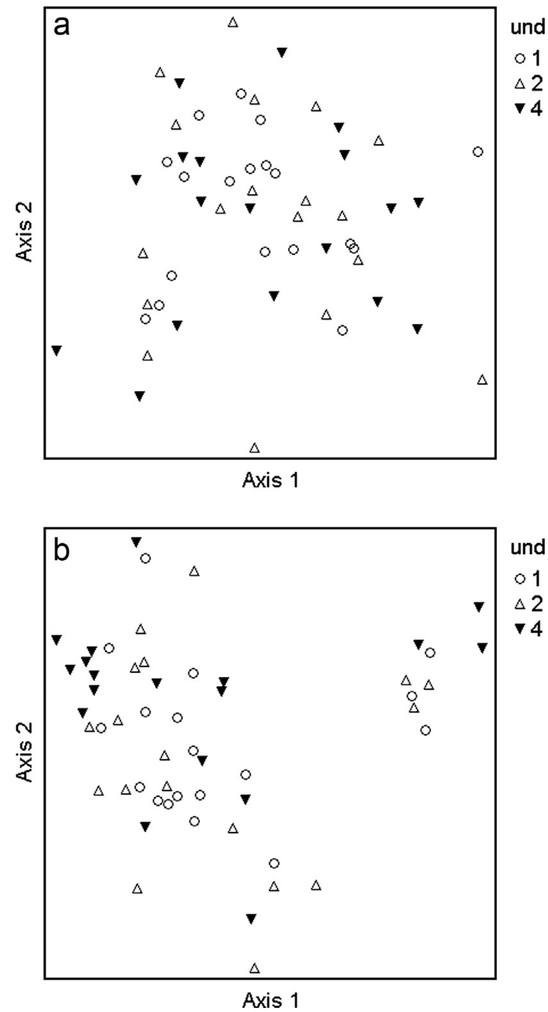

Fig. 10. Change over time in understory vegetation community ordination in Blodgett Forest treatment units over 15 years at the 5-m-radius scale: (a) year zero (pretreatment), and (b) year 15. Understory vegetation treatments are 1 No Plant, 2 Plant, and 4 Spray.

negatively associated with natural hemlock regeneration in years 10 and 15 (r^2 = 0.39–0.65), as well as with overstory cover through year 7 (r^2 = 0.21–0.54). Correlations were higher when sprayed and unsprayed sub-subplots were segregated for both individual points and sub-subplot means. When using means, r^2 value for non-conifer cover in the mid + low layers regressed against natural hemlock in the same two layers was 0.75 for all understory treatments combined, and 0.82 when understory treatments had different slopes and intercepts.

4. Discussion

Overstory density and canopy continuity consistently influence understory development over time across many forest types (Kie, 1985; Puettmann and Berger, 2006; Sabo et al., 2008). Thinning has been shown to increase understory production or cover (Uresk and Severson, 1989; Bailey et al., 1998; Ares et al., 2009), but the magnitude of responses can vary based on vegetation type (Nemati and Goetz, 1995; Sullivan et al., 2001). In our study, understory responses to thinning varied by site and species group, and through time. In general, shrub cover increased after thinning, while forb cover increased initially after thinning and then declined. Canopy cover (averaging less than 75 percent) allowed enough light to maintain many understory species but not stimulate and sustain vigorous communities. One of the primary species responses was with swordfern, a highly shade tolerant species.

Harvesting overstory trees typically reduces understory cover mechanically and can be severe enough to limit vegetation development for a short time (Chan et al., 1996; Wilson and Puettmann, 2007; Davis and Puettmann, 2009). Recovery to pre-thinning levels in our study was dependent upon species group, overstory density, and spraying; shrub cover recovered differently for the 0–1.5 m and the 1.5–5 m layer. Forbs rapidly increased after thinning under the lower overstory densities, but have started to decrease in all densities after 15 years. Decreases occurred sooner in the higher densities. For the low layer, shrub cover returned to pre-thinning levels in the first few years for all but the highest overstory density. For the mid layer shrubs, all densities increased above pre-thinning levels after about 5 years. This layer was comprised of primarily deciduous species at the drier Willamette Valley Fringe site and could provide habitat for certain wildlife, especially birds that are associated with deciduous shrub species (Hagar, 2007). In the Coast Range, however, the mid layer was comprised of natural hemlock regeneration that can shade out other species (Deal and Farr, 1994). The growth of hemlock in some of these plots (Nabel et al., 2013) indicated that hemlock could provide for a multi-layered conifer forest, desirable for certain wildlife species (Forsman et al., 1984).

Although light is a key driver in these systems, competition belowground can also affect vegetation responses to thinning (Riegel et al., 1992, 1995; Harrington et al., 2003; Devine and Harrington, 2008). Soil moisture measurements in our

Willamette Valley Fringe plots four years after thinning indicated that there were only small or no differences in soil moisture at 15, 45, 75, and 90 cm depth among the densities (Brandeis, 1999), but there were some differences among the densities for predawn moisture stress for some of the underplanted species (Brandeis, 1999). This indicated that there could be some moisture stress effects on vegetation development in addition to effects from reduced light. In a western Washington Douglas-fir thinning study, Devine and Harrington (2008) found both above- and belowground competition impacted understory Douglas-fir saplings, and it is likely that both types of effects would influence understory vegetation.

Long-term studies of herbicide applications on plant diversity show temporary reduction in cover and sometimes diversity. The herbicides we used decompose quickly, allowing vegetation to redevelop over time (Biring et al., 2003; Ristau et al., 2011). Understory cover was heavily and consistently impacted by herbicide application at two very different sites in our study, leading to reduced overall cover for 15 years after thinning. Species diversity was not decreased by spraying, but abundance of some species (e.g. swordfern) was decreased, which resulted in changes in community composition. At the wetter Coast Range site, the cover of salal and Oregon grape, both evergreen shrubs, was temporarily decreased by spraying but had returned to pretreatment levels by year 15. The recovery time required is highly dependent upon species, site quality, and treatment efficacy among other factors (McDonald and Fiddler, 1996; McDonald and Abbott, 1997; Miller and Miller, 2004). Spraying increased growth and survival of some underplanted conifers (Cole and Newton, 2009) and increased natural regeneration of Douglas-fir (Nabel et al., 2013). In the presence of abundant native shrub and herb communities, there was some conifer development in the absence of spraying. The lower numbers and slower growth may be adequate to meet objectives for structural diversity or habitat development, but longer-term development is less certain.

4.1. Management implications

Understory vegetation development 15 years after thinning and herbicide application was largely dependent upon the species present (and dominant) at the time of treatment, as well as the treatments applied. Though spraying effects were still visible 15 years after treatment in terms of reduced swordfern, one of the dominant understory species, it had little effect on the long-term development of structure at these overstory densities. Indeed, the range of overstory densities and spatial arrangements in our study did not have large effects because all of the thinning treatments resulted in increased light availability to the understory. As over- and mid-story conifers continue to develop crown beyond year 15, however, some differences in understory development may occur. The presence of dense natural regeneration of hemlock at the Coast Range site is likely to have greater long-term influence on the development of other understory vegetation than either overstory density or spraying.

Though we did not have an influx of early seral shrub species in our plots, we did see an increase in exotic forb species at both sites. Proximity to seed sources has been identified as a possible explanation for the spread or lack of invasion of exotics after thinning (Thysell and Carey, 2000; Sullivan et al., 2009). The drier Willamette Valley Fringe site was near roads with abundant truck and/or recreational traffic, including horses, mountain bikers, and hikers, which often serve as distributors of exotic species. Although more remote, the Coast Range site also had a road network and history of management from the 1930s, and we did see a minor increase in exotic species there. In total, however, exotic species responses were minor even with the heaviest disturbances. Responses could change if more invasive species become prevalent, or if forest harvesting activity were to increase.

Trends indicated that structural diversity was increasing, but a continuous-layered canopy needed for some late seral species (Forsman et al., 1984) had not developed fifteen years post-thinning. Cover of shrubs was increasing, but some of the species were unlikely to provide for tall structure within these stands. Underplanted conifers (Cole and Newton, 2009) and natural regeneration of western hemlock (Nabel et al., 2013) may reach heights that will allow for a continuous canopy, especially in larger gaps, but that is predicated on continued growth in these understory environments in the presence of continued overstory growth. Future measurements will be needed to monitor trends in understory development.

Our treatments were designed to determine if late-seral structure could be accelerated with thinning, but there were also insights for early seral species. Combining more extensive overstory and understory treatments can be used to stimulate heterogeneous structure and early-seral compositional development in these forests, including the possible stimulation of such species within older stands (Bailey et al., 1998). Ares et al. (2009) found greater early seral species in thinned areas with greater abundance of shade tolerant species in the denser areas of their stands. It is likely that shade-tolerant conifers will remain in thinned stands, however, often dominating understories as they develop over time. Early seral species that regenerate when seed sources are available and seedbed conditions are conducive may require subsequent disturbances and/or heavier disturbance in order to persist, as noted in burned-over sites. For those objectives and situations, heavier thinning, control of shade tolerant regeneration and heterogeneous overstory canopy could increase early-seral understory cover as well as diversity.

5. Disclaimer

This document contains information about herbicides, which are regulated by federal and state laws. Oregon State University is not responsible for misuse and does not endorse any of the products mentioned.

WARNING: This publication reports research involving pesticides. It does not contain recommendations for their use, nor does it imply that the uses discussed here have been registered. All uses of pesticides must be registered by appropriate state and federal agencies before they can be recommended.

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Appendix A

See Tables A.1–A.3

Table A1
Forb species present at Blodgett (B) and McDonald (M) sites. Species considered late seral (LS) (FEMAT, 1993) or exotic (EX) are noted. Scientific names and authorities are based on plants.usda.gov.

B	*Actaea rubra* (Aiton) Willd.	
B,M	*Achlys triphylla* (Sm.) DC.	LS
B,M	*Actaea rubra* (Aiton) Willd.	
B,M	*Adenocaulon bicolor* Hook.	LS
M	*Agoseris* Raf. species	
M	*Allium L.* species	
B,M	*Anaphalis margaritacea* (L.) Benth.	
B,M	*Anemone piperi* Britton ex Rydb.	LS
B,M	*Aquilegia formosa* Fisch. ex DC.	
M	*Arctium minus* Berhn.	EX
B,M	*Asarum caudatum* Lindl.	LS
B	*Astragalus* L. species	
M	*Brodiaea* Sm. species	
B,M	*Campanula scouleri* Hook. ex A. DC.	
B,M	*Cardamine angulata* Hook.	
B,M	*Cardamine oligosperma* Nutt.	
B,M	*Cardamine pulcherrima* Greene var. *nuttallii*	
M	*Carduus* L. spp.	EX
B,M	*Chamerion angustifolium* (L.) Holub ssp. *angustifolium*	
B	*Chrysosplenium glechomifolium* Nutt.	
B,M	*Circaea alpina* L.	
B,M	*Cirsium arvense* (L.) Scop.	EX
B,M	*Cirsium* Mill. spp.	EX
B,M	*Cirsium vulgare* (Savi) Ten.	EX
B,M	*Claytonia perfoliata* (Donn ex Willd. ssp. *perfoliata*	
B,M	*Claytonia sibirica* L. var. *sibirica*	
B,M	*Clinopodium douglasii* (Benth.) Kuntze	LS
B,M	*Clintonia uniflora* (Menzies ex Schult. & Schult. F.) Kunth	LS
M	*Collinsia parviflora* Lindl.	
B,M	*Collomia heterophylla* Douglas ex Hook.	
M	*Corallorhiza* species R. Br.	LS
M	*Crepis* L. species	EX
M	*Cynoglossum grande* Douglas ex Lehm.	
M	*Daucus carota* L.	EX
M	*Delphinium trolliifolium* A. Gray	
B,M	*Dicentra formosa* (Haw.) Walp.	
B,M	*Digitalis purpurea* L.	EX
B	*Epilobium brachycarpum* C. Presl.	
B,M	*Epilobium ciliatum Raf.*	
B,M	*Epilobium minutum* Lindl. ex Lehm.	
B,M	*Equisetum arvense* L.	
B,M	*Erechtites minima* (Poir.) DC.	EX
B,M	*Erodium cicutarium* (L.) L'Hér. ex Aiton	EX
B	*Euchiton japonicus* (Thunb.) Anderb.	EX
B,M	*Fragaria vesca* L.	
M	*Galium boreale L.*	
B,M	*Galium oreganum Britton*	
B,M	*Galium* L. species	
B,M	*Galium triflorum Michx.*	
M	*Geranium dissectum* L.	EX
M	*Geranium molle* L.	EX
M	*Geranium oreganum* Howell	
M	*Geranium robertianum* L.	
M	*Geum* spp.	
M	*Gilia* species	
B,M	*Goodyera oblongifolia* Raf.	LS
M	*Heracleum maximum* W. Bartram	
B	*Heuchera* L. species	
B,M	*Hieracium albiflorum* Hook.	
B,M	*Hydrophyllum tenuipes* A. Heller	
B,M	*Hypericum perforatum* L.	EX
B,M	*Hypochaeris radicata* L.	EX
B,M	*Iris tenax* Douglas ex Lindl.	
B,M	*Lactuca serriola* L.	EX
M	*Lapsana communis L.*	
M	*Lathyrus* L. species	EX
B,M	*Leucanthemum vulgare* Lam.	EX
M	*Ligusticum apiifolium* (Nutt. ex Torr. & A. Gray) A. Gray	
M	*Lilium columbianum Leichtlin*	
B,M	*Lotus crassifolius* (Benth.) Greene	
B,M	*Lotus L.* species	
B,M	*Lotus micranthus* Benth.	
B	*Lotus unifoliatus* (Hook.) Benth. var. *unifoliatus*	
M	*Lupinus* L. species	
B	*Lysichiton americanus* Hultén & H. St. John	LS
B,M	*Maianthemum dilatatum* (Alph. Wood) A. Nelson & J.F. Macbr.	
B,M	*Maianthemum racemosum* (L.) Link	
B,M	*Maianthemum stellatum* (L.) Link	LS
M	*Marah oreganus* (Torr. ex S. Watson) Howell	
B	*Mentha arvensis* L.	
B,M	*Mimulus dentatus* Nutt. ex Benth.	
B,M	*Mitella caulescens* Nutt.	LS
M	*Mitella pentandra* Hook.	
B,M	*Moehringia macrophylla (Hook.) Fenzl*	
B,M	*Mycelis muralis* (L.) Dumort.	EX
B,M	*Nemophila parviflora* Douglas ex Benth.	
B,M	*Oenanthe sarmentosa* C. Presl ex DC.	
B,M	*Olsynium douglasii* (A. Dietr.) E.P. Bicknell var. *douglasii*	
B,M	*Osmorhiza berteroi* DC.	
B	*Oxalis oregana* Nutt.	LS
B,M	*Petasites frigidus* (L.) Fr. ssp. *palmatus* (Aiton) Cronquist	
B,M	*Phacelia heterophylla* Pursh	
M	*Plantago major* L.	EX
M	*Potentilla congesta* (Hock) Jepson	
B,M	*Prosartes hookeri* Torr. Var. *oregana* (S. Watson) Kartesz	LS
B,M	*Prosartes smithii* (Hook.) Utech, Shinwari, & Kawano	
B,M	*Prunella vulgaris* L.	
M	*Ranunculus* L. species	
B,M	*Ranunculus occidentalis* Nutt.	
B,M	*Ranunculus repens* L.	EX
B,M	*Ranunculus uncinatus* D. Don ex G. Don	
B,M	*Rumex acetosella* L.	EX
M	*Rumex crispus* L.	EX
M	*Sanicula crassicaulis* Poepp. ex DC.	
M	*Scoliopus hallii* S. Watson	EX
B,M	*Scrophularia californica* Cham. & Schltdl.	
B,M	*Senecio jacobaea* L.	EX
B,M	*Senecio sylvaticus* L.	EX
B,M	*Silene douglasii Hook.*	
M	*Solanum dulcamara* L.	
M	*Sonchus asper* (L.) Hill	EX
B	*Stachys* L. species	
B,M	*Stellaria calycantha* (Ledeb.) Bong.	
B,M	*Stellaria crispa* Cham. & Schltdl.	
B,M	*Streptopus amplexifolius* (L.) DC	LS
B,M	*Streptopus lanceolatus* (Aiton) Reveal var. *roseus* (Michx.) Reveal	LS
B,M	*Synthyris reniformis* (Douglas ex Benth.) Benth.	
B,M	*Tellima grandiflora* (Pursh) Douglas ex Lindl.	
B,M	*Thalictrum occidentale* A. Gray	
B	*Tiarella trifoliata* L.	LS
B,M	*Tolmiea menziesii* (Pursh) Torr. & A. Gray.	
M	*Torilis nodosa* (L.) Gaertn.	EX
B,M	*Trientalis latifolia* Hook.	
B	*Trifolium repens* L.	
B,M	*Trillium ovatum* Pursh	LS
B,M	*Vancouveria hexandra* (Hook.) C. Morren & Decne.	LS
M	*Veratrum caudatum Durand var. caudatum* (*A. Heller*) *C.L. Hitchc.*	
B,M	*Veronica L.* species	
M	*Vicia americana Muhl. ex Willd.*	
B,M	*Vicia L.* species	EX
B,M	*Viola adunca* Sm.	
B,M	*Viola glabella* Nutt.	LS
B	*Viola sempervirens* Greene	

Table A2
Shrub, conifer, and fern species present at Blodgett (B) and McDonald (M). Scientific names and authorities are based on plants.usda.gov.

M	*Abies grandis* (Douglas ex D. Don) Lindl.
B,M	*Acer circinatum* Pursh
B,M	*Acer macrophyllum* Pursh
B	*Alnus rubra* Bong.
M	*Amelanchier alnifolia* (Nutt.) Nutt. ex M. Roem. var *semiintegrifolia* (Hook.) C.L. Hitchc.
M	*Arbutus menziesii* Pursh
M	*Baccharis pilularis* DC
B	*Blechnum spicant* (L.) Sm.
M	*Ceanothus sanguineus* Pursh
M	*Chamaecyparis lawsoniana* (A. Murray bis) Parl.
M	*Corylus cornuta* Marshall var. *californica* (A. DC.) Sharp
M	*Cornus nuttallii* Audubon ex Torr. & A. Gray
M	*Crataegus douglasii* Lindl.
M	*Dryopteris expansa* (C. Presl) Fraser-Jenkins& Jermy
B	*Gaultheria shallon* Pursh
B,M	*Frangula purshiana* (*DC.*) *A. Gray*
M	*Fraxinus latifolia* Benth
B,M	*Holodiscus discolor* (Pursh) Maxim.
M	*Ilex aquifolium L.*
B	*Linnaea borealis* L.
M	*Lonicera ciliosa* (Pursh) Poir. ex DC.
M	*Lonicera hispidula* (Lindl.) Douglas ex Torr. & A. Gray
M	*Lonicera involucrata* (Richardson)Banks ex Spreng. var. *ledebourii* (Eschsch.) Zabel
M	*Lonicera* species L.
M	*Mahonia aquifolium* (Pursh) Nutt.
B,M	*Mahonia nervosa* (Pursh) Nutt.
M	*Malus fusca* (Raf.) C.K. Schneid.
M	*Oemleria cerasiformis* (Torr. & A. Gray ex Hook. & Arn.)
B	*Oplopanax horridus* (Sm.) Miq.
B,M	*Polystichum munitum* (Kaulf.) C. Presl
M	*Populus balsamifera L. subsp. trichocarpa* (Torr. & A. Gray ex Hook) Brayshaw
B,M	*Prunus emarginata* (Douglas ex Hook.) D. Dietr. var. *mollis* (Douglas ex Hook.) W.H. Brewer
M	*Prunus* L. spp.
M	*Prunus virginiana* L.
B,M	*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*
B,M	*Pteridium aquilinum* (L.) Kuhn
M	*Quercus garryana* Douglas ex Hook.
B	*Ribes bracteosum* Douglas ex Hook.
B,M	*Ribes divaricatum* Douglas
B,M	*Ribes sanguineum* Pursh
M	*Rosa rubiginosa* L.
B,M	*Rosa gymnocarpa* Nutt.
M	*Rosa nutkana* C. Presl
M	*Rosa woodsii Lindl.*
M	*Robinia pseudoacacia* L.
B,M	*Rubus armeniacus Focke*
B,M	*Rubus laciniatus* Willd.
B,M	*Rubus leucodermis* Douglas ex Torr. & A. Gray Whitebark
B,M	*Rubus parviflorus* Nutt.
B,M	*Rubus spectabilis* Pursh
B,M	*Salix* L. species
M	*Sambucus nigra L.* supsp *ceralea* (Raf.) R. Bolli
B,M	*Sambucus racemosa* L. var. *arborescens*(T.&G.) Gray
M	*Sorbus sitchensis* M. Roem.
M	*Symphoricarpos albus* (L.) S.F. Blake
M	*Taxus brevifolia* Nutt.
B,M	*Thuja plicata* Donn ex D. Don
M	*Toxicodendron diversilobum (*Torr. & A. Gray) Greene
B,M	*Tsuga heterophylla* (Raf.) Sarg.
B	*Vaccinium alaskaense* Howell
B	*Vaccinium ovalifolium* Sm.
B	*Vaccinium parvifolium* Sm.

Table A3
Means for exotic and total species richness for McDonald Forest, pre-thinning (raw data means), and years 1 and 15 (ANOVA means) after thinning.

		Exotics			Total		
		Pre	1	15	Pre	1	15
LOW	No Plant	0.38	0.71	0.35	5.1	5.2	4.1
	Plant	0.40	0.99	0.82	5.9	5.1	3.7
	Release	0.40	0.61	0.13	5.2	4.4	4.5
	Spray	0.62	1.54	1.17	5.6	5.3	4.8
MED	No Plant	0.38	0.49	0.78	5.8	4.8	4.9
	Plant	0.25	0.13	0.33	4.7	4.4	4.2
	Release	0.28	0.67	0.45	5.3	4.6	4.6
	Spray	0.55	0.96	2.27	5.7	4.7	5.6
MHI	No Plant	0.53	0.81	0.66	5.9	4.8	4.6
	Plant	0.33	0.56	0.75	5.6	4.6	4.4
	Release	0.52	0.72	0.25	5.1	5.0	5.5
	Spray	0.60	1.10	1.33	5.4	5.2	4.6
HIGH	No Plant	0.42	0.49	0.28	5.4	4.2	4.3
	Plant	0.30	0.49	0.48	4.9	4.4	5.1
	Release	0.78	0.47	0.12	5.8	4.4	4.2
	Spray	0.68	0.82	0.72	6.1	4.3	5.4
Gap		0.47	0.59	0.47	5.6	4.8	4.5
Uniform		0.46	0.70	0.56	5.4	4.7	4.2

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