Growth and Mortality of Residual Douglas-Fir after Regeneration Harvests under Group Selection and Two-Story Silvicultural Systems

Sean Garber, Tzeng Yih Lam, and Douglas A. Maguire

ABSTRACT

Complex management objectives for many publicly owned Douglas-fir forests have prompted renewed interest in silvicultural systems other than clearcutting. The College of Forestry Integrated Research Project at Oregon State University was implemented to test for differences in economic, biological, and human responses to group selection and two-story silvicultural systems. Three separate blocks were established and treated between 1989 and 1991. Trees were measured immediately after the harvest treatments (1991 or 1992) and after the 2004 growing season. Responses of residual overstory trees to initial group selection and two-story treatments were tested relative to untreated controls units in terms of (1) gross basal area and stem volume growth of all residual trees and of the 10 largest trees per acre; (2) gross basal area and stem volume growth conditional on initial basal area and stem volume, respectively, of all residual trees and of the 10 largest trees per acre; and (3) mortality of all overstory trees. Basal area and volume growth were greatest in the control and least in the two-story treatment, but volume growth conditional on initial volume did not differ significantly among treatments. Mortality was significantly greater in the two-story treatment. Overstory growth release in residual Douglas-fir may require 10 years or more to appear after regeneration cuts on some sites, and the possibility of increased overstory mortality complicates attainment of desired long-term structure under two-story silvicultural systems.

Keywords: *Pseudotsuga menziesii*, residual trees, stand dynamics, group selection, two-story, shelterwood-with-reserves

Douglas-fir forests (*Pseudotsuga menziesii* [Mirb.] Franco) in the Pacific Northwest have been managed almost exclusively on an even-age basis, most commonly under the clearcutting silvicultural system. This system proved effective for meeting society's demand for timber, particularly when timber was the primary objective driving forest management; however, other services from Douglas-fir forests have since assumed greater importance, particularly on publicly owned land. The increasingly complex management objectives generated by society's concern for nontimber resources, including the conservation of forest biodiversity and the maintenance of aesthetic landscapes, suggest that more complex stand structures on at least part of the landscape may be more effective for meeting these objectives than a mosaic of different age classes (Franklin et al. 1997, Curtis et al. 1998). Many public and family forest landowners are now interested in developing or adapting silvicultural systems that can produce and maintain more complex stand structures while continuing to produce Douglas-fir timber.

Although traditional silvicultural systems offer a wide range of options for forest managers (Tappeiner et al. 2007), operational experience and the scientific basis required for their successful implementation in coastal Douglas-fir is limited, with the exception of clearcutting (Curtis et al. 1998, 2007). Several studies have been implemented within the last 10–15 years to test variable-retention systems and alternatives to clearcutting, particularly in regard to their efficacy for maintaining biodiversity, softening visual impacts, and minimizing adverse impacts on total stand growth (Monserud 2002, Peterson and Monserud 2002, Curtis et al. 2004, Poage and Anderson 2007). The major issue requiring resolution is the efficacy of these systems for achieving the desired sequence of stand structures and the resource values assumed to accompany those structures. The feasibility of any of these systems in Douglas-fir forests will depend on the long-term growth and survival of residual overstory trees, the performance of planted seedlings, and the dynamics of natural regeneration (e.g., Maguire et al. 2006).

The College of Forestry Integrated Research Project (CFIRP) at Oregon State University was established as a long-term trial of alternative silvicultural treatments and regimes on the College Forests (McComb and Chambers 2005). Three silvicultural systems are being tested for their relative feasibility and efficacy, including group selection, two-story (shelterwood-with-reserves), and clearcutting-with-reserves (Maguire and Chambers 2005). Control areas with no regeneration cutting have also been designated for comparison. Previous studies have documented wildlife, regeneration, and harvesting aspects of CFIRP (Maguire and Chambers 2005). One primary objective of CFIRP is to assess the dynamics of residual overstory

Manuscript received June 8, 2010, accepted November 5, 2010.

Tzeng Yih Lam (tylam.forest@gmail.com), College of Forestry, Oregon State University, Department of Forest Engineering, Resources and Management, 321 Richardson Hall, Corvallis, OR 97331. Sean Garber, Department of Forest Engineering, Resources, and Management, College of Forestry, Oregon State University, 321 Richardson Hall, Corvallis, OR 97331. Douglas A. Maguire, Department of Forest Engineering, Resources, and Management, College of Forestry, Oregon State University, 204 Peavy Hall, Corvallis, OR 97331. *We gratefully acknowledge the Edmund Hayes Endowment for Silviculture Alternatives for providing the funding to complete this analysis. The CFIRP study was made possible by the foresight of Brenda McComb and John Tappeiner. Furthermore, we gratefully acknowledge the technical assistance provided by Debbie Johnson and field assistance provided by Rick and Malia Allen, Terry Droessler and Duck Creek Associates, Michael Tobler, Aaron Weiskittel, and Doug Mainwaring. Finally, we thank the four anonymous reviewers and the associate editor for their constructive comments that have generally improved the manuscript.*

Table 1. Average overstory conditions (trees >8 in. in dbh) immediately after regeneration harvests in the College of Forestry Integrated Research Project study. Tree density, basal area, quadratic mean diameter, stand density index, stand volume, and top height were averaged across experimental units for a given treatment and block. For the group selection treatment, averages reflected the condition of entire experimental units, including both openings and the forest matrix.

Block and treatment	Number of plots/ experimental units	Tree density (stems/ac)	Basal area (ft^2/ac)	Quadratic mean diameter (in.)	Stand density index	Stand volume (ft^3/ac)	Stand top height (ft)[a]
Saddle							
Group selection	31/6	62	176.0	33.0	290.6	8,565.5	180.6
Two-story	16/2	13	71.0	42.9	103.8	3,929.2	182.4
Control	7/1	65	197.1	28.8	312.3	8,429.4	152.1
Peavy							
Group selection	63/6	47	142.2	34.6	273.0	6,558.0	162.7
Two-story	18/2	11	61.0	36.5	82.6	2,887.9	157.3
Control	6/1	65	273.3	38.6	524.9	16,099.8	194.6
Dunn							
Group selection	70/6	68	129.1	27.7	258.6	5,282.4	143.8
Two-story	22/2	9	35.3	34.4	50.36	1,542.9	126.3
Control	3/1	106	213.3	35.5	536.2	9,728.9	142.0

[a] Stand top height was estimated as the mean height of largest 40 trees/ac based on dbh.

trees following harvest, as well as the growth and productivity of understory cohorts. Residual tree density and average tree age in CFIRP treatment units covered a sufficiently wide range that the survival and growth rate of these residual overstory trees was not certain.

Although not many thinning studies in Douglas-fir have tracked growth through 50 years of age, Douglas-fir can maintain relatively strong diameter growth rates up to and beyond 150 years (Williamson and Price 1971, Williamson 1982, Newton and Cole 1987, Poage and Tappeiner 2002). Similarly, mature and very old (up to 650-year-old) Douglas-fir trees can accelerate basal area or volume growth in response to various types of stand density reduction (Newton and Cole 1987, Bailey and Tappeiner 1998, Buermeyer and Harrington 2002, Latham and Tappeiner 2002). Growth acceleration has also been documented for mature ponderosa pine (*Pinus ponderosa* Dougl. ex Laws; Latham and Tappeiner 2002, McDowell et al. 2003), eastern white pine (*Pinus strobus* L.; Bebber et al. 2004), and white spruce (*Picea glauca* [Moench] Voss; Youngblood 1991, Urban et al. 1994). However, contrasting results have been reported as well. Four or 5 years after variable-retention treatments in western Washington and Oregon, residual Douglas-fir had failed to accelerate significantly in volume growth relative to controls (Maguire et al. 2006). Likewise, diameter growth of residual Douglas-fir responded negatively to a variable-retention harvest in another western Washington study (North et al. 1996). Differences among species are also apparent. Sugar pine (*Pinus lambertiana* Dougl.) in southwestern Oregon did not accelerate in basal area growth after partial harvests to the same extent as Douglas-fir or ponderosa pine (Latham and Tappeiner 2002), perhaps because it tends to occupy a more dominant canopy position in unthinned stands.

The specific objective of this analysis was to test treatment effects on the following responses of overstory trees: (1) gross basal area and volume growth of surviving trees; (2) gross basal area and volume growth conditional on initial basal area and stem volume, respectively, of surviving trees; (3) gross basal area and volume growth of the 10 largest survivors per acre; (4) gross basal area and volume growth conditional on initial basal area and stem volume, respectively, of the 10 largest survivors per acre; and (5) mortality rate. The clearcutting-with-reserves treatment was eliminated from this analysis because an average of only one live residual tree was retained on every two acres (1.2 trees per hectare), leaving an insufficient number of residual overstory trees for analysis.

Methods

Study Sites

The CFIRP study was implemented on Oregon State University's 11,250-ac (4,555-ha) McDonald-Dunn Forest, northwest of Corvallis, Benton County, Oregon (44°40′N, 123°20′W). The McDonald-Dunn Forest is located in a transition zone between the Willamette Valley and the Coast Ranges and is characterized by two plant associations: Douglas-fir/hazelnut/bromegrass (*P. menziesii/Corylus cornuta californica/Bromus vulgaris*) and Douglas-fir/vine maple/salal (*P. menziesii/Acer circinatum/Gaultheria shallon*) (Maguire and Chambers 2005). Mean annual precipitation averages 39.4 in. (100 cm) and falls predominantly between November and May. Summers are generally hot and dry, with average maximum daily temperature of 80.8°F (27.1°C) in June and August. Treatment units for CFIRP were established on elevations ranging from 395 to 1,320 ft (120 to 400 m) and on a variety of slopes and aspects.

The study conformed to a generalized randomized block experiment with three blocks (Saddle, Peavy, and Dunn). These blocks were similar in initial structure, as measured by species composition, stand density, and vertical stratification. The initial stands contained mainly Douglas-fir (average basal area, 165 ft^2/ac [47.9 m^2/ha]), grand fir (*Abies grandis* [Dougl. ex D. Don] Lindl.; average basal area, 4.5 ft^2/ac [1.0 m^2/ha]), and hardwood species (average basal area, 14 ft^2/ac [3.2 m^2/ha]). The latter hardwood group included bigleaf maple (*Acer macrophyllum* Pursh), Oregon white oak (*Quercus garryana* Dougl. ex Hook.), and red alder (*Alnus rubra* Bong.). Douglas-fir site index (base age 50; King 1966) ranged from 92 to 130 ft (28–40 m), and average stand age for all residual trees within a treatment unit ranged from 45 to 144 years. The top height of treatment units covered a relatively narrow range, averaging approximately 180 ft at Saddle, 160 ft at Peavy, and 140 ft at Dunn (Table 1).

Silvicultural Treatments

Three silvicultural treatments were implemented in addition to an untreated control. The clearcut-with-reserves treatment was left out of the current analysis because of the low density of residual trees and their insufficient representation in the sample. The other two harvest treatments were designed as an initial entry in a group selection and two-story (shelterwood-with-reserves) silvicultural system that would be implemented over a long period of time (Maguire and Chambers 2005). Consistent with the generalized randomized block design, harvest treatments were replicated within each of the three blocks. In each block, the two harvest and single control treatment were randomly assigned to 11 experimental units ranging in size from 14 to 45 ac (5.7 to 18.2 ha). Group selection was assigned to six experimental units, two-story to two units, and the unmanaged control to one unit. The group selection treatment removed 33% of the wood volume by creating 0.5-ac (0.2-ha) openings of various shapes and leaving the surrounding matrix uncut. In the two-story stands, 75% of the standing volume was removed, leaving only 8–12 large residual live trees per acre (20–30 per hectare), so this treatment was analogous to the regeneration cut of a shelterwood-with-reserves system (Curtis et al. 1998) or to a variable-retention regeneration harvest (Franklin et al. 1997). The three blocks were harvested over 2 years, beginning in fall 1989 or spring 1990 and ending in spring 1991. Logs were ground skidded from units with slopes less than 30%, and uphill cable yarded from units with slopes greater than 30%. Group openings in the selection treatment and entire units receiving the two-story treatment were planted with Douglas-fir. Basal areas of the residual stands ranged from 35.5 to 71.0 ft^2/ac for the two-story treatment, 142.2 to 176.0 ft^2/ac for the group selection, and 197.1 to 273.3 ft^2/ac for the controls (Table 1).

Data Collection and Analysis

In 1981, a series of systematically located sample points was established at an intensity of 1–2 per acre (2.5–5.0 per hectare) across the McDonald-Dunn Forest. This permanent plot network was established as a linked inventory and growth forecasting system for the entire 11,250-ac (4,555-ha) forest (Marshall et al. 1997, Johnson et al. 2007). At each sample point, three nested subplots were established to sample trees across the diameter range and to characterize vegetation structure. All trees with dbh $>$8.0 in. (20.3 cm) were measured on a variable radius subplot with basal area factor 20 ft^2/ac (4.6 m^2/ha). All trees with dbh $>$4.0 and $\leq$8.0 in. ($>$10.2 cm and $\leq$20.3 cm) were measured on a fixed-area subplot of radius 15.56 ft (4.74 m). All trees with height $>$0.5 ft (0.15 m) and dbh $\leq$4.0 in. (10.2 cm) were measured on a fixed-area subplot of radius 7.78 ft (2.37 m). Inventory plots were established 10 years before CFIRP was initiated, so plot locations were independent of local conditions created by the CFIRP treatments (e.g., gaps in the group selection). In this analysis, no attempt was made to post-stratify plots by within-treatment conditions because responses were analyzed at the level of experimental units. In the group selection units, both group openings and forest matrix were represented in proportion to their respective areas, with totals of 31, 63, and 70 plots in treatment units at Saddle, Peavy, and Dunn, respectively (Table 1).

Plots were first measured in 1981 or 1982 (Y1981) and remeasured twice, once in 1991 or 1992 (Y1991) and once after the 2004 growing season (Y2004). The Y1991 inventory established initial conditions for the CFIRP experiment, and the growth period analyzed for treatment responses was the growth period starting with Y1991 and ending with Y2004, resulting in either a 13- or 14-year growth period. Tree dbh, total height, height to crown base, distance from plot center, and azimuth from plot center were recorded for each tree on each subplot. For trees that did not survive the intervening growth period, cause of death was recorded for each tree if the causal agent could be determined. If height of an undamaged tree in 2004 was less than its previously measured height, the 2004 height was remeasured to verify its accuracy.

Gross periodic annual increment of basal area and volume were computed for all residual Douglas-fir trees that survived from Y1991 to Y2004. Although volume growth was considered the primary treatment response, basal area growth was also analyzed as a check on volume growth. This confirmation was judged important to eliminate the possible influence of typical inaccuracies in height measurement and the possible influence of rules applied for dealing with top breakage. Also, basal area growth of survivors provided the same trend as would be expected for change in quadratic mean diameter. Tree volumes for each inventory were estimated from taper equations developed by Walters and Hann (1986). If the verified 2004 height measurement was less than the Y1991 measurement, the tree was assumed to have had negligible height growth, and the 2004 height was assigned to both measurement dates. For any trees that experienced severe top damage during the growth period, volume growth was estimated only for the portion of the bole below the point of breakage. Growth was summed across all survivors within each treatment unit to determine survivor periodic annual increment ($BPAI_{surv}$ and $VPAI_{surv}$ for basal area and volume increments of survivors, respectively) and was also summed across the largest 10 survivors per acre (25 survivors per hectare) to determine periodic annual increment of the dominant stand component ($BPAI_{10}$ and $VPAI_{10}$ for basal area and volume increments of the largest 10 trees per acre, respectively).

Treatment effects on several different responses were tested by a generalized randomized block analysis of variance, with block as a random factor. First, treatment differences in residual basal area and stem volume (Y1991) were tested to verify differences in residual stand density. Treatment effects were then tested on the following stand-level growth responses: $BPAI_{surv}$, $VPAI_{surv}$, $BPAI_{10}$, and $VPAI_{10}$. Because basal area and volume growth tended to increase linearly with initial stocking, analyses were also run with initial (residual) basal area or volume as covariates. Finally, periodic annualized mortality rate was tested for treatment differences after applying the arcsine square root transformation to homogenize variance (Draper and Smith 1998). Differences between treatment pairs were analyzed with Tukey-Kramer multiple-comparison tests. All analyses were done with the Mixed procedure in SAS 9.2 (SAS Institute, Cary, NC).

Results

Residual Basal Area and Stem Volume

Residual Douglas-fir basal areas averaged 230.6, 135.1, 59.7 ft^2/ac for the control, group selection, and two-story regimes, respectively. The treatment effect was significant ($P = 0.037$), with control units holding significantly greater basal area per acre than the two-story treatment ($P = 0.032$). However, evidence was weak for any difference between the group selection treatment and either the control treatment ($P = 0.141$) or the two-story treatment ($P = 0.175$).

Residual stem volumes were proportional to residual basal areas, averaging 10,538, 6,702, and 2,744 ft^3/ac for the control, group selection, and two-story treatments, respectively, with a marginally significant treatment effect ($P = 0.053$). The control units had significantly greater volume than the two-story treatment units ($P = 0.048$) but not significantly more than the group selection treatment

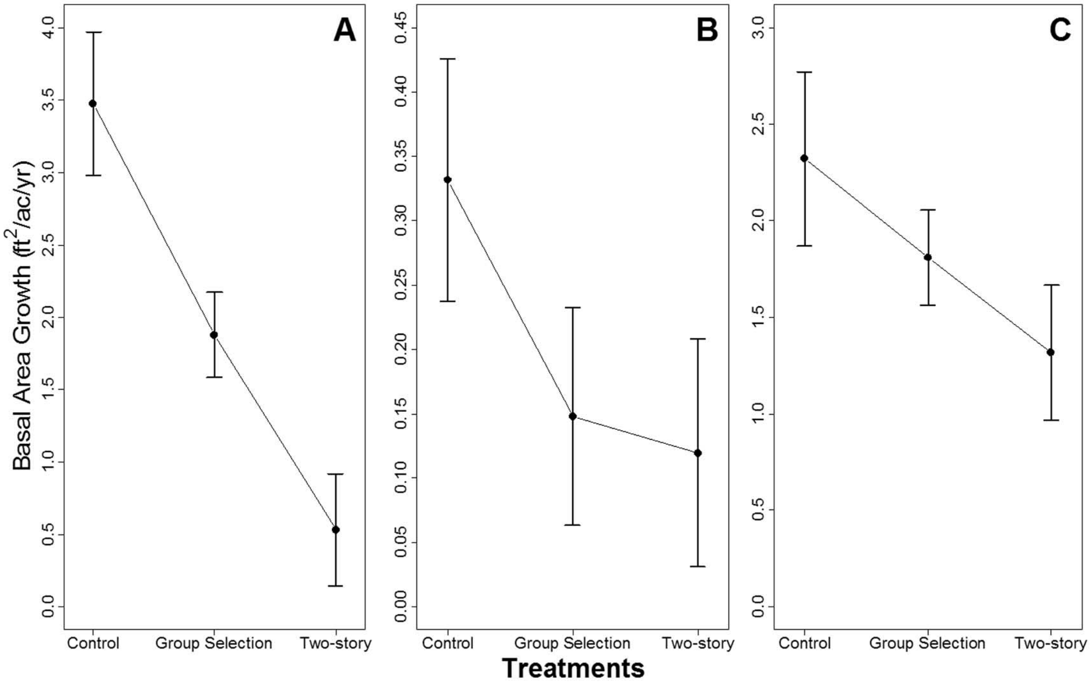

Figure 1. Average basal area growth (±1 standard error) of residual overstory Douglas-fir trees by treatment for all surviving trees independent of initial basal area ($BPAI_{surv}$) (A), the largest 10 surviving trees per acre independent of initial basal area ($BPAI_{10}$) (B), and all surviving trees conditional on initial basal area (C).

($P = 0.249$). Likewise, the group selection and two-story treatments did not have significantly different residual stand volumes ($P = 0.169$).

Basal Area Growth

Survivor basal area growth values at the stand level ($BPAI_{surv}$) were 3.5, 1.9, and 0.5 ft^2/ac per year for the control, group selection, and two-story treatments, respectively, and differed significantly among treatments ($P = 0.023$). The control grew more basal area than the two-story treatment units ($P = 0.021$; Figure 1A). Evidence was weak for any difference in basal area growth between the group selection and either the two-story ($P = 0.105$) or control ($P = 0.105$) treatments. $BPAI_{10}$ did not differ significantly among the treatments ($P = 0.313$; Figure 1B). After accounting for differences in initial basal area among treatment units (i.e., including initial basal area as a covariate), no treatment effects remained for either $BPAI_{surv}$ ($P = 0.289$; Figure 1C) or $BPAI_{10}$ ($P = 0.448$).

Total Volume Growth

Survivor volume growth values at the stand level ($VPAI_{surv}$) were 205.7, 116.0, and 33.9 ft^3/ac per year, for the control, group selection, and two-story treatments, respectively, and differed significantly among treatments ($P = 0.023$). The control grew significantly more volume than the two-story treatment ($P = 0.020$; Figure 2A); however, the difference in volume growth between the group selection and either the control or two-story treatment was only marginally significant ($P = 0.116$ and 0.097, respectively). In contrast to treatment effects on $VPAI_{surv}$, volume growth of the 10 largest trees per acre ($VPAI_{10}$) did not differ significantly among treatments ($P = 0.261$; Figure 2B). Similarly, after conditioning on initial volume of each treatment unit (i.e., computing volume growth per unit initial volume), the treatment effects on $VPAI_{surv}$ ($P = 0.134$, Figure 2C) and $VPAI_{10}$ ($P = 0.291$) became insignificant.

Annual Mortality Rate

Annualized mortality rates were 0.51, 0.76, and 2.26% for the control, group selection, and two-story treatments, respectively, and differed significantly among treatments ($P = 0.035$). Controls did not differ significantly from group selection ($P = 0.634$), but the two-story treatment had significantly greater mortality than the group selection treatment ($P = 0.040$) and marginally greater mortality than the control treatment ($P = 0.058$). Windthrow was the causal agent for 16% of all mortality, with wind-damaged trees concentrated in the two-story treatments. Another 6% of the mortality was associated with logging damage, whereas most of the remaining mortality could not be attributed to any specific causal agent. The mortality in the two-story treatment generally occurred on larger trees than in the control and group selection units (Figure 3).

Discussion

Greater basal area and volume growth of the control stands was not surprising given the consistent pattern of increasing growth with higher residual stocking in Douglas-fir thinning studies (King et al. 2002, Marshall and Curtis 2002). Higher residual stocking ensures more complete occupation of the site by trees and fuller utilization of site resources for tree growth, particularly for the period immediately following thinning. The pattern of greater growth with greater initial stocking was also consistent with growth patterns on Douglas-fir units receiving a range in variable-retention regeneration harvests in the Demonstration of Ecosystem Management Options study (Maguire et al. 2006). The lack of a significant treatment effect on growth of the largest 10 trees per acre can probably be

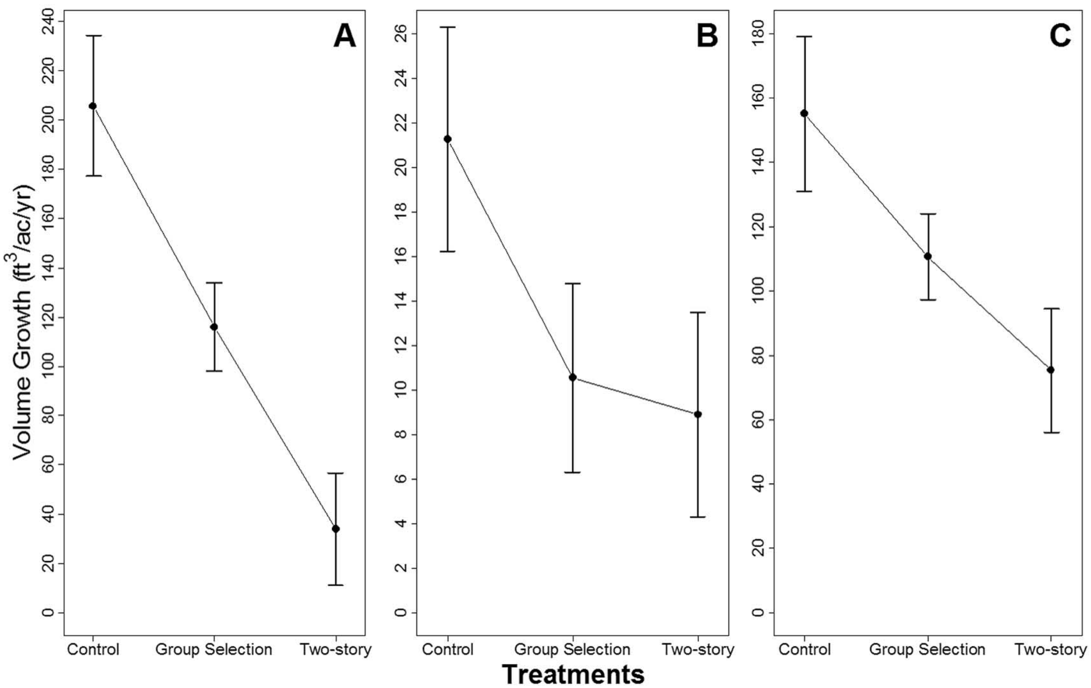

Figure 2. Average volume growth (±1 standard error) of residual overstory Douglas-fir trees by treatment for all surviving trees independent of initial volume ($VPAI_{surv}$) (A), the largest 10 surviving trees per acre independent of initial volume ($VPAI_{10}$) (B), and all surviving trees conditional on initial volume (C).

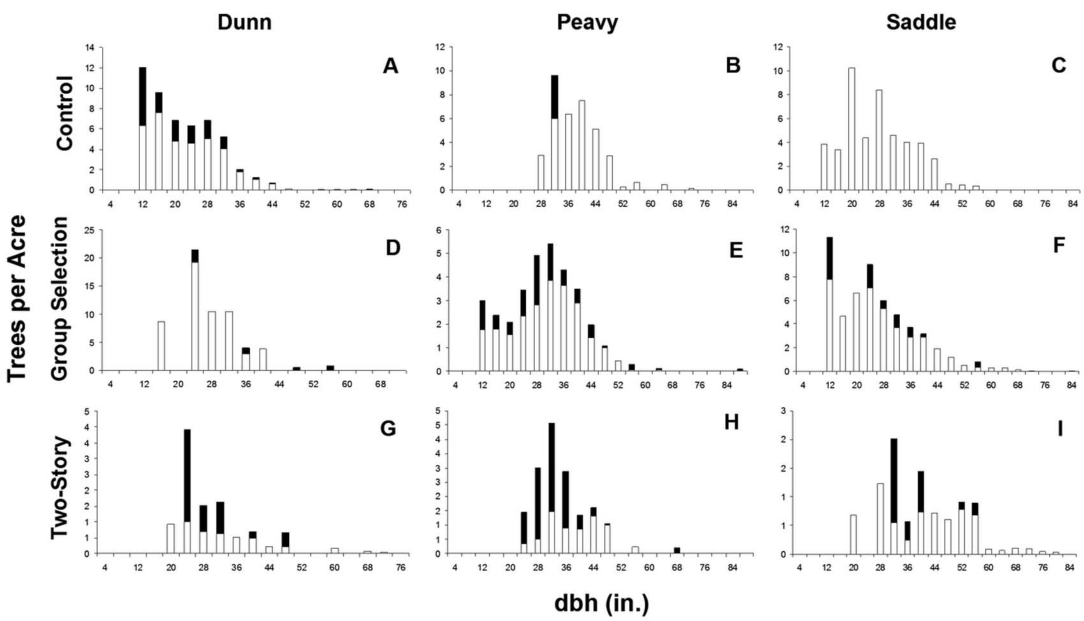

Figure 3. Diameter distribution of residual stand and periodic mortality for each of the College of Forestry Integrated Research Project treatments.

attributed to the fact that this fixed number of dominant trees standardized initial growing stock to some extent.

The growth responses per unit of initial basal area or per unit of initial volume in CFIRP suggested weak evidence for a decline in growth rate for a given initial stocking in the two-story treatment relative to controls. Possible adverse effects of uniform stand density reduction in the two-story treatment are further suggested by the significantly greater mortality rate, most of which was not attributable to wind damage. Greater exposure to solar radiation and wind may have imposed various physiological stresses, such as damage to shade foliage or desiccation caused by reduction in boundary layer resistance to evapotranspiration. Some of the two-story experimental units may even have been in a topographic position that allowed harvesting to induce a deleterious increase in the early-season water table.

Because growth rates vary among individual trees of differing initial size (and crown class), the growth rates per unit initial stocking for entire treatment units depend on the size-class distribution of the residual stand (Figure 3). The fact that the largest 10 trees per acre were not growing significantly better or worse across treatments, even after correcting for differences in initial size (i.e., conditioning on initial stocking), suggests that they had not experienced release. To the contrary, in fact, weak evidence ($P = 0.31$) suggested a trend toward a decline in growth similar to thinning shock (Harrington and Reukema 1983).

Apparent discrepancies in growth responses among studies of residual overstory trees may be due in part to differences in period of observation, the stand or tree dimensions analyzed for growth, and/or the assumed growth pattern in absence of stand density reduction. A lag time of 3–5 years in diameter growth response has been consistently demonstrated in most species (Youngblood 1991, Urban et al. 1994, Latham and Tappeiner 2002, McDowell et al. 2003). However, mature trees have been found to delay their growth response for 5 to 25 years (Latham and Tappeiner 2002). Thinning in 110-year-old Douglas-fir stimulated little apparent diameter growth after 6 years, but analysis of 11- and 19-year growth responses were more clearly positive, in part because of adjustments for site and stand density differences but also because of gradual acceleration in growth rate (Williamson 1982). The mechanisms causing growth delays may be similar to those leading to thinning shock in Douglas-fir (Harrington and Reukema 1983). Sudden exposure after a thinning or regeneration harvest may be more likely to affect trees in lower canopy positions, including those in residual patches or near edges of patch cuts (Maguire et al. 2006), particularly if the initial effect is damage to shade foliage and bark. Alternatively, net carbon assimilation may increase after release (McDowell et al. 2003), with more of it allocated to belowground components (Urban et al. 1994). This strategy may allow rapid improvement in mechanical stability after disturbance, or facilitate capture of newly available soil resources. Regardless, the studies by North et al. (1996) and Maguire et al. (2006) analyzed the growth response for only the first 4 or 5 years following harvest, leaving open the possibility that a longer or later growth period will show positive responses by these older trees. The time since harvest varied from 13 to 15 years among the CFIRP blocks (13, 14, and 15 years for Dunn, Peavy, and Saddle, respectively); therefore, a lag or decrease in diameter growth during the first 5 or so years after the CFIRP treatments could have masked a growth acceleration later in the 13–14-year growth period.

The greater mortality rate for residual trees in the two-story treatment was somewhat predictable given the openness of the stands and expected higher within-canopy wind speed, deeper penetration of wind into the canopy, and greater turbulence and shear stress associated with increased canopy roughness (Green et al. 1995). In another comparison of initial entries for differing silvicultural systems in western Washington, windthrow was also found to be higher after the regeneration cut for a two-story system relative to the patch or group selection system (Curtis et al. 2004). In a study of variable-retention harvests in the Oregon and Washington Cascades, mortality rate was higher for 15% overstory tree retention compared with control and 40% retention and was heaviest when the residual trees were dispersed rather than aggregated (Maguire et al. 2006).

The results presented in this study should be relevant to stands of similar initial structure in the eastern part of the Oregon Coast Ranges, but also more generally to other relatively dry parts of the Douglas-fir region west of the Cascades in Oregon and Washington. The treatments implemented in CFIRP represent only the initial phase of moving even-aged Douglas-fir stands toward more complex structures containing two or more age and size classes. Longer-term responses and the feasibility of the intended silvicultural systems require continued monitoring of tree growth, mortality, and regeneration. Responses to these initial treatments do, however, carry several implications for future stand dynamics. First, the residual trees have, on average, maintained preharvest growth rates. However, the residual overstory Douglas-fir showed no strong release 13–15 years after group selection or two-story regeneration cuts on these sites. Formal analyses of growth data and anecdotal observations of crown condition (density and transparency) suggested possible adverse effects of increased exposure. The scattered residual trees in the two-story treatment suffered losses not only from uprooting or stem breakage, but also from other causes that are not fully understood but could be related to a decline in vigor after treatment. Continued loss of these residual trees may prevent attainment or maintenance of a two-storied structure further into the future, so specification of residual density for initial regeneration cuts in two-story silvicultural systems should consider the possibility of increased overstory mortality. Conversely, continued growth of residual trees in both the group selection and two-story treatments will be accompanied by continued crown expansion (e.g., Reukema 1964, Chan et al. 2006) and probably by an increase in canopy density. The effects on tree regeneration therefore should be closely monitored so that additional overstory treatments can be implemented in time to maintain a healthy regenerating cohort (e.g., Newton and Cole 2006).

Literature Cited

Bailey, J.D., and J.C. Tappeiner. 1998. Effects of thinning on structural development in 40- to 100-year-old Douglas-fir stands in western Oregon. *For. Ecol. Manag.* 108:99–113.

Bebber, D.P., S.C. Thomas, W.G. Cole, and D. Balsillie. 2004. Diameter increment in mature eastern white pine *Pinus strobus* L. following partial harvest of old-growth stands in Ontario, Canada. *Trees Struct. Funct.* 18:29–34.

Buermeyer, K.R., and C.A. Harrington. 2002. Fate of overstory trees and patterns of regeneration 12 years after clearcutting with reserve trees in southwest Washington. *West. J. Appl. For.* 17:78–85.

Chan, S.S., D.J. Larson, K.G. Maas-Hebner, W.H. Emmingham, S.R. Johnston, and D.A. Mikowski. 2006. Overstory and understory development in thinned and underplanted Oregon Coast Range Douglas-fir stands. *Can. J. For. Res.* 36:2696–2711.

Curtis, R.O., D.S. DeBell, C.A. Harrington, D.P. Lavender, J.B. St. Clair, J.C. Tappeiner, and J.D. Walstad. 1998. *Silviculture for multiple objectives in the Douglas-fir region.* US For. Serv. Gen. Tech. Rep. PNW-GTR-435. 123 p.

Curtis, R.O., D.S. DeBell, R.E. Miller, M. Newton, J.B. St. Clair, and W.I. Stein. 2007. *Silvicultural research and the evolution of forest practices in the Douglas-fir region.* US For. Serv. Gen. Tech. Rep. PNW-GTR-696. 172 p.

Curtis, R.O., D.D. Marshall, and D.S. DeBell. 2004. *Silvicultural options for young-growth Douglas-fir forests: The Capitol Forest study—establishment and first results.* US For. Serv. Gen. Tech. Rep. PNW-GTR-598. 110 p.

Draper, N.R., and H. Smith. 1998. *Applied Regression Analysis,* 3rd ed. John Wiley and Sons, Inc., New York, NY. 706 p.

Franklin, J.F., D.R. Berg, D.A. Thornburgh, and J.C. Tappeiner. 1997. Alternative silvicultural approaches to timber harvesting: Variable retention harvest systems. P. 111–139 in *Creating a forestry for the 21st century: The science of ecosystem management*, Kohm, K.A., and J.F. Franklin (eds.). Island Press, Washington, DC.

Green, S.R., J. Grace, and N.J. Hutchings. 1995. Observations of turbulent air flow in three stands of widely spaced Sitka spruce. *Agric. For. Meteorol.* 74:205–225.

Harrington, C.A., and D.L. Reukema. 1983. Development following thinning in a Douglas-fir plantation. *For. Sci.* 29:33–46.

Johnson, D.L., K.N. Johnson, and D.W. Hann. 2007. The importance of forest stand-level inventory to sustain multiple forest values in the presence of endangered species. P. 238–256 in *Sustainable forestry: From monitoring and modeling to knowledge management and policy science*, Reynolds, K.M., A.J. Thompson, M. Köhl, M.A. Shannon, R. Ray, and K. Rennolls (eds.). CABI, Wallingford, U.K.

King, J.E. 1966. *Site index curves for Douglas-fir in the Pacific Northwest.* Weyerhaeuser Forestry Paper No. 8. Weyerhaeuser Co., Centralia, WA. 49 p.

King, J.E., D.D. Marshall, and J.F. Bell. 2002. *Levels-of-growing-stock cooperative study in Douglas-fir: Report no. 17: The Skykomish study, 1961–93; The Clemons study, 1963–94.* US For. Serv. Res. Pap. PNW-RP-548. 120 p.

Latham, P., and J.C. Tappeiner. 2002. Response of old-growth conifers to reduction in stand density in western Oregon forests. *Tree Physiol.* 22:137–146.

Maguire, C.C., and C.L. Chambers (eds.). 2005. *College of Forestry Integrated Research Project: Ecological and socioeconomic responses to alternative silvicultural treatments.* Forest Research Laboratory Research Contribution 46. 161 p.

Maguire, D.A., D.B. Mainwaring, and C.B. Halpern. 2006. Stand dynamics after variable-retention harvesting in mature Douglas-fir forest of western North America. *Allg. Forst-u. J.-Ztg.* 177:120–131.

Marshall, D.D., and R.O. Curtis. 2002. *Levels-of-growing-stock cooperative study in Douglas-fir: Report no. 15: Hoskins, 1963–98.* US For. Serv. Res. Pap. PNW-RP-537. 80 p.

Marshall, D.D., D.L. Johnson, and D.W. Hann. 1997. A forest management information system for education, research, and operations. *J. For.* 95:27–30.

McComb, B.C., and C.L. Chambers. 2005. Chapter 1: Introduction. P. 13–23 in *Ecological and socioeconomic responses to alternative silvicultural treatments*, Maguire, C.C., and C.L. Chambers (eds.). Research Contribution 46. Forest Research Laboratory, Oregon State University, Corvallis, OR.

McDowell, N., J.R. Brooks, and B.J. Bond. 2003. Carbon isotope discrimination and growth response of old Pinus ponderosa trees to stand density reduction. *Plant Cell Environ.* 26:631–644.

Monserud, R.A. 2002. Large-scale management experiments in the moist maritime forests of the Pacific Northwest. *Landscape Urban Plan.* 59:159–180.

Newton, M., and E.C. Cole. 1987. A sustained-yield scheme for old-growth Douglas-fir. *West. J. Appl. For.* 2:22–25.

Newton, M., and E.C. Cole. 2006. Regeneration in two-storied Douglas-fir stands. *West. J. Appl. For.* 21:14–18.

North, M., J. Chen, G. Smith, L. Krakowiak, and J. Franklin. 1996. Initial response of understory plant diversity and overstory diameter growth to a green tree retention harvest. *Northwest Sci.* 70:24–35.

Peterson, C.E., and R.A. Monserud. 2002. *Compatibility between wood production and other values and uses on forested lands: A problem analysis.* US For. Serv. Gen. Tech. Rep. PNW-GTR-564. 51 p.

Poage, N.J., and P.D. Anderson. 2007. *Large-scale silvicultural experiments in western Oregon and Washington.* US For. Serv. Gen. Tech. Rep. PNW-GTR-713. 44 p.

Poage, N.J., and J.C. Tappeiner. 2002. Long-term patterns of diameter and basal area growth of old-growth Douglas-fir trees in western Oregon. *Can. J. For. Res.* 32:1232–1243.

Reukema, D.L. 1964. Crown expansion and stem radial growth of Douglas-fir as influenced by release. *For. Sci.* 10:192–199.

Tappeiner, J.C., D.A. Maguire, and T.B. Harrington. 2007. *Silviculture and ecology of western U.S. Forests.* Oregon State University Press, Corvallis, OR. 440 p.

Urban, S.T., V.J. Lieffers, and S.E. Macdonald. 1994. Release in radial growth in the trunk and structural roots of white spruce as measured by dendrochronology. *Can. J. For. Res.* 24:1550–1556.

Walters, D.K., and D.W. Hann. 1986. *Taper equations for six major conifer species in southwest Oregon.* Oregon State Univ. For. Res. Lab. Res. Bull. 56. 41 p.

Williamson, R.L. 1982. *Response to commercial thinning in a 110-year-old Douglas-fir stand.* US For. Serv. Res. Paper PNW-296. US For. Serv. Pac. Northw. Stn., Portland, OR. 16 p.

Williamson, R.L., and F.E. Price. 1971. *Initial thinning effects in 70- to 150-year-old Douglas-fir—western Oregon and Washington.* US For. Serv. Res. Paper PNW-117. US For. Serv. Pac. Northw. Stn., Portland, OR. 15 p.

Youngblood, A.P. 1991. Radial growth after a shelterwood seed cut in a mature stand of white spruce in interior Alaska. *Can. J. For. Res.* 21:410–413.