Stand dynamics after variable-retention harvesting in mature Douglas-Fir forests of Western North America[1]

(With 9 Figures and 4 Tables)

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Biodiversität; Bestandesstruktur; Mortalität; Verjüngung.

1. INTRODUCTION

Variable-retention has been proposed as a way to mitigate the effects of timber harvest on biological diversity, particularly late-seral species (FRANKLIN et al., 1997). In the context of silvicultural systems, variable-retention harvests represent a regeneration cut because the primary objective is to regenerate the stand without clearcutting. In its implementation, variable-retention bears strong resemblance to the classical system of shelterwood with reserves (MATTHEWS, 1991). Past experience with traditional systems, therefore, can help with the design of new treatments that target specific structural objectives, such as multiple cohorts and layers of trees, or control growth rates of understory trees by varying overstory density. The objectives that motivate variable retention, however, are generally more complex than those implicit in classical systems or that their variants (MITCHELL and BEESE, 2002), and little experience has accrued on ecological responses to different levels or spatial patterns of overstory retention. Even if habitat requirements of key species are known, a coarse-filter approach (HUNTER et al., 1988) that yields a diversity of vegetation structures over time and space (SEYMOUR and HUNTER, 1999) remains the most promising way to avoid erosion of forest biodiversity. Achieving this goal, however, requires understanding how forest stands will respond to a wide range of silvicultural treatments applied at spatial scales that accommodate the organisms of interest, are operationally feasible, and yield information relevant to forest management and policy.

Many questions arise about basic aspects of forest stand dynamics in designing silvicultural regimes to meet timber, aesthetic, and biodiversity objectives. Can residual overstory trees be retained without significant loss to wind damage, and if they survive, will growth accelerate or decline? How quickly does advance regeneration respond to release, and how do species differ in their responses? Do planted seedlings perform as well as, or better than, advance regeneration or newly recruited natural seedlings? For a given level of retention, how variable is the impact on tree growth among differing spatial patterns of residual trees? What are the structural outcomes of retaining differing levels and/or patterns of residual trees? Without knowledge of these responses, design of variable-retention treatments and the silvicultural systems they comprise is tentative at best.

Answers to some of these questions are suggested, in part, by past work on shelterwood systems, clearcuts with reserve trees, clearcuts in the presence of advance regeneration, overstory removals from stands with naturally established understory trees, and sanitation cuts in mature or old-growth timber. Mortality of residual trees has been shown to accelerate at least temporarily when residuals were either dispersed (BUERMEYER and HARRINGTON, 2002) or left as intact fragments (ESSEEN, 1994). The mortality rate of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) left as reserves in one clearcut was 7% over a period of 12 years (BUERMEYER and HARRINGTON, 2002), suggesting an annualized mortality rate of approximately 0.6%. Growth responses of overstory trees may be positive or negative, depending on time since harvest, species, relative canopy position, logging damage, and various other biotic and abiotic factors. Although "thinning shock" (temporary decline in diameter and/or height growth) has been observed after stand density reduction (HARRINGTON and

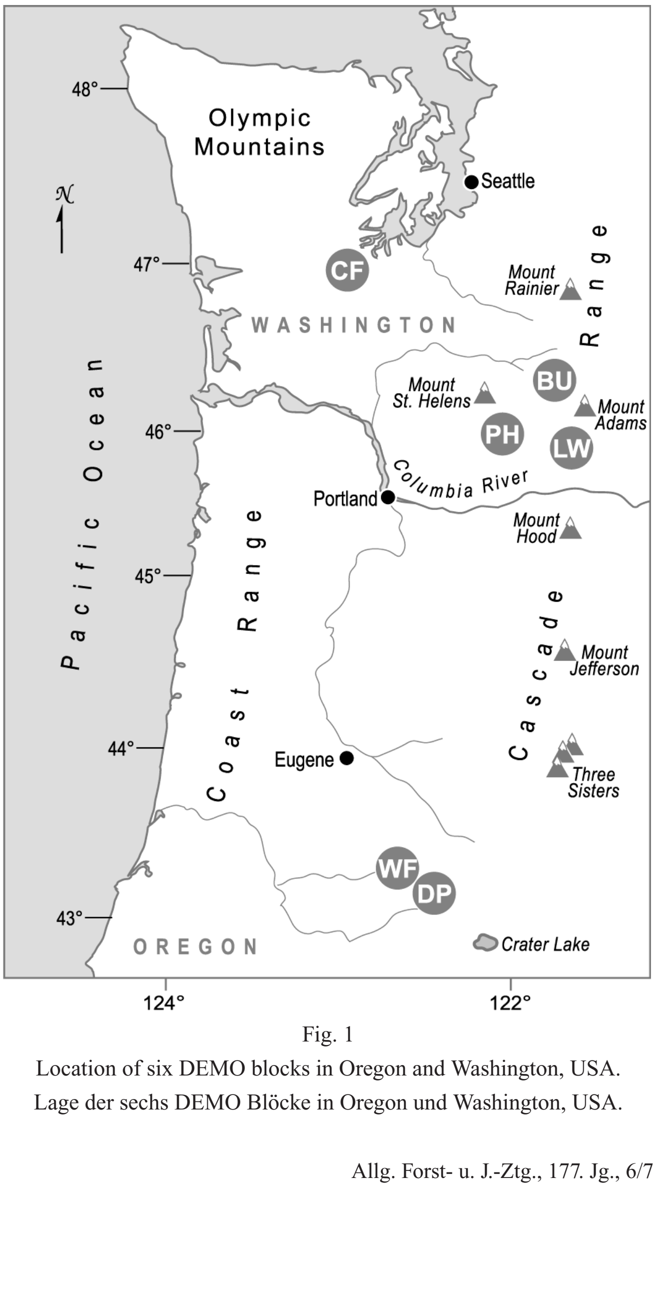

Fig. 1

Location of six DEMO blocks in Oregon and Washington, USA.

Lage der sechs DEMO Blöcke in Oregon und Washington, USA.

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[1]) This is a product of the Demonstration of Ecosystem Management Options (DEMO) study, a joint effort of the USDA Forest Service Region 6 and Pacific Northwest Research Station. Research partners include the University of Washington, Oregon State University, University of Oregon, Gifford Pinchot and Umpqua National Forests, and the Washington State Department of Natural Resources. Funds were provided by the USDA Forest Service, PNW Research Station (PNW-93-0455 and PNW 97-9021-1-CA).

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REUKEMA, 1983), even trees ranging in age from 160 to 650 years appear capable of responding to increases in growing space and resource availability after partial harvesting (LATHAM and TAPPEINER, 2002).

The behavior of advance regeneration after partial overstory removal will determine its contribution to the understory cohort. Thinning prior to a regeneration cut has been shown to promote establishment of advance regeneration (BUERMEYER and HARRINGTON, 2002; BAILEY and TAPPEINER, 1998), and subsequent height growth is greater under lower residual stand densities (DEL RIO and BERG, 1979; OLIVER and DOLPH, 1992; BAILEY and TAPPEINER, 1998). Overstory removal from natural two-storied stands in the Klamath Mountains of Oregon and California led to a doubling of height growth in understory Douglas-fir and white fir (*Abies concolor* (Gord. & Glend.) Lindl. ex. Hildebr) within 5 years after release (TESCH and KORPELA, 1993). Height growth of advance regeneration on these sites compared favorably with growth of the same species in plantations, particularly on poor sites (KORPELA et al., 1992). Growth of advance regeneration generally improves with greater removal of the overstory (GRANHUS and BRÆKKE, 2001; PAGE et al., 2001; TENG et al., 2003) and with greater distances from intact forest edge (HAWKINS et al., 2002). Similarly, height growth rates of seedlings that establish after harvest typically decline with increasing overstory density (WILLIAMSON and RUTH, 1976; NILSON and LUNDQVIST, 2001); with proximity to seed trees (MCDONALD, 1976; VALKONEN et al., 2002); or with declining opening size in group selection cuts (MCDONALD and ABBOTT, 1994). Comparable responses have been documented for planted seedlings of many conifer and broadleaved species (SUZUKI et al., 1996; DIGNAN et al., 1998; COATES, 2000; BRANDEIS et al., 2001; MITCHELL, 2001).

Relatively few studies have taken a long-term, comprehensive view of the dynamics of residual trees, advance regeneration, planted seedlings, and new germinants. Such studies are needed in the Douglas-fir region of the western United States where, despite little experience with producing and maintaining two-aged or multi-aged stands of Douglas-fir, the Northwest Forest Plan mandates a minimum of 15% retention in harvest units on federal land (TUCHMANN et al., 1996). The Demonstration of Ecosystem Management Options (DEMO) study was initiated as a regional experiment to test the roles of level and pattern of overstory retention under the dual objective of conserving biodiversity and ensuring regeneration and acceptable growth of timber species. The specific objective of this analysis was to test the effect of alternative variable-retention treatments on (1) mortality and volume growth of overstory trees, (2) mortality and recent height growth of planted seedlings, and (3) recent height growth and initial response to release of advance regeneration.

2. METHODS

2.1 Study Sites and Treatments

Six study locations (blocks) were selected to represent mature (65- to 170-yr-old) forests dominated by Douglas-fir (AUBRY et al., 2004) (*Fig. 1*). Two blocks were located in the Cascade Range in central Oregon, three in the Cascade Range in southern Washington, and one in the Coast Range in southwestern Washington (43°20'N to 47°00'N latitude and 121°50'W to 123°20'W longitude). Elevations ranged from ca. 200–1700 m and slopes varied from gentle to steep, with a broad range of aspects represented (*Table 1*). Three blocks (Butte, Capitol Forest, and Watson Falls) were in the western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) forest zone, one (Little White Salmon) was in the grand fir (*Abies grandis* (Dougl. ex. D. Don) Lindl.) zone, one (Dog Prairie) was in the white fir zone, and one (Paradise Hills) was in the Pacific silver fir (*Abies amabilis* Dougl. ex Forbes) zone (FRANKLIN and DYRNESS, 1973). Total stand basal area and tree density (breast height diameter ≥5 cm) ranged from 47 to 89 m^2 ha^{-1} and 345 to 1147 trees ha^{-1}, respectively (*Table 2*). The climate of the region is maritime with warm, dry summers and cool, wet winters. Most of the precipitation falls between October and April, with annual precipitation ranging from approximately 800 to 2500 mm (FRANKLIN and DYRNESS, 1973).

Table 1

Topographic features, forest attributes, and harvesting and planting dates for each of the six experimental blocks in the DEMO study. Minimum and maximum values represent treatment unit means.

Topografische Einzelheiten, Eigenschaften der Waldgebiete, sowie Nutzungs- und Pflanzdaten der sechs Versuchsblöcke in der DEMO Studie. Die Maximal- und Minimalwerte beziehen sich auf die Mittelwerte der Behandlungseinheiten.

Location/ Block	Elevation (m)	Slope (%)	Aspect	Age (yr)	Site index (m at 50 yr)	Harvest date	Planting date
Oregon:							
Umpqua National Forest							
Watson Falls	945-1310	4-7	flat	110-130	40-43	7/1998	5/1999
Dog Prairie	1460-1710	34-62	SW	165	30	8/1998	5/1999
Washington:							
Gifford Pinchot NF							
Butte	975-1280	40-53	E-SE	70-80	27-32	6/1997	5/1998
Little White Salmon	825-975	40-60	NW-NE	140-170	30	6/1998	6/1999
Paradise Hills	850-1035	9-33	variable	110-140	26-33	8/1997	5/1998
Dept of Natural Resources							
Capitol Forest	210-275	28-52	variable	65	37-41	2/1998	2/1999

Table 2
Average overstory conditions in the six experimental blocks prior to harvest.
Durchschnittswerte für den Oberstand in den sechs Versuchsblöcken vor dem Eingriff.

Attribute	Watson Falls	Dog Prairie	Butte	Little White Salmon	Paradise Hills	Capitol Forest
Douglas-fir						
Tree density (no. ha^{-1})*	246	219	798	124	191	232
Basal area (m^2 ha^{-1})	34.0	73.9	50.1	66.4	39.7	56.4
Quadratic mean diameter (cm)	43	66	29	83	52	57
Stand density index†	547	1001	944	823	590	815
Stem volume (m^3 ha^{-1})‡	502	1181	567	1211	511	936
Other conifers						
Tree density (no./ha)	144	126	348	37	551	94
Basal area (m^2 ha^{-1})	13.4	15.1	5.8	3.6	33.3	4.7
Quadratic mean diameter (cm)	31	40	16	32	28	26
Stand density index	229	250	142	62	631	93
Stem volume (m^3 ha^{-1})	224	238	50	55	399	56
All species						
Tree density (no. ha^{-1})	397	345	1147	237	742	362
Basal area (m^2 ha^{-1})	47.4	89.0	56.0	70.7	73.1	64.1
Quadratic mean diameter (cm)	39	58	26	63	36	48
Stand density index	786	1269	1105	978	1259	985
Stem volume (m^3 ha^{-1})	750	1423	613	1269	903	1040

* Trees with diameter > 5 cm...
† REINEKE (1933).
‡ Based on equations from BRACKETT (1973).

At each block, five harvest treatments and a control were randomly assigned to 13-ha experimental (treatment) units (*Fig. 2*). Treatments differed by the level (percentage of initial basal area) and spatial pattern (dispersed vs. aggregated) of retained trees as follows: (1) 100%: 100% retention (control); (2) 75%A: 75% aggregated retention (three circular, 1-ha patch cuts in an uncut matrix); (3) 40%D: 40% dispersed retention (uniform spatial distribution of residual trees); (4) 40%A: 40% aggregated retention (five circular 1-ha forest aggregates in a cut matrix); (5) 15%D: 15% dispersed retention (uniform distribution of residual trees); and (6) 15%A: 15% aggregated retention (two circular 1-ha forest aggregates in a cut matrix). Residual trees in the dispersed treatments were selected from larger and more wind-stable dominants and co-dominants. The 75%A treatment was excluded from the present analysis.

Treatment units were logged by a skyline cable system (Capitol Forest), ground-based system (Watson Falls, Paradise Hills), or helicopter (Dog Prairie, Butte, Little White Salmon) (HALPERN and MCKENZIE, 2001). Harvesting in all treatment units was completed in 3–7 mo at each block (*Table 1*), and damage to residual stems was generally low (MOORE et al., 2002). Residual basal areas ranged from 8 to 100 m^2 ha^{-1} (*Fig. 3*). At one block (Watson Falls), logging slash was piled away from vegetation sampling points and burned to reduce fuel loadings to permissible levels. Logging slash was left untreated at the remaining blocks. Harvested portions of all treatment units within a block were planted with the species mix most likely to lead to reforestation success (*Table 3*). Target planting densities on the harvested portions of individual treatment units ranged from 476–741 seedlings ha^{-1} (HALPERN et al., 2005), and the species mix was predominantly Douglas-fir with one to four additional species (except Capitol Forest). Species mixes and planting densities were chosen to promote natural regeneration but to ensure adequate stocking through planting (AUBRY et al., 1999).

2.2 Plot and Tree Measurements

Overstory and understory trees were sampled in each treatment unit by using a systematic grid of points (8 x 8 or 9 x 7 with 40-m spacing of grid points; AUBRY et al., 1999). In the control and dispersed-retention treatments, 32 permanent plots were placed systematically at alternate grid points for the pre-harvest inventory. The aggregated treatments were characterized by two distinct post-harvest conditions (cut and uncut), so plots were placed at all five grid points within each aggregate (40%A and 15%A), and at a subset of points in the surrounding matrix. This design resulted in 36 or 37 plots in 40%A and 32 plots in each of the other treatments. Pre-harvest overstory conditions were sampled between 1994 and 1996 with nested circular plots: 0.01 ha for trees with diameter at breast height (D) of 5–15 cm, and 0.04 ha for larger trees. Within each plot, species and diameter (nearest 1 cm) were recorded for each tree. Total height and height to crown base were measured on a subsample of trees of each species within each treatment unit; if fewer than 40 trees were available for a given species, all individuals were measured.

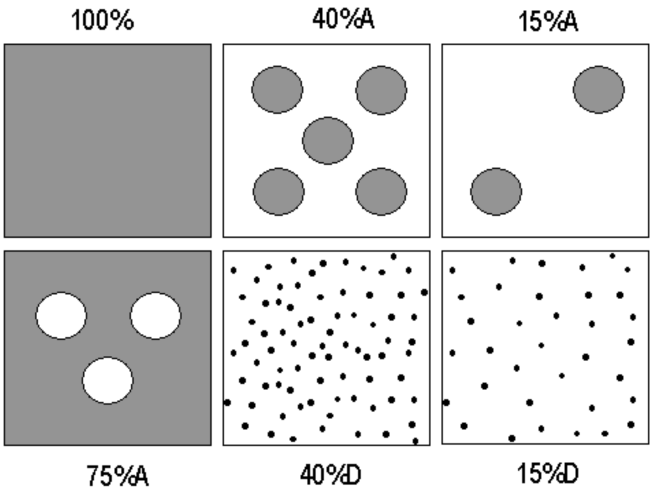

Fig. 2

Schematic diagram of DEMO variable-retention harvest treatments imposed on 13-ha treatment units. (1) 100%: 100% retention (control); (2) 75%A: 75% aggregated retention; (3) 40%D: 40% dispersed retention; (4) 40%A: 40% aggregated retention; (5) 15%D: 15% dispersed retention; and (6) 15%A: 15% aggregated retention

Schematisches Diagramm der DEMO-Behandlungen mit der Bezeichnung „variable retention harvest“ (Variable Retention), die in 13-ha Versuchseinheiten implementiert wurde. (1) 100% Retention (Kontrolle; kein Eingriff); (2) 75%A: 75% aggregierte Retention; (3) 40%D: 40% verteilte Retention; (4) 40%A: 40% aggregierte Retention; (5) 15%D: 15% verteilte Retention; and (6) 15%A: 15% aggregierte Retention.

Post-harvest overstory conditions were sampled with a 0.04-ha circular plot for all trees with D ≥ 5 cm. Sampling intensity was increased to all 63 or 64 grid points in the dispersed treatments (where tree densities were greatly reduced), but remained the same in the others. During the growing season after harvest (1998 or 1999), an aluminum tag was nailed to each tree at breast height, and species and diameter (nearest 0.1 cm) were recorded. In the same plot, all planted trees were tagged and measured for total height (nearest cm) (1998 for Butte, 1999 elsewhere).

Overstory trees were assessed for mortality annually for 2–3 years (1999 or 2000 to 2001, reflecting different harvest dates among blocks), and again in 2003. Diameter of all live trees was also remeasured in 2003 to assess growth over the 4- or 5-year remeasurement interval. Height and height to crown base (nearest 0.1 m) were measured on a subsample of 40 trees of each species within each treatment unit (or all trees if there were fewer than 40). Planted trees were also measured in 2003 for 2002 height growth (nearest 0.1 cm), and tree condition was recorded.

Growth of advance regeneration was measured in 2003 at only two blocks, Watson Falls and Paradise Hills. Advance regeneration was uncommon at the remaining blocks. Within each plot, saplings (D < 5 cm, height > 10 cm) of the primary species, Douglas-fir and true firs (*Abies* spp.), were tallied by species on 1x6 m strip plots along four perpendicular radii starting 4 m from the center of each 0.04-ha circular plot. Small saplings (≤1.5 m) were tallied by species and height class (0.1–0.2 m, 0.2–0.5 m, 0.5–1.0 m, and >1.0–1.5 m). One sapling (height <1.5 m) of each species and size class was then tagged and measured for annual height growth (nearest 0.1 cm) in 2002 and in previous years as far back as branch whorls and bud scale scars allowed.

2.3 Statistical Analysis

DEMO was designed as a completely randomized block experiment, so treatment effects were tested by ANOVA, or in some cases ANCOVA (Steel and Torrie, 1980). For overstory and advance

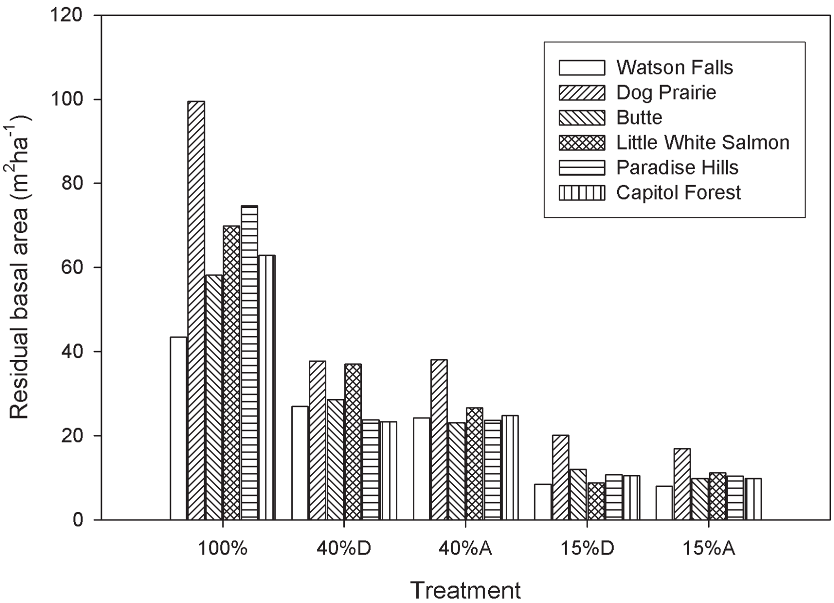

Fig. 3

Residual basal area immediately after harvest in each treatment unit and block.

Grundfläche des verbleibenden Bestandes unmittelbar nach der Nutzung in jeder Versuchseinheit und jedem Block.

Table 3

Mean density (trees ha^{-1}) of planted seedlings in the harvested portions of treatment units within each DEMO block, estimated from the number of tagged seedlings in 1998 or 1999.

Mittlere Dichte (Bäume pro ha) der gepflanzten Jungpflanzen in den geernteten Bereichen der Behandlungseinheiten innerhalb der DEMO Blöcke, geschätzt aufgrund der in den Jahren 1998 oder 1999 markierten Jungpflanzen.

Block	*Pseudotsuga menziesii*	*Pinus monticola*	*Pinus ponderosa*	*Abies magnifica*	*Abies procera*	*Abies amabilis*	*Thuja plicata*	*Tsuga heterophylla*	All species
Watson Falls	199	84	160	0	0	0	0	0	443
Dog Prairie	353	74	0	99	0	0	0	0	526
Butte	343	40	0	0	0	0	0	0	383
Little White Salmon	222	54	38	0	29	0	0	0	343
Paradise Hills	179	37	0	0	58	0	46	21	341
Capitol Forest	604	0	0	0	0	0	0	0	604

regeneration responses, treatment effects (4 df) were decomposed into four orthogonal contrasts: (1) harvest vs. control; (2) level of retention (40% vs. 15%); (3) pattern of retention (dispersed vs. aggregated); and (4) interaction of level and pattern. Because the control was not planted, treatment effects (3 df) on mortality and growth of planted seedlings were decomposed into only the last three orthogonal contrasts. All statistical tests were performed at $\alpha = 0.05$ unless otherwise noted, but p-values in the range 0.051 to 0.10 were considered marginally significant.

Annualized periodic mortality of overstory trees was expressed as a proportion of live trees tagged immediately after harvest. Only trees killed directly by wind or wet snow (stem break or uprooting) were included. Treatment effects on mortality were tested by ANOVA on the arcsin square root of this proportion, with separate tests for Douglas-fir and all other species combined.

Total stem volume of overstory trees was estimated with equations from BRACKETT (1973). Missing heights were filled in with a set of height-diameter equations fitted to the height subsample for each treatment unit and constrained to maintain consistency with expected height growth of the dominant Douglas-fir (BRUCE, 1981; HANN and SCRIVANI, 1987). In addition to the randomized block ANOVA, treatment effects on total overstory volume growth were assessed by randomized block ANCOVA with initial post-treatment volume as the covariate. The ANCOVA was repeated for the volume growth of only the 25 largest trees per ha. The latter focus on dominant-codominant trees ensured that the growth of residual trees was assessed relative to the same stand component across all treatments, including the control. Overstory growth was assessed for all species combined.

Annualized periodic mortality of planted seedlings was expressed as a proportion of seedlings planted. The ANOVA was performed on the arcsin square root of annualized mortality rate for four separate species (or species groups) – Douglas-fir, ponderosa pine (*Pinus ponderosa* Dougl. ex. Laws), western white pine (*Pinus monticola* Dougl. ex D. Don), and noble fir (*A. procera*, Rehd)./Shasta red fir (*A. magnifica* var. *Shastensis*, A. Murr). Treatment effects on 2002 height growth of undamaged planted seedlings were tested by ANOVA on the same species/species groups.

Average annual (2002) height growth of advance regeneration was similarly tested by randomized block ANCOVA, with average initial tree height of the treatment unit as a covariate (0.2–1.5 m in 2001). The statistical power of the analysis was low because only two blocks had sufficient advance regeneration to be included, and the analysis was limited to two species groups that occurred in sufficient abundance, Douglas-fir and two true fir species, Pacific silver fir and white fir.

Sudden exposure of advance regeneration after overstory removal can sometimes cause "shock" or temporary reduction in height growth and, at other times, in rapid release (increase in height growth). A release index was computed as the ratio of height growth during the first growing season after treatment to height growth during the previous growing season. Treatment effects were tested by ANOVA on the average release index of all trees from the control units and from only harvested areas in other treatments (i.e., no trees from the aggregates in 40%A and 15%A). Only the true firs (*Abies* spp.) had a sufficient number of individuals with height growth identifiable back to 1997. As with height growth, the availability of only two blocks limited the power of this test.

3. RESULTS

3.1 Overstory Trees

Across all blocks and treatments, 111 Douglas-fir trees were uprooted or broken off from wind or snow loading. Overstory mortality attributable to this cause was higher for this species in harvested than in control units ($p = 0.007$), and was significantly higher in 15% vs. 40% retention ($p < 0.0001$). The interaction between level and pattern was significant ($p = 0.007$) because Douglas-fir mortality was similar in the aggregated and dispersed treatments at 40% retention, but much greater for the dispersed treatment at 15% retention (*Fig. 4*). For all other species combined, average annualized mortality in the control was not significantly different from that in harvested treatments. However, both level and pattern had significant effects ($p = 0.0066$, $p = 0.014$; *Fig. 4*). In 15%D, annualized mortality from wind and snow damage reached 0.65% yr^{-1} for Douglas-fir and 1.15% yr^{-1} for all other species combined (*Fig. 4*). Overstory mortality rates for the other treatments were <0.2% for Douglas-fir and <0.3% for all other species combined.

As expected, total stem volume growth of the overstory was proportional to level of retention in the ANOVA (*Fig. 5a*), so initial volume was a very significant covariate in the ANCOVA (no significant interaction with treatment). However, initial volume did not account for the greater volume growth per unit initial volume in dispersed vs. aggregated treatments ($p = 0.036$; *Fig. 5b*). Volume growth per unit initial volume for the 25 largest trees ha^{-1} was not affected by either level or pattern of retention, although harvest was marginally significant ($p = 0.085$; *Fig. 5c*).

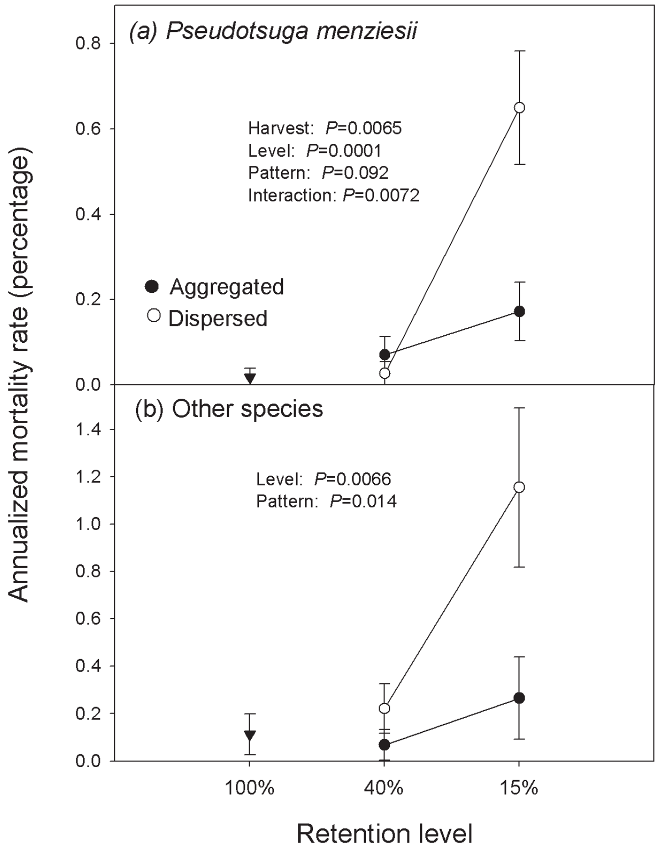

Fig. 4

Annualized mortality rate (±1 SE) of residual overstory trees by treatment and species/species group, expressed as a proportion of initial live trees.

Jährliche Mortalitätsrate (±1 SE) der verbleibenden Bäume im Oberstand für unterschiedliche Behandlungen und Baumarten/ Baumartengruppen, als Anteil der ursprünglich lebenden Bäume.

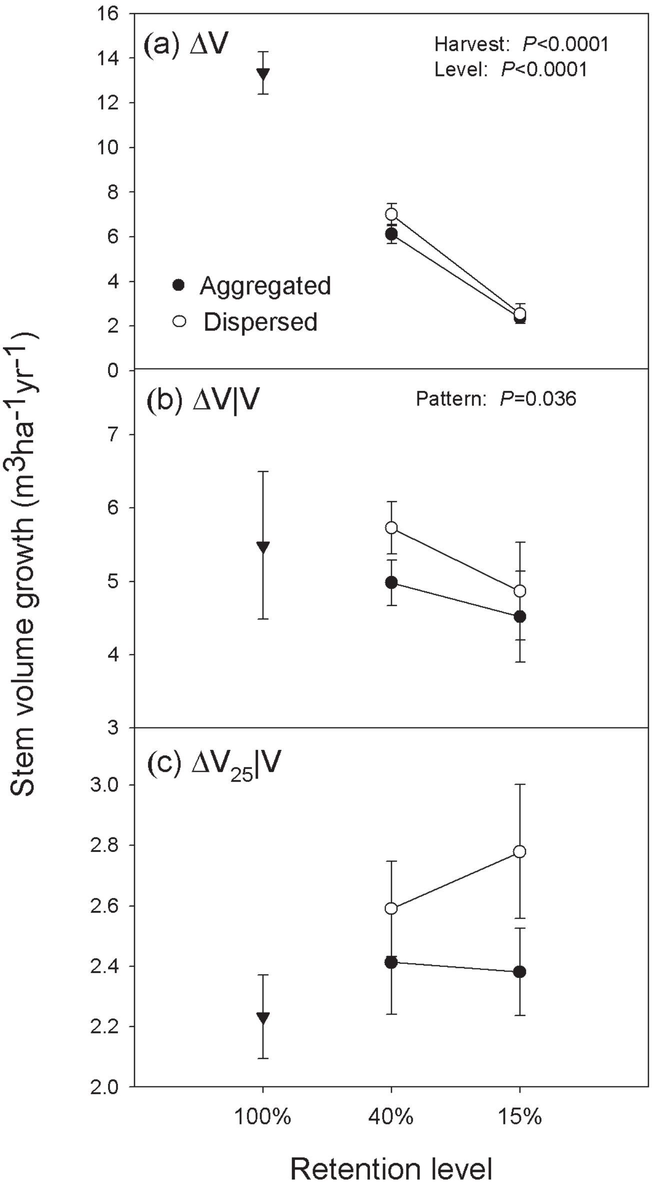

Fig. 5

Average volume growth (± 1 SE) of residual overstory trees by treatment for: (a) all trees without correction for initial stand volume (ΔV), (b) all trees with correction for initial stand volume (ΔV|V), and (c) the largest 25 trees ha^{-1} with correction for initial volume (ΔV_{25}/V).

Durchschnittlicher Volumenzuwachs (ΔV; ±1 SE) der verbleibenden Bäume im Oberstand, getrennt nach Behandlungen für: (a) alle Bäume ohne Abgleich mit dem ursprünglichen Bestandesvorrat (ΔV), (b) alle Bäume mit Abgleich mit dem ursprünglichen Bestandesvorrat (ΔV|V), und (c) die größten 25 Bäume pro ha mit Abgleich mit dem ursprünglichen Bestandesvorrat (ΔV_{25}/V).

3.2 Planted Seedlings

Annualized mortality of planted seedlings varied from 1 to 14% among treatment units, with greatest mortality in the true firs (noble fir and Shasta red fir) and least in ponderosa pine (*Fig. 6*). Ponderosa pine mortality was significantly less in 15% vs. 40% retention ($p < 0.035$; *Fig. 6c*). In contrast, mortality of Douglas-fir seedlings did not differ among treatments (*Fig. 6d*). In western white pine, the marginally significant effect of pattern ($p = 0.063$) and slightly insignificant effect of its interaction with level ($p = 0.106$) reflected the significantly greater mortality in aggregated vs. dispersed patterns at 40% retention, and the lack of significant difference between aggregated and dispersed treatments at 15% retention (*Fig. 6b*). In the true fir species, mortality was significantly greater under aggregated treatments ($p = 0.0043$; *Fig. 6a*), but the smaller difference between aggregated and dispersed patterns at 15% retention led to a marginally significant interaction effect ($p = 0.084$).

Average height growth of planted trees in 2002 ranged from 6 to 21 cm, and was greatest for ponderosa pine and least for noble fir/red fir (*Fig. 7*). Height growth for true fir was significantly greater in 15% than in 40% retention ($p = 0.030$), but pattern had no significant effect ($p = 0.13$; *Fig. 7a*). In both western white pine and Douglas-fir (*Fig. 7b, d*), height growth was significantly greater in aggregated vs. dispersed treatments at 40% retention, but the effect of pattern was much greater at 40% retention, resulting in a significant interaction effect on western white pine ($p < 0.015$). Height growth in ponderosa pine was marginally greater in aggregated vs. dispersed treatments ($p = 0.076$; *Fig. 7c*).

3.3 Advance Regeneration

Advance regeneration was relatively abundant at only two blocks, Watson Falls and Paradise Hills (*Table 4*). Average height growth in 2002 (representing the fourth or fifth growing season after harvest) ranged from 2 to 12 cm for true fir (white fir and Pacific silver fir) and 6 to 11 cm for Douglas-fir. Advance regeneration of true fir grew significantly less in the controls than in treated units ($p = 0.035$), and greater under 15% retention than 40%

retention (p = 0.036; *Fig. 8a*). In Douglas-fir, no significant treatment effects were apparent (*Fig. 8b*). Maximum growth occurred in 15%A for Pacific silver fir and in 15%D for white fir (data not shown). A marginally significant effect of pattern (p = 0.073) on release index (ratio of post- to pre-harvest height growth) was negated by the significant interaction between level and pattern in true fir release index (p = 0.0058;). In this species group, 15% retention induced accelerated growth (index > 1) in dispersed treatments but decelerated growth in aggregated treatments, relative to controls and 40% retention (*Fig. 9*).

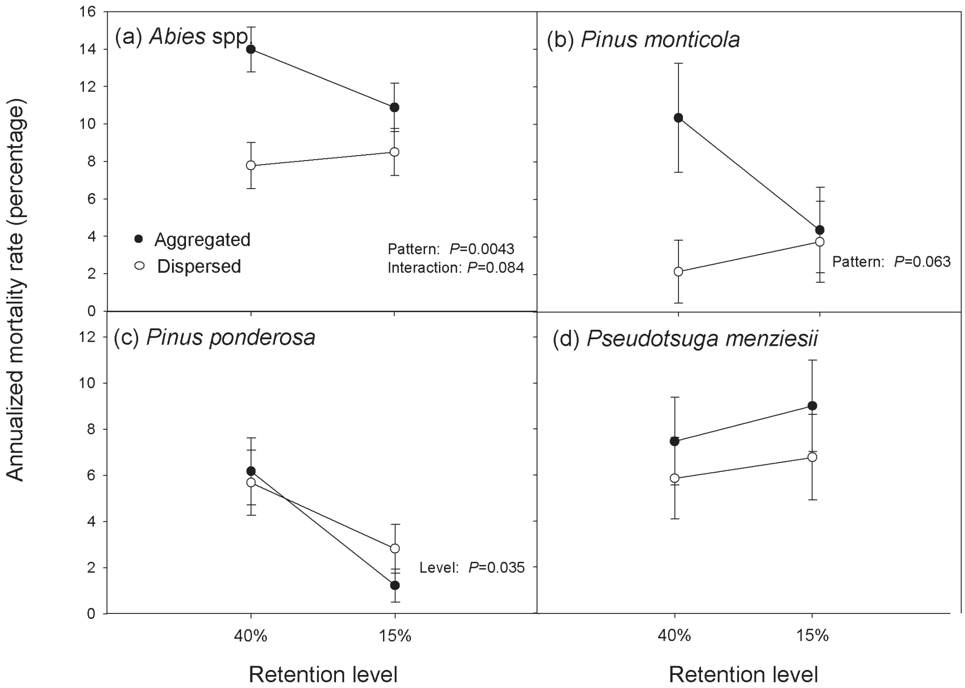

Fig. 6

Annualized mortality rate (± 1 SE) of planted seedlings by treatment and species/species group.

Jährliche Mortalitätsrate (±1 SE) der gepflanzten Jungpflanzen getrennt nach Behandlung und Baumart/Baumartengruppe.

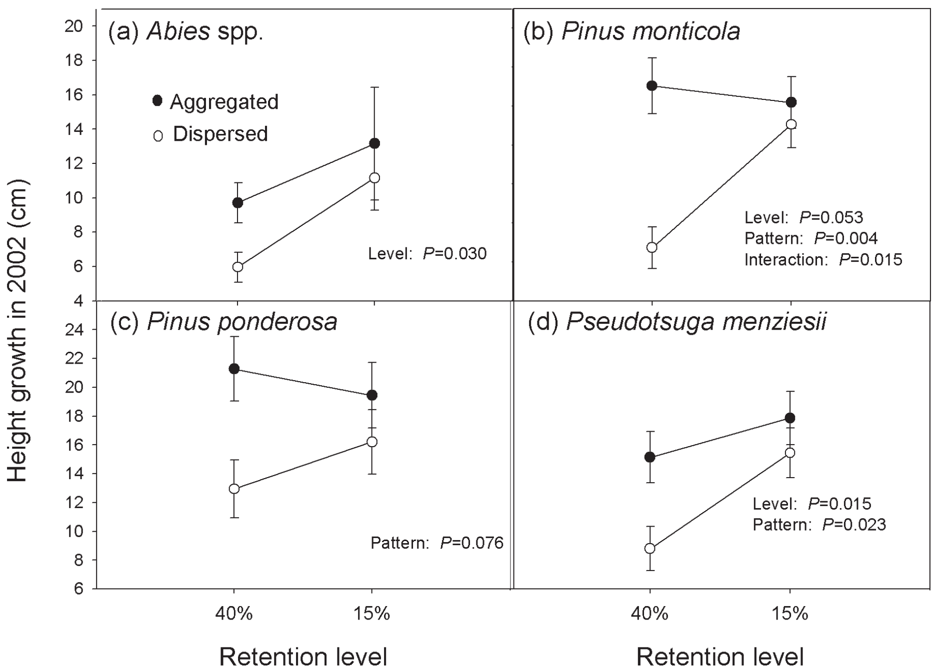

Fig. 7

Average height growth (± 1 SE) of planted seedlings in 2002 by treatment and species/species group.

Durchschnittlicher Höhenzuwachs (±1 SE) der gepflanzten Jungpflanzen im Jahr 2002 getrennt nach Behandlung und Baumart/Baumartengruppe.

Table 4

Mean density (trees ha^{-1}) of advance regeneration in all treatment units within each DEMO block, estimated from four 1x 6 m strip plots per tree plot.

Mittlere Dichte (Bäume pro ha) der Naturverjüngung in allen Behandlungseinheiten innerhalb der DEMO Blöcke, geschätzt mit Hilfe von je vier 1 x 6 m Aufnahmeflächen pro Baum-Stichprobe.

Species	*Abies amabilis*	*Abies concolor*	*Abies grandis*	*Pseudotsuga menziesii*	*Tsuga heterophylla*	*Thuja plicata*	All species
Watson Falls	0	4293	0	2078	174	0	6545
Dog Prairie	6	385	0	209	4	0	604
Butte	53	0	6	108	413	270	850
Little White Salmon	4	0	68	50	17	0	139
Paradise Hills	1074	0	1035	15	455	88	2667
Capitol	0	0	0	2	29	2	33

4. DISCUSSION

4.1 Overstory Trees

The greater overstory mortality rate for 15%D was expected given the greater exposure of the residual trees to wind and snow damage (GREEN et al., 1995). The higher mortality of Douglas-fir vs. other species is attributable to its dominant canopy position in these stands, reflecting its initial status and its selection as a priority leave species under variable retention. Mortality from wind and snow was also common on the edges bordering treatment units and on the edges of aggregates within treatment units. Wind damage on the edges of aggregates and edges of treatment units is consistent with patterns of wind damage on landscapes managed under even-age silvicultural systems (MATTHEWS, 1991).

The increase in total stem volume growth with increasing retention is well documented in numerous thinning studies (NYLAND, 2002). In general, unthinned or very lightly thinned stands maintain continuous occupancy of the site, whereas heavily thinned stands under-utilize the site temporarily, at least until the residual trees expand into the vacated growing space. The spatial distribution of residual trees was also a factor in DEMO, however. Total growth per unit initial volume was greater under dispersed treatments for at least two reasons: (1) growth efficiency of trees in lower crown classes is lower, and these trees are largely removed in dispersed retention; and (2) trees were more uniformly distributed in dispersed retention and, therefore, could more completely utilize the

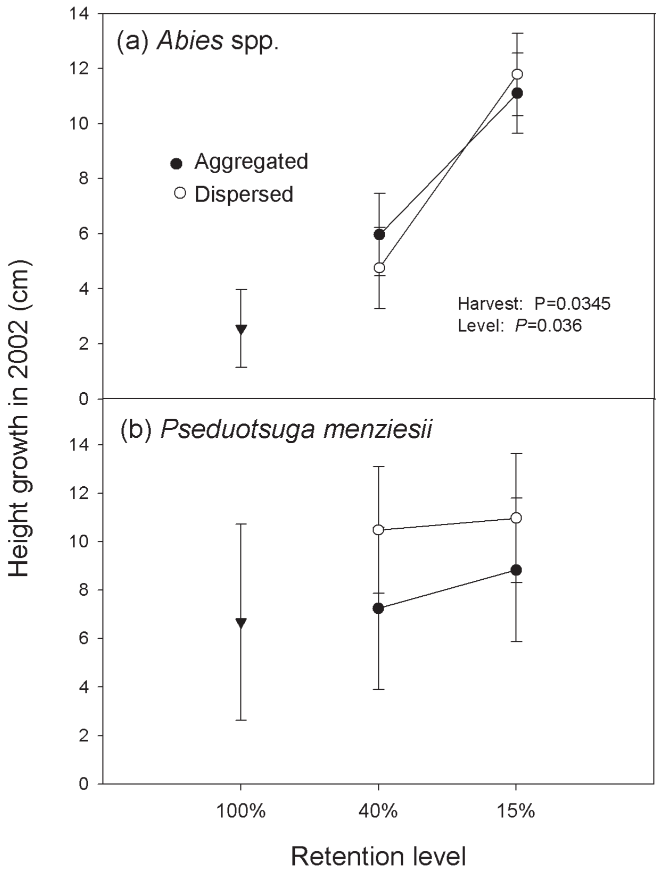

Fig. 8

Average height growth (± 1 SE) of advance regeneration in 2002 by treatment and species/species group.

Durchschnittlicher Höhenzuwachs (±1 SE) der Naturverjüngung im Jahr 2002 getrennt nach Behandlung und Baumart/Baumartengruppe.

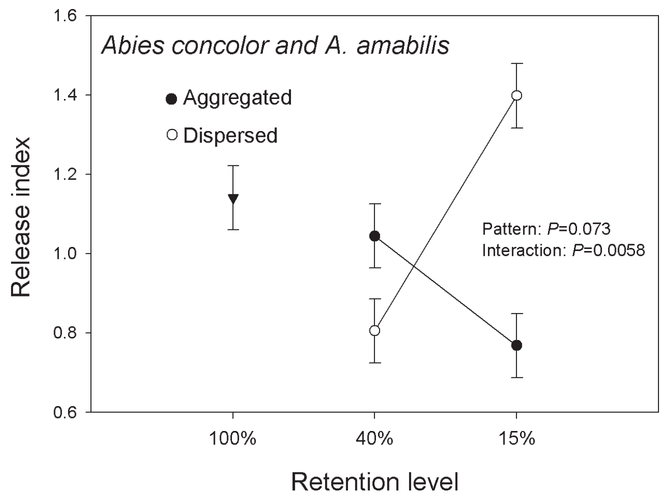

Fig. 9

Average release index (± 1 SE) by treatment and species/species group, expressed as the ratio of post- to pre-harvest height growth.

Durchschnittlicher Freistellungsindex (±1 SE) getrennt nach Behandlung und Baumart/Baumartengruppe, ausgedrückt als das Verhältnis der Höhenzuwächse vor und nach dem Eingriff.

site resources. The uniformity in tree arrangement and consequent minimal crown overlap are underscored by significantly greater canopy cover in the dispersed treatments at a given level of retention (MAGUIRE et al., in review). Some of the slower growth in aggregated treatments may also be attributable to the shock of sudden exposure, particularly for trees in lower crown classes near the exposed edge of the aggregates. Growth reduction in edge trees is analogous to thinning shock observed in some Douglas-fir stands (HARRINGTON and REUKEMA, 1983). Thinning shock could conceivably accentuate the stand density-growth correlation observed among differing levels of retention. However, the largest trees did not experience the same decline, suggesting that any growth reduction occurred only in trees of lower crown class (shorter relative height), as would be expected given their greater proportion of shade foliage (SPRUGEL et al., 1996). We expect individual-tree volume growth to accelerate during the next growth period as residual trees adjust to the new environmental conditions.

4.2 Planted Seedlings

Seedling mortality varied significantly among species, but was consistent with their ecophysiological characteristics. Mortality of shade-intolerant ponderosa pine was significantly greater under 40% retention, suggesting that light levels were too low. Mortality of western white pine was higher under aggregated retention, likely due to the relatively harsh conditions of the cut areas between aggregates. However, this effect was stronger at 40% than at 15% retention, suggesting that aspect and other factors must have contributed to mortality patterns. Regardless, the partial shade in dispersed retention units should generally benefit seedlings of this species by moderating environmental conditions while transmitting sufficient light to promote seedling survival and early growth (GRAHAM, 1990).

Height growth of all planted species in 40%D averaged only about half that in the other treatments, suggesting that additional overstory reduction may be needed to maintain understory vigor at this level of retention. In addition, because crown expansion typically reduces light levels more rapidly at higher stocking levels (CHAN et al., in review), seedling growth is likely to continue to decline in absence of further treatment. The contrast between treatment effects on mortality and those on growth has important silvicultural implications for artificial regeneration strategy in variable retention systems. For example, pattern of retention did not significantly affect ponderosa pine mortality, but growth was marginally greater under aggregated treatments, most likely due to greater light availability. In Douglas-fir, neither level nor pattern of retention affected seedling survival, but both significantly affected height growth. However, initial shade with gradual reduction in canopy cover after seedlings are established seems a reasonable strategy for establishing an understory cohort of this species. In contrast, the greater mortality of ponderosa pine under 40% retention and greater growth under aggregated retention supports previous observations that this species grows best in full sunlight (e.g., CHEN, 1997). The best retention strategy for establishment and growth of an understory cohort, therefore, varies by species and stage of seedling development. If retention of overstory trees proves successful for sustaining biodiversity, a balance must be struck between this function and ensuring adequate survival and growth of both planted and natural seedlings.

In the long run, selection of the appropriate retention level and pattern for achieving the desired stand structure must consider not only survival and early growth of understory trees, but also the vigor of both understory and overstory trees. The long-term productivity of variable-retention systems will depend strongly on the influence of residual overstory trees on understory growth and yield. Evidence to date suggests that retention of overstory trees will result in forfeiture of some growth in Douglas-fir. Several field studies and model simulations have quantified this loss in growth and/or yield, ranging from 20–30% for understory trees and slightly less for the overstory and understory together (BIRCH and JOHNSON, 1992; ACKER et al., 1998; ZENNER et al., 1998).

4.3 Advance Regeneration

In 2002, height growth of true fir advance regeneration increased as retention level declined. After four growing seasons, true fir advance regeneration may still be adjusting to the greater exposure in cut portions of aggregated treatments, although by this time seedlings have acquired four or five new age classes of needles acclimated to current light levels. The low release index (0.77) in 15%A indicated that height growth was inhibited immediately after the treatment, a conclusion corroborated by the control release index of 1.14 (*Fig. 9*). Conversely, the larger release index (1.4) in 15%D indicated a relatively rapid increase in growth during the year after harvest. By 2002, true fir advance regeneration was growing significantly better in 15% than 40% retention, and better in 40% than 100% retention (control). Despite some inhibition immediately after harvest, advance regeneration of true fir recovered quickly and accelerated growth in response to all retention levels and patterns.

By 2002, height growth of Douglas-fir advance regeneration in variable retention treatments did not differ significantly among any treatments. Height growth could not be reconstructed on any Douglas-fir seedlings back to 1997, so a release index could not be computed. The very slow growth implied by these indiscernible growth patterns and the relatively slow growth in 2002 suggest that this species may take considerably longer than true fir to fully respond to release. However, current height growth of Douglas-fir is comparable to that of true fir at retention levels of 40% and greater. Ongoing analysis of within-treatment heterogeneity in both local growing conditions and height growth will help identify the mechanisms leading to observed patterns in treatment-level averages. Height growth of advance regeneration reflects a balance between enhanced resource availability and increased stress imposed by sudden exposure of shade foliage. Increased rates of height and diameter growth are common responses of advance regeneration to various types of release treatments (HELMS and STANDIFORD, 1985; LUSSIER et al., 1992; PAQUIN and DOUCET, 1992; BOILY and DUCET, 1993; POTHIER et al., 1995). However, accurate assessment of the degree and timing of release depends on comparison to performance in both uncut controls and the open-grown condition. Two primary issues are (1) the degree and duration of any growth shock and (2) the degree and duration of suppression effects (i.e., growth that is less than expected for a tree of the same size but open-grown from germination). In black spruce (*Picea mariana* (Mill.) B. S. P.), GROOT and HÖKKÄ (2000) established an expectation based on the growth of even-aged stands, concluding that basal area growth of individual trees was less than expected for about 12 years after release. The growth shock in white fir/Pacific silver fir under variable retention apparently lasted 1 to 3 years, and perhaps longer in Douglas-fir. More detailed analysis of annual height growth is currently underway to test for the duration and degree of suppression under the various retention treatments. This test requires comparison of height growth patterns under variable retention to those from advance regeneration in the uncut controls and open-grown natural seedlings in the DEMO blocks.

4.4 Stand Dynamics

Barring catastrophic disturbance, residual overstory trees in all treatments except perhaps 15%D will persist well into the next rotation of the understory cohort. In 15%D, overstory density has continued to decline due to wind and snow damage, despite the fact that individual trees have maintained constant growth. Other causes of mortality beyond wind and snow have also contributed to losses, although most show little relation to treatments imposed in this experiment. Regardless, the erosion of overstory density will probably continue in at least some of the units and, where it does, it may frustrate efforts to achieve and maintain a two-layered structure.

In general, height growth of advance regeneration is currently slower than that of planted seedlings, although advance regeneration of white fir and Pacific silver fir is growing as well as planted stock of noble fir and Shasta red fir under 15% retention. Although these height growth responses to variable retention are probably representative of the target population, advance regeneration is patchy and infrequent in many of the DEMO units, suggesting that its future importance will be limited in some areas. In contrast, at Watson Falls and Paradise Hills, advance regeneration is relatively abundant and generally taller than planted seedlings. As a result, it will probably accelerate in growth, maintain a competitive position, and contribute significantly to understory structure and diversity. Although we did not address seedlings that established naturally after harvest in this analysis, recruitment has occurred in some locations and may contribute to understory development. In the absence of silvicultural intervention, however, we expect that in most geographic locations and treatments, the predominant component of the forest understory will derive from planted trees. Future growth of this cohort will be rapid in 40%A, 15%D, and 15%A, but its fate in 40%D remains unclear, given the continued growth of the residual overstory. Maintaining an understory that includes trees with sufficient vigor to become potential overstory trees will probably require additional overstory reduction, or starting with a lower retention level, particularly if the objective is to maintain a significant portion of Douglas-fir. However, ensuring recruitment of an understory cohort and availability of overstory replacements must be balanced against the biodiversity objectives motivating variable retention.

Understory density reduction may be a desirable component of a variable-retention system as well. As the understory cohorts continue to develop, some reduction in density may be necessary to maintain or produce stand structures that are consistent with biodiversity objectives. The understory cohort will reach crown closure in most of tested treatments and induce predictable declines in both understory vegetation and associated wildlife populations (e.g., ALABACK, 1982). Continued treatment of both the overstory and understory will be essential components of a system designed to conserve biodiversity while providing for tree regeneration, a minimal level of understory growth and vigor, and sustained timber productivity.

5. ABSTRACT

The Demonstration of Ecosystem Management Options (DEMO) study was established in mature Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) forests to test the effects of varying levels and patterns of residual trees on various forest taxa and stand dynamics. Six treatments were implemented in 1997 or 1998 on 13-ha treatment units at each of six blocks in western Oregon and Washington, USA. Treatments were specified by the following levels and patterns of retained basal area: 100% retention, 75% aggregated retention, 40% dispersed retention, 40% aggregated retention, 15% dispersed retention, and 15% aggregated retention. By summer of 2003, annualized cumulative mortality of retained trees was significantly higher in 15% vs. 40% and in 15% dispersed vs. 15% aggregated retention. Retained trees failed to show any acceleration of growth in stem volume 4 or 5 yr after harvest. Four- and five-year mortality of planted seedlings was significantly greater under 40% than 15% retention for ponderosa pine (*Pinus ponderosa* Dougl. ex. Laws), but did not differ among treatments for Douglas-fir. In 2002, height growth of planted seedlings was generally least under 40% dispersed retention and was greater under aggregated than dispersed retention. In 2002, height growth of advance regeneration of white fir (*Abies concolor* (Gord. & Glend.) Lindl. ex. Hildebr) and Pacific silver fir (*Abies amabilis* Dougl. ex Forbes) was greatest under 15% retention. Continuing wind damage in 15% dispersed retention and suppression effects of overstory trees in 40% dispersed retention may complicate attainment of vigorous two-layered stands.

6. Zusammenfassung

Titel des Beitrages: *Auswirkungen partieller Hiebseingriffe auf Altbestand und Verjüngung von Douglasienwäldern im westlichen Nordamerika.*

Der Demonstration of Ecosystem Management Options (DEMO) Feldversuch untersucht in Altbeständen der Douglasie (*Pseudotsuga menziesii* (Mirb.) Franco) Auswirkungen von Hiebmaßnahmen unterschiedlicher Eingriffsstärken mit variierender räumlicher Verteilung des verbleibenden Bestandes auf verschiedene forstliche Taxa. In den Jahren 1997 und 1998 wurden hierzu im westlichen Oregon und Washington (USA) sechs Versuchsblöcke mit jeweils sechs unterschiedlichen waldbaulichen Behandlungen eingerichtet. Die auf je 13 ha-grossen Block-Untereinheiten realisierten waldbaulichen Varianten unterscheiden sich in Bezug auf die relativ verbleibende Bestandesgrundfläche und deren Struktur wie folgt: 100% (Kontrolle), 75% konzentriert, 40% gleichmäßig verteilt, 40% konzentriert, 15% gleichmäßig verteilt und 15% konzentriert. Bis zum Sommer des Jahres 2003 war die kumulative Mortalität der verbliebenen Bäume in der 15%-Variante gleichmäßiger Verteilung signifikant höher als bei den anderen Varianten. Eine Wuchsbeschleunigung wurde in den ersten vier bzw. fünf Jahren nach den Hiebseingriffen an den verbliebenen Altbäumen nicht beobachtet. Die Mortalität gepflanzter Sämlinge der Gelbkiefer (Pinus ponderosa Dougl. ex. Laws) war in den 40%-Varianten signifikant höher als in den 15%-Varianten. Die höchste Sterblichkeitsrate gepflanzter Douglasiensämlinge fand sich in der 15%-Variante mit geklumpter Verteilung der verbliebenen Bäume. Das Höhenwachstum der gepflanzten Sämlinge war im Jahr 2002 in der 40%-Variante gleichmäßiger Verteilung am geringsten und in den 15 und 40%-Varianten mit geklumpter Verteilung am größten. Das Höhenwachstum der gesicherten Verjüngung von Douglasie, Coloradotanne (*Abies concolor* (Gord. & Glend.) Lindl. ex. Hildebr) und Purpurtanne (*Abies amabilis* Dougl. ex Forbes) war in den Varianten mit 15%-verbliebener Grundfläche im allgemeinen größer.

7. Résumé

Titre de l'article: *Conséquences d'une récolte partielle dans des peuplements de Douglas à maturité et régénération des forêts de cette essence dans l'ouest de l'Amérique du Nord.*

Le dispositif expérimental «Demonstation of Ecosystem Management Options (DEMO)» a pour but l'étude, dans des peuplements de Douglas ayant atteint l'âge d'exploitabilité, des conséquences de prélèvements d'intensités variables et des distributions diverses sur le terrain du peuplement maintenu sur pied sur la mortalité et la croissance des essences utilisées pour la régénération. Pour ce faire on a installé en 1997 et en 1998 dans l'ouest de l'Oregon et de l'Etat de Washington (U.S.A.) six blocs expérimentaux, chacun comprenant six traitements sylvicoles différents. Les sous-parcelles de ces blocs, d'une surface unitaire de 13 ha, différaient entre elles, par la surface terrière relative du peuplement maintenu sur pied et de la structure de celui-ci, comme suit: 100% (contrôle),

75% concentrés, 40% régulièrement répartis, 40% concentrés, 15% régulièrement répartis et 15% concentrés. Jusqu'à l'été 2003 la mortalité cumulée dans le peuplement maintenu sur pied a été significativement plus élevée dans la variante 15%-distribution régulière que dans les autres variantes. Au cours des quatre ou cinq premières années après l'intervention aucune augmentation de la croissance de rieux peuplement resté sur pied n'a été observée. La mortalité des plants de *Pinus ponderosa* Dougl. Ex Laws mis en place a été plus élevée dans les variantes 40% que dans les 15%. Pour les plants de Douglas le plus fort pourcentage de mortalité a été constatée dans la variante 15%, avec peuplement laissé sur pied concentre. La croissance en hauteur des plants en 2002 a été la plus faible dans les variantes 15% et 40% avec répartition régulière et la plus forte avec les variantes 15% et 40% avec peuplement maintenu concentré. La croissance en hauteur de la régénération acquise de Douglas, *Abies concolor* (Gord. & Glend.) Lindl. Ex. Hildebr. et *Abies amabilis* Dougl. ex Forbes était en général dans les variantes avec une surface terrière restante de 15%. J. M.

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Challenges in statistical inference for large operational experiments

(With 1 Figure)

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Waldbaulicher Feldversuch; Großräumige Versuchsanlage; Versuchsdesign; statistische Analyse.

1. INTRODUCTION

A number of large-scale silviculture experiments have been implemented in the Pacific Northwest region of North America. These experiments utilize treatment units that range from tens of hectares to more than 100 hectares to investigate effects on the scale of timber production. These operationally scaled forestry experiments are multi-disciplinary, with multiple stakeholders and multiple areas of investigation, e.g., forestry management practices, wildlife, understory vegetation, and hydrology responses. Priorities for study outcomes are based on criteria that may differ among the stakeholders and information that can be generalized broadly is important. For some disciplines, obtaining *any* information is a priority and will add substantially to existing knowledge. For land managers, information to inform management decisions is a priority. Broad scale data may be a priority in large operational experiments. Being able to meet the most objectives for the least cost may produce prioritizations. Alternatively, the strength of statistical inference, or the degree of precision, can be used to establish priorities. With potentially multiple and competing priorities, identifying high priority objectives is challenging in large-scale experiments.

Statistical inference is the process used to infer the responses of individuals in a large group based on data collected from a sample of that group. Implicitly we believe that individuals in the large group (statistical population) encompass a distribution of the response and we attempt to summarize the distribution by estimating the mean and variance of that distribution. Our ability to produce good inference is directly related to our ability to represent and estimate the variation that is present in the population. Study designs that facilitate good inference have well-defined statistical populations from which representative samples are drawn with high precision.

The paper discusses the challenge of constructing designs for operationally scaled studies where strong statistical inference is a priority. In this context, the value of information is measured by its precision, its ability to represent a larger population (scope of inference) and its unbiasedness (accuracy). In broad-scale studies with multiple researchers and areas of interest, it is unlikely that study outcomes for all researchers can achieve the same level of statistical rigor. I propose that the desire for strong statistical inference for each objective and its associated responses be prioritized among all disciplines prior to designing the study. High priority objectives can be used to design the study to produce strong statistical information and inference. During the design phase, it is crucial that these priorities are communicated and coordinated among participants so that resources can be conserved and resultant data will address inter- and multi- disciplinary questions.

In this classification scheme, *primary statistical objectives* are those objectives that drive the study design because they dictate the level of replication, the scope of inference and the spatial and temporal scales associated with treatments and measurements. *Secondary statistical objectives* are those which can be met within the structure of the primary objectives but secondary objectives have reduced precision and inferential power. In the study design process, the evaluation and refinement of design components can improve the statistical value of the ensuing information.

But as noted earlier, non-statistical criteria also generate priorities and are important. The final study design is arrived at through a process of coordinated and frank discussion that acknowledges statistical and non-statistical priorities and seeks to obtain balance among them.

2. LINKING DESIGN COMPONENTS AND THE SCOPE OF INFERENCE

The study design phase provides an opportunity to evaluate how potential, planned, or unplanned outcomes for each design component affect other components before the study is carried out. The

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