Thirteen-Year Height and Diameter Growth of Douglas-Fir Seedlings under Alternative Regeneration Cuts in Pacific Northwest

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ABSTRACT

Interest in managing Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) forests in the Pacific Northwest under silvicultural systems other than traditional clearcutting has prompted research on the efficacy of alternative systems for successful regeneration and sustained timber productivity of Douglas-fir. The College of Forestry Integrated Research Project, implemented by Oregon State University, was established to compare various ecosystem responses and public perceptions among treatments implemented under clearcutting, shelterwood-with-reserves, and group selection silvicultural systems. The objective of this analysis was to quantify the following three responses of planted Douglas-fir seedlings to initial regeneration cuts: cumulative 13-year height growth (H_{13yr}; 1992–2004), cumulative 13-year diameter growth (D_{13yr}; 1992–2004), and most recent 5-year height growth (ΔH_{5yr}; 2000–2004). Differences in variability of overstory density at the treatment level led to significant differences in the variance of understory growth responses. After accounting for heterogeneous variance, analysis of variance indicated significant treatment effects for all three responses. Treatment effects were explained by the decline in H_{13yr}, D_{13yr}, and ΔH_{5yr} with increasing overstory competition as represented by basal area of residual trees immediately after harvesting (initial basal area). Predicted height:diameter ratio of Douglas-fir seedlings increased as IBA increased. Under regeneration methods that retain a portion of the overstory, a residual overstory with basal area <80 ft^2/ac allows establishment, growth, and continued survival of Douglas-fir regeneration during the 13 years following harvest.

Keywords: shelterwood with reserves, group selection, patch cut, clearcut with reserves, light availability, residual density, uneven-aged management, even-aged management

Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) forests in the Pacific Northwest have been managed predominantly under the clearcutting system, especially where the primary objective has been timber production. Alternative silvicultural systems such as shelterwood with reserves (Matthews 1989) and innovations such as variable-retention harvesting (Franklin et al. 1997) have been proposed as ways to meet more effectively the numerous implicit and explicit coobjectives of forest management, particularly on public lands. The exploration of alternatives has been partly fueled by increasing public concern about dramatic reductions in the area of old-growth forests and potential declines in forest biodiversity. Many of the alternative silvicultural systems garner appeal by promoting more complex stand structures that may help meet nontimber objectives, such as biodiversity conservation and aesthetic quality.

The success of any silviculture system depends on its capability to procure adequate regeneration of the desired species through release of existing advance regeneration, establishment, and development of new seedlings from seedfall or by planting. Regeneration dynamics strongly influence future stand development and both structural and compositional diversity. Long-term observation of the composition, growth, and survival of regeneration is needed to determine the feasibility of these systems for maintaining and managing Douglas-fir forests in the Pacific Northwest.

Regeneration methods are designed to increase resource availability to understory trees by reducing overstory stocking. Reductions in light interception by the overstory canopy can be achieved by reducing overstory stocking uniformly or by creating discrete gaps; however, the common challenge in both approaches is to identify residual overstory stocking that achieves acceptable understory tree growth. In one experiment that created gaps of different sizes in northwestern British Columbia, Coates (2000) found that height and diameter growth of planted western redcedar (*Thuja plicata* Donn. ex D. Don), western hemlock (*Tsuga heterophylla* [Raf.] Sarg.), and subalpine fir (*Abies lasiocarpa* [Hooks.] Nutt.) is enhanced by an opening size up to 0.25 ac (0.1 ha) but that growth rates do not increase with larger openings. The average width of this threshold gap size (56 m) was approximately 1.9 times the average dominant tree height (approximately 30 m). The more light-demanding species, such as lodgepole pine (*Pinus contorta* Douglas), however, do benefit from gaps larger than 0.25 ac (0.1 ha) (Coates 2000). In northern California, York et al. (2003, 2004, 2007) studied the effect of group selection treatments on early height growth of

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planted seedlings after their third, fifth, and seventh growing seasons in a naturally regenerated mixed-conifer forest. Cumulative height growth of Douglas-fir and ponderosa pine (*Pinus ponderosa* Douglas) increases asymptotically with opening size. However, planted Douglas-fir seedlings do not seem to benefit from openings greater than 1.48 ac (0.6 ha) (York et al. 2004). In western Oregon, Brandeis et al. (2001), by studying different intensities of thinning and patch cut sizes, found that increasing residual overstory density negatively affects height growth of planted Douglas-fir seedlings 4 years after planting. In the same region, Chan et al. (2007) showed that after 5 years, the average height and diameter of Douglas-fir seedlings underplanted in thinned even-aged Douglas-fir stands are significantly related to the intensity of thinning. At the 8th year, seedlings under the heavy thinning (residual trees of about 30 trees/ac [75 trees/ha]) had the largest diameter, height, and height growth rate (Chan et al. 2007). However, diameter growth and height growth are affected to differing degrees by increasing overstory. In interior British Columbia, diameter growth of underplanted Douglas-fir seedlings decline more rapidly than height growth with decreasing light availability (Chen 1997).

Numerous studies have also focused on the responses of natural Douglas-fir regeneration to a range in light conditions. One difficulty with interpreting these studies is accurate determination of the timing of regeneration establishment. After a combination of controlled experiments and field observations in western Washington, Isaac (1943) concluded that opening size >1 ac or overstory removal >50% is required to obtain satisfactory Douglas-fir regeneration. Williams et al. (1999) showed that under low-light conditions in interior British Columbia, a Douglas-fir with total height of 9.8 ft (3 m) could be 50 years old. Responses to overstory density reduction may also vary by time since treatment. Kneeshaw et al. (2002) found that height growth Douglas-fir advance regeneration reduces after harvesting before responding positively to increased light availability after 2–3 years in partially cut stands, apparently because of an initial acceleration in root growth. Working on the east coast of Vancouver Island, British Columbia, Drever and Lertzman (2001) concluded that 40% of full sunlight is required for natural Douglas-fir seedlings to achieve height growth comparable to that of seedlings growing under full sunlight.

The College of Forestry Integrated Research Project (CFIRP) was established in the late 1980s at Oregon State University as a long-term interdisciplinary research study to compare responses to initial treatments implemented under three silvicultural systems to be tested in Douglas-fir forests at the western edge of the Willamette Valley: group selection, shelterwood with reserves, and clearcutting with reserves (Maguire and Chambers 2005). Treatments implemented to date include only a set of initial regeneration cuts, but the long-term goal is to develop the specifications required for successful implementation of corresponding silvicultural systems and to understand the interactions and tradeoffs among timber production, social acceptance, and wildlife habitat (Maguire and Chambers 2005). One primary objective of these initial treatments was to assess seedling growth and survival, including both planted and naturally regenerated seedlings (Maguire and Chambers 2005), under a management objective that included continued production of Douglas-fir timber. The main objectives of this analysis were to (1) test the null hypothesis that planted Douglas-fir seedling growth was not different among the three alternative silvicultural treatments, (2) quantify growth responses, and (3) test whether any treatment differences could be accounted for by residual overstory basal area alone. Growth responses included cumulative height and diameter growth 13 years after initial regeneration harvests (1992 to 2004) and more recent 5-year height growth (2000 to 2004).

Methods and Materials

Study Area

The CFIRP study was implemented on Oregon State University's 10,117-ac (4,096-ha) McDonald-Dunn Forests, 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 an average maximum daily temperature of 80.8°F (27.1°C) in June and August. The treatment units of the study are established on elevations ranging from 395 to 1,320 ft (120 to 400 m) and on a variety of slopes and aspects.

Experimental Design

CFIRP was established as a generalized randomized complete block design with three blocks (Saddle, Peavy, and Dunn). Blocks were similar in initial stand structures as defined by species composition, stand density, tree age, and general vertical structure. Initial stands contained mainly Douglas-fir (average basal area, 165 ft^2/ac [37.9 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.). The Douglas-fir site index (base age, 50; King 1966) ranged from 92 to 130 ft (28 to 40 m), and the average stand age for all trees in the treatment units ranged from 45 to 144 years. However, the top height of treatment units, which can be important for determining effective opening size under a group selection system, covered a relatively narrow range and averaged approximately 180 ft (54.9 m; range, 150–203 ft [45.7–61.9 m]) at Saddle, 160 ft (48.8 m; range, 158–182 ft [48.2–55.5 m]) at Peavy, and 140 ft (42.7 m; range, 110–161 ft [33.5–49.1 m]) at Dunn (Table 1).

In each block, one of four treatments were randomly assigned to 11 experimental units, ranging in size from 14 to 45 ac (5.7 to 18.2 ha). The first treatment was an uncut control, and the other three treatments were referred to as "small patch," "two-story," and "modified clearcut" (Maguire and Chambers 2005). To reflect the longer-term silvicultural objectives and the silvicultural system that these treatments were intended to initiate, we hereafter refer to these silvicultural treatments as "group selection," "shelterwood with reserves," and "clearcut with reserves." Six units were assigned to the group selection treatment, two to the clearcut-with-reserves treatment, two to the shelterwood-with-reserves treatment, and one to an unharvested control (Table 1). The group selection treatment removed 33% of stem volume in 0.5-ac (0.2-ha) circular to square openings, the shelterwood-with-reserves treatment removed 75% of the stem volume and left only 8 to 12 large residual live trees per acre (20 to 30 per ha) scattered uniformly throughout the experimental unit, and the clearcut-with-reserves treatment removed all of the stand volume except for approximately one reserve tree for every 2 ac

Table 1. Average overstory conditions (trees >8 in. in dbh) immediately after regeneration harvests in the College of Forestry Integrated Research Project study.

Block and treatment	Number of plots/experimental units	Trees/ac	Basal area (ft^2/ac)	Stand density index	Stand volume (ft^3/ac)	Stand top height (ft)[a]
Saddle						
Clearcut	16/2	0	0.0	0.0	0.0	0.0
Group selection	31/6	62	176.0	290.6	8,565.5	180.6
Shelterwood-with-reserves	16/2	13	71.0	103.8	3,929.2	182.4
Control	7/1	65	197.1	312.3	8,429.4	152.1
Peavy						
Clearcut	21/3	9	0.4	35.4	242.5	90.5
Group selection	63/6	47	142.2	273.0	6,558.0	162.7
Shelterwood-with-reserves	18/2	11	61.0	82.6	2,887.9	157.3
Control	6/1	65	273.3	524.9	16,099.8	194.6
Dunn						
Clearcut	26/2	0	0.0	0.0	0.0	0.0
Group selection	70/6	68	129.1	258.6	5,282.4	143.8
Shelterwood-with-reserves	22/2	9	35.3	50.36	1,542.9	126.3
Control	3/1	106	213.3	536.2	9,728.9	142.0

Trees per acre, basal area, stand density, stand volume, and stand 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 uncut matrix.

[a] Stand top height in shelterwood-with-reserves and group selection was estimated as the mean height of largest 40 trees/ac based on dbh; stand top height in the clearcut with reserves was the mean height of all residual overstory trees.

(1.2 per ha). The width of openings in the group selection treatments (166 ft) was approximately 92, 104, and 120% of the surrounding stand top height at Saddle, Peavy, and Dunn, respectively.

The three blocks were harvested over 2 years beginning in fall 1989/spring 1990 and ending in spring 1991. Logs were ground skidded from units with slope <30% and uphill cable yarded from units with slope >30%. The entire experimental units receiving initial cuts under the shelterwood-with-reserves and clearcut treatments were planted with Douglas-fir in early 1992, as were the 0.5-ac (0.2-ha) openings in the group selection entry. A mix of 1-1 and P-1 Douglas-fir seedlings were planted at a spacing ranging from 11 to 13 ft (3.3 to 4.0 m) (Maguire and Chambers 2005). Additional detail on CFIRP experimental designs and related topics is provided by Maguire and Chambers (2005).

Data Collection and Statistical Analysis

In 1981 a series of systematically located sample points was established at an intensity of 1 to 2 per ac (2.5 to 5.0 per ha) across the McDonald-Dunn Forest. These points were established as a permanent plot network for inventory and growth and yield projection. Any sample points containing planted seedlings within the group selection, shelterwood-with-reserves, and clearcut-with-reserves units were compiled for analysis of CFIRP growth responses. At each sample point, three nested subplots were established to sample the range in tree size. 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 ≤8.0 in. (>10.2 cm and ≤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 ≤ 4.0 in. (10.2 cm) were measured on a fixed area subplot of radius 7.78 ft (2.37 m). This plot design allowed characterization of local stand density for planted seedlings that occurred on any of the nested plots.

All inventory plots were remeasured immediately after harvest treatments in 1991 or 1992 and then again after the 2004 growing season. Trees planted in 1992 were included in the 2004 remeasurement. Measured variables included tree species, cumulative 13-year dbh growth (D_{13yr}; 1992–2004), and cumulative 13-year height growth (H_{13yr}; 1992–2004). For Douglas-fir with H_{13yr} <40 ft, 5-year height growth (ΔH_{5yr}) was recorded by taking the difference between 2004 height and height to the fifth whorl from the tip of the tree. Although Douglas-fir seedlings planted in early 1992 after regeneration harvests were not tagged, we assumed that the vast majority of Douglas-fir trees with H_{13yr} <40 ft in 2004 originated from planted seedlings and that only a very small proportion of trees were natural or advance regeneration. It was important to note that understory trees from all plots in the shelterwood-with-reserves and clearcut treatments were used for analysis but that only trees from plots located within the openings of the group selection units were used (the uncut matrix was not underplanted). The response variables were mean D_{13yr}, H_{13yr}, and ΔH_{5yr} of planted Douglas-fir (H_{13yr} <40 ft in 2004) for an experimental unit. Treatment effects on the response variables were tested by a generalized randomized complete block analysis of variance (ANOVA), where the block was considered a random factor and tests were performed at $\alpha = 0.05$. Preliminary exploratory analysis revealed that the ANOVA assumption of homogeneous variance across treatments might not be tenable, and Levene's test of homogeneity of variance was applied to test the assumption. We attempted various transformations of the response variables, but the results were not satisfactory. Therefore, to ensure valid inferences about treatment effects, we applied ANOVA methods that assumed heterogeneous variance or, more specifically, methods that assumed each treatment had its own variance in the context of linear mixed models (Littell et al. 2006). No analyses provided any evidence of significant block × treatment interaction, so they were excluded from final analyses. To account for variation in stand density among group selection units (proximity to edge of group opening) and among shelterwood-with-reserves units (proximity to reserve trees), initial basal area (IBA, ft^2/ac) of each experimental unit immediately after harvest (1989 to 1991) was also tested as a covariate in an analysis of covariance (ANCOVA). For the shelterwood-with-reserves treatments, IBA for an experimental unit was estimated as the average plot-level IBAs of all plots within the unit. For the group selection, IBA of an experimental unit was estimated as the average of plot-level IBAs for plots

Table 2. Descriptive statistics for 5-year height growth (ΔH_{5yr}; 2000 to 2004), 13-year cumulative dbh growth (D_{13yr}; 1992 to 2004), and cumulative height growth (H_{13yr}; 1992 to 2004) of planted Douglas-fir trees in the College of Forestry Integrated Research Project study.

Treatment	Minimum	Maximum	Median	Mean	SD
ΔH_{5yr} (ft)					
Clearcut	10.18	13.91	12.96	12.45	1.26
Group selection	6.90	12.44	11.24	10.04	1.99
Shelterwood-with-reserves	7.45	13.23	10.83	10.58	1.96
H_{13yr} (ft)					
Clearcut	16.26	27.62	25.31	23.92	3.81
Group selection	9.90	31.91	22.69	22.12	6.73
Shelterwood-with-reserves	12.06	23.95	21.01	19.56	4.66
D_{13yr} (in.)					
Clearcut	3.18	5.66	4.89	4.66	0.82
Group selection	1.40	4.90	3.76	3.62	1.15
Shelterwood-with-reserves	1.57	3.98	3.47	3.12	0.97

Table 3. Mean treatment differences in 5-year height growth (ΔH_{5yr}; 2000 to 2004), 13-year cumulative dbh growth (D_{13yr}; 1992 to 2004), and cumulative height growth (H_{13yr}; 1992 to 2004) of planted trees in College of Forestry Integrated Research Project regeneration units.

Treatment	Mean difference	Standard error	Adjusted *P* value
ΔH_{5yr} (ft)			
Clearcut versus group selection	2.41	0.77	0.027
Clearcut versus shelterwood-with-reserves	1.87	0.58	0.024
Shelterwood-with-reserves versus group selection	-0.54	0.88	0.814
H_{13yr} (ft)			
Clearcut versus group selection	3.51	2.41	0.346
Clearcut versus shelterwood-with-reserves	4.16	1.24	0.016
Shelterwood-with-reserves versus group selection	0.64	2.32	0.958
D_{13yr} (in.)			
Clearcut versus group selection	1.37	0.41	0.006
Clearcut versus shelterwood-with-reserves	1.48	0.21	<0.001
Shelterwood-with-reserves versus group selection	0.11	0.41	0.790

Standard errors and *P* values were estimated under the analysis of variance assumption of heterogeneous variance and have been adjusted for multiple comparisons.

Table 4. Parameter estimates (intercept and slope) and their standard errors for analysis of covariance of 5-year height growth (ΔH_{5yr}), 13 year cumulative height growth (H_{13yr}), and cumulative dbh growth (D_{13yr}) on residual basal area immediately after regeneration harvest in the College of Forestry Integrated Research Project study.

Treatment	Parameter estimate	Standard error
ΔH_{5yr}		
Slope	−0.035	0.012
Intercept		
Group selection	12.31	1.79
Shelterwood-with-reserves	12.52	0.95
H_{13yr}		
Slope	−0.108	0.054
Intercept		
Group selection	27.47	6.28
Shelterwood-with-reserves	25.56	3.61
D_{13yr}		
Slope	−0.021	0.010
Intercept		
Group selection	4.68	1.17
Shelterwood-with-reserves	4.29	0.69

Planted seedlings in the group selection treatment were available only on plots located within patch openings.

containing planted seedlings within group openings. Treatment effects were compared by Tukey-Kramer multiple-comparison tests. All analyses were carried out using the MIXED procedure in SAS 9.2 (SAS Institute, Cary, NC).

Results

The number of plots in experimental units for a given treatment varied from 3 in the control plots at the Dunn block to 70 in the group selection units at the same block (Table 1). Among the three blocks, the ranges in mean residual basal area for the control units and those receiving regeneration harvests under the group selection, shelterwood-with-reserves, and clearcutting treatments were 197.1–273.3, 129.1–176.0, 35.3–71.0, and 0.0–0.4 ft^2/ac, respectively (Table 1).

The variance in response variables was greatest in the group selection treatment and least in the clearcut-with-reserves group. Introduction of IBA as a covariate eliminated this trend of unequal variance, suggesting that the variation in growth of planted trees could be attributed largely to the range in overstory competition experienced under each treatment.

Five-Year Height Growth

Treatment significantly affected 5-year height growth of understory Douglas-fir trees during the 2000–2004 growth period ($P = 0.009$). Mean ΔH_{5yr} values for clearcut, group selection, and shelterwood-with-reserves treatments were 12.45, 10.04, and 10.58 ft, respectively (Table 2). The mean ΔH_{5yr} in the clearcut treatment was significantly higher than in the group selection and shelterwood-with-reserves treatments (adjusted $P = 0.027$ and 0.024, respectively; Table 3). However, the group selection and shelterwood-with-reserves treatments were not significantly different from each other (adjusted $P = 0.814$; Table 3). The standard deviation (SD) of ΔH_{5yr} for clearcut treatment was the lowest (1.26; Table 2) suggesting that average ΔH_{5yr} values among the clearcut experimental units were fairly homogeneous compared with the group selection and shelterwood-with-reserves treatments.

The ANCOVA indicated that the covariate IBA had a significantly negative effect on ΔH_{5yr} in the shelterwood-with-reserves and group selection treatments ($P = 0.014$). Each 10 ft^2/ac increase in IBA was associated with a decrease of 0.35 ft in ΔH_{5yr} (see slope coefficient in Table 4; the coefficient of determination, $R^2 = 0.38$, and the residual standard error [RSE] = 1.61). As there was no evidence of interaction between IBA and treatment ($P = 0.39$), ΔH_{5yr} decreased linearly with increasing IBA for both treatments (Figure 1A). After adjusting for the covariate effect, there were no significant treatment effects on ΔH_{5yr} ($P = 0.80$) suggesting that residual basal area accounted for treatment effects (Figure 1A; no significant differences between treatment regression lines).

Cumulative 13-Year Height Growth

The results for cumulative 13-year height growth (H_{13yr}) generally followed those for the recent 5-year height growth; i.e., treatment effects on H_{13yr} were significant ($P = 0.022$). As with ΔH_{5yr}, the SD of H_{13yr} for the group selection treatment was the largest (6.73), and those for the clearcut and shelterwood-with-reserves treatments were 3.81 and 4.66, respectively (Table 2). The near 2-fold difference in standard deviations between treatments justified ANOVA methods that assumed heterogeneous variance.

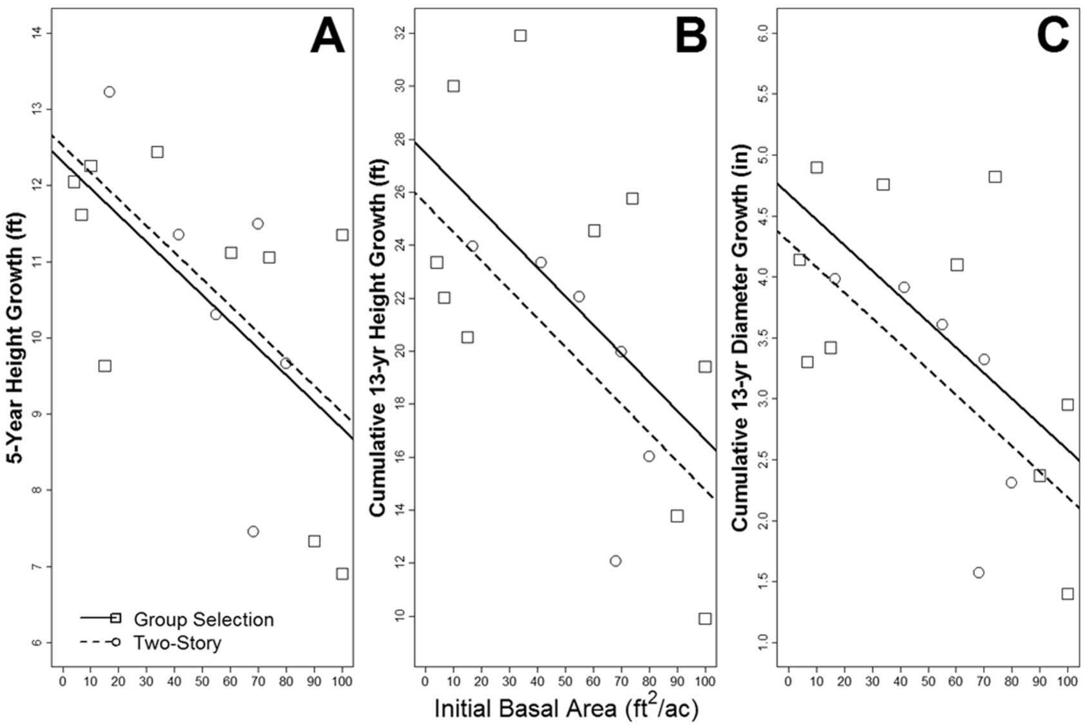

Figure 1. Analysis of covariance for response of 5-year height growth, 13-year cumulative dbh growth, and cumulative height growth to group selection and shelterwood-with-reserves regeneration treatments in the College of Forestry Integrated Research Project study, with initial basal area of residual trees as the covariate. Planted seedlings in the group selection treatment were available only on plots located within patch openings.

The mean H_{13yr} values under the clearcut, group selection, and shelterwood-with-reserves treatments were 23.9, 22.1, and 19.6 ft, respectively (Table 2). In contrast to ΔH_{5yr}, the estimated H_{13yr} under the clearcutting treatment was not significantly different from that of group selection ($P = 0.346$; Table 3). However, it was significantly greater than under the shelterwood-with-reserves treatment ($P = 0.016$; Table 3).

Treatment effects on H_{13yr} were not significant after accounting for IBA ($P = 0.48$). The H_{13yr} decreased linearly with increasing IBA (Figure 1B). For each 10 ft²/ac increase in IBA there was a corresponding decrease of 1.08 ft in H_{13yr} (Table 4; $R^2 = 0.32$, RSE = 4.95). ANCOVA indicated that there was no significant difference between the regression lines of the group selection and shelterwood-with-reserves treatments ($P = 0.48$).

Cumulative 13-Year Diameter Growth

The ANOVA indicated that there was a significant treatment effect on D_{13yr} ($P < 0.001$). The SD of D_{13yr} was the largest for group selection treatment (1.15) but was comparable between clearcut and shelterwood-with-reserves treatments (0.82 and 0.97, respectively; Table 2).

The mean D_{13yr} values for clearcut, group selection, and shelterwood-with-reserves treatments were 4.66, 3.62, and 3.12 in., respectively (Table 2). As with ΔH_{5yr}, the estimated mean D_{13yr} 13 years after planting in the clearcut treatment was significantly greater than in the group selection and shelterwood-with-reserves regeneration treatments (Table 3).

Treatment effects on D_{13yr} were completely accounted for by IBA (ANCOVA P for treatment effect = 0.42). A 10 ft²/ac increase in IBA implied a 0.21-in. decrease in mean D_{13yr} (Figure 1C; Table 4; $R^2 = 0.29$, RSE = 0.90).

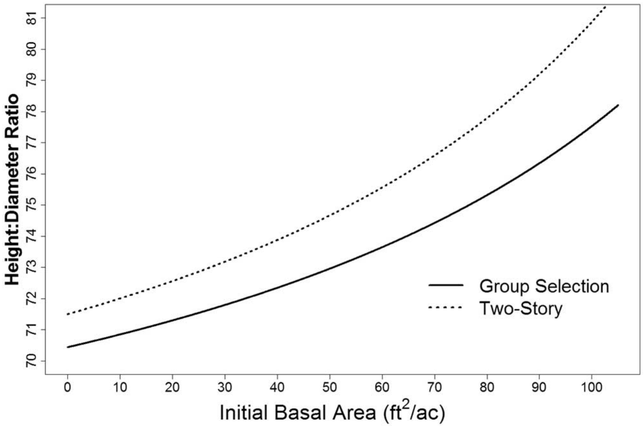

Figure 2. Average trend in 13-year height:diameter ratio over initial basal area of residual trees for the group selection and shelterwood-with-reserves regeneration treatments in the College of Forestry Integrated Research Project study.

Height:Diameter Ratio

The height:diameter ratio inferred from parameter estimates for predicted H_{13yr} and D_{13yr} (Table 4) increased with IBA for the shelterwood-with-reserves and group selection treatments, with the shelterwood-with-reserves treatment averaging greater in height:diameter diameter than group selection (Figure 2).

Discussion

In the growth analysis of CFIRP understory trees, IBA of residual trees immediately after harvesting represented the effects of overstory competition for light and for soil moisture and nutrients.

However, the spatial arrangement of overstory competition for a given IBA differed among the silvicultural treatments. In the shelterwood-with-reserves treatments, IBA implied the average shading and competition from residual overstory trees that were more or less uniformly distributed across the entire experimental unit. In contrast, IBA in the group selection treatment implied the proximity of plots to the edge of patch openings, and to a lesser extent the size of patch opening in which the plot fell; i.e., plots with a high IBA in the group selection treatment were generally located near the edge of openings where overstory trees from the uncut matrix contributed to the sample. Almost complete overlap in the range of IBA between the shelterwood-with-reserves and group selection treatments and the lack of any significant differences between treatment regression lines suggested that IBA effects at the plot level were indistinct despite differences in spatial pattern of the overstory.

The observed general trend of decreasing ΔH_{5yr}, H_{13yr}, and D_{13yr} with increasing IBA was consistent with other studies documenting seedling growth both in regeneration cuts with residual overstory trees (DeLong et al. 2003, Mitchell et al. 2004) and under a range of thinning intensities (Brandeis et al. 2001, Maas-Hebner et al. 2005). However, direct comparisons are difficult because of differences in sampling design, tree measurements, and indices of overstory competition (e.g., percentage of full sunlight; Drever and Lertzman 2001, Chen 1997). IBA commands appeal as an index of overstory competition not only because it is correlated with above- and below-ground overstory competition but also because it is easily obtained from standard inventory plots and is typically the basis for defining and implementing silvicultural prescriptions. Brandeis et al. (2001) suggested that basal area of overstory trees should be maintained below 90 ft^2/ac to regenerate Douglas-fir satisfactorily in thinned stands. Basal area of 80 ft^2/ac was the upper limit of IBA for the shelterwood-with-reserves treatment in CFIRP (Figure 1), so we could not quantify the trend in growth responses across the higher threshold of 90 ft^2/ac. However, CFIRP results did suggest that as overstory basal area declined below 80 ft^2/ac, there was a continuous linear gain in ΔH_{5yr}, H_{13yr}, and D_{13yr} down to the lowest density of overstory trees in the group selection and shelterwood-with-reserves treatments. Extrapolation of these regression lines to zero overstory basal area also yielded growth estimates that were consistent with the averages for the clearcut treatment (Table 2 versus Figure 1).

Under group selection, the decreasing trend in periodic and cumulative growth with increasing residual overstory corroborated several studies looking at growth responses as a function of distance-to-edge and gap size. Coates (2000) showed that the largest trees of several planted coniferous species were generally found in the middle part of patch openings. Seedlings planted on gap edges generally performed poorly in height growth and by year 5 had lower total height and dbh because of overshadowing by residual overstory trees on the gap edge (Coates 2000). York et al. (2007) noted a large gain in 7-year height of planted Douglas-fir seedlings as gap size increased from 0.74 ac to 1.48 ac, but little additional gain at larger gap sizes.

A wide range of average growth response was observed for treatment units starting with a similar residual basal area (IBA) in the group selection treatment (Figure 1). Without removing the portion of the variance accounted by IBA as a covariate, the estimated standard deviations of ΔH_{5yr}, H_{13yr}, and D_{13yr} for the group selection treatment were 5–9 times larger than under the shelterwood-with-reserves treatments (Table 2). Thus for a given IBA, planted Douglas-fir seedlings were likely growing under a wider range in light and other resource availability than was represented by total plot IBA, and that may have been operating at a different spatial scale. Further characterization of overstory and understory competitive environment under the contrasting regeneration cuts would likely account for some of the residual variation in growth for a given IBA. Brandeis et al. (2001) noted that competition from neighboring understory vegetation strongly affected growth of underplanted seedlings, especially in stands with low density of residual trees. Anecdotal observation of the CFIRP study sites indicated variable growing conditions between the group selection experimental units, caused primarily by patchy but locally intense competition from Himalayan blackberry (*Rubus discolor* Weihe & Nees). Likewise, varying combinations of aspect, slope and height of overstory edge trees resulted in widely differing levels of solar radiation reaching the understory trees. Chen et al. (1996) and Williams et al. (1999) noted that Douglas-fir seedlings were sufficiently plastic and adaptable that they modified their growth form in response to differences in resource availability. The growth variability observed in the CFIRP group selection units was consistent with a plastic response to variability in local light environment and other growing conditions.

This plastic response of planted Douglas-fir seedlings was further demonstrated by the trend of increasing height:diameter ratio over increasing IBA, indicating that increasing overstory competition resulting thinner trees for a given height. Chen (1997) likewise found increasing height:diameter ratio of interior Douglas-fir seedlings with decreasing light availability. Wang et al. (1994) observed similar trends for western redcedar (*Thuja plicata* Donn ex D. Don). Drever and Lertzman (2001) and others (see Tilman 1988, Chen and Klinka 1998) generalized that species of intermediate (e.g., Douglas-fir) or greater shade-tolerance preferentially allocate photosynthate under low-light conditions to height growth relative to diameter growth.

CFIRP results suggest that managers can predict growth responses of underplanted Douglas-fir seedlings by considering the residual basal area of overstory trees left after regeneration harvests. Further refinements are undoubtedly possible by also accounting for the rate of overstory basal area growth over the 13-year period. Nonetheless, insights into the ultimate driving variables such as nutrient, light, and moisture availability can help design treatments for silvicultural control of growth and survival of underplanted seedlings (see Carter and Klinka 1992, Davies-Colley et al. 2000). It should also be kept in mind that residual stand structures were more variable and complex than could be accounted for simply by IBA. The shelterwood-with-reserves and group selection treatments are inherently quite different with respect to the spatial distribution and vertical structure of residual overstory trees. These structural differences and associated differences in microclimate and resource availability cannot be captured entirely by plot average IBA. Other responses of interest, such as public perception of aesthetic quality, will likewise depend on aspects of stand structure that are poorly depicted by IBA alone. Results from CFIRP can be applied from two slightly different perspectives, i.e., performance of the nominal silvicultural treatment and response across a gradient in residual overstory density. Aspects of both perspectives provide guidelines on the likely regeneration success under silvicultural alternatives and the level of retention that will be most likely to balance desired growth of Douglas-fir regeneration against other management objectives.

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