Conifer response to three silvicultural treatments in the Oregon Coast Range foothills

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Abstract: This study assessed growth, condition, and mortality of residual trees one decade after harvest across three silvicultural treatments in thirty 85- to 125-year-old Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) stands in the Oregon Coast Range foothills. Group-selection cuts had 33% of the entire stand volume extracted as patches approximately 0.2–0.8 ha in size; two-story regeneration harvests had 75% of the volume extracted, and 20–30 residual trees/ha were left; clearcuts had all trees removed, except for 1.2 trees/ha. One decade after harvest, tree basal area, diameter, and height growth, and crown width and fullness did not differ between silvicultural treatments. In contrast, live crown ratio was largest in clearcuts (0.74), and the proportion of trees with epicormic branching was highest in two-story stands (35%). Overall, 45% of trees had more basal area growth in the decade after harvest than in the previous decade. Residual green trees in clearcuts and group-selection stands experienced the highest and lowest percentage mortality, respectively (30.6% vs. 0.2%). Our results reflect little differentiation in the characteristics of trees growing under three silvicultural conditions one decade after harvest. However, percent residual green tree mortality increased with increasing harvest intensity.

Résumé : Cette étude visait à évaluer l'effet de trois traitements sylvicoles sur la croissance, l'état de santé et la mortalité des arbres résiduels dix ans après la récolte dans 30 peuplements de douglas de Menzies (*Pseudotsuga menziesii* (Mirb.) Franco) âgés de 85 à 125 ans et situés dans les contreforts de la chaîne côtière en Oregon. La coupe de jardinage par groupe consistait à couper 33 % du volume total du peuplement en îlots de 0,2 à 0,8 ha; la coupe de régénération à deux étages consistait à couper 75 % du volume en laissant 20–30 arbres résiduels à l'hectare; la coupe à blanc consistait à couper tous les arbres à l'exception de 1,2 arbre à l'hectare. Dix ans après la récolte, la surface terrière, le diamètre et la croissance en hauteur des arbres ainsi que la largeur et la densité de la cime ne différaient pas selon le traitement sylvicole. Par contre, le rapport de cime vivante était le plus élevé dans la coupe à blanc (0,74) et la proportion d'arbres avec des branches épicormiques était la plus élevée (35 %) dans les peuplements à deux étages. Dans l'ensemble, 45 % des arbres ont eu une croissance en surface terrière plus élevée dans la décade qui a suivi la récolte que dans celle qui a précédé. Les arbres résiduels dans la coupe à blanc et la coupe de jardinage ont connu respectivement le plus haut et le plus faible taux de mortalité (30,6 % versus 0,2 %). Nos résultats indiquent qu'il y a peu de différentiation dans les caractéristiques de croissance des arbres dans trois traitements sylvicoles dix ans après la récolte. Cependant, le pourcentage de mortalité des arbres résiduels augmente avec l'intensité de la récolte.

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Introduction

The Pacific Northwest, particularly the Coast Ranges in Oregon and Washington, holds some of the most productive forestland in North America (Curtis and Carey 1996). Extensive Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) forests in this region have provided trees for more than 150 years to support a valuable commercial logging industry. During the late 1800s and early 1900s, large trees were selectively cut under the perception of a seemingly endless supply of timber (Curtis and Carey 1996). In the middle to late 1900s, intensive forest management, such as clear-cutting and short-rotation plantation management, was used to meet growing demands for wood products (Franklin 1989; Salwasser 1990) and to increase profits through the regeneration of a single, productive tree species (Swanson and Franklin 1992).

Douglas-fir was typically the regeneration species of choice because of its rapid growth rate, tall and straight growth form, and high wood quality (Curtis and Carey 1996; Emmingham 1998). To accelerate stand regeneration, increase tree growth, and protect forest resources, a number of management practices such as vegetation and pest control, fertilization, tree improvement, and fire suppression were used (Perry 1998). As a result, young, densely stocked, multiaged Douglas-fir plantations became common (Spies and Franklin 1991; Barbour et al. 1997; Emmingham 1998).

In the 1980s, concerns developed about the impact that the extensive plantations were having on the range and variability of forest structure and function (Franklin 1989; Spies and Franklin 1991). As a result of public pressure (Curtis and Carey 1996), harvest practices in the Pacific Northwest,

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particularly on federal lands, began to accommodate multiple management objectives that included the maintenance of biodiversity and ecosystem processes (Birch and Johnson 1992; Swanson and Franklin 1992; Franklin et al. 1997; Miller and Emmingham 2001). To meet these objectives, partial harvest treatments that retain both large and healthy as well as old and decadent trees were advocated to bring the structural diversity of managed forests more into line with unmanaged forests (Salwasser 1990; Curtis and Marshall 1993; Hunter and Bond 2001). These alternative treatments have been found to benefit many wildlife species (Hagar et al. 1996; Chambers and McComb 1997; Hayes et al. 1997; Tittler et al. 2001).

Despite the value and increasing use of partial harvests to meet ecological goals, questions remain regarding the effects of alternative silvicultural treatments on residual green trees and stand structure, particularly in mature (>100-year-old) forest stands (Emmingham 1998; Latham and Tappeiner 2002). Residual trees may experience increased mortality rates relative to those in intact forest because of blowdown resulting from wind exposure (Swanson and Franklin 1992; Franklin et al. 1997), harvest damage (Cline et al. 1991; Han et al. 2000; Youngblood 2000; Hartsough 2003), or elevation of the local water table following extensive tree removal (Franklin et al. 1987). Consequently, a better understanding of the creation and management of productive, multiaged forests that include a variety of structural components typical of natural forests will be necessary before alternatives to conventional even-aged management are considered an acceptable option for timber production (Swanson and Franklin 1992; Barbour et al. 1997; Emmingham 1998). The challenge in managing forests for multiple objectives, therefore, is to maintain the ecological integrity of forests while simultaneously protecting the timber resource.

In this study, we quantified 10-year impacts of three types of silvicultural treatments on the growth, death, and structure of residual green trees. Harvests were designed to mimic a range of natural disturbances, such as fire, wind, and tree disease, that historically maintained forest structural diversity in the Pacific Northwest (Spies and Franklin 1991; Curtis and Carey 1996; Franklin et al. 2002). We hypothesized that tree growth would improve as a consequence of relaxed competition when stand density decreased through harvest. We also expected mortality to increase with decreasing stand density, because of reduced protection of neighboring trees against unfavorable environmental conditions.

Materials and methods

Study area and experimental design

This study was undertaken on Oregon State University College of Forestry Integrated Research Project (CFIRP) units in McDonald–Dunn Research Forest in the Oregon Coast Range foothills northwest of Corvallis (Fig. 1a). CFIRP was initiated in 1989 to study the effects of three alternative silvicultural treatments on vegetation and wildlife. At the time of treatment, stands were 85–125 years old. They ranged in size from 5.5 to 17.8 ha and in elevation from 120 to 400 m above sea level. The 30 Douglas-fir-dominated stands studied regenerated naturally to even-aged conditions after elimination of regional burning by Native Americans (Chambers et al. 1997). Additional tree species on the site included grand fir (*Abies grandis* (Dougl.) Lindl.), bigleaf maple (*Acer macrophyllum* Pursh), Oregon white oak (*Quercus garryana* Dougl.), Pacific madrone (*Arbutus menziesii* Pursh), red alder (*Alnus rubra* Bong.), Pacific dogwood (*Cornus nuttallii* Audub.), Oregon ash (*Fraxinus latifolia* Benth.), and bitter cherry (*Prunus emarginata* Dougl.). Common shrubs included vine maple (*Acer circinatum* Pursh), salal (*Gaultheria shallon* Pursh), and Oregon-grape (*Berberis nervosa* Pursh). McDonald–Dunn Research Forest has warm summers and cool winters; most of the annual precipitation falls as rain between October and June (95 cm), and only 5 cm of rain falls in summer (Franklin and Dyrness 1988).

Harvest treatments were implemented between 1989 and 1991 across three blocks (Dunn, Peavy, and Lewisburg Saddle) in a randomized complete block design (Fig. 1b). Silvicultural treatments were designed to mimic fine-, moderate-, and large-scale disturbances (Chambers et al. 1999), to create stand structure more in line with that of historic, mixed-aged forests (Franklin et al. 2002). Treatments consisted of group-selection cuts (18 stands), two-story regeneration harvests (6 stands), and clearcuts with retained green trees (6 stands). In group-selection stands, 33% of the entire stand volume was extracted as patches approximately 0.2–0.8 ha in size. In two-story stands, 75% of the stand volume was removed, and 20–30 dispersed residual trees/ha were retained. In clear-cut stands, all but 1.2 mature green trees/ha were harvested. Before harvest, mean Douglas-fir (diameter at breast height (DBH) > 20 cm) basal area was 38 m^2/ha; after harvest, it was 29 m^2/ha in group-selection stands, 12 m^2/ha in two-story stands, and 1 m^2/ha in clearcuts (Chambers et al. 1997). Lewisburg Saddle was harvested in 1989; Peavy, in 1990; and Dunn, in 1991. Additional study area and harvest information is located in Kellogg et al. (1996), Chambers et al. (1999), and Maguire and Chambers (unpublished data)[3].

Green tree measurements

Plot surveys

In 1992, 1 year after the final CFIRP harvest, 0.08- to 0.4-ha fixed-radius circular plots (*n* = 33) were established in 14 of the 30 study stands to gather baseline information on residual conifers (Douglas-fir, grand fir); 10 group-selection and all clear-cut stands lacked plots. The number of plots per stand, when incorporated, varied between one and five. Within each plot, 2–21 trees (total number, 204 trees) were measured for height, DBH, and live crown ratio (live crown length/total tree height) (J.C. Tappeiner, Oregon State University, unpublished data). Trees were not individually tagged for future identification. In February 2002, all variables were remeasured for comparison with 1992 information on two to eight randomly selected trees per plot in 31 (94%) of the original plots (two plots were not located; of those, one was

[3] C.C. Maguire and C.L. Chambers (*Editors*). College of Forestry Integrated Research Project: ecological and socioeconomic responses to alternative silvicultural treatments. Ore. State Univ. For. Res. Lab. Res. Contrib. In press.

Fig. 1. Locations of the (*a*) Oregon State University McDonald–Dunn Research Forest in Oregon; and (*b*) stands managed by the College of Forestry Integrated Research Project (CFIRP) (*n* = 30) in three blocks within the research forest. Broken lines delineate the CFIRP blocks: Dunn, Peavy, and Lewisburg Saddle.
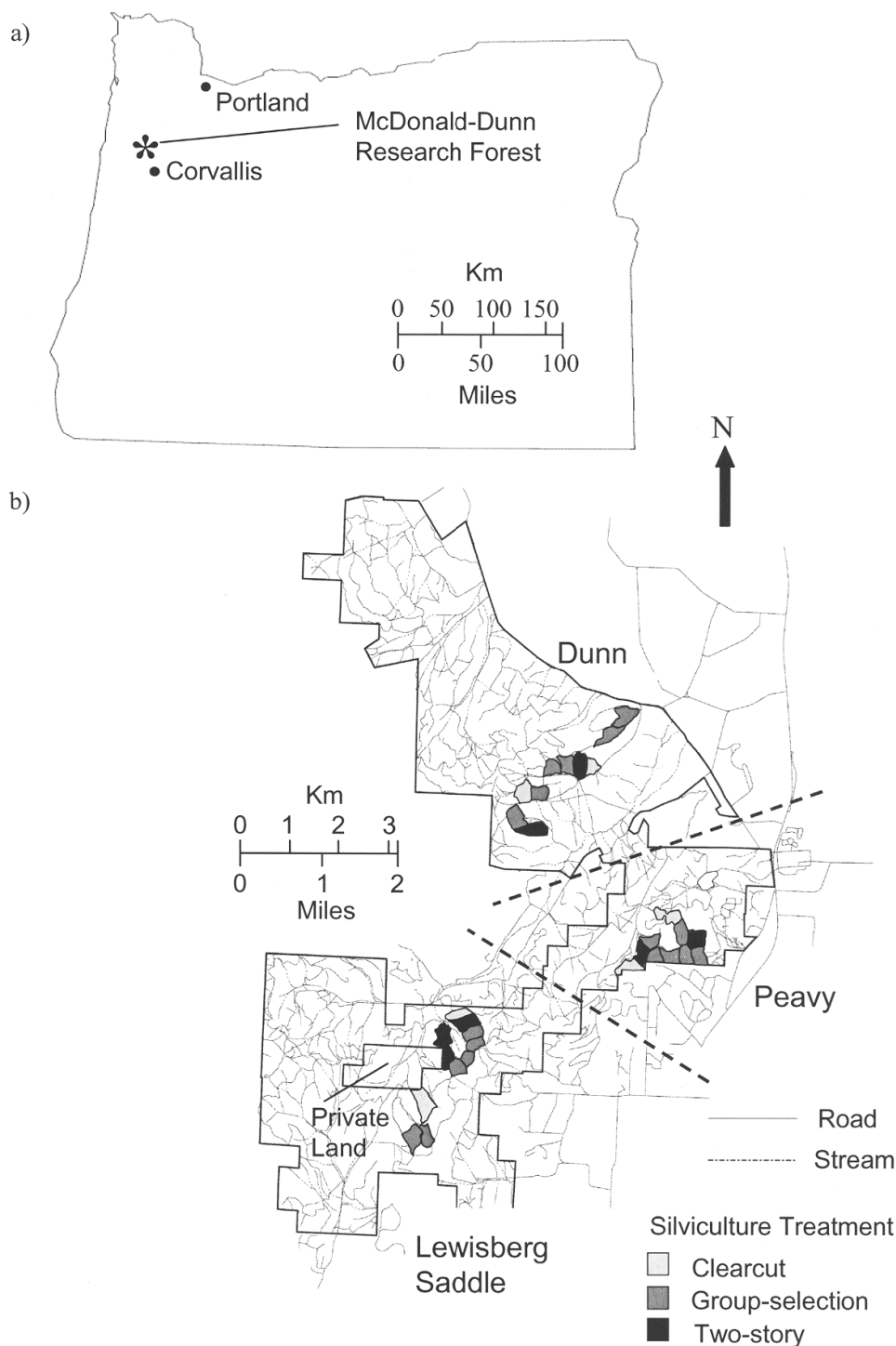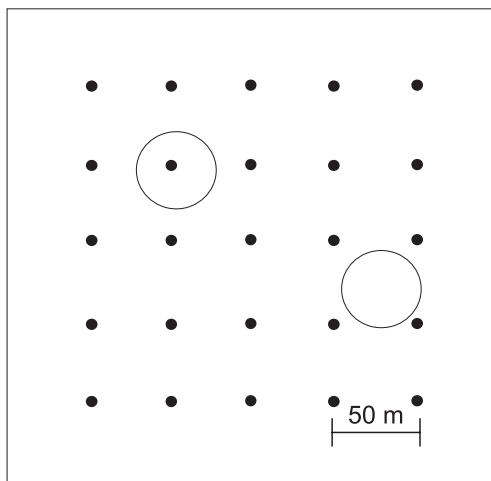

the only plot in a group-selection stand) across 13 group-selection and two-story stands.

Grid surveys

Between November 2001 and February 2002, a permanent grid was established for gathering tree data from all 30 stands and for tagging the individual sample trees for temporal data acquisition. We measured 20–25 conifers (DBH > 10 cm) in each group-selection (*n* = 423 trees) and two-story (*n* = 147 trees) stand by selecting the tree nearest the intersections of a 50 m × 50 m grid (4 ha) overlain on each stand (Fig. 2). Individual trees were not measured more than once. Grids were established 50 m away from stand boundaries. Because of low numbers of residual trees in clearcuts (8–18

Fig. 2. Schematic of plot (open circles; not to scale; number and position vary by stand) and grid (dots) surveys to assess residual green tree growth across study stands that received silvicultural treatments between 1989 and 1991. Randomly located plots (1–5/stand) were established in 14 of the 30 stands at the time of treatment, and grids (entire grid area = 4 ha) were established in all 30 stands in 2001 and 2002. Trees (diameter at breast height > 10 cm) within the 0.08- to 0.4-ha fixed-radius plots were measured in 1992 and 2002, and the tree nearest each grid point was measured between November 2001 and February 2002.

Table 1. Randomized block, one-factor ANOVA model structures used to test for silvicultural treatment effects on growth, size, and condition of residual green trees measured in small fixed-radius circular plots (0.08–0.4 ha) and large square grids (4 ha) in McDonald–Dunn Research Forest, Oregon.

Source of variation	df
Plot surveys[a]	
Block	2
Silviculture treatment (GS and TS)	1
Error (block × treatment)	2
Replication (block × treatment)	7
Total	12
Grid surveys[b]	
Block	2
Silviculture treatment (GS, TS, and CC)	2
Error (block × treatment)	4
Replication (block × treatment)	21
Total	29

Note: Treatments consisted of group-selection (GS) cuts ($n = 18$ stands), two-story (TS) regeneration harvests ($n = 6$ stands), and clear-cut (CC) with reserve green trees ($n = 6$ stands). ANOVA, analysis of variance; df, degrees of freedom.
[a]Trees were measured in 13 of 30 stands.
[b]Trees were measured in all 30 stands.

trees/stand), all trees were measured ($n = 74$ trees). All trees selected for measurement were individually tagged for future identification. Trees were measured for DBH, height (determined with a clinometer and a laser distance finder (Bushnell Yardage Pro® 500, Bushnell Performance Optics, Overland Park, Kansas), mean crown width (the average of two crown widths measured perpendicular to each other; the first width was taken parallel to the stand slope, and crown edges were estimated with the naked eye from the ground), live crown ratio, epicormic branching ratio (length of tree bole below the live crown with epicormic branching/total tree height), and percentage crown fullness (visually estimated and quantified as a visualized complete crown (100%) minus the percentage of crown missing as a result of broken branches (crown raggedness) as calculated with the formula described in Ferrell (1983)).

In addition to the measurements described above, 11–12 randomly selected sample trees per group-selection ($n = 202$ trees) and two-story ($n = 70$ trees) stand and all trees in clearcuts ($n = 74$ trees) were cored to quantify growth rates. Growth rings were measured to the nearest 0.1 mm with electronic calipers for an equal number of years (10, 11, and 12 years for trees in Dunn, Peavy, and Saddle stands, respectively) before and after harvest, for calculating pre- and post-harvest mean basal area growth increment (Avery and Burkhart 1994). Postharvest/preharvest basal area growth ratios <1 represent greater growth before harvest, and ratios >1 indicate greater growth after harvest.

Density and mortality

Mean retained tree (DBH > 10 cm) density in group-selection and two-story stands was calculated from five randomly located 0.1-ha (20 m × 50 m) tree count

plots/stand. In group-selection stands, plots were not located in cut patches. All retained trees (DBH > 53 cm) that had died since harvest were surveyed and identified as snags or blowdowns.

### Statistical analyses

Plot trees

Randomized block, one-factor analysis of variance (ANOVA) (SAS Institute Inc. 1999; PROC MIXED) was used with plot data from the 13 stands with remeasured plots to test for effects of silvicultural treatment (group selection, two story) on residual tree development one decade after harvest (Table 1). Three separate analyses were performed on the mean ratio of 2002/1992 tree DBH, height, and live crown ratio response variables. Responses were averaged over plots within stands to produce a single value for each stand that contained plots. Significant differences were tested at $\alpha = 0.05$; when significance was detected, a Tukey adjustment was used for multiple comparisons.

Grid trees

Randomized block, one-factor ANOVA (SAS Institute Inc. 1999; PROC MIXED) was performed with grid data to test for differences in tree size and condition across the three silvicultural treatments one decade after harvest (Table 1). Separate ANOVAs were used for (1) DBH; (2) height; (3) mean crown width; (4) live crown ratio; (5) epicormic branching ratio; (6) percentage crown fullness; and (7) basal area growth ratio. To assess how the largest and presumably most fit trees (Franklin et al. 2002) were responding to the silvicultural treatments, we repeated the ANOVAs with only the largest 70% of the survey trees (DBH > 48 cm). Further-

Fig. 3. Mean 1992 and 2002 plot survey results for tree (*a*) diameter at breast height (DBH), (*b*) height, and (*c*) live crown ratio across silvicultural harvest treatments (group-selection, *n* = 5; two-story, *n* = 6) implemented between 1989 and 1991. Silvicultural treatments did not significantly affect ($p \geq 0.33$) increases in any of the three response variables (tested as 2002/1992 mean ratios) in the decade since harvest. Multiplicative increases during 1992–2002 are presented above each group of bars; error bars represent 1 SD around means.
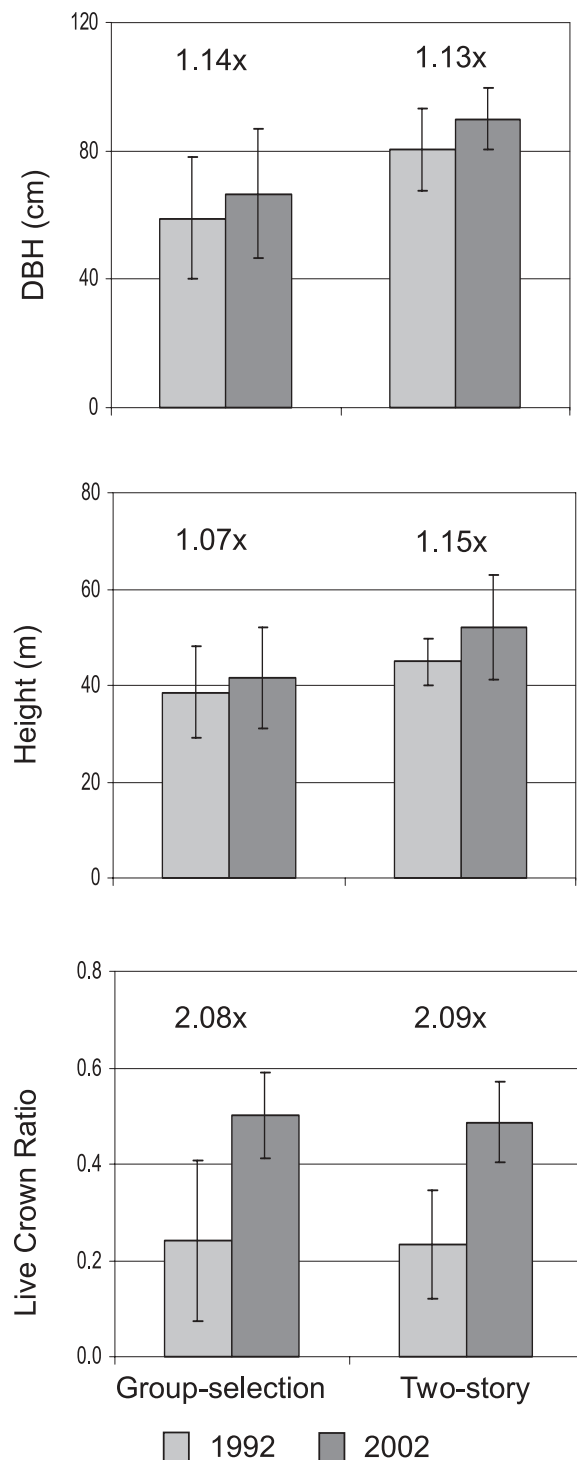
more, a similar ANOVA was performed on diameters at the time of harvest, estimated from tree cores, to determine whether survey trees had similar diameters at the time of treatment. A Tukey adjustment was used for multiple comparisons when significant differences were found at $\alpha = 0.05$. Stand averages were used to standardize for differences in numbers of trees sampled per stand. Data for ANOVAs met statistical requirements of normality and equality of variance, including percentage response variables, and were not transformed for analysis.

A 2 × 3 contingency table (Ramsey and Schafer 1997) was used to test for differences in the number of trees with and without epicormic branches for the largest 70% of the survey trees across silvicultural treatments.

Plot and grid survey comparison

Two-sided paired *t* tests (SAS Institute Inc. 1999; PROC TTEST) were used to determine the comparability of plot and grid survey data and thereby to assess the suitability of using the grid trees for future green tree diameter growth in each stand. Separate tests were used with group-selection and two-story stands to compare 2002 tree diameters obtained from plots and those obtained from grids. Similar tests were used for 1992 tree diameters, but grid survey diameters were estimated from tree core measurements. Significant differences were tested at $\alpha = 0.05$.

Results

Tree growth

Plot trees

Trees in group-selection and two-story stands had similar mean diameter growth ($F_{[1,2]} = 0.11$, $p = 0.77$), height growth ($F_{[1,2]} = 1.61$, $p = 0.33$), and change in live crown ratio ($F_{[1,2]} = 0.0$ $p = 0.98$) after the first decade postharvest (Fig. 3).

Grid trees

Basal area growth ratios of all survey trees and of the largest 70% were similar across silvicultural treatments one decade after harvest (Table 2). The mean postharvest/preharvest basal area growth ratios were 1.08 for group-selection, 1.14 for two-story, and 1.31 for clear-cut treatments. For the largest 70% of the survey trees, the ratios were 0.95, 1.02, and 0.98 for the same treatments, respectively. Overall, 45% of the trees showed greater growth in the decade after harvest than in the decade before (group selection, 40%; two story, 51%; clearcut, 53%) (Fig. 4).

In 2001, tree diameters of the largest 70% of the survey trees did not differ across silvicultural treatments one decade after harvest; there was marginal evidence to suggest that diameters of all trees differed across treatments (Table 2, Fig. 5). For all trees, Tukey's multiple comparison tests indicated that mean DBH in two-story stands was 1.31 times greater than that in group-selection stands ($t_4 = 3.52$, $p = 0.05$), although there were no differences in diameters between clearcuts and group-selection stands ($t_4 = 2.21$, $p = 0.18$) or clearcuts and two-story stands ($t_4 = 0.41$, $p = 0.91$). Diameter estimates from tree cores also provided marginal evidence to suggest that diameters differed at the time of harvest

Table 2. ANOVA results for silvicultural effects on residual green tree attributes 10–12 years after stand harvest in McDonald–Dunn Research Forest, Oregon.

Response variable	All trees (DBH > 10 cm)		Largest 70% of trees (DBH > 48 cm)	
	$F_{[2,4]}$	p	$F_{[2,4]}$	p
Basal area growth ratio[a]	0.49	0.65	0.54	0.62
Crown width (m)	4.06	0.11	1.02	0.44
DBH (cm)	7.39	0.05	5.07	0.08
Epicormic branching ratio[b]	6.12	0.06	4.25	0.10
Height (m)	4.34	0.10	0.90	0.47
Live crown ratio[c]	10.95	0.02	7.43	0.05
Percent crown fullness	0.86	0.49	1.08	0.42

Note: Treatments were group-selection cuts ($n = 18$ stands), two-story regeneration harvests ($n = 6$ stands), and clearcuts with reserve green trees ($n = 6$ stands). ANOVA, analysis of variance; DBH, diameter at breast height.

[a]Basal area growth ratio is expressed as postharvest/preharvest basal area growth.

[b]Epicormic branching ratio is expressed as length of the tree bole below the live crown with epicormic branching/total tree height.

[c]Live crown ratio is expressed as live crown length/total tree height.

($F_{[2,4]} = 6.70$, $p = 0.05$), and diameter trends across treatments noted a decade after harvest mimicked those observed 10 years earlier (two story vs. group selection, $t = 3.35$, $p = 0.06$; clearcut vs. group selection, $t = 2.26$, $p = 0.17$; clearcut vs. two story: $t = 0.89$, $p = 0.67$). Therefore, the marginal differences in 2001 diameters likely are not attributable to silvicultural treatment effects. Tree heights of all survey trees and the largest 70% were similar across treatments one decade postharvest (Table 2, Fig. 5).

Plot and grid survey comparison

Tree diameters for 1992 estimated from 2002 tree cores were similar to diameters measured in 1992 plot surveys in both group-selection ($t_7 = 0.27$, $p = 0.80$) and two-story stands ($t_5 = 0.89$, $p = 0.41$). Similarly, 2002 tree diameters measured in plot surveys were comparable to diameters measured in grid surveys in both group-selection ($t_6 = 0.20$ $p = 0.84$) and two-story stands ($t_5 = 0.79$, $p = 0.46$).

Tree condition

Mean live crown ratios for all grid survey trees and the largest 70% differed across treatments one decade after harvest (Table 2, Fig. 5). For all trees, the mean live crown ratio for trees in clearcuts was 1.32 times greater than that of trees in two-story stands ($t_4 = 4.25$, $p = 0.03$) and 1.29 times greater than that of trees in group-selection stands ($t_4 = 4.35$, $p = 0.03$). There was no difference in ratios between group-selection and two-story stands ($t_4 = 0.37$, $p = 0.93$). For the largest 70% of the trees, the mean live crown ratio in clearcuts was 1.33 times that in group-selection stands ($t_4 = 3.56$, $p = 0.05$). There were no differences in live crown ratios between two-story and group-selection ($t_4 = 3.56$, $p = 0.99$) or clear-cut stands ($t_4 = 3.45$, $p = 0.06$).

For all survey trees and for the largest 70%, tree crown width, percentage crown fullness, and percentage epicormic branching did not differ across treatments one decade postharvest (Table 2, Fig. 5). For the largest 70% of the grid trees, the number of residual green trees with epicormic branching differed across silvicultural treatments ($\chi^2_{[0.05,2]} = 14.77$, $p < 0.0001$). The percentage of trees with epicormic branching in group-selection and clear-cut stands was half that in two-story stands (Table 3).

Density and mortality

Tree density was estimated at 156.7 trees/ha within the matrix of retained forest in group-selection stands, 16.3 trees/ha in two-story stands, and 1.38 trees/ha in clearcuts one decade after harvest. Residual green tree mortality, evident as both blowdowns and snags, occurred across the majority (87%) of study stands (Fig. 6). Among silvicultural treatments, clear-cut stands experienced the greatest overall mean tree mortality (15.3%), and group-selection stands experienced the lowest (0.1%), based on estimated numbers of residual green trees retained at harvest (Chambers et al. 1997) (Table 4).
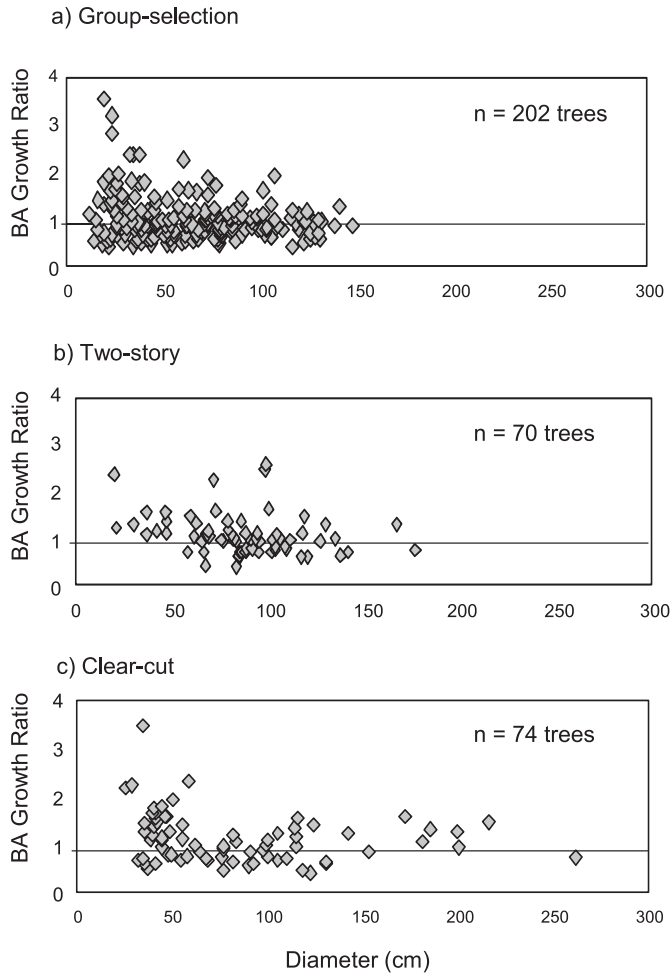
Discussion

Tree growth

Tree growth rates are influenced by a combination of resources that include nutrients, water, and light. Partial harvests can affect tree growth by reducing competition for these growth resources (Harrington and Ruekema 1983; Franklin et al. 1987; Marshall et al. 1992; Smith et al. 1997). Despite the expectation in this study of greater residual green tree growth in two-story and clear-cut stands than in group-selection stands, because of reduced tree competition in the former, tree basal area growth ratio did not differ across treatments one decade after harvest. In addition, 55% of trees did not respond with increased basal area growth over the same period.

Mature conifers, like those in this study, are capable of elevated growth in response to reductions in stand density (Newton and Cole 1987; Youngblood 1991). In a study of thinned (4–38 trees of >75-cm DBH retained/ha) conifer stands (158–650 years old) in the Oregon Coast Range, only 36.8% of the trees had not responded with increased growth one decade after thinning (Latham and Tappeiner 2002). Some studies, however, report a lag time of ≥10 years before a growth rate increase is observed. In southwest Washington, it took Williamson (1982) 19 years after treatment to observe an 8%–30% greater volume growth in 110-year-old thinned Douglas-fir (25%–50% stand basal area removed), compared with unthinned stands; the extended observation period was considered an important factor in the detection of

Fig. 4. Ratios of postharvest/preharvest basal area (BA) growth for conifers (diameter at breast height (DBH) > 10 cm) measured one decade before and after harvest across three silvicultural treatments (group-selection (GS), $n = 18$; two-story (TS), $n = 6$; clear-cut (CC), $n = 6$). Ratios < 1 represent greater growth before harvest, and ratios > 1 indicate greater growth following harvest. Four trees are not graphically presented; their growth ratios are as follows; GS, 12.64 (DBH 29.5 cm); TS, 5.71 (DBH 38.9 cm); and CC, 4.5 (DBH 35.2 cm) and 8.54 (DBH 39.1 cm).

turity and establish codominance or dominance in the canopy, growth rates naturally diminish (Poage and Tappeiner 2002), as indicated from relative basal area growth ratio responses in our study. The highest individual basal growth ratios were mostly associated with small-diameter trees (DBH < 40 cm; Fig. 4), possibly intermediates in the preharvest stands that could have experienced greater release after harvest than the larger dominant and codominant trees. When only the largest 70% of the survey trees were analyzed, mean basal area growth ratios approximated 1, suggesting a fairly constant basal area growth rate for trees in the upper canopy.

Despite the lack of differences to date, basal area growth ratios of the CFIRP residual green trees are expected to diverge across silvicultural treatments in the future. More than a decade after stand density reductions, mature residual trees have shown increased growth relative to trees in dense forest stands. For instance, in a shelterwood seed cut that retained 100 trees/ha in a 160-year-old spruce stand in Alaska, residual tree basal area growth was 10.3% greater than that of trees in an adjacent unharvested stand (494 trees/ha) 14 years after harvest (Youngblood 1991). Also, Latham and Tappeiner (2002) found greater basal area growth in mature and old-growth conifers (DBH > 75 cm) in thinned stands (4–38 trees/ha) than in unthinned stands (24–60 trees/ha) 20 years after thinning in Oregon.

Tree growth is typically greatest in stands with the heaviest uniform thinning prescriptions. This trend is exemplified in a study in southwest Washington that compared residual growth of 110-year-old Douglas-fir in stands with heavy and light thinnings (50% and 25% reductions in basal area, respectively) and no thinning (Williamson 1982). Nineteen years after treatment, individual tree volume growth was 22% greater in heavily thinned stands than in lightly thinned stands; growth rates in both thinning treatments were greater than in unthinned stands.

In our study, retained trees in group-selection stands were clustered within the forest matrix, whereas trees in two-story and clear-cut stands were scattered at low densities throughout the stands. Although basal area growth across treatments was not different one decade after harvest, we predict future basal area growth will eventually be greatest in clear-cut stands, because of low tree competition; and lowest in group-selection stands, because of high competition within the uncut matrix.

differences. The faster growth response in the former study (Latham and Tappeiner 2002) may be explained by the species included in the survey trees. The authors pointed out that the inclusion of ponderosa pine (*Pinus ponderosa* Laws.), with its relatively high growth response, increased overall tree response. In this same study, the magnitude of tree growth progressively increased over time, and the fastest growth occurred 15–20 years after thinning.

The inherently slow basal area growth rates of mature (>100 years old) Douglas-fir trees relative to those of young (<50 years old) ones (Poage and Tappeiner 2002) help explain why differences in basal area growth increment across silvicultural treatments may be difficult to detect one decade after harvest. Young trees typically grow vigorously, particularly after thinning (Williamson and Price 1971), to avoid suppression mortality from competing neighbors (Harrington and Reukema 1983; Peet and Christensen 1987; Marshall et al. 1992; Smith et al. 1997). However, as trees approach ma-

Tree condition

With the exception of live crown ratio and the number of trees with epicormic branching, most tree attributes were similar across treatments one decade after harvest. However, because immediate postharvest data for crowns and epicormic branching are not available for comparison, we cannot attribute the observed differences in the two tree characteristics to silvicultural treatments. Nonetheless, in the interest of meeting multiple stand management goals that include increased stand structural diversity (Franklin et al. 1997; Hunter and Bond 2001), longer crown lengths and higher numbers of trees with epicormic branching can increase tree and crown structural diversity (Berg et al. 1996; Van Pelt and North 1996; Ishii and Wilson 2001; Miller and Emmingham 2001; Ishii and McDowell 2002).

Fig. 5. Mean diameter at breast height (DBH), live crown ratio, basal area (BA) growth, height, crown width, percent crown fullness, and percent epicormic branching ratio of all survey trees (DBH >10 cm, *n* = 452 trees) and the largest 70% of the survey trees (DBH > 48 cm, *n* = 192 trees) across three silvicultural treatments (group-selection, *n* = 18; two-story, *n* = 6; and clear-cut, *n* = 6) one decade after harvest. BA growth during the decade before and the decade after harvest is expressed as postharvest/preharvest growth. Epicormic branching ratio = length of the tree bole below the live crown with epicormic branching/total tree height. Live crown ratio = live crown length/total tree height. Error bars represent 95% confidence intervals around means. Significant differences tested at α = 0.05, as determined from Tukey's multiple comparison tests, are represented by different lowercase letters for all survey trees and by different uppercase letters for the largest 70% of survey trees.
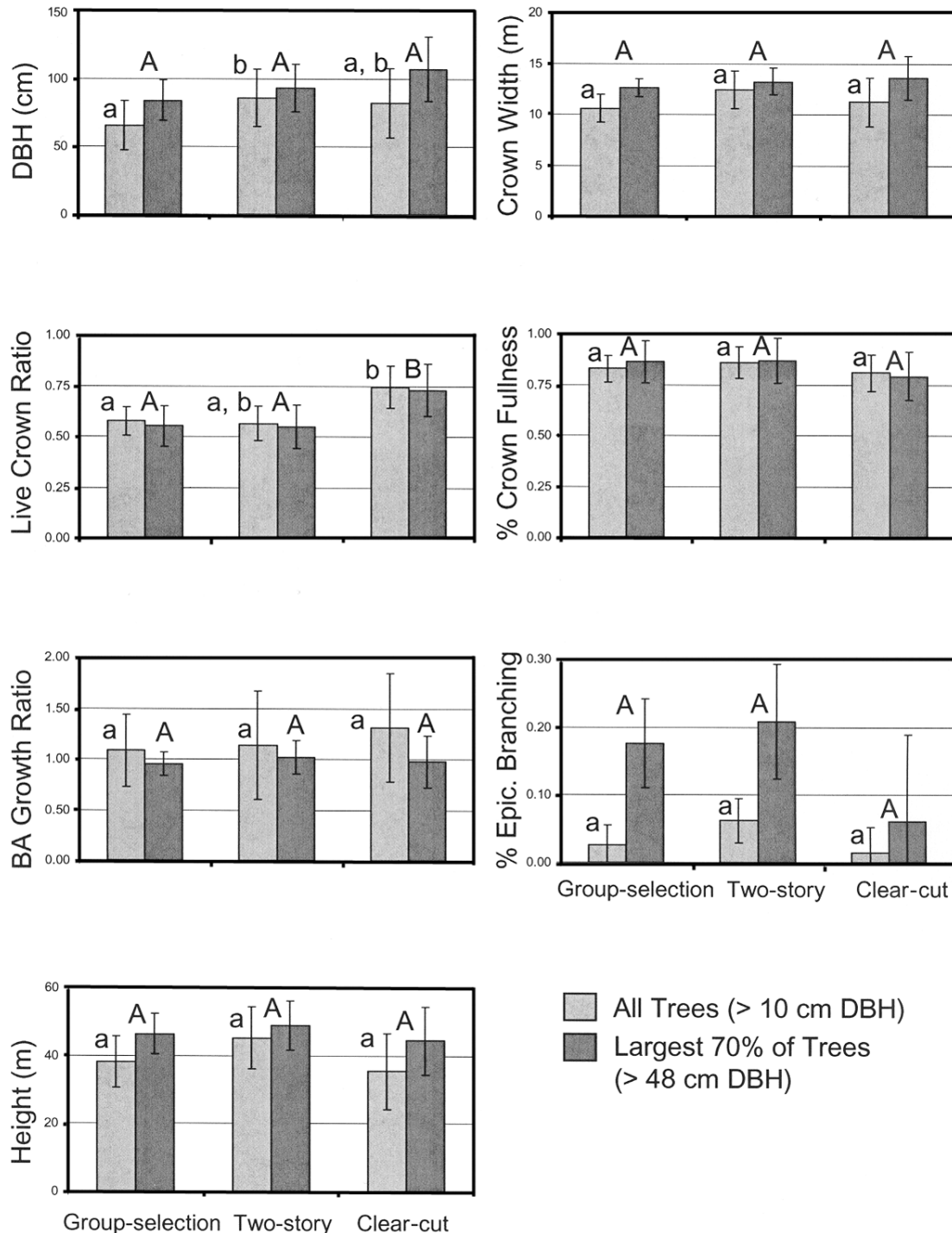
When trees are harvested from closed-canopy stands, increased light levels can affect various residual tree characteristics, such as live crown length (Emmingham 1998; Buermeyer and Harrington 2002). Closed forest canopies limit light penetration to the lower crown and can cause lower branch death and crown recession (Franklin et al. 2002). Open can-

Table 3. Number and percentage of the largest 70% of the survey trees with and without epicormic branching on the tree bole below the live crown across three silvicultural treatments one decade after harvest in McDonald–Dunn Research Forest, Oregon.

Silvicultural treatment	Epicormic branching				
	Trees with		Trees without		Total
GS	50	(18.0)	228	(82.0)	278
TS	44	(34.6)	83	(65.4)	127
CC	8	(17.0)	39	(83.0)	47
Total	102	(22.6)	350	(77.4)	452

Note: Percentages given in parentheses. Treatments consisted of group-selection (GS) cuts ($n = 18$ stands), two-story (TS) regeneration harvests ($n = 6$ stands), and clear-cut (CC) with reserve green trees ($n = 6$ stands).

opies expose the entire crown to light and allow persistence of the lower crown. Maintenance of the live lower crown can lead to longer crown lengths as trees grow in height (Van Pelt and North 1996). In this study, higher live crown ratios in clearcuts relative to group-selection and two-story stands have implications for long-term tree vertical structure, as suggested by Miller and Emmingham (2001). These authors demonstrated that selection thinning (170–353 trees retained/ha) in 50- to 85-year-old stands in western Oregon slowed canopy closure and crown recession and resulted in increased stand structural diversity as a result of the maintenance of lower crowns 16–30 years after thinning. Retention of lower crowns after thinnings, which increase light levels farther down the canopy, may ultimately result in more complex tree crown structure relative to that of trees in dense stands (Berg et al. 1996; Curtis and Carey 1996; Van Pelt and North 1996; Miller and Emmingham 2001; Ishii and McDowell 2002).

In addition to promoting retention of long live crowns, epicormic branching also adds to tree structural complexity (Ishii and Wilson 2001; Ishii and McDowell 2002). Epicormic branches originate from dormant buds under the bark throughout the bole, and they can sprout in response to partial loss of the live crown and (or) increased tree exposure to sunlight and heat (Collier and Turnblom 2001; Franklin et al. 2002). Growth of epicormic branches below the live crown allows trees to reestablish crown lengths reduced by crown recession and partial breakage during windstorms (Spies and Franklin 1991; Emmingham 1998; Franklin et al. 2002). Among silvicultural treatments in this study, two-story stands had the greatest proportion of trees with epicormic branching. In another study, conducted in southwest Washington, in which 18 trees were retained per hectare (similar to CFIRP two-story stand densities), epicormic branching was observed but not quantified on tree boles of 145-year-old Douglas-fir 12 years after thinning (Buermeyer and Harrington 2002). In the CFIRP stands, it is unclear why similar numbers of retained trees with epicormic branching were not found in two-story and clear-cut stands, given that both had open canopies that exposed retained tree boles to light. Branch breakage during harvest also may promote epicormic branching (Cline et al. 1991; Han et al. 2000; Youngblood 2000; Collier and Turnblom 2001; Hartsough

2003), but similar degrees of crown fullness across treatments suggest that differences in crown damage did not cause the higher percentage of trees with epicormic branching in two-story stands.

Tree mortality

Tree fall from wind is a natural process of forest ecosystems (Franklin et al. 1987; Franklin and Forman 1987; Veblen et al. 2001). However, after partial harvest of dense and mature stands, particularly when >30% of the tree volume is uniformly removed, wind easily passes through the stand, and retained trees become more susceptible to blowdown than under preharvest conditions (Franklin et al. 1997; Walter 2003). Among silvicultural treatments in this study, two-story and clear-cut stands experienced substantially greater blowdown (4% and 14% of retained trees, respectively) than group-selection stands (0.1%). In southwest Washington, 7% of Douglas-fir (145 years old) retained at 18 trees/ha had fallen in the 12 years following harvest (Buermeyer and Harrington 2002). In contrast to uniform thinnings, dense aggregates of retained trees in group-selection stands function as windbreaks that can reduce wind speeds within the stand (Franklin et al. 1997). Thus, when silvicultural treatments retain isolated trees in open stands, scattered residual trees tend to be more susceptible to blowdown than trees in groups (Franklin et al. 1997).

In addition to tree density and arrangement within a stand, adjacent areas can influence wind patterns within managed stands (Franklin et al. 1997). Large open areas ranging in size from road clearings to entire clear-cut stands have been identified as wind sources that cause blowdown in neighboring forest stands (Williamson and Price 1971), and the larger the open area that borders forest stands, the greater the opportunity for winds to enter the stand and cause blowdown (Franklin and Forman 1987). In one particular assessment of blowdown across thousands of hectares of forestland in Oregon and Washington, up to 81% of treefall occurred in stands adjacent to open areas (Franklin and Forman 1987). Among the CFIRP stands, three stands (two group-selection and one two-story stand in the Dunn block) that experienced relatively high rates of blowdown bordered a 750-ha farm with open fields. Another two-story stand in the Saddle block that experienced high windthrow was adjacent to both a clearcut and a road clearing. Within-stand blowdown locations were not assessed.

Besides mortality by windthrow, other retained trees in this study died but remained standing as snags. Following harvest, retained trees may experience increased environmental stress that may eventually lead to death (Franklin et al. 1987; Franklin et al. 1997). Trees reduce or limit soil moisture through transpiration and interception and evaporation of rainfall in the crown (Rose 1996; Shaw and Bible 1996). Removal of trees in forest stands can increase soil moisture levels for the first 2 years following harvest (Adams et al. 1991) and render Douglas-fir, which is intolerant of poorly drained soils (Minore 1979), susceptible to death. In Peavy, one low-lying two-story stand experienced high tree mortality. Ruling out insect and disease problems, some local researchers speculate that the water table rose in this stand following harvest (G.M. Filip, Oregon State University, personal communication).

Fig. 6. Number of reserve green trees per hectare in each study stand in 2001 that died (blowdowns and snags) across three silvicultural treatments (group-selection, $n = 18$; two-story, $n = 6$; and clear-cut, $n = 6$) implemented between 1989 and 1991 in McDonald–Dunn Research Forest, Oregon. Stands are listed by block and number. D, Dunn; P, Peavy; and S, Lewisburg Saddle.
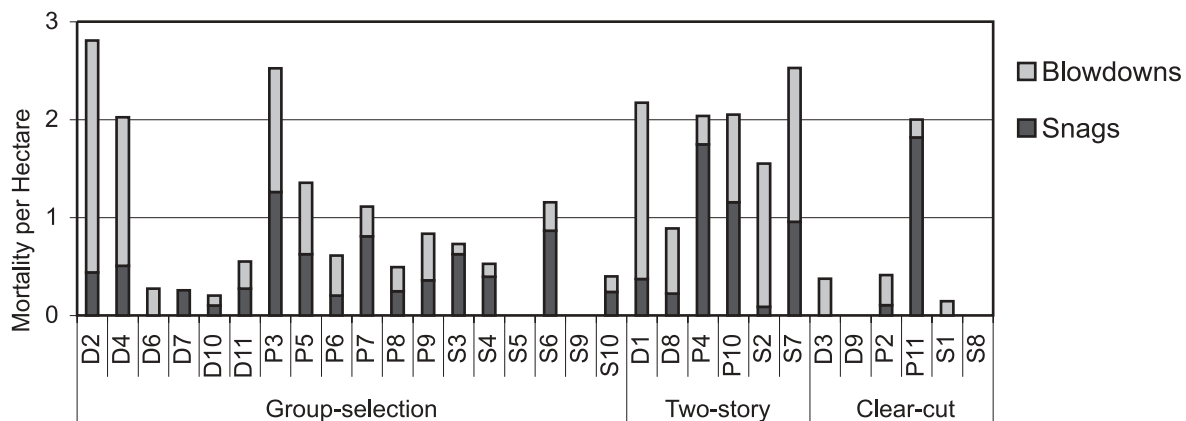

Table 4. Total number, number per hectare, and percent residual green mortality as blowdowns and snags across three silvicultural treatments one decade after harvest in McDonald–Dunn Research Forest, Oregon.

Silvicultural treatment	Blowdowns			Snags			Total mortality		
	n	n/ha	%	n	n/ha	%	n	n/ha	Mean %
GS	86	0.48	0.11	72	0.40	0.09	158	0.88	0.10
TS	90	1.12	4.46	53	0.76	0.30	143	1.88	2.38
CC	9	0.17	14.03	9	0.20	16.60	18	0.37	15.32

Note: Percent mortality is based on estimated numbers of residual green trees retained at harvest (Chambers et al. 1997).Treatments consisted of group-selection (GS) cuts ($n = 18$ stands), two-story (TS) regeneration harvests ($n = 6$ stands), and clear-cut (CC) with reserve green trees ($n = 6$ stands).

Logging damage also contributes to residual green tree mortality in partial harvests. When harvest occurs throughout a stand, falling trees and (or) harvest equipment can damage retained trees (Cline et al. 1991; Han et al. 2000; Youngblood 2000; Hartsough 2003). Consequently, scattered residual trees will experience greater damage than trees retained within intact patches of forest (Moore et al. 2002). Decay organisms may enter tree wounds sustained during harvest (Han et al. 2000; Matzka and Kellogg 2003) and promote tree death (Franklin et al. 1987; Emmingham 1998). Although tree damage was not measured in CFIRP, two-story and clear-cut stands experienced substantially greater tree mortality than group-selection stands (Table 4). Percentages of retained trees damaged during other uniform stand density reduction studies in the Pacific Northwest have been substantial (27%–39%) (Howard 1996; Youngblood 2000).

Management implications

As observed in this study, regardless of the range of harvest intensities and patterns, mature residual Douglas-fir may not show differential growth responses in the first decade after harvest in the Oregon Coast Range. This does not preclude the possibility of greater growth among open-grown trees in clear-cut and two-story stands than among clustered trees in group-selection stands as time progresses.

Alternative silvicultural treatments can also affect the structural attributes of trees. Longer crown ratios and higher numbers of residual trees with epicormic branching appeared to be associated with open-canopy harvests (two-story and clear-cut harvests in our study), as a result of the increased exposure of retained trees to light.

Tree mortality is significantly influenced by harvest intensity and pattern. Trees retained in groups, such as in our group-selection treatment, provide windbreaks that can reduce tree fall relative to isolated trees. Also, because areas adjacent to managed stands may be sources of wind, avoidance of intensive harvests near clearcuts or road clearings may reduce blowdown. Environmental stress (e.g., an increase in the local water-table level) and logging damage also contribute to residual tree death. Their impacts may be reduced by using group-selection harvesting methods rather than uniform harvests, because grouped trees offer greater tree protection from harvest activities and minimize evapotranspiration. Despite losses of timber volume through green tree mortality, however, down logs and snags contribute to stand structural diversity and are beneficial for stand biodiversity.

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