

Ten-year Douglas-fir regeneration and stand productivity differ among contrasting silvicultural regimes in western Washington, USA

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ABSTRACT

In the Pacific Northwestern USA, concerns regarding impacts of forest harvesting on visual quality, wildlife habitat, and carbon management have prompted evaluations of alternative silvicultural regimes for coast Douglas-fir (*Pseudotsuga menziesii* var. *menziesii*). Research was initiated in 1998 near Olympia WA USA to conduct long-term comparisons among six silvicultural regimes: clearcut (harvest all trees), two age (harvest all except 38 mature trees ha⁻¹), patches (harvest 20% of the area in 0.6–2.0 ha tracts), groups (harvest 20% of the area in 0.1–0.5 ha tracts), thinning (reduce stand density to 45% of the biological maximum for Douglas-fir), and a non-treated control. Harvested areas in the first four regimes were planted with Douglas-fir seedlings. This report focuses on tree regeneration and stand productivity during the first decade of the study. Fifth year height of planted Douglas-fir was greater in the clearcut regime (1.8 m) than in the patches and groups regimes (1.1–1.2 m). Fifth year tree regeneration in the clearcut and two-age regimes was dominated by Douglas-fir (80–86% of seedlings), but regeneration in the patches and groups regimes was composed of a mixture of conifer and hardwood species. Ten-year periodic annual increment (PAI) in Douglas-fir ingrowth volume was greater in the clearcut regime (1.4 m³ ha⁻¹ yr⁻¹) than in the control (0.1 m³ ha⁻¹ yr⁻¹), whereas ingrowth volume PAI of other conifer species was greater in the two-age regime (0.4 m³ ha⁻¹ yr⁻¹) than in the control (0.0 m³ ha⁻¹ yr⁻¹). Tree regeneration responses indicated increasing abundance of shade tolerant species in the non-clearcut regimes, especially western hemlock (*Tsuga heterophylla*). Fifth year cover of the vine, California blackberry (*Rubus ursinus*), in the clearcut regime (21%) was over four times that in the control (5%). Ground disturbance in the clearcut regime reduced 5th-year height of the shrubs, salal (*Gaultheria shallon*) and red huckleberry (*Vaccinium parvifolium*), by 40–50% compared to the control. Ten-year volume PAI of Douglas-fir was linearly related to post-harvest stand basal area ($r^2 = 0.94$), and the relationship did not vary significantly among the three replicate sites. During the first decade of the study, Douglas-fir regeneration and stand productivity differed among silvicultural regimes because of post-harvest variation in stand edge competition, species composition of tree seedlings and ingrowth, and residual stand density.

1. Introduction

A silvicultural system is a planned process whereby a forest stand is tended, harvested, and re-established (Smith et al., 1997; Tappeiner et al., 2015). It combines a method of tree regeneration with associated stand tending treatments, such as competing vegetation control, soil nutrient amendment, or tree density management. Methods of regeneration include those that perpetuate even-aged, two-aged, or uneven-aged stand structures having one, two, and three or more distinct age

classes, respectively. Globally, a wide variety of silvicultural systems have been tested and sometimes adopted depending on numerous ecological and social constraints (Puettmann et al., 2015). In various forest types of North America there has been considerable research that compares a wide range of silvicultural systems (Dale et al., 1995; Schuler, 2004; Maguire et al., 2007; Mitchell et al., 2007; Rogers et al., 2017). These authors have reported on single-tree selection, group selection, two-aged stand management, and small clearcuts as potential silvicultural systems for mitigating visual impacts of commercial

Abbreviations: PAI, periodic annual increment; RD, Curtis relative density; dbh, stem diameter at breast height (1.37 m); d15, stem diameter at 0.15 m height; qmd, quadratic mean stem diameter.

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clearcutting and improving wildlife habitat while maintaining wood production. In the western Pacific Northwest USA, clearcutting with either planted or natural regeneration is the prevailing silvicultural system for regenerating coast Douglas-fir (*Pseudotsuga menziesii* var. *menziesii* Mirb. (Franco)), because it is supported by a long history of experience and research on implementation techniques, costs, and consequences.

Previous research on reproductive requirements of Douglas-fir has shown that successful regeneration and adequate early growth on mesic sites generally require overstory densities of <50% of full stocking (Isaac, 1956). Retaining 23–41 m² ha⁻¹ of overstory basal area in a shelterwood system moderated seedbeds adequately on higher-elevation, droughty sites in western Oregon USA to achieve 70% stocking of natural regeneration, but site preparation (i.e., 25% exposure of mineral soil) was necessary to achieve this goal (Williamson, 1973). In a meta-analysis of previous studies of the interactive effects of light and soil water availability, Holmgren et al. (2012) demonstrated that intermediate levels of shade provide plants with relief from soil drought. Several retrospective studies of green-tree retention in western Oregon USA have reported exponential declines in density and growth of mature (i.e., 70–139 years old) mid-story conifers as density of overstory old-growth trees (i.e., >200 years old) exceeded 15 trees ha⁻¹ (Rose and Muir, 1997) or 5 m² ha⁻¹ of stand basal area (Acker et al., 1998). For either planted or naturally regenerated Douglas-fir, the effects of overstory competition on seedling growth decreased with increasing overstory density, confirming the dominating influence of root competition from overstory trees on tree regeneration (Harrington, 2006; Devine and Harrington, 2008).

Replicated experimental trials that statistically compare various levels of overstory retention on conifer regeneration are in the early to middle stages of testing (Brandeis et al., 2001; Maas-Hebner et al., 2005; Chan et al., 2006; Harrington, 2006; Cole and Newton, 2009; Brodie and DeBell, 2013). These studies have shown marked reductions in growth of understory conifers associated with increasing density of overstory trees. Acker et al. (1998) found that the greatest negative impact of overstory trees on understory conifers occurred at low residual basal areas (<10 m² ha⁻¹), with the effects per unit residual basal area decreasing as residual basal area increased, indicating a threshold competitive relationship. A meta-analysis of underplanting studies indicated that only small reductions in overstory density are needed in most biomes to ensure high survival of underplanted seedlings; however, higher reductions are required to achieve acceptable levels of seedling growth (Paquette et al., 2006). Questions remain regarding the extent to which volume growth of residual trees may compensate for reduced production of the younger cohort. Brodie and DeBell (2013) estimated that retention of 22–59 trees ha⁻¹ of overstory Douglas-fir after partial cutting would produce about 3 m³ ha⁻¹ yr⁻¹ of wood volume over a ten-year period.

Harvested openings of 0.4 ha or larger were required to naturally regenerate Douglas-fir with the group selection system (Isaac, 1943). Worthington (1953) reported success in naturally regenerating harvested openings of 0.8–1.6 ha. Deposition and germination viability of individual seeds from neighboring Douglas-fir did not differ significantly among harvested openings of 0.1–0.4 ha (Devine and Harrington, 2016). For a wide variety of conifer species in western North America, growth of planted seedlings increases either as asymptotic or quadratic functions of the size of harvested openings, with maximum growth occurring in openings of 0.1–0.6 ha (Coates, 2000; York et al., 2004; de Montigny and Smith, 2017; Harrington and Devine, 2018). Variation in these relationships among and within species can be attributed to the species' shade tolerance and early growth rates, seedling age and size at the time of the assessment, abundance and type of competing vegetation, and site quality.

In the western Pacific Northwest, large areas of young Douglas-fir plantations are now reaching a stage in which either commercial thinning, partial harvest, or final harvest are economically feasible and

desirable. Major questions are arising about the future disposition of these plantations, especially regarding density management, silvicultural inputs, and age at final harvest. For public ownerships, and to some extent for private ownerships, it is crucial that the adopted silvicultural regimes minimize conflicts among wood production objectives and other forest values, such as visual quality (Kearney et al., 2010), wildlife habitat, and carbon management. The Capitol State Forest of the Washington State Department of Natural Resources near Olympia WA USA is almost entirely second-growth Douglas-fir, and although the older stands are of natural origin after clearcutting and fire, much of it is probably not greatly different from the expected future condition of contemporary plantations. Capitol Forest, therefore, provides a test environment that will be widely applicable to future stand management in the western Pacific Northwest.

The Silvicultural Options Study was initiated in 1998 to provide examples of a range of harvesting, tending, and regeneration practices that could be used to achieve a wide variety of management objectives, including improved visual quality (Curtis et al., 2004). Silvicultural regimes selected for the study included those that integrate production of wood and other forest values in the Douglas-fir region (DeBell and Curtis, 1993; Curtis and Carey, 1996). This long-term study is serving as both a visual demonstration area for foresters, planners, and the public, and as the basis for comparing regeneration efficacy and wood production among alternative silvicultural systems for Douglas-fir. Six silvicultural regimes were selected to represent a wide range of management alternatives thought to be biologically, operationally, and economically feasible based on existing knowledge and experience. The objective of this report is to compare regeneration and stand productivity among the six silvicultural regimes during the first decade of the study in terms of density, size, and species composition of regeneration and mature trees and changes in stand volume (i.e., harvested volume, growth of surviving trees, ingrowth, and mortality).

2. Methods

2.1. Study sites

The study was conducted on the Capitol State Forest, Washington State Department of Natural Resources, near Olympia WA USA. Capitol Forest includes 37,090 ha of primarily second-growth Douglas-fir. Most of the original old-growth trees were harvested in the early 1900s (Felt, 1975), and the forest is currently being managed under Washington State regulations to provide mandated financial support for schools and roads. The regional climate is characterized as Mediterranean with moist, cool winters and warm, dry summers having prolonged periods (i.e., 1–3 months) of drought (Franklin and Dyrness, 1988).

Three replicate sites were selected for the study: Blue Ridge, Copper Ridge, and Rusty Ridge (Table 1). Soils include primarily deep silt loams of the Olympic, Raught, Bunker, and Boistfort series with water holding capacities of 25–30 cm within the top 152 cm of soil profile (USDA NRCS, 2021). Soils at Copper Ridge also include Schneider very gravelly loam (36% of the area), Katula very cobbly loam (4%), Delphi very gravelly loam (4%), and Kapowsin silt loam (6%), the latter two of which formed in compacted glacial till (Peter, 2006; USDA NRCS, 2021). The coarse textured soils at Copper Ridge have water holding capacities that are half or less than those for the silt loams found elsewhere on the site and at Blue Ridge and Rusty Ridge. Long-term (i.e., 1981–2010) estimates of average annual precipitation (1607–2696 mm) vary considerably more among the three study sites than estimates of January minimum temperature (0.7–0.8 °C) or July maximum temperature (23.5–25.1 °C) (PRISM Climate Group, 2021). The primary plant associations include *Tsuga heterophylla*/*Polystichum munitum* – *Oxalis oregana* (TSHE/POMU-OXOR) at Blue Ridge and Rusty Ridge and *Tsuga heterophylla*/*Gaultheria shallon* – *Mahonia nervosa* (TSHE/GASH-MANE2) and *Tsuga heterophylla*/*Gaultheria shallon* – *Polystichum munitum* (TSHE/GASH-POMU) at Copper Ridge (Henderson et al., 1989; Peter, 2006).

Table 1

Characteristics of the three replicate sites of the Silvicultural Options Study, Olympia WA USA.

Characteristics	Study site		
	Blue Ridge	Copper Ridge	Rusty Ridge
Latitude, longitude (°) ^a	46.86035, −123.15803	47.03060, −123.05355	46.93867, −123.23918
Total area (ha)	117	111	80
Elevation (m) ^a	329	241	387
Slope intensity	Gentle to moderate	Moderate to steep	Gentle to moderate
Primary site exposures	S-NE	S	W-S
Annual precipitation ^b (mm)	1607	1835	2696
Primary soil series ^c and textures (% of area)	Olympic ^d silt loam (98), Raught ^e silt loam (2)	Raught silt loam (42), Schneider ^f very gravelly loam (36), Olympic silt loam (11)	Bunker ^g gravelly silt loam (86), Boistfort ^h silt loam (14)
Primary plant associations	TSHE/POMU-OXOR	TSHE/GASH-MANE2, TSHE/GASH-POMU	TSHE/POMU-OXOR
Stand origin	Natural regeneration	Natural regeneration	Planted
Douglas-fir site index ⁱ _{50-year} (m)	38.8	37.6	39.6
Date of previous thinning (yr)	1971	–	1993–1994
Date of first harvest for this study (yr)	Spring 1998	Spring 2002	Spring 2004
Average Douglas-fir age at first harvest (yr)	69	72	44
Harvesting system	Ground based	Cable	Ground based

^a Latitude, longitude, and elevation were estimated for the approximate midpoint of the Control silvicultural regime at each study site.^b PRISM Climate Group (2021).^c USDA NRCS (2021).^d Fine, mixed, active, mesic Xeric Palehumults.^e Fine, parasesquic, mesic Typic Palehumults.^f Loamy-skeletal, isotic, mesic Andic Humixerepts.^g Medial over clayey, ferrihydritic over parasesquic, mesic Typic Fulvudands.^h Medial over clayey, ferrihydritic over parasesquic, mesic Typic Fulvudands.ⁱ King (1966).

The plant associations at Copper Ridge are indicative of the coarse-textured, droughty soils present on about 50% of the site. In the dormant season prior to the first harvest of this study, five tree species accounted for over 99% of the mean stand basal area for the three sites: Douglas-fir (45.0 m²ha^{−1}; 87% of total), western hemlock (4.3 m²ha^{−1}; 8%), red alder (*Alnus rubra* Bong.) (1.0 m²ha^{−1}; 2%), bigleaf maple (*Acer macrophyllum* Pursh) (1.0 m²ha^{−1}; 2%), and western redcedar (*Thuja plicata* Donn ex D. Don) (0.4 m²ha^{−1}; <1%).

2.2. Experimental design and treatments

Six treatment areas having relatively uniform stand characteristics,

each 12–28 ha, were located at each of the three study sites. One of the following six silvicultural regimes was randomly assigned to each treatment area per site (Table 2):

1. *Clearcut*. All trees were harvested, and the entire treatment area was planted with Douglas-fir seedlings. Harvesting will be repeated each time the planted stand reaches a rotation age of 50 years.
2. *Two age*. All but 38 mature conifers ha^{−1} were harvested, and the entire treatment area was planted with Douglas-fir seedlings. Retained trees were selected for their uniform spacing and stem quality. When the planted stand reaches a rotation age of 50 years, the original retained trees will be harvested, all but 38 planted

Table 2

Sequence of stand treatments to date for the six silvicultural regimes of the Silvicultural Options Study, Olympia WA USA.

Treatment	Year	Silvicultural regimes					
		Clearcut	Two age	Patches	Groups	Thinning	Control
First harvest	0	Harvest entire stand	Harvest all but 38 overstory trees ha ^{−1}	Harvest 20% of the area in 0.6–2.0 ha tracts	Harvest 20% of the area in 0.1–0.5 ha tracts	Reduce RD ^a from 53% to 45% of the Douglas-fir maximum	No harvesting
Regeneration Vegetation management	1–2–5	Planted Competition release ^b	Planted & natural Competition release	Planted & natural Competition release	Planted & natural Competition release	Deferred ^c	Deferred
Second harvest	10	–	–	Harvest 20% of the area in 0.6–2.0 ha tracts	Harvest 20% of the area in 0.1–0.5 ha tracts	–	–
Vegetation management	10	–	–	Site preparation ^d	Site preparation	–	–
Regeneration	11	–	–	Planted & natural	Planted & natural	Deferred	Deferred
Stand tending	15–17	PCT ^e to 3.7 m crop tree spacing	PCT to 3.7 m crop tree spacing	PCT to 3.7 m crop tree spacing	PCT to 3.7 m crop tree spacing	–	–
Third harvest ^f	20	–	–	Harvest 20% of the area in 0.6–2.0 ha tracts	Harvest 20% of the area in 0.1–0.5 ha tracts	Reduce RD from ≈ 55% to 40% of the Douglas-fir maximum	–

^a Curtis relative density (Curtis, 1982).^b Conifer seedling release from competition of associated vegetation via manual cutting or herbicide spot treatments.^c Not applicable.^d Broadcast or spot application of herbicides in the late summer or early fall to prepare harvested areas for planting.^e Precommercial thinning with residues left on site.^f The third harvest occurred at Blue Ridge in 2018 and it is planned for Copper Ridge and Rusty Ridge in 2022 and 2024, respectively.

- conifers ha^{-1} will be harvested, and the entire treatment area will be planted with Douglas-fir seedlings.
3. **Patches.** All trees were harvested within four pre-selected tracts, each 0.6–2.0 ha in area (i.e., “patches”), totaling approximately 20% of the treatment area, and the new openings were planted with Douglas-fir seedlings. This method of regeneration will be repeated at 10-year intervals, and at the beginning of the sixth decade, harvesting will be repeated in the first set of patches to reinitiate the cycle.
 4. **Groups.** All trees were harvested within 12–23 pre-selected tracts, each 0.1–0.5 ha in area (i.e., “groups”), totaling approximately 20% of the treatment area, and the new openings were planted with Douglas-fir seedlings. This method of regeneration will be repeated at 10-year intervals, and at the beginning of the sixth decade, harvesting will be repeated in the first set of groups to reinitiate the cycle.
 5. **Thinning.** Treatment areas at Blue Ridge and Copper Ridge were thinned at study initiation, while that at Rusty Ridge was not thinned because it had been thinned recently. Prior to thinning at Blue Ridge and Copper Ridge, Curtis relative density (RD) (Curtis, 1982) averaged 53% of the maximum biological density for Douglas-fir; after thinning it averaged 45% of maximum density. Crop trees selected for retention were primarily evenly spaced Douglas-fir from the upper crown classes. No planting of Douglas-fir seedlings occurred in

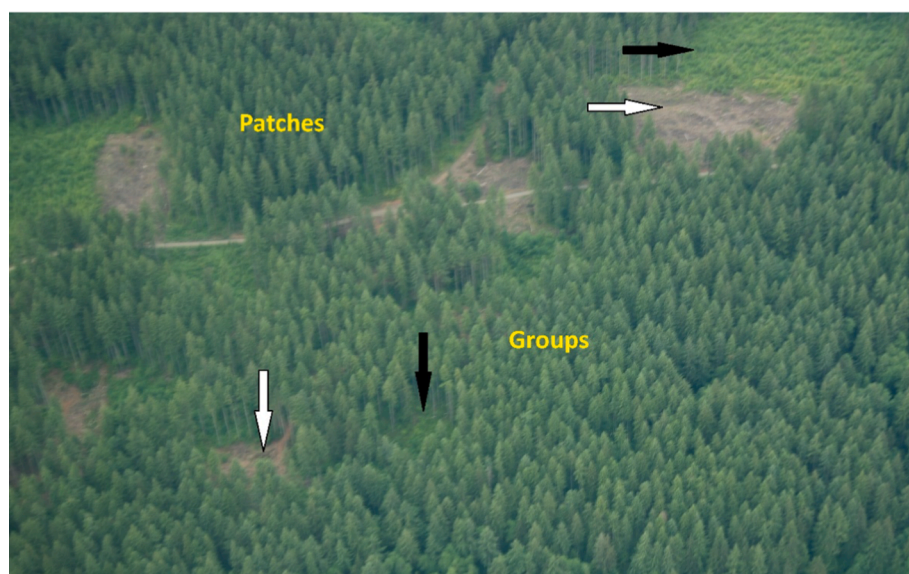
the treatment area. At 20-year intervals, thinning will be repeated at each of the three sites to leave about 40% of the maximum biological density for Douglas-fir.

6. **Non-treated control.** No harvesting of trees occurred within the treatment area, and no harvesting is planned for the duration of the study.

The experimental design is a randomized complete block with three replications (i.e., sites) of the six silvicultural regimes. Four of the six silvicultural regimes include regeneration harvests (i.e., clearcut, two age, patches, and groups) in which harvested areas were planted with bare-root, 1 + 1 Douglas-fir seedlings at a 3-m spacing. In the first 2–5 years after the first harvest, manual cutting of woody vegetation was applied to reduce competition for the planted seedlings. The clearcut regime maintains an even-aged stand structure, the two-age regime maintains two age-classes of conifers, and the patches and groups regimes maintain uneven-aged stands with five age-classes of conifers (Fig. 1). The thinning and control silvicultural regimes do not include a method of regeneration; therefore, they represent two methods for deferring harvest and maintaining an even-aged stand structure – one with and one without commercial thinning. For the second decade of the study, new tracts for the second harvest of the patches and groups regimes were located strategically to facilitate harvesting operability and to increase light availability to previously harvested areas (Fig. 1).



Fig. 1. Aerial photographs from 2009 of the Blue Ridge site, Silvicultural Options Study, Olympia WA USA (photograph by James Dollins, USDA Forest Service). Top photograph shows portions of the clearcut and two-age silvicultural regimes 11 years after the first harvest in 1998; a portion of the non-treated control regime is shown in the lower left. Bottom photograph shows portions of the patches and groups silvicultural regimes with openings from the first harvest (1998; black arrows) and second harvest (2008; white arrows). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



2.3. Vegetation measurements

Vegetation measurements were taken from a systematic grid of permanent circular 0.08-ha plots ($r = 16.1$ m) within each silvicultural regime. At each site, the uneven-aged patches and groups regimes each had 20–26 plots per site because of their greater heterogeneity in stand structure, whereas the other silvicultural regimes had 15–16 plots per site (Curtis et al., 1997). To estimate proportionate area harvested (PAH) in the patches and groups regimes, each 0.08-ha plot was divided into four quadrants, and each quadrant was visually assessed in the dormant season after the first harvest to determine if it was either partially in (PAH = 0.5), completely in (PAH = 1.0), or completely out (PAH = 0.0) of the harvested area. The visual estimates of PAH were repeated 10 years after the first harvest. The total number of plots monitored in the study was 308. Plot centers were marked with PVC tubing and trees were marked with consecutively numbered aluminum tags.

Each 0.08-ha measurement plot had nested circular 0.01-ha ($r = 5.7$ m) and 0.04-ha ($r = 11.3$ m) subplots for measuring trees according to three stem diameter size classes. In the dormant season prior to the first harvest (i.e., year 'P'), in the dormant season after the first harvest (i.e., year 0), and 10 years thereafter, stem diameter (nearest 0.25 cm) and species of each live tree having a dbh (i.e., stem diameter at breast height (1.37 m)) ≥ 4.1 cm were recorded as follows. Trees 4.1–14.0 cm in dbh were measured within the 0.01-ha circular subplot, trees > 14.0 cm and ≤ 24.4 cm in dbh were measured within the 0.04-ha circular subplot, and trees > 24.4 cm in dbh were measured within the full 0.08-ha plot. Newly regenerated trees (i.e., those that achieved a dbh ≥ 4.1 cm since the previous measurement) were recorded as ingrowth at their first measurement. Height measurement trees were selected across the range of stem diameters, and height (nearest 0.03–0.3 m, depending on tree size) was measured with a Vertex VL5 rangefinder/hypsometer (Haglöf Sweden AB, Klockargatan 8, 882 30 Långsele, Sweden) on a minimum of two undamaged trees per species present in each plot. Crown height (i.e., height to the lowest point on the stem where 50% or more of the whorl branches remained alive) was measured similarly on each height measurement tree, and crown ratio was calculated as crown length (i.e., total height minus crown height) divided by total height. Crown height was not measured at the Blue Ridge site in year P. Initial tree measurements for the non-treated control were taken in year 0 instead of year P because one-year changes in its stand characteristics were assumed to be negligible. To enable calculation of 10th-year tree size and stand growth variables for the patches and groups regimes, survival status and dbh were re-measured in the dormant season prior to the second harvest.

To monitor the density, size, and species composition of tree regeneration, a circular "satellite" subplot (0.0016 ha; $r = 2.3$ m) was centered on the perimeter of the 0.08-ha plot at each of the north, east, south, and west directions. Each planted Douglas-fir seedling within a given satellite subplot of the clearcut, two-age, patches, and groups regimes (i.e., those having a regeneration harvest) was flagged for future reference soon after planting. In the dormant season of the fifth year, the following measurements were taken on each planted Douglas-fir seedling of height ≥ 0.3 m and dbh < 4.1 cm rooted within each satellite subplot: height (nearest 0.03 m), d15 (i.e., stem diameter at 0.15 m height for seedlings < 1.37 m height; nearest 0.025 cm), dbh (diameter at breast height (1.37 m) for seedlings ≥ 1.37 m height; nearest 0.25 cm), and presence or absence of damage from wildlife browsing. Species, height, d15, and dbh also were recorded on the tallest two tree seedlings per satellite subplot (i.e., the tallest 1236 seedlings ha⁻¹), potentially including the planted Douglas-fir, to assess the characteristics of dominant tree regeneration. Percentage cover (nearest 5%) was visually estimated and average height (nearest 0.3 m) was measured on each shrub species having at least 10% cover within a 0.01-ha circular area ($r = 5.7$ m) that encompassed each satellite subplot.

2.4. Data analysis

All data analyses were conducted in SAS version 9.4 (SAS Institute Inc, 2013) with a significance level (α) of 0.05. To predict heights of trees that were measured only for dbh, adequate data existed to fit height: dbh regression models for the following six species: Douglas-fir ($n = 3513$), western hemlock ($n = 926$), western redcedar ($n = 105$), Pacific silver fir (*Abies amabilis* (Douglas ex Loudon) Douglas ex Forbes) ($n = 28$), red alder ($n = 153$), and bigleaf maple ($n = 129$). The following power function (1) was fitted to height and dbh data for each species using nonlinear regression in SAS PROC Nlin:

$$HT = (b_0 + b_{01}(T))(DBH^{(b_1 + b_{12}(S_2) + b_{13}(S_3))}) \quad (1)$$

where HT is tree height (m), $T = 1$ if dbh ≤ 12.7 cm or otherwise $T = 0$, DBH is diameter at breast height (cm), $S_2 = 1$ if the study site is Copper Ridge or otherwise $S_2 = 0$, $S_3 = 1$ if the study site is Rusty Ridge or otherwise $S_3 = 0$, and b_0 , b_{01} , b_1 , b_{12} and b_{13} are regression coefficients to be estimated. The indicator variable, T , adjusts the model for the observed lower values of height per unit dbh for newly regenerated, small-diameter trees relative to older trees of similar dbh. The threshold value for assigning T (i.e., dbh = 12.7 cm) was selected after visual examination of height: dbh scatterplots for each of the six tree species. The indicator variables, S_2 and S_3 , adjust the model for potential differences in height per unit dbh of trees at Copper Ridge and Rusty Ridge, respectively, relative to those found at Blue Ridge. After fitting the full model for a given species, non-significant variables ($P > 0.05$) were removed incrementally until all remaining variables were statistically significant. Coefficients of determination (R^2 ; based on regression of observed versus predicted values for height) for the height: dbh models were 0.80–0.92 for the four conifer species and 0.51–0.87 for the two hardwood species. None of the species' models suffered from heteroskedasticity based on scatterplots of residual versus predicted values. The height: dbh model for Douglas-fir also was used to predict heights for grand fir (*Abies grandis* (Douglas ex D. Don) Lindl.) and Sitka spruce (*Picea sitchensis* (Bong.) Carrière).

Individual-tree values of dbh and measured or predicted height of Douglas-fir, Pacific silver fir, grand fir, and Sitka spruce were applied to the equations of Bruce and DeMars (1974) to predict stem volume per tree, and these values were summed by plot and expressed on a per-hectare basis to equal stand volume (m³ ha⁻¹). Stem volumes for western hemlock and western redcedar were predicted with the equation in Wiley et al. (1978), while those for the hardwood species were predicted with the equations in Snell and Little (1983). The volume equation for red alder (*Alnus rubra* Bong.) in Snell and Little (1983) was used to predict stem volumes of hardwood species not specifically addressed in their publication.

Plot means were calculated for dbh (expressed as quadratic mean diameter (qmd)), height, and crown ratio for prior to and 10 years after harvest for the following three species groups: Douglas-fir, other conifers, and hardwoods. Likewise, the following stand statistics were calculated by plot for each species group: stem density (trees ha⁻¹), stand basal area (m² ha⁻¹), and stand volume (m³ ha⁻¹). Additionally, Curtis RD for Douglas-fir was calculated for each plot (Curtis, 1982). Means values for crown ratio and Curtis RD of Douglas-fir also were calculated for non-harvested plots of the patches and groups regimes to assess 10-year changes relative to the non-treated control. Volume removed in the first harvest was calculated by plot for each species group as the difference between pre- and post-harvest (i.e., year P – year 0) values. Plot values of 10-year change in stand volume for each species group were partitioned into growth of the surviving trees, ingrowth of newly regenerated trees, and mortality of the original trees with each variable expressed as periodic annual increment (PAI; m³ ha⁻¹ yr⁻¹). Stem density of planted Douglas-fir seedlings was adjusted for the actual area that was planted by dividing by the proportionate area harvested per plot (PAH). Plot means for fifth year stem density, height, d15, dbh

Table 3

Mean stem density, size, and percentage browsing by wildlife (standard error in parentheses) of planted Douglas-fir seedlings by height class and silvicultural regime 5 years after the first harvest of the Silvicultural Options Study, Olympia WA USA. For a given height class and variable, means followed by the same letter do not differ significantly among silvicultural regimes ($P > 0.05$).

Height class	Variable	Silvicultural regime ^a			
		Clearcut	Two age	Patches	Groups
≥0.30 m	Stem density (seedlings ha ⁻¹)	851.3 (113.9) a	757.1 (101.3) a	578.7 (77.4) a	645.1 (86.3) a
	Height (m)	1.8 (0.2) a	1.6 (0.2) ab	1.2 (0.2) bc	1.1 (0.2) c
	D15 ^b (cm)	2.3 (0.2) a	1.9 (0.2) ab	1.6 (0.2) b	1.5 (0.2) b
	Browsing (%)	0.0 (0.0) a	3.4 (5.3) a	11.6 (9.5) a	13.4 (10.0) a
≥1.37 m	Stem density (seedlings ha ⁻¹)	562.5 (220.1) a	471.3 (184.4) a	92.4 (36.2) b	75.7 (29.6) b
	Height (m)	2.0 (0.1) a	1.9 (0.1) ab	1.9 (0.1) ab	1.6 (0.1) b
	Dbh ^c (cm)	1.3 (0.2) a	1.1 (0.2) a	1.2 (0.2) a	0.6 (0.2) a

^a Only the four silvicultural regimes that had a regeneration harvest were included in this comparison.

^b Stem diameter at 0.15 m height, expressed as quadratic mean diameter.

^c Stem diameter at breast height (i.e., 1.37 m), expressed as quadratic mean diameter.

(with each measure of stem diameter expressed as qmd), proportionate browsing of planted Douglas-fir seedlings, and fifth year cover and height of each shrub species also were calculated. Plots having <10% cover of a given shrub species were assigned a value of 5% to represent the midpoint of the 0–10% cover class. Size measurements for the tallest two tree seedlings per satellite subplot were divided into species groups of Douglas-fir, other conifers, and hardwoods, and plot means were calculated for each species group. The relative frequency (%) by species group for the tallest tree seedlings also was calculated for each plot. To estimate crown encroachment of overstory trees into harvested areas of the patches and groups regimes, ten-year change in PAH was calculated for measurement plots in these regimes that had been impacted by the first harvest.

For each response variable described above, treatment area means were calculated from the plot means, and values for each variable were subjected to mixed-model analysis of variance (ANOVA) in SAS PROC Mixed to test the significance of fixed effects of silvicultural regime after adjusting for random effects of blocks. Because the thinning treatment at Rusty Ridge was not thinned at the time of study initiation, this treatment replication was excluded from all statistical analyses. Plots in the patches and groups regimes having no harvested area were excluded from calculations of treatment area means for planted Douglas-fir stem density. Prior to ANOVA, stem density, stand basal area, stand volume, and changes in stand volume (i.e., harvested volume, survivor growth, ingrowth, and mortality) per species group were transformed to natural logarithms (i.e., $X' = \text{Log}_e(X + 1)$) to correct for non-homogeneity of residual variances (Sokal and Rohlf, 1981). An angular transformation (i.e., arc-sine, square root) was applied to each proportionate variable (i.e., proportion of seedlings browsed, relative frequency by species group for the tallest tree seedlings, and cover of shrub species) prior to ANOVA to normalize their residual variances. Only the four silvicultural regimes having a regeneration harvest (i.e., clearcut, two age, patches, and groups) were included in the ANOVA's for stem density, size, and proportionate browsing of planted Douglas-fir, and the analysis was conducted separately for two height classes of seedlings: those ≥0.3 m and those ≥1.37 m. If a significant F statistic ($P \leq 0.05$) was observed for silvicultural regimes in a given ANOVA, Tukey's HSD test was used to conduct multiple comparisons among regime means (Sokal and Rohlf, 1981). Treatment area means for response variables of the tallest tree seedlings were subjected to ANOVA in SAS Proc MIXED to test the significance of fixed effects of silvicultural regime, species group, and their interaction after adjusting for random effects of blocks. If a significant F statistic was observed for the interaction of silvicultural regime and species group, multiple comparisons of simple effect means were conducted with a Bonferroni adjustment to the statistical probabilities to control the Type I error rate (Quinn and Keough, 2002).

The extra sums-of-squares approach in linear regression (Neter et al.,

1989) was used in SAS PROC Reg to test for potential site differences in the relationship of Douglas-fir stand volume PAI (i.e., survivor growth) versus stand basal area after the first harvest (i.e., year 0). Indicator variables were specified for the Copper Ridge and Rusty Ridge sites to enable fitting of separate regression intercepts and slopes for each site. F -tests were applied sequentially to compare the full model to reduced models having a common intercept, a common slope, or both.

3. Results

3.1. Tree regeneration

Density and size of Douglas-fir regeneration differed among silvicultural regimes depending on the height class of seedlings. The following results are for planted Douglas-fir seedlings ≥ 0.3 m height. Mean 5th-year stem density (579–851 seedlings ha⁻¹) did not differ significantly among silvicultural regimes ($P = 0.275$; Table 3). Mean 5th-year height in the clearcut regime (1.8 m) was greater than in the patches (1.2 m) and groups (1.1 m) regimes, and 5th-year height was greater in the two-age regime (1.6 m) than in the groups regime (1.1 m). Mean 5th-year d15 in the clearcut regime (2.3 cm) was greater than in the patches (1.6 cm) and groups (1.5 cm) regimes. Mean 5th-year percentage browsing of Douglas-fir seedlings by wildlife (0–13%) did not differ significantly among silvicultural regimes ($P = 0.095$), although there was a trend of increasing percentage browsing with decreasing size of harvested openings. The following results are for planted Douglas-fir ≥ 1.37 m height. The numbers of seedlings that had achieved breast height during the first 5 years of the clearcut and two-age regimes (471–563 seedlings ha⁻¹) were five to seven times those observed in the patches and groups regimes (76–92 seedlings ha⁻¹). Mean 5th-year height in the clearcut regime (2.0 m) was greater than in the groups regime (1.6 m). However, mean 5th-year dbh (0.6–1.3 cm) did not differ significantly among silvicultural regimes ($P = 0.069$). In the 10 years following the first harvest, edge overstory trees encroached into the harvested openings of the patches and groups regimes by 6% and 4% of the area, respectively.

Five years after the first harvest, mean height and mean dbh of the tallest 1236 tree seedlings ha⁻¹ (i.e., planted or naturally regenerated) did not differ significantly among silvicultural regimes, species groups, or their interaction ($P \geq 0.140$; data not shown). The relative frequencies by species group for the tallest seedlings 5 years after the first harvest had a significant interaction between silvicultural regime and species group ($P = 0.017$). Multiple comparisons of interaction means revealed that, in the clearcut and two-age regimes, mean 5th-year relative frequency of Douglas-fir (80–86% of seedlings) was significantly greater than those of other conifers (11–13%) or hardwoods (1–9%) (Fig. 2). In the patches and groups regimes, mean 5th-year

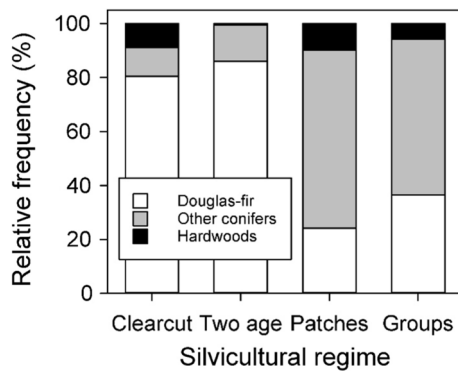


Fig. 2. Mean relative frequencies of the tallest 1236 tree seedlings ha^{-1} (i.e., planted or naturally regenerated) by species group and silvicultural regime (Only the four silvicultural regimes that had a regeneration harvest were included in this comparison.) 5 years after the first harvest of the Silvicultural Options Study, Olympia WA USA. For the clearcut and two-age regimes, frequencies of Douglas-fir were significantly greater than the respective frequencies of other conifers and hardwoods ($P \leq 0.05$).

relative frequency of Douglas-fir (24–36% of seedlings) did not differ significantly from those of other conifers (58–66%) or hardwoods (6–10%).

3.2. Shrub cover and height

Five years after the first harvest, mean cover of California blackberry (*Rubus ursinus* Cham. & Schltdl.) in the clearcut regime (21%) was greater than in the control regime (5%), but it did not differ significantly from those in the other regimes (Table 4). Mean 5th-year height of salal (*Gaultheria shallon* Pursh) in the clearcut regime (0.3 m) was less than in the patches, groups, thinning, and control regimes (0.5–0.6 m), but it did not differ significantly from that in the two-age regime. Mean 5th-year heights of red huckleberry (*Vaccinium parvifolium* Sm.) in the clearcut and two-age regimes (1.2 and 1.2 m, respectively) were lower than in the control regime (2.0 m), but they did not differ significantly from those in the patches, groups, or thinning regimes.

3.3. Tree size ($\text{dbh} \geq 4.1 \text{ cm}$) and crown ratio

Each of mean height, dbh, and crown ratio prior to the first harvest did not differ significantly ($P \geq 0.112$) among silvicultural regimes for any of the tree species groups (Table 5). In year 10, mean height was smaller and mean crown ratio was larger for Douglas-fir and for other conifers in both the clearcut and two-age regimes than in the non-treated control. Mean 10th-year heights of other conifers in the two-age and groups regimes also were smaller than in the control. Mean 10th-year dbh of Douglas-fir in the clearcut regime (8 cm) was smaller than in each of the other regimes (41–58 cm). Mean 10th-year crown ratio of Douglas-fir was ranked statistically among regimes as: clearcut > two

Table 4

Mean cover or height (standard error in parentheses) by shrub species and silvicultural regime 5 years after the first harvest of the Silvicultural Options Study, Olympia WA USA. For a given species and variable, means followed by the same letter do not differ significantly among silvicultural regimes ($P > 0.05$).

Species	Variable	Silvicultural regime					
		Clearcut	Two age	Patches	Groups	Thinning	Control
<i>Rubus ursinus</i>	Cover (%)	20.8 (6.1) a	11.9 (5.6) ab	6.8 (5.1) ab	10.1 (5.3) ab	7.4 (3.3) ab	5.0 (0.0) b
<i>Gaultheria shallon</i>	Height (m)	0.3 (0.1) b	0.5 (0.1) ab	0.5 (0.1) a	0.6 (0.1) a	0.6 (0.1) a	0.6 (0.1) a
<i>Vaccinium parvifolium</i>	Height (m)	1.2 (0.2) b	1.2 (0.2) b	1.9 (0.2) ab	1.8 (0.2) ab	1.9 (0.2) ab	2.0 (0.2) a

Table 5

Mean tree size and crown ratio ($\text{dbh} \geq 4.1 \text{ cm}$; standard error in parentheses) by species group and silvicultural regime before (year 'P') and 10 years after the first harvest of the Silvicultural Options Study, Olympia WA USA. For a given species group, variable, and year, means followed by the same letter do not differ significantly among silvicultural regimes ($P > 0.05$).

Species group	Variable	Year	Silvicultural regime					
			Clearcut	Two age	Patches	Groups	Thinning	Control
Douglas-fir	Height (m)	P ^a	34.7 (3.5) a	36.4 (3.5) a	36.4 (3.5) a	34.9 (3.5) a	36.0 (3.6) a	36.5 (3.5) a
		10	6.6 (4.1) c	20.9 (4.1) b	35.2 (4.1) a	35.5 (4.1) a	39.0 (4.6) a	37.9 (4.1) a
	Dbh ^b (cm)	P	46.1 (5.7) a	50.4 (5.7) a	50.4 (5.7) a	46.5 (5.7) a	49.3 (6.2) a	50.8 (5.7) a
		10	7.8 (6.2) b	40.9 (6.2) a	52.8 (6.2) a	51.1 (6.2) a	57.7 (7.3) a	55.5 (6.2) a
	Crown ratio ^c	P	0.45 (0.04) a	0.42 (0.04) a	0.45 (0.04) a	0.48 (0.04) a	0.44 (0.05) a	0.43 (0.04) a
		10	0.93 (0.04) a	0.62 (0.04) b	0.46 (0.04) c	0.44 (0.04) c	0.36 (0.05) c	0.38 (0.04) c
Other conifers	Height (m)	P	21.9 (2.7) a	25.2 (2.7) a	25.8 (2.7) a	22.2 (2.7) a	18.3 (3.0) a	25.6 (2.7) a
		10	5.8 (2.4) c	11.7 (2.4) bc	19.9 (2.4) ab	14.9 (2.4) bc	15.8 (3.0) abc	27.4 (2.4) a
	Dbh (cm)	P	31.5 (4.8) a	38.2 (4.8) a	39.8 (4.8) a	34.1 (4.8) a	25.2 (5.4) a	39.4 (4.8) a
		10	6.3 (4.7) c	15.9 (4.7) bc	31.7 (4.7) ab	23.8 (4.7) abc	19.9 (5.8) abc	44.0 (4.7) a
	Crown ratio	P	0.67 (0.08) a	0.61 (0.08) a	0.76 (0.08) a	0.76 (0.08) a	0.57 (0.11) a	0.68 (0.06) a
		10	0.92 (0.05) a	0.86 (0.05) a	0.71 (0.05) ab	0.85 (0.05) a	0.77 (0.05) ab	0.64 (0.05) b
Hardwoods	Height (m)	P	27.9 (2.4) a	29.8 (2.4) a	29.1 (2.4) a	28.4 (2.0) a	27.8 (2.4) a	29.8 (2.0) a
		10	5.4 (7.7) a	11.5 (7.7) a	22.0 (5.5) a	15.7 (4.5) a	26.1 (5.5) a	30.2 (4.5) a
	Dbh (cm)	P	32.5 (3.4) a	37.9 (3.4) a	35.7 (2.8) a	33.3 (2.8) a	30.2 (3.4) a	32.9 (2.8) a
		10	0.0 (9.0) a	4.5 (11.1) a	21.2 (9.0) a	18.6 (8.1) a	23.5 (9.0) a	28.1 (8.1) a
	Crown ratio	P	— ^d	0.31 (0.10)	—	—	—	0.44 (0.06)
		10	0.88 (0.14) a	0.96 (0.17) a	0.76 (0.14) a	0.74 (0.12) a	0.57 (0.14) a	0.50 (0.12) a

^a Measured in the dormant season prior to harvest.

^b Stem diameter at breast height (i.e., 1.37 m).

^c Ratio of crown length to tree height.

^d Only two silvicultural regimes had adequate sample sizes to estimate mean crown ratio of hardwood species prior to the first harvest.

Table 6

Mean stand density (dbh ≥ 4.1 cm; standard error in parentheses) by species group and silvicultural regime before (year 'P') and 10 years after the first harvest of the Silvicultural Options Study, Olympia WA USA. For a given species group, variable, and year, means followed by the same letter do not differ significantly among silvicultural regimes ($P > 0.05$).

Species group	Variable	Year	Silvicultural regime					
			Clearcut	Two age	Patches	Groups	Thinning	Control
Douglas-fir	Stem density (trees ha ⁻¹)	P ^a	271.6 (83.3) a	246.8 (75.7) a	247.3 (75.8) a	311.3 (95.5) a	296.2 (99.4) a	247.0 (75.7) a
		10	903.1 (256.7) a	513.2 (145.9) a	290.0 (82.4) a	273.1 (77.7) a	207.1 (72.0) a	235.7 (67.0) a
	Stand basal area (m ² ha ⁻¹)	P	40.1 (3.2) a	46.7 (3.7) a	44.3 (3.5) a	45.3 (3.6) a	52.2 (4.8) a	40.8 (3.3) a
		10	4.2 (0.7) c	13.7 (2.3) b	51.1 (8.7) a	43.2 (7.4) a	53.6 (11.2) a	46.9 (8.0) a
	Stand volume (m ³ ha ⁻¹)	P	534.3 (61.8) a	640.6 (74.1) a	604.8 (69.9) a	605.7 (70.0) a	711.7 (88.5) a	552.9 (63.9) a
		10	13.9 (3.1) c	171.2 (37.8) b	715.1 (158.0) a	597.2 (132.0) a	800.0 (216.5) a	646.7 (142.9) a
Other conifers	Curtis relative density ^b	P	6.0 (0.6) a	6.6 (0.6) a	6.4 (0.6) a	6.8 (0.7) a	7.4 (0.8) a	5.9 (0.6) a
		10	1.6 (0.2) b	2.2 (0.2) b	5.4 (0.6) a	5.0 (0.6) a	6.9 (0.9) a	6.5 (0.7) a
	Stem density (trees ha ⁻¹)	P	85.3 (58.0) a	62.3 (42.3) a	23.0 (15.7) a	51.3 (34.8) a	34.2 (24.6) a	35.1 (23.9) a
		10	49.3 (42.3) a	188.1 (161.6) a	66.4 (57.1) a	92.9 (79.9) a	74.3 (70.5) a	37.0 (31.8) a
	Stand basal area (m ² ha ⁻¹)	P	4.9 (3.0) a	5.1 (3.1) a	2.1 (1.3) a	2.5 (1.5) a	0.6 (0.4) a	3.5 (2.1) a
		10	0.3 (0.2) a	1.5 (0.8) a	2.0 (1.1) a	1.5 (0.8) a	1.2 (0.8) a	4.1 (2.3) a
Hardwoods	Stand volume (m ³ ha ⁻¹)	P	55.8 (42.3) a	62.3 (47.2) a	25.8 (19.6) a	26.9 (20.4) a	4.3 (3.6) a	37.9 (28.7) a
		10	0.5 (0.4) b	8.6 (7.0) ab	20.6 (16.8) a	12.0 (9.7) a	9.8 (9.1) ab	47.3 (38.6) a
	Stem density (trees ha ⁻¹)	P	7.9 (6.0) a	10.7 (8.2) a	12.7 (9.7) a	12.8 (9.8) a	28.4 (22.5) a	25.2 (19.3) a
		10	16.5 (15.6) a	5.9 (5.6) a	13.3 (12.6) a	60.5 (57.1) a	22.7 (24.6) a	43.7 (41.2) a
	Stand basal area (m ² ha ⁻¹)	P	0.5 (0.4) a	1.0 (0.8) a	1.1 (0.8) a	0.9 (0.6) a	2.0 (1.6) a	1.8 (1.3) a
		10	0.1 (0.1) bc	0.1 (0.1) c	0.6 (0.4) abc	0.6 (0.4) abc	1.0 (0.7) ab	1.3 (0.8) a
	Stand volume (m ³ ha ⁻¹)	P	2.0 (2.7) a	3.7 (5.1) a	8.5 (11.7) a	7.7 (10.5) a	11.8 (17.2) a	16.2 (22.2) a
		10	0.2 (0.3) bc	0.2 (0.2) c	2.0 (2.6) abc	2.8 (3.6) abc	5.4 (7.3) ab	11.1 (14.2) a

^a Measured in the dormant season prior to harvest.

^b Curtis (1982).

age > all other regimes. Mean 10th-year crown ratios of other conifers in the clearcut, two-age, and groups regimes (0.85–0.92) were greater than in the control (0.64). However, for hardwoods, mean 10th-year size and crown ratio did not differ significantly among silvicultural regimes ($P \geq 0.112$).

3.4. Stand density

Prior to the first harvest, each of mean stem density, stand basal area, and stand volume did not differ significantly among silvicultural regimes for any tree species group ($P \geq 0.066$) (Table 6). Although the ANOVA *F*-test was significant for mean 10th-year Douglas-fir stem density ($P = 0.039$), multiple comparisons of regime means failed to detect any differences. Mean 10th-year stand basal areas of Douglas-fir were ranked statistically among silvicultural regimes as clearcut < two age < all other regimes. Mean 10th-year stand volume and Curtis RD of Douglas-fir were smaller in the clearcut and two-age regimes than

in all other regimes.

Mean 10th-year stem density of other conifers (37–188 trees ha⁻¹) and that of hardwoods (6–60 trees ha⁻¹) did not differ significantly among silvicultural regimes ($P \geq 0.411$) (Table 6). Although mean 10th-year stand basal area of other conifers did not differ significantly among silvicultural regimes ($P = 0.073$), mean 10th-year stand volume of this species group in the clearcut regime was less than in the patches, groups, and control regimes. Mean 10th-year stand basal area and volume of hardwoods in the clearcut and two-age regimes were less than in the non-treated control.

3.5. Changes in stand volume

Douglas-fir volume percentages removed in the first harvest were 100%, 78%, 21%, 35%, 10%, and 0% for the clearcut, two-age, patches, groups, thinning, and control regimes, respectively. Douglas-fir volumes removed in the first harvest were ranked statistically among silvicultural

Table 7

Mean changes in stand volume (standard error in parentheses) by species group and silvicultural regime during 10 years after the first harvest of the Silvicultural Options Study, Olympia WA USA. For a given species group and variable, means followed by the same letter do not differ significantly among silvicultural regimes ($P > 0.05$). Units for first and second harvest volumes are m³ha⁻¹; units for all other variables are m³ha⁻¹yr⁻¹.

Species group	Variable	Silvicultural regime					
		Clearcut	Two age	Patches	Groups	Thinning	Control
Douglas-fir	First harvest	534.3 (135.0) a	500.2 (126.4) a	124.4 (31.4) b	212.5 (53.7) ab	74.6 (22.6) b	0.0 (0.0) c
	Survivor growth	0.0 (0.0) d	4.0 (0.3) c	9.9 (0.7) ab	8.7 (0.6) b	13.9 (1.2) a	11.2 (0.8) ab
	Ingrowth	1.4 (0.6) a	0.5 (0.2) ab	0.1 (0.0) ab	0.1 (0.1) ab	0.1 (0.1) ab	0.1 (0.0) b
	Mortality	0.0 (0.0) b	1.1 (0.5) a	1.7 (0.7) a	0.6 (0.2) a	2.0 (1.0) a	1.7 (0.7) a
	Second harvest	0.0 (0.0) b	0.0 (0.0) b	156.6 (24.6) a	118.7 (18.7) a	0.0 (0.0) b	0.0 (0.0) b
Other conifers	First harvest	55.7 (53.2) a	55.4 (53.0) a	6.6 (6.3) ab	13.3 (12.7) ab	0.5 (0.6) bc	0.0 (0.0) c
	Survivor growth	0.0 (0.0) a	0.2 (0.1) a	0.4 (0.2) a	0.3 (0.2) a	0.3 (0.2) a	1.1 (0.6) a
	Ingrowth	0.1 (0.0) ab	0.4 (0.2) a	0.1 (0.1) ab	0.1 (0.1) ab	0.2 (0.1) ab	0.0 (0.0) b
	Mortality	0.0 (0.0) a	0.4 (0.3) a	0.2 (0.2) a	0.0 (0.0) a	0.0 (0.0) a	0.2 (0.1) a
	Second harvest	0.0 (0.0) b	0.0 (0.0) b	3.0 (1.8) a	0.4 (0.3) ab	0.0 (0.0) b	0.0 (0.0) b
Hardwoods	First harvest	2.0 (2.6) a	3.7 (4.9) a	6.0 (8.1) a	4.2 (5.6) a	2.6 (3.9) a	0.0 (0.0) a
	Survivor growth	0.0 (0.0) a	0.0 (0.0) a	0.1 (0.0) a	0.1 (0.0) a	0.1 (0.1) a	0.1 (0.1) a
	Ingrowth	0.1 (0.0) a	0.0 (0.0) a	0.0 (0.0) a	0.1 (0.0) a	0.0 (0.0) a	0.1 (0.0) a
	Mortality	0.0 (0.0) b	0.0 (0.0) b	0.0 (0.0) b	0.1 (0.0) b	0.2 (0.1) ab	0.8 (0.3) a
	Second harvest	0.0 (0.0) a	0.0 (0.0) a	0.9 (0.8) a	0.3 (0.2) a	0.0 (0.0) a	0.0 (0.0) a

regimes as: clearcut $\approx$ two age $>$ patches, thinning $>$ control; volume removed in the groups regime was greater than in the control but intermediate to the other regimes (Table 7). Note that the first harvest in the groups regime removed greater than the targeted amount of 20% of the total Douglas-fir volume; whereas, that removed in the patches regime was close to the target. The second harvest was very close to target values with 22% and 20% of the total Douglas-fir volume removed in the patches and groups regimes, respectively.

Douglas-fir survivor growth was ranked statistically among regimes as clearcut $<$ two age $<$ groups $<$ thinning; survivor growth in the patches and control regimes did not differ statistically from either the groups or thinning regimes (Table 7). Douglas-fir ingrowth in the clearcut regime ($1.4 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$) was significantly greater than in the control regime ($0.1 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$). Douglas-fir mortality in the clearcut regime ($0.0 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$) was significantly less than in each of the other regimes ($0.6\text{--}2.0 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$).

Harvested volume of other conifer species was ranked statistically as: clearcut $\approx$ two age $>$ thinning $\approx$ control; the intermediate levels of volume removed in the patches and groups regimes were greater than in the control but they did not differ statistically from the other regimes (Table 7). Ingrowth of other conifers in the two-age regime ($0.4 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$) was greater than in the control ($0.0 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$). Mortality of hardwoods in the control ($0.8 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$) was greater than in the clearcut, two-age, patches, and groups regimes ($0.0\text{--}0.1 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$). All other variables of stand volume change for hardwoods did not differ significantly among regimes ($P \geq 0.065$).

Douglas-fir survivor growth was linearly related ($r^2 = 0.94$) to the species' initial stand basal area after the first harvest (Fig. 3). In this relationship, the regression intercept and slope parameters did not differ significantly among sites ($P \geq 0.314$), indicating similar Douglas-fir survivor growth per unit initial stand basal area.

4. Discussion

4.1. Tree regeneration

Among the four silvicultural regimes that had a regeneration harvest, differences in mean 5th-year height and d15 of planted Douglas-fir were likely attributable to effects of stand edge competition from mature trees growing adjacent to harvested areas, which limited availability of light and possibly also soil water and nutrients. However, absence of differences in density of planted Douglas-fir (i.e., seedlings $\geq 0.3 \text{ m}$ height) suggests that effects of stand edge competition were not severe enough

by the 5th year after harvest to reduce seedling survival.

As the size of a forest canopy opening decreases, a greater proportion of the area is affected by stand edge competition. For example, in a circular 0.1-ha opening within a mature forest, little or no direct sunlight reaches the forest floor because of shading from neighboring trees (Pickett and White, 1985; Harrington and Devine, 2018). In this study, Douglas-fir seedlings planted in the patches and groups regimes were more likely to encounter stand edge competition than those planted in the clearcut and two-age regimes because of differences in size of harvested openings. In the ten years following the first harvest, edge trees were estimated to encroach into the harvested areas of the patches and groups regimes by 4–6%. As a result of this stand edge competition, fewer Douglas-fir seedlings in the patches and groups regimes were able to reach breast height during the first 5 years after planting, potentially affecting the future species composition of crop trees. Smith and Beese (2021) found that stand edge competition reduced growth of Douglas-fir seedlings that had been planted within 10 m of the edge, but it had little or no influence on seedlings planted further away. Site factors, such as topography, soil quality, and competing vegetation abundance, play a role in determining the influence of stand edge competition and the most efficacious sizes of harvested openings for supporting conifer seedling growth.

Mean height and dbh of the tallest 1236 seedlings ha^{-1} did not differ significantly among silvicultural regimes, species groups, or their interaction, indicating that despite differences in stand edge competition among regimes, the dominant seedlings had approximately the same mean size. The greater relative frequency of Douglas-fir in the tallest seedlings for the clearcut and two-age regimes probably resulted from the destruction of advance regeneration of other conifers and hardwoods from ground disturbances during harvest, as observed by Harrington and Devine (2018). The patches and groups regimes, having smaller harvested areas and less ground disturbance, provided a refuge for advance regeneration of other conifers and hardwoods. As a result, relative frequencies did not differ among species groups for the patches and groups regimes. This finding suggests that future crop trees in the patches and groups regimes will have a mixed species composition, as opposed to a more monospecific composition (i.e., dominated by Douglas-fir) in the clearcut and two-age regimes. As noted previously for the two-age regime, ingrowth of other conifer species was similar to that observed for Douglas-fir, which is contrary to the 5th-year finding of a higher relative frequency of Douglas-fir than other conifers for the tallest regeneration. This discrepancy probably reflects trends in stand development that occurred during years 6–10 and that were not captured in the 5th-year regeneration survey. In small gaps ($<0.1 \text{ ha}$) of mesic Pacific Northwestern coniferous forests, only shade tolerant tree species, such as western hemlock and Pacific silver fir, can regenerate successfully; light intensity in such canopy openings is not sufficient to promote Douglas-fir regeneration into the upper canopy (Spies and Franklin, 1989; Spies et al., 1990).

Mean 5th-year stem density and size of planted Douglas-fir did not differ significantly between the clearcut and two-age regimes likely because of the relatively brief assessment period and the fact that residual stand basal area of Douglas-fir in the two-age regime averaged $10 \text{ m}^2 \text{ ha}^{-1}$. Based on a 5-year study in western Oregon, Brandeis et al. (2001) recommended retention of $<20 \text{ m}^2 \text{ ha}^{-1}$ of residual stand basal area to support acceptable growth of planted Douglas-fir, and the need for repeated thinning and control of overtopping vegetation to maintain these seedling growth rates. Brodie and Debell (2013) found that 9 years of competition from overstory trees reduced stem diameter of planted Douglas-fir by 35% compared to seedlings growing in clearcuts. These studies, as well as the updated report on the Brandeis et al. (2001) study (Cole and Newton, 2009), confirm the need for ongoing density management of overstory and understory vegetation if the objectives are to grow a productive cohort of understory conifers.

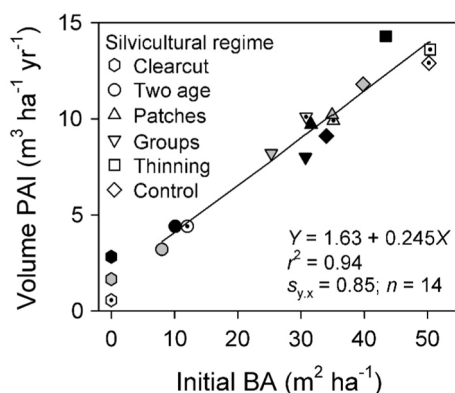


Fig. 3. Regression relationship of Douglas-fir 10-year periodic annual increment (PAI) in stand volume (i.e., survivor growth) versus initial stand basal area (BA) after the first harvest of the Silvicultural Options Study, Olympia WA USA. Symbol fills indicate study site: black = Blue Ridge, dotted white = Copper Ridge, and gray = Rusty Ridge. Ingrowth volume PAI for the clearcut regime was plotted for illustration purposes only (i.e., data were not included in the regression).

4.2. Shrub cover and height

The observed differences among silvicultural regimes in abundance and size of three shrub species are a direct result of harvesting effects on ground disturbance, abundance of logging debris, and light availability. California blackberry is a heliophytic vine that benefits from ground disturbance and presence of logging debris. [Peter and Harrington \(2018\)](#) observed greater cover of California blackberry in experimental areas that contained high levels of logging debris (38% cover) versus those with lower levels (25% cover). The finding of low abundance of California blackberry in the control regime (5% cover) is probably an indication of presence of significant shade and absence of ground disturbance and logging debris.

Reduced height of salal in the clearcut regime (0.3 m) relative to most of the other regimes (0.5–0.6 m) is probably a response to the extensive ground disturbance that occurred there, similar to the destruction of the advance regeneration of other conifers and hardwoods. A similar trend occurred for red huckleberry. These reductions in shrub height are temporary, as both species are known to recover from the moderate intensity disturbances associated with forest harvesting ([Yerkes, 1960](#); [D'Anjou, 1990](#)).

4.3. Tree size (dbh $\geq$ 4.1 cm) and crown ratio

In the four silvicultural regimes that had a regeneration harvest (i.e., clearcut, two age, patches, and groups), decreases in mean tree size and increases in mean crown ratio for Douglas-fir from prior to harvest to year 10 corresponded with the proportionate area harvested at study initiation. Mature trees were removed during harvest and replaced with planted seedlings, resulting in smaller mean height and larger mean crown ratio than observed in the non-treated control. Similar trends were observed for other conifer species, but not for hardwood species likely because of a limited sample size for that species group. Although mean 10th-year height and dbh of Douglas-fir in the thinning regime numerically exceeded those in the control, these differences were not statistically significant likely because the comparison included only two replications (i.e., thinning effects were not evaluated at Rusty Ridge, as reported previously). In addition, pre-harvest Curtis relative density (RD) of Douglas-fir in the thinning treatment was only 53% of the species' biological maximum (i.e., density was not greatly limiting to tree growth; [Long, 1985](#)), and the treatment reduced Curtis RD by only 15%.

Mean crown ratio of Douglas-fir in the non-treated control declined 12% from year 0 to 10, likely in response to increased crowding among individual trees. In non-harvested plots of the patches and groups regimes, crown ratio declined 3–5% from year 0 to 10. In general, a mean crown ratio below 0.40, as found in year 10 for the control (0.38) regime and for non-harvested plots in the patches (0.37) and groups (0.37) regimes, indicates reduced tree vigor and increased probability of density-associated mortality ([Long, 1985](#)). Therefore, there is an expectation of increased Douglas-fir mortality in the second decade of the study for the control and non-harvested plots of the patches and groups regimes.

4.4. Stand density

The first harvest resulted in lower values for 10th-year stand basal area, volume, and Curtis RD of Douglas-fir in the clearcut and two-age silvicultural regimes than in the patch, thinning, and control regimes. A similar but smaller reduction in stand density was observed for hardwoods and other conifer species, because some or all of the large trees for these species were removed during harvest.

Tenth year stand basal area and volume of Douglas-fir in the thinning regime did not differ significantly from the control regime likely because the thinning treatment only reduced Curtis RD by 15%. Based on this finding, as well as the absence of a statistically significant mean-tree growth response from thinning, future thinning treatments will be applied at 20-year intervals, at which time Curtis RD should equal or

exceed 55% of the Douglas-fir biological maximum – the lower limit for density-associated mortality ([Drew and Flewelling, 1979](#)). Future thinning treatments also will reduce Curtis RD to about 40% of the biological maximum – a density reduction of at least 27%, making them more likely to stimulate a mean-tree growth response.

The 10-year declines in crown ratio below 0.40 in the non-treated control and in non-harvested plots of the patches and groups regimes are being driven by increases in stand density as individual trees grow in stem diameter. Curtis RD increased 9%, 9%, and 12% in the control and in non-harvested plots of the patches and groups regimes, respectively, during the 10-year assessment period. Mean 10th-year values for Curtis RD in each of these non-harvested conditions averaged 46–48% of the Douglas-fir biological maximum density ([Curtis, 1982](#)), indicating that stand growing conditions were below the zone of density-associated tree mortality ([Drew and Flewelling, 1979](#)).

4.5. Changes in stand volume

In the two-age regime, ingrowth of other conifers ($0.4 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$) was similar to that observed for Douglas-fir ($0.5 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$), suggesting a shift towards a mixed tree species composition and greater representation of shade tolerant species, especially western hemlock. This contrasts with that observed in the clearcut regime, where ingrowth was dominated by Douglas-fir ($1.4 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$) and ingrowth of other conifers was minor ($0.1 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$). Although the first harvest likely destroyed most of the advance regeneration of other conifer species in both the clearcut and two-age regimes, as observed by [Harrington and Devine \(2018\)](#), surviving western hemlock in the two-age regime probably benefitted from the partial shade of the retained overstory trees.

Survivor growth of all tree species in the two-age regime ($4.2 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$) was somewhat higher than that estimated by [Brodie and DeBell \(2013; 3 m³ ha⁻¹ yr⁻¹\)](#) for stands of similar density. When combined with total ingrowth ($0.9 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$), 10-year net production of the two-age regime in this study was 41% of that observed in the control regime, whereas net production of the clearcut regime (i.e., ingrowth only) was only 13% of the control. However, total ingrowth in the two-age regime was 56% of that in the clearcut regime because of competition from overstory trees. This indicates that wood production from overstory trees in the two-age regime is compensating for the loss of production from understory trees. Because these overstory-understory interactions vary dynamically over time and on different sites, longer-term comparisons, or model simulation studies, are needed to understand the best density management approaches for maximizing wood production and economic value of a two-age silvicultural regime.

Douglas-fir mortality in the clearcut regime was lower than in the other five regimes because clearcutting eliminated all mature trees and replaced them with seedlings that had considerably less total volume, eliminating all potential sources of overstory tree mortality for the first decade of the study. Hardwood mortality in the non-treated control was greater than those observed in the clearcut, two-age, patch, and group regimes. Observed causes of the hardwood mortality included wind-throw and competitive exclusion by overstory conifers. [Long et al. \(2018\)](#) observed a decline in the abundance of large-crowned hardwoods in the Pacific Northwest during the past 25 years that was potentially associated with increasing density of conifer-dominant forests.

Absence of differences among sites in the relationship of survivor growth versus initial stand basal area after harvest for Douglas-fir ([Fig. 3](#)) indicates that 10-year stand productivity was primarily dependent on the stand's residual density. The strength of this relationship ($r^2 = 0.94$) is likely attributable to similarity among sites in soil texture (i.e., primarily deep silt loams) and stand structure (i.e., stands were even aged, fully stocked, and did not differ among silvicultural regimes in pre-harvest tree size or stand density). The relationship is linear and lacks an approach to an asymptote or a peak, as in [Marshall and Curtis \(2002\)](#),

likely because the treatment area having the highest density (i.e., the control regime at Rusty Ridge; Curtis RD = 8.2) was only 59% of the maximum biological density for Douglas-fir (Curtis, 1982; Tappeiner et al. 2015). Allen et al. (2021) observed a peaked relationship for stand volume PAI versus residual stand basal area of Norway spruce (*Picea abies* (L.) Karst), with maximum growth occurring at a residual basal area of $43 \text{ m}^2 \text{ ha}^{-1}$. However, in the relationship for Norway spruce there was a broad range of residual basal areas that produced similar growth, as found previously for coast Douglas-fir (Curtis, 1995) and red pine (*Pinus resinosa* A. it.) (D'Amato et al., 2010).

5. Conclusions and management implications

The comparisons of regeneration characteristics among silvicultural regimes provide a glimpse into the future species composition and growth rates of replacement trees in the recently harvested areas. Silvicultural regimes with extensive ground disturbance from forest harvesting (i.e., clearcut and two age) favored Douglas-fir as the dominant regeneration species because the disturbance destroyed most of the advance regeneration of other conifers and hardwoods which would have competed with planted Douglas-fir seedlings. The patches and groups regimes, with their smaller overall harvest areas and their smaller sizes of harvested openings, resulted in less extensive ground disturbance and the creation of numerous shaded edges between harvested and non-harvested areas. Thus, the patches and groups regimes provided a refuge for advance regeneration of shade-tolerant species, such as western hemlock, western redcedar, and bigleaf maple. Planted Douglas-fir seedlings in harvested areas of the patches and groups regimes, therefore, must overcome competition from both stand-edge trees and advance regeneration. The advance regeneration, usually western hemlock, is more shade tolerant and often larger than the planted Douglas-fir seedlings, giving it a competitive advantage in moderate shade. As a result, the clearcut and two-age regimes are likely to favor Douglas-fir as the dominant tree species, as found in the pre-harvest stand, and the patches and groups regimes are likely to favor western hemlock as the dominant species. None of the silvicultural regimes favored development of large hardwoods, which requires creation of dedicated growing space that will not be significantly encroached upon by conifers during the lifespan of the stand (Tappeiner et al., 2015). It is noteworthy that the reported annual rates of ingrowth are probably underestimated because recruitment of new trees from the first harvest is likely to continue beyond the 10-year assessment period of this report. In addition, several harvest entries are probably necessary to estimate a stable rate of ingrowth for the patches and groups regimes.

In this comparison of silvicultural regimes 10 years after their implementation, variation in growth of the residual stand after harvest had the single largest impact on Douglas-fir stand productivity. This variation can be attributed almost entirely to initial stand density after harvest; variation among the three replicate sites did not affect the stand growth: density relationship. Ingrowth and mortality had secondary and opposing impacts on Douglas-fir stand productivity having a magnitude of 30% or less than that of growth. In future decades, we expect that growth will continue to be the primary driver of differences in productivity among silvicultural regimes because, ultimately, newly harvested areas will reach the stem exclusion stage of stand development (Oliver, 1981) and no further ingrowth will be possible. Density-associated mortality is not likely to have a strong influence on overall stand productivity because each of the regimes having regeneration harvests includes pre-commercial thinning. Thus, mortality impacts will be limited to minor losses of trees from the lower crown classes and from shade-intolerant hardwood species as the stands differentiate and competition intensifies over time.

A recent review of scientific journal articles comparing effects of even- and uneven-aged silvicultural systems on ecological diversity and processes revealed the absence of a clear winner: each system had benefits and risks, and choice of the best system was taxon- and scale-

dependent (Nolet et al., 2018). Nonetheless, the current study has several important implications to management of coast Douglas-fir. First, large landowners will benefit from maintaining a mixed portfolio of silvicultural regimes across their managed landscapes because it will provide variation in the amount, timing, and species composition of harvest removals, making their economic decisions less susceptible to market swings. Maintenance of Douglas-fir as the primary crop species is likely to provide the most stable future source of income for large landowners. Second, for smaller landowners, the patches regime is most likely to provide the best balance among management objectives of a steady income from harvesting, a moderate level of ongoing silvicultural activity because of smaller harvest areas, and limited risk because silvicultural investments are being applied infrequently to relatively small areas. Based on this research, precommercial thinning would be essential to the patches regime to ensure that the planted Douglas-fir are not out-competed by western hemlock advance regeneration. Although the groups regime has many of the same positive features as the patches regime, its implementation could be cumbersome to small landowners because of the considerable planning and record-keeping required to appropriately track and tend the numerous harvested openings over time.

The two-age silvicultural regime, while interesting to attempt as a case study, suffers from excessive complexity of management decisions as well as vulnerability from catastrophic loss of the entire mature age class from windthrow or snow and ice. Deferred harvesting with repeated thinning has many desirable features, including continuous maintenance of a forest canopy and intermittent cashflow. However, by the second or third thinning, residual trees may not be considered merchantable in current markets because of their excessive size. Deferred harvesting, therefore, could result in set-aside acreages that can no longer be managed for harvest income because their older-forest characteristics create the illusion of wilderness and absence of human intervention, effectively removing them from future wood production. Nonetheless, these set-aside acreages would provide other forest values for a comprehensive land management portfolio, including enhanced visual quality, mature-forest wildlife habitat, and carbon stores. However, instead of conducting another thinning that would stimulate further increases in tree size, a forest manager could decide to implement one of the four methods of regeneration from this study (i.e., clearcutting, two-age, patches, or groups regimes).

In the coming decades, this study will provide important clues regarding how the regenerating stands or deferred harvest areas contribute to the overall productivity of a given silvicultural regime. For example, it is currently unknown: (1) how stand edge competition in the patches and groups regimes will influence their yield per area, (2) how domination of western hemlock advance regeneration in the patches and groups regimes will affect the amount and types of harvested forest products, and (3) whether repeated thinning will limit merchantability of large-diameter trees.

CRediT authorship contribution statement

Timothy B. Harrington: Conceptualization, Methodology, Visualization, Supervision, Project administration, Data curation, Writing – original draft. **David H. Peter:** Methodology, Writing – review & editing. **David D. Marshall:** Conceptualization, Methodology, Project administration, Writing – review & editing. **Dean S. DeBell:** Conceptualization, Methodology, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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