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Forest Ecology and Management 159 (2002) 173–186

Forest Ecology and Management

www.elsevier.com/locate/foreco

The effects of partial cutting on stand structure and growth of western hemlock–Sitka spruce stands in southeast Alaska

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Received 9 September 2000; accepted 11 December 2000

Abstract

The effects of partial cutting on species composition, new and residual-tree cohorts, tree size distribution, and tree growth was evaluated on 73 plots in 18 stands throughout southeast Alaska. These partially cut stands were harvested 12–96 years ago, when 16–96% of the former stand basal area was removed.

Partial cutting maintained stand structures similar to uncut old-growth stands, and the cutting had no significant effects on tree species composition. The establishment of new-tree cohorts was positively related to the proportion of basal-area cut. The current stand basal area, tree species composition, and stand growth were significantly related to trees left after harvest ($p < 0.001$). Trees that were 20–80 cm dbh at the time of cutting had the greatest tree-diameter and basal-area growth and contributed the most to stand growth. Diameter growth of Sitka spruce and western hemlock was similar, and the proportion of stand basal-area growth between species was consistent for different cutting intensities.

Concerns about changing tree species composition, lack of spruce regeneration, and greatly reduced stand growth and vigor with partial cuts were largely unsubstantiated. Silvicultural systems based on partial cutting can provide rapidly growing trees for timber production while maintaining complex stand structures with mixtures of spruce and hemlock trees similar to old-growth stands. Published by Elsevier Science B.V.

Keywords: Partial cutting; Stand structure; Tree growth; Residual trees; Regeneration; Sitka spruce; Western hemlock; Southeast Alaska

1. Introduction

Recent region-wide forest-management plans in Alaska (Record of Decision, 1997) have prescribed guidelines for timber management in southeast Alaska that use alternatives to clearcutting. However, very little is known about forest management in southeast Alaska, other than even-aged silvicultural systems, because clearcutting and even-aged management have been used almost exclusively since the early 1950s (Farr and Harris, 1971; Harris and Farr, 1974). Before undertaking a widespread shift to partial cutting, understanding how regeneration, tree growth, and stand development might occur is essential. In particular, knowing if Sitka spruce (*Picea sitchensis* (Bong.) Carr.) can be maintained in mixed hemlock–spruce stands is important because spruce is much less shade tolerant than western hemlock (*Tsuga heterophylla* (Raf.) Sarg.).

In southeast Alaska, stand development after major disturbances such as clearcutting follows a clearly

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0378-1127/02/$ – see front matter. Published by Elsevier Science B.V.
PII: S0378-1127(00)00727-1

defined pattern; a new cohort of western hemlock and Sitka spruce develops from the establishment of new seedlings and the release of advance regeneration. Tree density is high (>10,000 trees ha^{-1}), the canopy closes in 15–25 years, and a period of stem exclusion begins (Oliver, 1981; Alaback, 1982a; Deal et al., 1991). During this stage of stem exclusion, no new trees regenerate, and other understory vegetation is suppressed for up to 100 years (Alaback, 1982b, 1984; Tappeiner and Alaback, 1989). These dense young-growth stands have uniform tree height and diameter distributions and notably lack the multi-layered, diverse structures of old-growth stands.

Small-scale, low-intensity disturbances are common in the coastal regions of southeast Alaska (Alaback, 1984; Alaback and Juday, 1989; Harris, 1989; Ott, 1997). The ability of the very shade-tolerant western hemlock (Minore, 1979) to release and rapidly grow following overstory removal from small-scale disturbances has been documented in the region (Alaback and Tappeiner, 1991; Deal et al., 1991; Ott, 1997). The response of Sitka spruce to partial cutting is unknown, and spruce's ability to maintain itself in a natural gap-phase disturbance regime was reported to be substantially less than for hemlock (Ott, 1997). Deal et al. (1991), however, found that Sitka spruce regenerated in an all-aged stand with no major disturbances for more than 300 years. Studies in other forest types suggest that small-scale disturbances such as partial cutting often result in stands with multiple canopy layers and complex old-growth stand structures (Lorimer, 1983; Gottfried, 1992; Lertzman et al., 1996). However, the effects of small-scale disturbances on stand structure and species composition in mixed hemlock–spruce stands in southeast Alaska are not well understood.

Partial cutting of forests was a common practice in southeast Alaska from 1900 to 1950, until pulp mills were established in the region. Usually, individual Sitka spruce trees were cut for sawtimber, or western hemlocks were harvested for piling, leaving stands with variable density, species composition, and sizes. We studied 18 of these stands to determine the effects of partial cutting on species composition, tree age, tree size distribution, and tree growth. In particular, we sought to determine if spruce can be maintained in these partially cut stands over a wide range of cutting intensities. To assess any potential changes after partial cutting, we studied the establishment and growth of new-tree and residual-tree cohorts, the density and growth of western hemlock and Sitka spruce trees, and the current stand structure and species composition of partially cut stands.

2. Methods

2.1. Study areas and stand selection

Eighteen stands were selected to sample a range of time since cutting, intensity of cutting and geographic distribution throughout southeast Alaska. Potential study areas were selected from 200+ sites identified from a variety of sources including USDA Forest Service district files, historical records and maps. Study areas were selected under the following criteria: a range of "time since cutting", with study areas selected from stands cut at least 10–100 years ago; stands with only one cutting entry; a partial cut area of at least 10 ha, with an apparent range of cutting intensities at each site, including an uncut area; relatively uniform topography, soils, forest type and plant associations (climax vegetation-based classification) within each stand; and distribution throughout the Tongass National Forest. Research sites were generally near the shoreline, less than 100 m in elevation, and located throughout southeast Alaska (Fig. 1).

2.2. Plot selection, installation, and measurement

We thoroughly surveyed each stand to assess and find a range of current stand densities and cutting intensities, noting the number and size of cut stumps and overstory trees. An uncut control and generally three partially cut areas (light, medium, and heavy) were located in each stand in 1995 and 1996. Plots were centrally located within each area. A total of 73 0.2-ha plots were installed in 18 stands.

Each 0.2 ha plot contained three circular nested plots (0.02, 0.05, and 0.2 ha plots) to sample trees in different size classes (Deal, 1999). All trees, snags, and cut stumps greater or equal to 2.5 cm dbh (1.3 m) were measured in the 0.02 ha plot. Trees, snags, and stumps greater than 24.9 cm dbh were measured in the 0.05 ha plot, and trees, snags and stumps greater than

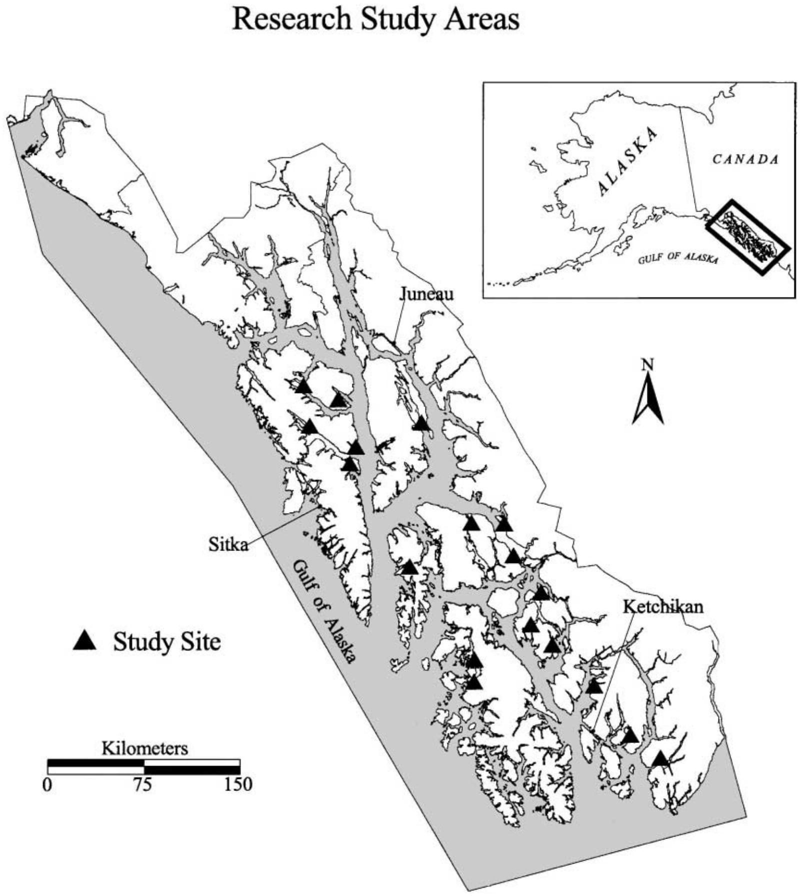

Fig. 1. The 18 study sites in southeast Alaska.

49.9 cm dbh were measured in the 0.2 ha plot. These plot sizes were chosen to provide 10–20 trees per plot in each tree-diameter size class. The 0.02 ha plots had greater variability in tree numbers than the larger plots, and we added two additional 0.02 ha plots at a random bearing 17 m from plot center in each of the large 0.2 ha plots to increase sample size and improve sample reliability.

Tree species, crown class, and dbh were measured for all live trees to provide current stand structural information. Species, dbh, and decay class data were determined for snags to provide information on tree mortality. The diameter of cut stumps at a height of 0.5 m (the highest common stump height) was measured to determine basal area of cut trees. Increment cores or stem sections were taken at breast height from 10 to 20 trees on each plot for each tree species and crown class to determine tree age, diameter and basal-area growth, and cutting date for each stand.

2.3. Procedures for tree-ring data

Tree increment cores and stem sections were measured in the laboratory. Cores were mounted on grooved boards with tracheids perpendicular to the board surface to provide the best resolution of tree-ring boundaries (Stokes and Smiley, 1968). Cores and stem sections were sanded, and tree rings were measured under a dissection microscope using the methods of Swetnam et al. (1985). Each tree's radial growth since time of cutting was calculated. Tree dbh at the time of cutting was determined by using radial-width adjustment equations for off-center cores and species-specific bark thickness equations (Deal, 1999).

2.4. Determination of cutting date and cutting intensity

The date of cutting was determined by using tree-radial growth analyses (Lutz, 1928; Stephens, 1953; Henry and Swan, 1974; Oliver, 1982; Lorimer, 1985; Bailey and Tappeiner, 1998) and verified by historical data, if available. Patterns of tree release indicating an abrupt and sustained increase in growth for at least 10 consecutive years averaging at least 50–100% greater than the previous 10 years (Lorimer et al., 1988) were used to determine the date of partial cutting. Of the 12 stands with historical records, nine stands had cutting dates match within 1 year of the cutting date determined from increase in tree-radial growth. The other three stands, which were cut at least 70 years before the study, had unreliable records, and we determined cutting dates from tree-radial growth and the onset of callus wound tissue around tree scars caused by logging.

We developed stump-to-breast-height equations to predict tree dbh from the stump diameter, by using forward stepwise regression analysis (Snedecor and Cochran, 1980). The basal area of each stump was multiplied by the appropriate plot-expansion factor to determine basal-area cut per hectare for each plot.

The diameter at the time of cutting of current live trees was determined by using increment cores and stem sections from 986 western hemlock, Sitka spruce, western red cedar (*Thuja plicata* Donn ex D. Don), and yellow-cedar trees (*Chamaecyparis nootkatensis* (D. Don) Spach). We developed site-specific regression equations to predict dbh at the time of cutting for all trees, relating dbh at the time of cutting to current tree dbh, basal area, species, and plot cutting intensity (Deal, 1999). These equations ($p < 0.001$) explained 77–99% of the variation in tree dbh at the time of cutting. The basal area of all trees at the time of cutting was multiplied by the appropriate plot-expansion factor to determine stand basal areaper hectare for each plot at the time of cutting.

We used snag class and snag age data to determine the snag dbh at cutting date, and then estimated stand mortality since cutting. Each snag was assigned a decay class, and an average age for each decay class was determined (Hennon et al., 1990; Palkovic, unpublished data). The live-tree regression equations were used for snags, and the snag's dbh was predicted at the date of cutting. Periodic basal-area mortality per hectare was estimated for each plot.

We determined the proportion of stand basal-area cut (PROPCUT) for each plot from

$$\text{PROPCUT} = \left[\frac{\text{CUTBA}}{\text{RESBA} + \text{CUTBA} + \text{MORTBA}}\right] \times 100 \quad (1)$$

where CUTBA is the stand basal-area cut, RESBA the live-tree stand basal area at cutting date, and MORTBA the periodic stand basal-area mortality since the cutting date. We then used the proportion of stand basal-area cut as a continuous variable in regression analyses to analyze changes in tree species composition, tree cohorts, and tree-diameter and stand basal-area growth after cutting.

2.5. Data analysis

To determine the effect of partial cutting on tree cohorts, species composition, and stand basal-area and tree-diameter growth, we blocked plots by stand and tested for differences among cut and uncut plots by using contrast analysis (SAS, 1989). We then blocked plots by stand and determined the effect of cutting intensity on species composition, tree cohorts, and stand basal-area and tree-diameter growth.

Tree cohorts were separated into new-tree cohorts (new regeneration and trees that were shorter than 1.3 m in height at date of cutting, defined hereafter as C-1 trees), and residual-tree cohorts (trees at least 1.3 m tall at date of cutting, defined hereafter as C-2 trees). We used forward stepwise regression analysis to relate the proportion of C-1 tree density and basal area for both hemlock and spruce on stand variables including the stand basal-area cut, stand residual basal area, proportion of stand basal-area cut and residual basal area of different tree species. We regressed the proportion of spruce and hemlock tree density and basal area in the current stand, on stand variables including the stand basal-area cut, stand residual basal area, proportion of stand basal-area cut and residual basal area of different tree species. We also regressed the proportion of stand basal-area growth for C-1 trees in each stand on the previously stated stand variables. We used the arc-sin square-root transformation of proportional data for tree density, basal area and C-1 basal-area growth for all analyses.

We used trees that had grown for 60 years since cutting in 11 stands cut 64–96 years ago to determine diameter growth differences between C-1 and C-2 western hemlock and Sitka spruce, and between C-2 trees of different size classes. Regression models to predict tree dbh 60 years after cutting were developed similarly to the models used to predict tree dbh at cutting date (Deal, 1999). We compared average tree-diameter growth by tree size at the time of cutting, using 20 cm diameter classes for C-1 and C-2 trees. We tested for average diameter growth differences (cut vs. uncut plots) for each diameter class, using a paired-sample *t*-test ($\alpha = 0.05$; Zar, 1996). We also tested for average diameter growth differences between western hemlock and Sitka spruce in the partially cut plots for each diameter class by using a paired-sample *t*-test, $\alpha = 0.05$.

The density and composition of trees in current stands were analyzed by tree cohort and cutting treatment. The frequency of medium (41–70 cm dbh), medium-large (71–100 cm dbh) and large (100+ cm dbh) trees per hectare, were compared for stands after cutting, before cutting, and in the current stand 60 years after cutting. We tested for average frequency differences in each diameter class for stands before cutting, after cutting and in the current stand 60 years after cutting using a paired-sample *t*-test.

3. Results

3.1. Cutting date and cutting intensity

The time from cutting date ranged from 12 years for the stands at Thomas Bay and Granite, to 96 years for Weasel Cove. Of the 18 stands, 13 were cut between 1900 and 1942 and five stands were cut since 1958 (Table 1). The intensity of cutting varied both within and among stands. Cutting intensity varied from an absolute basal-area cut of 85 $m^2\ ha^{-1}$ (96% of original basal area), at Hanus Bay, to only 7 $m^2\ ha^{-1}$ (26% of original basal area) at Portage Bay (Table 1). Some stands had wide ranges in cutting intensity both for the absolute basal-area cut (e.g., Margarita Bay) and in the proportion of basal-area cut (e.g., Elf Point and Granite). Other stands, however, had higher initial basal areas and relatively high residual basal areas left after cutting (e.g., Winter Harbor), and stands like Kutlaku Lake and Salt Lake Bay had relatively small amounts of basal-area cut but grew vigorously after cutting (Table 1). We found that the proportion of stand basal-area cut explained more of the variation in species composition, tree cohort structure, and stand basal-area growth than either absolute basal-area cut or basal area left after cutting.

3.2. Density, basal area and species composition of C-1 trees

Both density and basal area of C-1 trees were greater in cut plots than in uncut plots, and both were positively related to cutting intensity. The average proportion of C-1 trees in cut plots was 35.0% (S.E. = 3.7) and was significantly greater ($p < 0.001$) than in the uncut plots (average = 12.4%, S.E. = 4.1; Fig. 2a). Although the proportion of C-1 trees generally increased with increasing cutting intensity, several cut plots had no C-1 trees (Fig. 3a), particularly in lightly cut stands (e.g., Finger Creek and Big Bear Creek, Table 1). We found a statistically significant increase ($p < 0.001$) in the proportion of C-1 trees with increasing cutting intensity ($R^2 = 0.675$ for transformed tree density). The proportion of C-1 basal area was also significantly greater ($p = 0.0002$) in the partially cut plots (average = 6.3%, S.E. = 1.4) than in uncut plots (average = 0.3%, S.E. = 0.1). In the current stand, the C-2 basal area dominated on all plots, with more than 97% of stand basal area in C-2 trees for plots with less than 50% of the basal-area cut (Fig. 2b). The proportion of C-1 basal area also increased with increasing cutting intensity. The C-1 basal area, however, was a minor component in all the cut plots; even in the heaviest cutting plot (96% basal-area removal), almost half of the current stand basal area was from C-2 trees (Fig. 3b). We found a statistically significant increase ($p < 0.001$, $R^2 = 0.634$ for transformed basal area) in the proportion of C-1 basal area with increasing cutting intensity.

C-1 hemlock trees were consistently more numerous than the C-1 spruce trees. C-1 hemlock trees were found on 78% of the cut plots, and 51% of these plots had more than 200 C-1 hemlock trees ha^{-1}

Table 1
Range of cutting intensity and current stand composition for plots at the 18 research sites

Research site	Cutting intensity[a]				Current stand[b] composition						
	Cutting date (year)	Basal area			Basal area ($m^2\ ha^{-1}$)	Proportion of C-2 and C-1 trees		C-2 trees[c]		C-1 trees[d]	
		Cut (%)	Cut ($m^2\ ha^{-1}$)	Left ($m^2\ ha^{-1}$)		(% Spruce)	(% Hemlock)	Spruce (trees ha^{-1})	Hemlock (trees ha^{-1})	Spruce (trees ha^{-1})	Hemlock (trees ha^{-1})
Thomas Bay	1984	20–29	18–19	42–77	49–70	1–17	83–99	5–117	232–617	0–17	0–17
Granite	1983	18–86	9–51	9–50	13–70	0–7	93–100	0–25	190–1970	0–100	0–1250
Pavlof River	1977	36–58	21–43	31–47	37–69	4–29	42–96	0–113	230–338	0–83	0–233
Big Bear Creek	1958	17–36	9–27	47–63	53–79	15–47	53–85	40–202	228–552	0	0–50
Margarita Bay	1958	23–83	9–48	10–30	41–63	4–24	76–96	42–260	243–947	0–233	283–2117
Rainbow Falls	1942	34–61	15–25	16–29	44–66	0–28	63–100	0–70	110–1060	0–120	0–560
Finger Creek	1941	18–41	11–33	44–51	58–75	5–60	40–95	20–315	207–385	0	0
Winter Harbor	1932	24–38	19–39	56–70	73–95	2–33	67–98	10–262	240–813	0–17	283–550
Salt Lake Bay	1928	48–55	28–35	29–31	63–87	17–73	27–83	25–115	43–437	0–87	0–167
Canoe Passage	1927	16–75	9–57	19–46	44–66	2–13	74–92	17–160	153–1945	0–17	0–917
Elf Point	1927	17–73	12–36	13–57	42–116	2–4	72–96	15–30	200–848	0–33	100–417
Sarkar	1925	27–59	14–28	19–37	57–76	0–11	89–100	0–30	225–583	0–35	0–933
Hanus Bay	1922	49–96	24–85	3–25	56–83	6–62	38–94	25–105	55–433	0–702	0–393
Kutlaku Lake	1920	31–63	17–31	18–37	58–139	5–49	35–95	15–40	65–205	0–133	42–327
Portage Bay	1918	26–65	7–28	14–25	47–56	5–33	67–95	22–218	303–572	0–183	133–350
Florence Bay	1914	50–57	33–38	26–38	56–83	18–75	25–82	25–155	30–205	0–65	0
Glass Peninsula	1911	23–69	15–41	17–47	60–84	11–34	28–83	35–52	62–290	0–73	0–153
Weasel Cove	1900	17–51	9–23	22–45	53–75	0–24	67–100	0–217	287–645	0	17–517

[a] Cutting intensity data are only for the partially cut plots.
[b] Current stand data include both uncut and cut plots; stand data for trees and basal area include all trees that are at least 2.5 cm dbh.
[c] C-2 trees were at least 1.3 m tall at date of cutting.
[d] C-1 trees include new regeneration and trees shorter than 1.3 m tall at date of cutting.

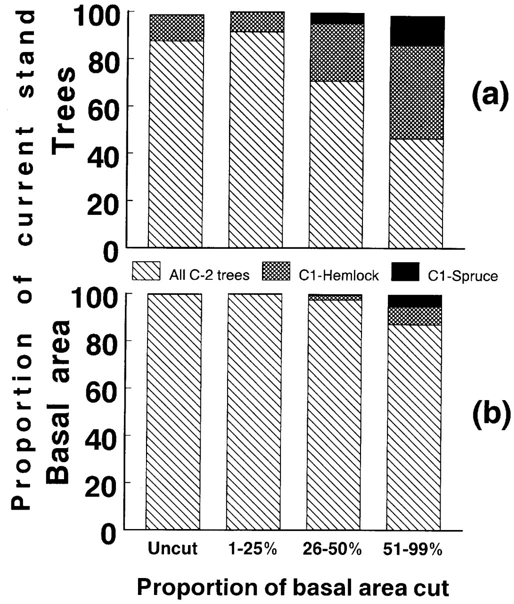

Fig. 2. The proportion of tree density (a) and basal area (b) in the current stand, by cutting intensity class. The tree cohorts shown include all the C-2 cohorts (trees that were at least 1.3 m tall at cutting date), and the spruce and hemlock C-1 cohorts (new regeneration and trees that were shorter than 1.3 m in height at cutting date).

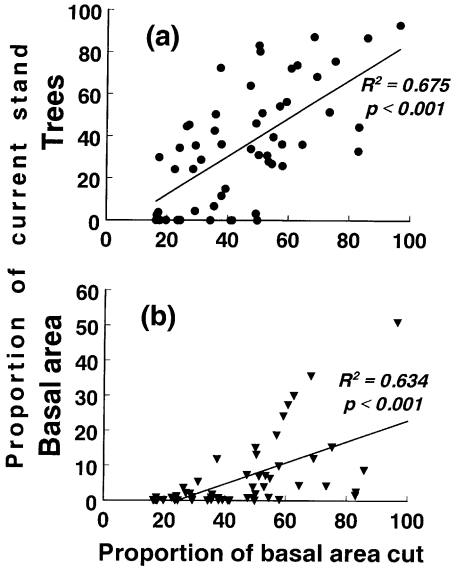

Fig. 3. The proportion of tree density (a) and basal area (b) of C-1 cohorts in the current stand, as a function of cutting intensity for the 55 partially cut plots. The reported R^2 and p-values are the arcsin square-root transformations of proportional data for tree density and basal area.

(Table 2). Many cut plots had more than 500 C-1 hemlock trees ha^{-1} and two stands (Granite and Margarita Bay) had more than 1000 C-1 hemlock trees ha^{-1} (Table 1). The C-1 spruce trees were found on 44% of the cut plots, and 10% of these plots had more than 100 C-1 spruce trees ha^{-1}. More important, C-1 spruce trees were four times more frequent in the cut plots than in the uncut plots. Only 11% of the uncut plots had C-1 spruce trees, and all of these plots had less than 100 C-1 spruce trees ha^{-1} (Table 2). Models for predicting the proportion of C-1 hemlock tree density and basal area were based on the proportion of basal-area cut, and our models explained 65–70% of the variability (Table 3). The model for predicting the proportion of C-1 spruce tree density was based on total stand residual basal area and accounted for 56% of the variability. The model for predicting the proportion of spruce basal area included both the

Table 2
The density and composition of trees of at least 2.5 cm dbh in current stands, expressed as a proportion of treatment plots

Density (trees ha^{-1})	C-2 trees[a]				C-1 trees[b]			
	Uncut		Cut		Uncut		Cut	
	Spruce	Hemlock	Spruce	Hemlock	Spruce	Hemlock	Spruce	Hemlock
0	0	0	15	0	89	61	56	22
1–100	72	6	64	13	11	6	34	22
101–200	22	11	13	18	0	17	5	5
200+	6	83	9	69	0	17	5	51

[a] C-2 trees were at least 1.3 m tall at date of cutting.
[b] C-1 trees include new regeneration and trees shorter than 1.3 m tall at date of cutting.

Table 3
The current stand species composition, tree cohorts, and stand growth regressions fitted to the data to predict the proportion of western hemlock and Sitka spruce tree density and basal area for both C-1 and C-2 cohorts, for C-1 cohorts, and C-1 net basal-area growth in the 55 partially cut plots[a]

Dependent variable	n	B_0	B_1	X_1	B_2	X_2	R^2	p
C-1 and C-2 cohorts								
Western hemlock								
Tree density[b]	55	69.885	0.763	HMRESBA			0.701	<0.001
Basal area[c]	55	90.643	2.196	HMRESBA	−1.549	TRESBA	0.845	<0.001
Sitka spruce								
Tree density[b]	55	23.566	−0.698	HMRESBA			0.758	<0.001
Basal area[c]	55	9.989	2.207	SPRESBA	−0.563	TRESBA	0.845	<0.001
C-1 cohorts								
Western hemlock								
Tree density[d]	55	0.220	0.010	PROPCUT			0.695	<0.001
Basal area[e]	55	−0.012	0.004	PROPCUT			0.650	<0.001
Sitka spruce								
Tree density[d]	55	0.210	−0.006	TRESBA			0.555	0.001
Basal area[e]	55	0.064	0.001	PROPCUT	−0.003	TRESBA	0.478	0.089
C-1 basal-area growth								
Net BAGR[f]	55	0.188	0.004	PROPCUT	−0.005	TRESBA	0.644	0.001

[a] n is the number of observations, B_0 the intercept, and B_1 and B_2 the slope coefficients of the regression line, R^2 the adjusted coefficient of determination, and p the probability value using the F-statistic. HMRESBA is the hemlock residual basal area left after cutting, SPRESBA the spruce residual basal area left after cutting, TRESBA the total residual basal area for all trees left after cutting, and PROPCUT the proportion of stand basal-area cut.
[b] The proportion of trees in the stand.
[c] The proportion of basal area in the stand.
[d] The arc-sin square-root transformation of the proportion of trees in the stand.
[e] The arc-sin square-root transformation of the proportion of basal area in the stand.
[f] The arc-sin square-root transformation of the proportion of net basal-area growth.

proportion of basal-area cut and total stand residual basal area; this model explained only 48% of the variability (Table 3).

3.3. Current tree species composition

Partial cutting appeared to have little effect on tree species composition. The proportion of Sitka spruce trees (C-1 and C-2 trees combined) was similar in the cut (average = 17.5%, S.E. = 2.4) and uncut plots (average = 15.2%, S.E. = 4.4, and the proportion of western hemlock trees was 78.8% (S.E. = 2.7) in the cut and 79.4% (S.E. = 4.9) in the uncut plots. We found no significant difference between cut and uncut plots in either the proportion of hemlock trees ($p = 0.842$) or spruce trees ($p = 0.460$). The species proportions of basal area in the uncut and partially cut plots were also similar. The average proportion of spruce basal area was somewhat less in the cut plots (25.3%, S.E. = 3.0) compared with 35.4% (S.E. = 5.9) in the uncut plots ($p = 0.126$), and the proportion of hemlock basal area was 69.3% (S.E. = 3.2) in the cut plots and 57.8% (S.E. = 6.0) in the uncut plots ($p = 0.064$). Approximately 6–7% of the basal area in uncut and cut plots was in western red cedar and yellow-cedar trees.

The proportions of trees and basal area (C-1 and C-2 trees combined) in Sitka spruce and western hemlock were not closely related to cutting intensity. The proportion of hemlock trees decreased slightly and the proportion of spruce trees increased slightly with increasing cutting intensity (Fig. 4a), but cutting intensity explained only 3–5% of the variation in tree species proportion. The proportion of current stand

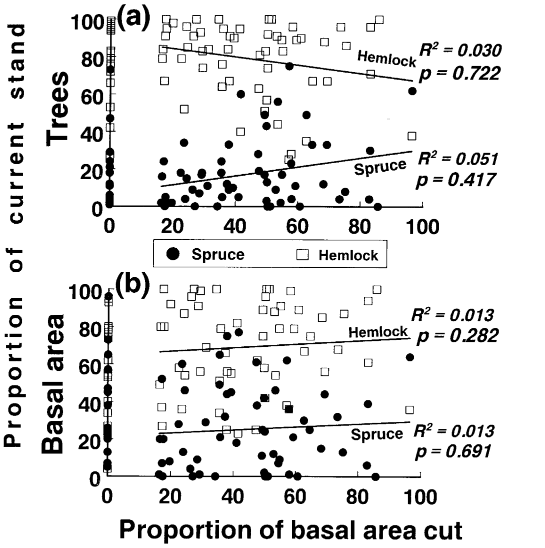

Fig. 4. The proportion of western hemlock and Sitka spruce densities (a) and basal areas (b) in the current stand as a function of cutting intensity. The reported R^2 and p-values are the relation of the proportion of basal-area cut to tree density and basal area, using data from the 55 partially cut treatment plots. Tree density and basal area include combined data from all C-1 and C-2 trees 2.5 cm dbh and greater.

basal area for both hemlock and spruce increased slightly with increasing cutting intensity (Fig. 4b), but cutting intensity only explained about 1% of the variability in basal area. We found no significant relation between cutting intensity and the proportion of either spruce or hemlock trees ($p = 0.417$ and 0.722, respectively) or the proportion of spruce and hemlock basal area ($p = 0.691$ and 0.282, respectively).

The wide variation in current species composition in stands was largely explained by the amount of C-2 hemlock and spruce basal area left after cutting. The proportion of the combined C-1 and C-2 hemlock trees was highly positively correlated with the amount of C-2 hemlock basal area left after cutting ($R^2 = 0.701$, $p < 0.001$), and the proportion of the combined C-1 and C-2 hemlock basal area was explained by the amount of C-2 hemlock basal area and total stand C-2 basal area ($R^2 = 0.845$, $p < 0.001$; Table 3). The proportion of the combined C-1 and C-2 spruce trees was highly negatively correlated with hemlock C-2 basal area left after cutting ($R^2 = 0.758$, $p < 0.001$), and the proportion of the combined C-1 and C-2 spruce basal area was largely explained by the amount of C-2 spruce basal area and C-2 total stand basal area ($R^2 = 0.845$, $p < 0.001$; Table 3).

3.4. Stand growth and growth of different tree cohorts

The net basal-area growth (all stand growth less mortality based on diameter of trees at 1.3 m) was greater in the partially cut plots than in the uncut plots, and basal-area growth generally increased with increasing cutting intensity. The differences in net basal-area growth among stands, however, were significant ($p < 0.01$). Therefore, we blocked by stand and found statistically significant increases in net basal-area growth between uncut and cut plots ($p < 0.001$) and significant increases in growth with increasing cutting intensity ($R^2 = 0.769$, $p < 0.001$).

The proportion of stand basal-area growth was much greater for C-2 trees than for C-1 trees. The C-2 trees accounted for more than 99% of the basal-area growth for plots with less than 26% of the basal-area cut, and more than 95% of the growth for plots with 26–50% of the basal-area cut (Fig. 5). In plots where more than 50% of the stand basal areas were cut, C-1 basal-area growth was greater, but C-2 trees still

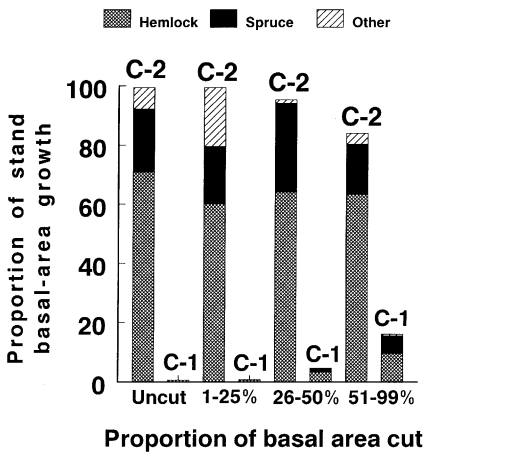

Fig. 5. The proportion of stand basal-area growth by cutting intensity class for Sitka spruce, western hemlock and other species. The other minor species include western red cedar (*T. plicata* Donn ex D. Don), yellow cedar (*C. nootkatensis* (D. Don) Spach), red alder (*Alnus rubra* Bong.), and mountain hemlock (*Tsuga mertensiana* (Bong.) Carr.). The distribution of C-1 and C-2 trees is shown by cutting intensity class and tree species composition.

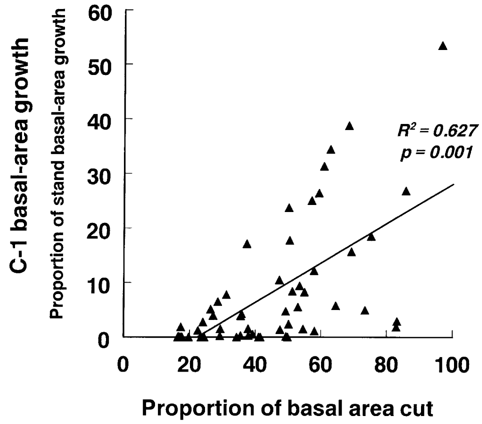

Fig. 6. The proportion of stand basal-area growth for C-1 trees, since date of cutting, as a function of cutting intensity for the 55 partially cut plots. The reported R^2 and p-value is the arc-sin square-root transformation of proportional data for C-1 basal-area growth.

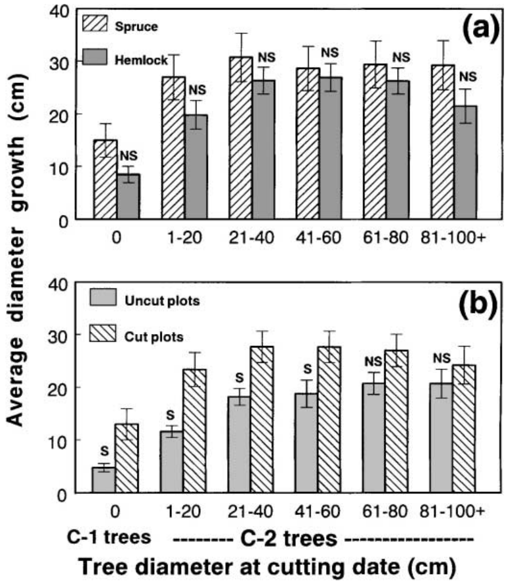

Fig. 7. The average diameter growth for 60 years since cutting for Sitka spruce and western hemlock in the cut plots (a), and in the uncut and partially cut plots (b). The diameters at cutting date are the midpoints of trees by 20 cm diameter classes for C-1 and C-2 trees. Vertical lines represent standard errors, "S" is a significant difference, and "NS" is a non-significant difference ($\alpha = 0.05$) in diameter growth for each diameter class.

contributed over 84% of the stand basal-area growth (Fig. 5). In this study, only one plot had greater than 50% of the stand basal-area growth from C-1 trees, and stand basal-area growth was dominated by C-2 trees (Fig. 6). We found a statistically significant difference ($p < 0.001$) in the proportion of stand basal-area growth between the C-1 and C-2 trees. We also found a statistically significant increase in the proportion of C-1 net basal-area growth with increasing cutting intensity ($R^2 = 0.627$ for transformed basal area, $p = 0.001$). The model for predicting the proportion of C-1 net basal-area growth included both the proportion of basal-area cut and total stand residual basal area, but this model explained only about 1% more of the variability ($R^2 = 0.644$; Table 3) than just the proportion of basal-area cut. The proportion of stand basal-area growth was also consistent for hemlock and spruce. In all cutting treatments, about 60–70% of the stand basal-area growth was on C-2 hemlock trees and about 15–30% on C-2 spruce trees (Fig. 5).

3.5. Diameter growth by species, tree cohorts, and diameter class

Sitka spruce diameter growth was slightly greater than western hemlock growth for all tree-diameter classes, but growth differences between species were not statistically significant ($p > 0.05$) for any diameter class (Fig. 7a). The C-1 60-year diameter-growth average was less than C-2 growth for both hemlock and spruce. The average C-1 growth of spruce was 14.9 cm (S.E. = 3.2) and 8.4 cm (S.E. = 1.5) for C-1 hemlock (Fig. 7a). The C-2 diameter growth rates were generally consistent for both hemlock and spruce in all diameter classes, averaging about 20–30 cm for 60 years.

The diameter growth was also consistently higher in the cut plots than in the uncut plots for all diameter classes. The average diameter growth for 60 years since cutting for C-1 trees was significantly less ($p = 0.022$) in the uncut plots (average = 4.8 cm, S.E. = 0.7), compared with an average of 12.9 cm (S.E. = 0.7) in the cut plots (Fig. 7b). The average diameter growth for C-2 trees 1–20 cm in diameter at date of cutting was 11.5 cm (S.E. = 1.1) in the uncut plots and 23.4 cm (S.E. = 3.2) in the cut plots ($p = 0.005$). The average diameter growth for C-2 trees in the 21–40 and 41–60 cm diameter classes was also significantly higher in the cut plots than in the uncut plots ($p = 0.014$ and 0.039, respectively). The growth of C-2 trees in the 61–80 and 81–100 cm diameter classes, however, did not differ significantly between the cut and uncut plots ($p = 0.119$ and 0.494, respectively).

Analysis of diameter growth for the uncut and cut plots showed that the best growth was from C-2 trees in the cut plots with diameters of 20–80 cm at date of cutting (Fig. 7b). The C-2 trees in the cut plots had a 60-year diameter-growth average of between 23 and 27 cm. The C-1 trees grew the least, with a 60-year diameter-growth average of only 12.9 cm in the cut plots (Fig. 7b).

3.6. Current and former stand structure

Most trees cut were large-diameter spruce trees and more C-2 hemlock than C-2 spruce trees were left in almost all plots (Tables 1 and 2) but usually some large-diameter trees (hemlock, spruce or cedar) were left after cutting. The number of trees in large (>100 cm), medium-large (71–100 cm), and medium (41–70 cm) diameter classes left after cutting averaged 7, 14, and 43 trees ha^{-1}, respectively (Fig. 8). Before cutting, an average of 18, 32, and 64 trees ha^{-1} were in these diameter classes, and we found significant differences ($p < 0.005$) between stands before and after cutting in the number of medium, medium-large, and large-diameter trees. After 60 years, however, the number of trees in these size classes was similar to the stands before cutting, with an average of 16, 29, and 81 trees ha^{-1} in the large-, medium-large-, and medium-diameter-classes, respectively (Fig. 8). The current stands had slightly more trees of medium diameter (+17 trees ha^{-1}) and slightly fewer trees of medium-large (−3 trees ha^{-1}) and large diameter (−3 trees ha^{-1}) than the stands before cutting, but no significant differences were found in the frequency of trees for any diameter class ($p = 0.201$, 0.401, and 0.422, respectively).

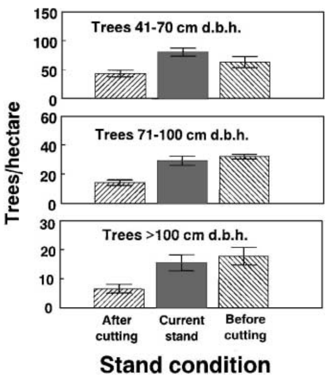

Fig. 8. The numbers of trees per hectare by size classes in the partially cut plots before and immediately after cutting, and in the current stand 60 years after cutting. Vertical lines represent standard errors.

Stands with at least 85% hemlock had higher numbers of trees per hectare than other stands. For instance, the highest density plots at Granite, Canoe Passage and Rainbow Falls were at least 92% hemlock. Also, the highest C-1 densities (1250–2117 trees ha^{-1}) at Granite and Margarita Bay were in plots with at least 95% hemlock (Table 1). Total tree density and density of hemlocks were substantially less in stands where spruce comprised at least 12% of the trees. Stands with the highest proportion of spruce were those with the lowest density (120–372 trees ha^{-1} at Florence Bay, Kutlaku Lake and Salt Lake Bay; Table 1). Most of the unexplained variation in species composition was probably related to differences in regeneration among stands. For example, at Margarita Bay and Hanus Bay, hundreds of C-1 hemlock and spruce trees per hectare were established after partial cutting (Table 1). Other stands, such as Big Bear Creek and Finger Creek had numerous C-2 trees that grew rapidly after partial cutting and prevented C-1 spruce and hemlock from becoming established in the stand (Table 1).

4. Discussion

The results of this study strongly indicate that silvicultural systems using partial cutting can be successfully applied to maintain spruce in mixed western hemlock–Sitka spruce forests in southeast Alaska. Our results show that the establishment of new regeneration (C-1 trees) and the growth of larger pre-existing trees (C-2 trees) of both hemlock and spruce can maintain species composition and stand structures similar to that of study plots before cutting.

New regeneration was generally plentiful on cut plots; however, most C-1 trees were hemlock (Tables 1 and 2). Heavy cutting intensity favored establishment of both species and C-1 trees were always established in plots with at least 50% or more of the basal-area cut (Fig. 3a). However, some of the lightly cut plots had no C-1 trees and instead of the establishment of a new cohort it appears that C-2 trees expanded their crowns and filled in the available growing space. C-1 spruce trees were found on 44% of the cut plots and on only 11% of the uncut plots (Table 2). The variation in establishment of C-1 spruce trees may be explained by differences among stands in seed availability, or differences in regeneration related to the presence of advanced regeneration, soil disturbance from logging, and competition from shrubs and C-2 trees. It appears that many of the C-1 trees came from seedling banks (Grime, 1979). Yount (1997), who studied spruce and hemlock seedling population on these same sites, found that the numbers and composition of seedlings on cut plots was generally the same as on the uncut plots. Spruce density ranged from 3000 to 114,000 seedlings ha^{-1} and hemlock density ranged from 47,000 to 723,000 seedlings ha^{-1}. Both species were common on logs. Spruce seedlings were found at all sites except one where there was a dense hemlock overstory. It is also important to note that spruce regeneration is not always established after clearcutting, and the relative proportion of C-1 spruce and hemlock found in this study was within the range of reported data from Tongass NF regeneration surveys following clearcutting (USFS regeneration and survival data on file at Forestry Sciences Lab). These results indicate that partial cutting can generally enable regeneration of spruce and hemlock, and that in contrast to other opinions (Andersen, 1955; Harris and Farr, 1974) spruce will regenerate after partial cutting.

C-2 trees of both species in all size classes responded to partial cutting by increasing diameter growth. Sitka spruce consistently grew more rapidly than western hemlock, but growth differences were not statistically significant (Fig. 7a). Diameter growth was significantly greater in cut plots compared to uncut plots (Fig. 7b). The current stand basal area, tree species composition, and stand growth for all cutting intensities was strongly related to trees left after harvest. The C-2 trees (either large residuals or small advance regeneration) grew rapidly after partial cutting and were a significant and dominant component of the current stand. These results run contrary to conventional knowledge about partial cutting in southeast Alaska, that residual trees left after partial cutting are of poor quality and low vigor (Harris and Farr, 1974). These researchers also speculated that these trees would lead to significant reduction in future yields. However, release of residual western hemlock trees after overstory removal has been well documented in other regions (Meyer, 1937; Williamson and Ruth, 1976; Oliver, 1976; Tucker and Emmingham, 1977; Wiley, 1978; Hoyer, 1980; Jaeck et al., 1984). Some researchers report poor height growth of residual hemlock trees (Williamson and Ruth, 1976; Jaeck et al., 1984), and the advance regeneration tended to be crooked and of poor quality (Jaeck et al., 1984). Prior to this study, little research has been conducted on the ability of advance regeneration Sitka spruce to respond to release. In another reconstruction study, Deal et al. (1991) reported the establishment and rapid growth of some spruce trees after partial stand blowdown. These spruce grew rapidly in height and reached the mid to upper canopy of the stand but few spruce survived in the lower canopy layers. In this study, we found that C-2 trees responded with rapid and sustained growth after overstory removal, and that the diameter growth of spruce trees was slightly but consistently greater than for hemlock trees (Fig. 7).

It appears that with careful tree selection and regulation of stand density it will be possible to maintain diverse tree size structures with silvicultural systems that use partial cutting. The basal area and species composition left after cutting explained about 70–85% of the variation in density and basal area of hemlock and spruce (Table 3). Immediately after cutting there were few trees on our plots greater than 70 cm dbh, and these cut stands had very different tree size structures than the old-growth stands prior to cutting (Fig. 8). Sixty years after cutting, however, these stands had similar numbers of large-sized (>100 cm dbh) trees compared with the old-growth stands, and these similar structures were largely a result of the growth of the medium-diameter (70–100 cm dbh) trees into the larger diameter classes. This result is particularly important to replace large-diameter trees that are cut. When the goal is to maintain stand structures similar to those in old-growth stands, it will be important to select individual or groups of trees of both species in large or medium-large size classes to leave. Tree and stand growth may also increase, if vigorous spruce and hemlock trees are left after cutting. In addition, maintaining some large spruce as seed trees, thinning overstocked patches of hemlock, and planting spruce in some cases would increase or maintain spruce densities. Thus, by thoughtfully implementing normal silvicultural practices, new silvicultural systems could be developed to further enhance desirable tree species composition, provide productive stands for timber, and also maintain diverse stand structures similar to old-growth forests.

It is important to remember that the stands we studied were cut to provide specific wood products such as spruce sawtimber and hemlock pilings. Cutting occurred without a planned silvicultural system with little effort taken to ensure spruce regeneration, stand growth, or maintenance of complex stand structures found in old-growth forests. Nevertheless Sitka spruce was maintained in these stands and greatly reduced stand growth did not occur. We also found similar tree size structures in these current stands that developed following partial cutting compared with the original old-growth forest. Therefore, well-planned silvicultural systems based on partial cutting could provide rapidly growing trees for timber production and maintain complex stand structures with mixtures of spruce and hemlock trees similar to old-growth forests.

Acknowledgements

This project is a contribution from the USDA Forest Service study, alternatives to clearcutting in the old-growth forests of southeast Alaska, a joint effort of the Pacific Northwest Research Station, the Alaska Region, and the Tongass National Forest. We thank our field crew and research associates, David Bassett, Ellen Anderson, Louise Yount and Pat Palkovic. We are grateful for the review of earlier versions of this paper from Mike McClellan, Steve Tesch, Pat Muir, Bruce McCune, Charley Peterson, and Dean DeBell and the technical editing of Martha Brookes.

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