

FOREST SERVICE
U. S. DEPARTMENT OF AGRICULTURE
P.O. BOX 245, BERKELEY, CALIFORNIA 94701

PACIFIC SOUTHWEST Forest and Range Experiment Station



Growth and Mortality after Regeneration Cuttings in Old-Growth Redwood

Kenneth N. Boe

CONTENTS

	<i>Page</i>
Summary	1
Introduction	3
The Study	3
Methods	4
Results	5
Impact on Reserved Trees	5
Growth	7
Discussion and Conclusions	11
Application	13
Literature Cited	13

The Author

KENNETH N. BOE was formerly in charge of the Station's research unit on the silviculture of redwood and associated species, with headquarters at Arcata, California. A native of Montana, he earned bachelor's (1946) and master's (1948) degrees in forestry at Montana State University. He joined the Station in 1956 and retired in March 1974 after more than 33 years in Federal service. He is currently engaged in teaching and consulting work.

SUMMARY

Boe, Kenneth, N.

1974. **Growth and mortality after regeneration cuttings in old-growth redwood.** USDA Forest Serv. Res. Paper PSW-104. 13 p., illus. Pacific Southwest Forest and Range Exp. Stn., Berkeley, Calif.

Oxford: 174.7 *Sequoia sempervirens*: 221.2:228

Retrieval Terms: *Sequoia sempervirens*; regeneration cuttings; stand development; logging damage; mortality.

Growth and mortality factors associated with three regeneration cutting methods—clearcutting, shelterwood, and selection cutting—were studied during an investigation of the most effective way to convert old-growth redwood (*Sequoia sempervirens* [D. Don] Endl.) into younger managed stands. Each method was tried twice on the Redwood Experimental Forest, Del Norte County, in north coastal California. The clearcuttings were in small blocks of 10 to 20 acres and alternated with reserve seed blocks about the same size. Like the shelterwood cuttings, they will result in even-aged stands. On each shelterwood, about 75 percent of the merchantable volume was harvested in the first cutting; on one half of each shelterwood all the overstory will be harvested after reproduction is established; on the other half the overstory will be removed in two cuts about 10 years apart. The selection method is aimed at producing and maintaining uneven-aged forests by recutting every 10 years for a planned rotation of 80 to 100 years.

In these old-growth stands, crown improvement to reserved redwood a few years after harvesting was highly variable. There was no consistent tendency of crowns to improve or decline more on the shelterwood than on the selection cuttings.

Mortality of reserved trees caused by logging was in direct proportion to the volume cut. Where about half the volume was harvested on selection cuttings, 20 percent of sawtimber, 70 percent of pole timber, and 80 percent of saplings were killed. But where 75 percent was cut on the shelterwood, the losses were 50 percent of sawtimber, 90 percent of poletimber, and 90 percent of saplings.

The implications of growth in basal area and cubic volume vary with the kind of regeneration cutting. On clearcuttings, since few if any residual trees remain, the basal area and cubic volume growth accrue on the new young stand 5 or more years after regeneration is established. For the shelterwood method,

the reserved sawtimber stand is kept for a short period; therefore, growth on these trees is short-term gain. On selection cuttings, however, it is theoretically possible to have a continuous intermixed producing and regenerating forest—but proportions differ between old and young stands.

For sawtimber trees, the selection cuttings had a larger negative net basal area growth than did the shelterwood, because mortality was high on the selection. Even increment on surviving trees on both cuttings was only poor to fair, considering the voluminous growing stock. As expected, net growth on the uncut stand was near zero because of mortality.

On all the cuttings, net growth of poletimber was slightly positive or nearly so mainly because of ingrowth. Mortality was a significant amount.

For saplings, the increment and ingrowth were already one-half or more of that on the heavy sawtimber growing stock of corresponding shelterwood cuttings and one-eighth or more on selection cuttings, by the end of the second growth period. Because of well-stocked reproduction, increment and ingrowth were relatively large on the clearcuttings.

Growth of sawtimber in terms of cubic volume paralleled that for basal area. High mortality resulted in negative net growth; the largest was on the selection cuttings. Increment on surviving trees was fair on a per acre basis, but very poor as a percent of growing stock.

On poletimber, net cubic volume was largely the result of ingrowth from saplings. The largest amounts were measured on the two clearcuttings. And increases would probably be at an accelerating rate.

For redwood, the diameter was significantly correlated with age. Therefore, initial diameter was a principal independent variable for analyzing diameter growth after harvesting. Crown change and competition from other reserved trees as expressed by basal area were inadequate variables to account for diameter growth in multiple regression equations.

During the first postlogging period (about 5 years), diameter growth accelerated on redwood trees less than 100 inches (254 cm) d.b.h, and rate decreased as diameter increased on all but one cutting. The same acceleration pattern prevailed during the second postlogging period of 5 years and on all cuttings. The growth, by diameter class, however, was at a higher level on the uncut stands during the second than during the first period. This difference suggests a climatic effect; part of the higher level of growth on the regeneration cuttings was probably due to climate.

Since diameter was significantly correlated with diameter increase on the individual cuttings, a single equation was computed for all cuttings and for both growth periods. This equation may be used on other cutover stands of site class I for redwood having similar stand characteristics to predict diameter growth by which the future stand volume may be computed:

$$Y = 4.009 - 0.026X$$

in which Y = diameter growth ratio for a 10-year period and X = initial d.b.h. (inches).

The forest manager responsible for harvesting stands of old-growth redwood (*Sequoia sempervirens* [D. Don] Endl.) has a choice of regeneration cutting methods. If he wants to develop and maintain an uneven-aged forest, he would choose the selection method. If his objective is even-aged management, then his choices would be shelterwood, seed tree, or clearcutting. To decide, he has to consider many factors. Among them are the growth and mortality of the reserve and new growing stock.

In the past, the timber industry varied its cutting practices in old-growth redwood from what was essentially clearcutting, adopted before 1930, to selective cutting, which was used until about 1960. Shaw (1932) proposed a deliberate saving of seed trees and documented that higher grades of lumber could be attained in the future from small trees reserved from cutting than from new young-growth. Furthermore these small trees had negative value when cut, and if left they would accelerate their growth. Person (1947) reported similar results supporting selective cuttings in which the financially immature trees were left. And Fritz (1951) developed additional evidence of the great potential for growth acceleration by the suppressed trees left after cutting old-growth redwood. In present industry operations, however, economic changes have made clearcutting feasible. Fur-

thermore, artificial regeneration, and in the right situations, natural regeneration, are considered quick, sure means of starting new crops. Some industrial foresters, however, are continuing selective harvesting of old-growth to capitalize on growth of reserved trees and to obtain natural regeneration for the new crop.

To obtain information about growth of reserved stands, the Pacific Southwest Forest and Range Experiment Station started test regeneration cuttings on the Redwood Experimental Forest in northern California in 1959, and completed the first series in 1960 and the second series in 1964. Two remeasurement periods have now passed. During the first period after harvesting we usually expect heaviest mortality. In an earlier report I summarized findings on wind mortality (Boe 1965).

This paper documents logging mortality and damage and growth and mortality following three types of cuttings: clearcutting, selection, and shelterwood. Annual increment of the reduced sawtimber volume in selection and shelterwood cuttings was below that in the uncut stand. Average net growth—especially on the selection cuttings—was strongly negative because of high mortality. Net growth and increment of saplings and poles began to be a significant amount in the second period—particularly on clearcuttings—because of ingrowth.

THE STUDY

A major goal of the study was to analyze growth and mortality associated with regeneration cutting methods that could effectively convert old-growth redwood into younger managed stands. For the experiments, three methods were tried in each of two areas.

The first method was clearcutting (*fig. 1*) of all sawtimber in small blocks ranging in size from 10 to 20 acres and alternated with reserve seed blocks about the same size. This method results in future even-aged young stands.

The second method was a shelterwood cutting (*fig. 1*), which also results in even-aged new stands. About 75 percent of the sawtimber volume was harvested. Vigorous codominant trees were reserved to help protect the site, furnish seed, and add growth.

After reproduction was satisfactorily established, all of the reserved overstory was to be removed on one half of each shelterwood cutting. On the other half, the overstory was to be removed in two equal cuts—the first after reproduction was established, and the second about 10 years later. Because regeneration was adequate, and windfalls required salvage, shelterwood cutting A was reharvested in 1965. Shelterwood cutting B was scheduled for reharvesting in 1974, the planned 10 years after the first cutting.

The third method, selection cutting (*fig. 1*), is aimed at producing and maintaining uneven-aged forests. The first harvest removed about 50 percent of the volume in sawtimber of all sizes. Selected larger older trees were cut on about 10 percent of the area and additional smaller trees were cut because they

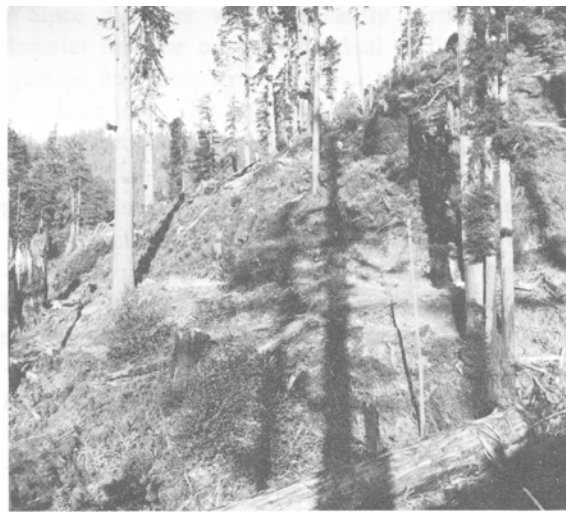


Figure 1—Reserved growing stock after regeneration cuttings ranged from none on the clearcutting (upper left) and light on shelterwood (upper right) to moderate on the selection cutting (lower left). The uncut stand (lower right) illustrates full stocking.

were defective or dying, or had to be removed to provide space to fell the larger trees. The reserved trees of all sizes tend to be arranged either in groups or alone and are unevenly spaced throughout the stand. The selection cuttings were to be reharvested

every 10 years with a planned rotation of 80 to 100 years. The windfalls were salvaged on selection cutting A in 1965 after 5 years, but selection cutting B was to be recut in 1974–10 years after the initial harvest.

METHODS

To study the growth and mortality on these series of cuttings, 0.4-acre (0.16-hectare) sample plots were randomly located on each of the cuttings. There are 10 plots on each of two shelterwood and two selec-

tion cuttings, five plots on each of four clearcuttings, and eight plots in the adjacent uncut reserve stands. On each of the growth plots, all redwood and Douglas-fir were measured. Other species were measured

on a subsample of one-quarter of each growth plot. All plots were established before the cuttings to permit an evaluation of the impact of cutting on the reserve trees.

The initial information recorded consisted of measurements of diameter and of merchantable and total heights of a subsample of trees; descriptions of crown vigor and sizes; and estimates of the kind and amount of understory vegetation. From the crown estimates, made initially and after one remeasurement, I computed a crown index which is a numeric expression in whole numbers of the product of tree crown relative length, relative width, and density. Length and width were estimated as a percent of the total height of each sample tree. Arbitrarily, I assigned the value 3 to a dense foliage crown, 2 to medium, and 1 to thin and open. A typical crown index is $50 \times 25 \times 2 = 2500$.

After logging was completed, we made several remeasurements. First, we recorded the kind and amount of logging damage before burning slash on the cuttings. Then after an interval of 4 or 5 years the

diameters of trees were redetermined—by tape on trees generally 24 inches d.b.h. and less and by increment borings on the larger trees, with no allowance for bark growth. The crowns were reestimated for length, width, and vigor. Mortality was noted and new trees that exceeded the minimum measurable size, i.e., ingrowth, were recorded.

Growth was analyzed in two principal ways: (1) an evaluation of basal area and cubic volume growth on reserve and new trees in the cuttings, relative to each other and to growth in the uncut stands, and (2) an analysis of redwood diameter growth by regression.

For evaluation of basal area and cubic volume growth, the individual tree data were calculated by plots and all species were combined. The growth components are (a) increment on surviving trees, (b) mortality, and (c) ingrowth into the size group being considered. Cubic volume growth was calculated for sawtimber (trees 11 inches d.b.h. in size and larger) and for poletimber (trees 5 to 10.9 inches d.b.h.). Basal area growth was determined for saplings (1 to 5 inches d.b.h.), poletimber, and sawtimber.

RESULTS

Impact on Reserved Trees

Crown Change

The crown indexes after 5 or more years showed there was no consistent pattern of crown improvement (*fig. 2*). On shelterwood A there were general declines in crown areas; on shelterwood B, a slight improvement; on selection A, a definite improvement; and on selection B, a definite decline. These ratings are evidence that short-time change of old-growth redwood crowns by epicormic and other needle and branch growth is highly variable between cuttings and for all crown sizes.

Logging Damage

The principal logging damage was the immediate death of a sizeable portion of the intended sawtimber reserve—21 to 22 percent on selection and 49 to 57 percent on shelterwood cuttings (*table 1*). Logging also caused destruction of many smaller trees, much of it unavoidable: on selection cuttings about 70 percent of saplings and 62 percent of poletimber; on shelterwood about 82 percent of saplings and 80 percent of poletimber. Nearly all poletimber and saplings on clearcuttings were also killed, but they were usual-

ly considered unneeded or expendable during slash disposal. This damage is from felling, bucking, building tractor layout and skidroads, and skidding logs. This damage is instant loss of growing stock. And although most of the sawtimber trees were utilized, the reduction greatly changed the intended differences between cuttings. The level of losses was in direct proportion to the level of cut—heaviest for the 75 percent cut on the shelterwood and least for the 50 percent cut on the selection area. During a given season, the same crew worked on both selection and shelterwood cuttings; therefore, its logging techniques were judged to be alike irrespective of regeneration method.

The nonfatal damage to the residual growing stock has impact of a different kind on future growth. This impact, such as rot encroachment on debarked portions of trees and in broken tops, will require separate study and evaluation. The listing of damage (*table 1*), however, suggests its extent and possible potential for growth loss. Debarking was proportionately the greatest of all nonfatal damage on sawtimber on both the selection and shelterwood cuttings. Many of these trees will be held through several cutting cycles, hence there will be opportunity for varying amounts of trunk rot.

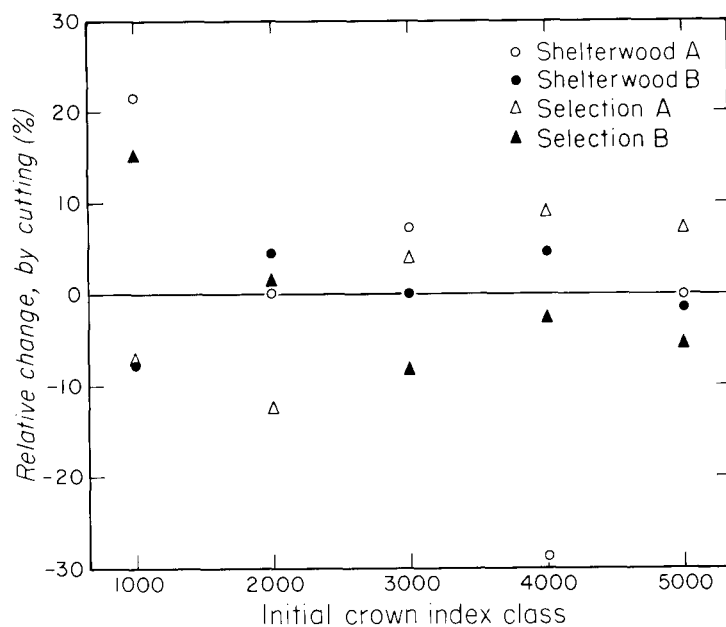


Figure 2—Crown index change in redwood 5 or more years after cutting shows no consistent pattern of crown improvement.

Table 1—Principal logging damage¹ to the reserve stand, by cutting and three size groups, Redwood Experimental Forest, California

Cutting and size group	Dead	Sprung roots	Broken top	Debarked	Stripped crown	None
	Percent of trees					
Selection A:						
Saplings	70.5	0	1.7	9.8	0	18.0
Poletimber	74.3	0	0	3.2	3.2	19.3
Sawtimber	20.7	7.5	3.3	33.3	0	35.2
Selection B:						
Saplings	93.0	1.6	0	0	3.1	2.3
Poletimber	62.4	2.1	2.1	6.3	0	27.1
Sawtimber	21.7	3.6	2.2	36.2	0	36.2
Shelterwood A:						
Saplings	81.3	2.0	3.0	3.0	0	10.7
Poletimber	80.4	3.1	0	10.3	1.0	5.2
Sawtimber	49.2	9.5	6.4	19.0	0.8	15.1
Shelterwood B:						
Saplings	95.9	0	0	0	0	4.1
Poletimber	96.8	0	0	3.2	0	0
Sawtimber	56.9	0	4.9	32.5	0	5.5

¹Priority for determining damage class (for other than dead trees) if more than one kind of damage was present: (a) sprung roots, (b) broken top, (c) debarked, (d) stripped crown.

Growth

The sawtimber, poletimber, and saplings were grouped according to size at the beginning of each measurement period. Essentially the data represent Site I for old-growth redwood although part of shelterwood A and clearcutting A are Site II. Site I corresponds approximately to site index 200 and above for base age 100 years.

Original sawtimber stand volumes varied considerably, some because of site, and others because of irregular stocking from past mortality or original density:

	<u>Trees/acre (ha)</u>	<u>Volume/acre (ha)</u>
		<u>Cu ft (m³)</u>
Cutting:		
Selection A	44.8 (110.7)	55,199 (3862)
Selection B	51.7 (127.8)	78,897 (5520)
Shelterwood A	54.5 (134.7)	36,384 (2546)
Shelterwood B	80.5 (198.9)	66,499 (4653)
Clearcutting A	36.2 (89.4)	48,840 (3417)
Clearcutting B	33.2 (82.0)	57,248 (4006)
Uncut area	48.8 (120.6)	52,946 (3705)
Average	50.0 (123.6)	56,573 (3958)

The numbers and volume of trees cut per acre varied according to the regeneration method being tried and the density of original stands:

	<u>Trees/acre (ha)</u>		<u>Volume/acre (ha)</u>	
	<u>Number</u>	<u>Percent</u>	<u>Cu ft (m³)</u>	<u>Percent</u>
Cutting:				
Selection A	14.8 (36.6)	33.0	27,515 (1925)	49.8
Selection B	17.2 (42.5)	33.3	41,680 (2916)	52.8
Shelterwood A	23.0 (56.8)	42.2	29,847 (2089)	82.0
Shelterwood B	39.8 (98.3)	49.4	50,309 (3520)	75.7
Clearcutting A1	31.0 (77.5)	85.6	48,193 (3372)	98.7
Clearcutting B1	32.2 (79.6)	97.0	57,226 (4004)	99.9

¹A few small trees were missed during the logging.

In both the selection and shelterwood cuttings a full range of tree sizes was cut, but the relative reduction in average diameter calculated by cutting areas was highest on the shelterwood cuttings. The average tree diameters before and after cutting, and for the cut trees, are shown to be:

	<u>Average diameter</u>		
	<u>Before</u>	<u>Cut</u>	<u>Reserve</u>
	<u>Inches (cm)</u>		
Cutting:			
Selection A	60.8 (154.4)	74.5 (189.2)	52.6 (133.6)
Selection B	65.3 (165.9)	80.8 (205.2)	56.0 (142.2)
Shelterwood A	43.3 (110.0)	56.7 (144.0)	30.0 (76.2)
Shelterwood B	49.6 (126.0)	60.3 (153.2)	36.1 (91.7)

Basal Area

For the sawtimber-size group and the four partial cuttings (table 2), all the average net growth in annual basal area for 10+ years was negative. And that for the two selection cuttings represented the greatest loss—exceeding by a factor of 10 or more the net growth on the shelterwood and uncut stands. The high mortality rates on the selection cuttings were responsible for this large negative result. Furthermore, increment on surviving trees is relatively poor, considering the great amount of growing stock. Mortality was considerably lower on the shelterwood cuttings and accordingly the negative net growth was smaller. For the lower growing stock the increment on shelterwood B, which had not been recut, was fair. I had expected and found the uncut stand to be near zero or negative net growth because of the constant mortality. For this old stand the increment on surviving trees was poor, considering the large growing stock.

Mortality on selection A and shelterwood A were mainly from windfalls. But about 10 percent of the trees had been previously weakened by the logging (table 1); hence both wind and logging were involved in killing these trees. In 1962, an unusual phenomenon for north coastal California—a hurricane—increased mortality by wind an estimated three to six times above previous post-logging losses (Boe 1965). However, high windfall losses also occurred on selection A and shelterwood B several years after the hurricane, illustrating that damaging winter storms are not rare. On the selection B cutting, about 17 percent of mortality resulted from fire damage incurred while

the heavy volume of slash among the reserved trees was burned. The remaining mortality was caused by wind and other conditions.

The small basal area of poletimber growing stock in the original stands was further reduced to negligible amounts by logging mortality on the partial cut-

tings (table 2). On clearcuttings, however, the remaining poletimber was removed in slash disposal as unneeded trees. Net annual basal area growth was positive or nearly so for all cuttings mainly because of ingrowth. In addition, some poletimber became ingrowth in the sawtimber group during the two growth

Table 2—Annual basal area growth during two 5- to 6-year periods after cutting, by method, Redwood Experimental Forest, California

Mortality and Growth	Selection		Shelterwood		Clearcutting		Uncut
	A	B	A	B	A	B	
	————— <i>Sq ft/acre (m²/ha)</i> —————						
	Sawtimber 11+ inches d.b.h.						
Growing stock	405.03	573.52	123.08 ¹	242.58	0	0	849.68
Mortality 1st period	-15.84	-24.16	-2.43	-.31	0	0	-4.28
Increment 1st period	1.56	1.01	.78	.87	0	0	1.64
Ingrowth 1st period	.07	0	.04	0	0	0	.04
Mortality 2nd period	-10.19	-1.28	-.33	-3.40	0	0	-1.85
Increment 2nd period	1.82	2.19	.19	1.64	0	0	2.35
Ingrowth 2nd period	.16	.50	.04	.05	0	0	.04
Average net growth ²	-11.82	-10.87	-.86	-.57	0	0	-1.03
	(-2.7)	(-2.5)	(-.2)	(-.1)	0	0	(-.2)
Average gross growth ²	14.82	14.57	1.90	3.14	0	0	5.10
	(3.4)	(3.3)	(.4)	(.7)	0	0	(1.2)
	Poletimber 5 to 10.9 inches d.b.h.						
Growing stock	0.58	1.83	1.60	0.43	0	0	1.48
Mortality 1st period	-.02	-.11	-.21	-.02	0	0	0
Increment 1st period	.03	.03	.01	.01	0	0	0
Ingrowth 1st period	0	0	.01	0	0	0	.03
Mortality 2nd period	0	-.15	-.05	-.04	0	0	-.03
Increment 2nd period	0	.03	.02	0	0	0	.03
Ingrowth 2nd period	.19	.15	.62	.04	1.02	.60	0
Average net growth	.10	-.03	.20	-.01	.51	.30	.02
	(.02)	(-.01)	(.04)	(.00)	(.12)	(.07)	(.01)
Average gross growth	.12	.24	.46	.06	.51	.30	.05
	(.03)	(.06)	(.11)	(.01)	(.12)	(.07)	(.01)
	Saplings 1 to 4.9 inches d.b.h.						
Growing stock	0.13	0.19	0.13	0.08	0	0	0.06
Mortality 1st period	-.02	-.03	-.01	-.02	0	0	-.01
Increment 1st period	.04	0	.03	0	0	0	.01
Ingrowth 1st period	.02	.02	.07	.03	.13	.23	0
Mortality 2nd period	-.04	-.01	-.01	-.01	0	-.04	-.01
Increment 2nd period	.13	.21	.08	.27	.26	.61	.01
Ingrowth 2nd period	.11	.53	.20	.60	1.46	.62	0
Average net growth	.12	.36	.18	.41	.95	.71	0
	(.03)	(.08)	(.04)	(.09)	(.22)	(.16)	0
Average gross growth	.18	.40	.20	.44	.95	.75	.04
	(.04)	(.09)	(.04)	(.10)	(.22)	(.17)	(.01)

¹Growing stock the second period was reduced to 33.82 square feet by a second cutting.

²Net growth = increment + ingrowth - mortality. Gross growth equals the sum of the three components.

periods being measured. On the uncut stand, the average net growth was very small but positive because some trees became sawtimber ingrowth during the period and there was little initial growing stock upon which to accumulate wood.

In the sapling-size group, on all of the cuttings the ingrowth and the increment on that ingrowth were both substantial. Together they amounted to more average net growth than on the poletimber stand. Furthermore, the sapling stand furnished the ingrowth to the pole stand. The ingrowth and increment were relatively large, especially on the two clearcuttings, because of well-stocked reproduction. At the end of the second period, basal area increment and ingrowth on the clearcuttings were already one-half or more of that on the heavy sawtimber growing stock of corresponding shelterwood cuttings, and one-eighth or more on selection cuttings. On the uncut stand the increment and ingrowth of saplings, as expected, was negligible.

Volume

For growth expressed in annual cubic feet, the net growth values of sawtimber are negative and large (*table 3*) for the two selection cuttings in comparison to those for the shelterwood and uncut stand. Again the high mortality offset increment. Increment on surviving trees is fair on a per acre basis on all except shelterwood A. But increment as a percent of growing stock is poor; it is lowest on the uncut stand. Shelterwood A was recut after the first period; hence its growing stock was greatly reduced. Clearcuttings had no sawtimber growing stock.

In poletimber, the annual net volume growth in cubic feet was only minor and slightly negative on two cuttings (*table 3*). On the two clearcuttings, ingrowth during the second period accounted for all of the net growth. This condition is a sign of the accelerating rate of cubic volume to be expected on these cuttings. The ingrowth accumulates from the sapling stand, where it had no measurable cubic volume be-

Table 3—Annual cubic-foot volume growth during two 5- to 6-year periods after cutting, by method, Redwood Experimental Forest, California

Mortality and Growth	Selection		Shelterwood		Clearcutting		Uncut
	A	B	A	B	A	B	
	Cu ft/acre (m ³ /ha)						
	Sawtimber 11+ inches d.b.h.						
Growing stock	24,962.3	36,591.6	5,520.9	14,589.8	0	0	52,945.8
Mortality 1st period	-972.1	-1,533.8	-89.9	-6.9	0	0	-217.7
Increment 1st period	100.3	70.2	41.7	57.4	0	0	109.8
Ingrowth 1st period	1.3	0	.5	0	0	0	.8
Mortality 2nd period	-604.6	-56.2	-11.3	-181.1	0	0	-87.5
Increment 2nd period	111.5	152.5	10.9	100.0	0	0	154.6
Ingrowth 2nd period	2.9	1.0	.1	.9	0	0	.8
Average net growth ¹	-680.4	-683.2	-24.0	-14.8	0	0	-19.3
	(-47.6)	(-47.8)	(-1.7)	(-1.0)	0	0	(-1.4)
Average gross growth ¹	896.4	906.8	77.2	173.2	0	0	285.3
	(62.7)	(63.4)	(5.4)	(12.1)			(20.0)
	Poletimber 5 to 10.9 inches d.b.h.						
Growing stock	7.2	34.8	30.3	5.6	0	0	20.4
Mortality 1st period	-.2	-.6	-4.1	-.3	0	0	0
Increment 1st period	.5	.4	.2	.3	0	0	.7
Ingrowth 1st period	0	0	.1	0	0	0	0
Mortality 2nd period	0	-3.9	-1.3	-.5	0	0	-.6
Increment 2nd period	0	1.0	.4	0	0	0	.2
Ingrowth 2nd period	1.9	1.0	7.1	.4	10.8	4.7	0
Average net growth	1.1	-1.5	1.2	-.1	5.4	2.3	.2
	(.08)	(-.10)	(.08)	(-.01)	(.38)	(.16)	(.01)
Average gross growth ¹	1.3	4.0	6.6	.8	5.4	2.3	.8
	(.09)	(.28)	(.46)	(.06)	(.38)	(.16)	(.06)

¹ Net growth = increment + ingrowth - mortality. Gross growth equals the sum of the three components.

cause the minimum tree for volume determination was 5 inches d.b.h.

Diameter

Diameter and Age—If d.b.h. and age are highly correlated, then d.b.h.—an easily measured variable—can be used alone to analyze diameter increment. For 78 observations, I found the correlation coefficient to be highly significant at the 0.01 level in a regression of age (Y) on d.b.h. in inches (X):

$$Y = 103.95 + 5.27 X; r = 0.81$$

Because of this significant correlation, diameter was used as the principal independent variable in evaluating diameter growth.

Growth and Crown Index—The crown index and its change with time seemed to be a useful variable to explain and predict diameter growth. By separate regression analyses for each cutting, I first determined that crown index increased as diameter increased. This relationship would result in a confounding effect with diameter as an independent variable in multiple regression; therefore, I discarded the initial crown index.

Next I examined the relationship of crown index ratio (ratio of crown index at the end of a growth period to that of the crown index at the beginning) to diameter. The result was that crown index ratio was independent of diameter; therefore, it would be a useful independent variable for diameter growth analysis.

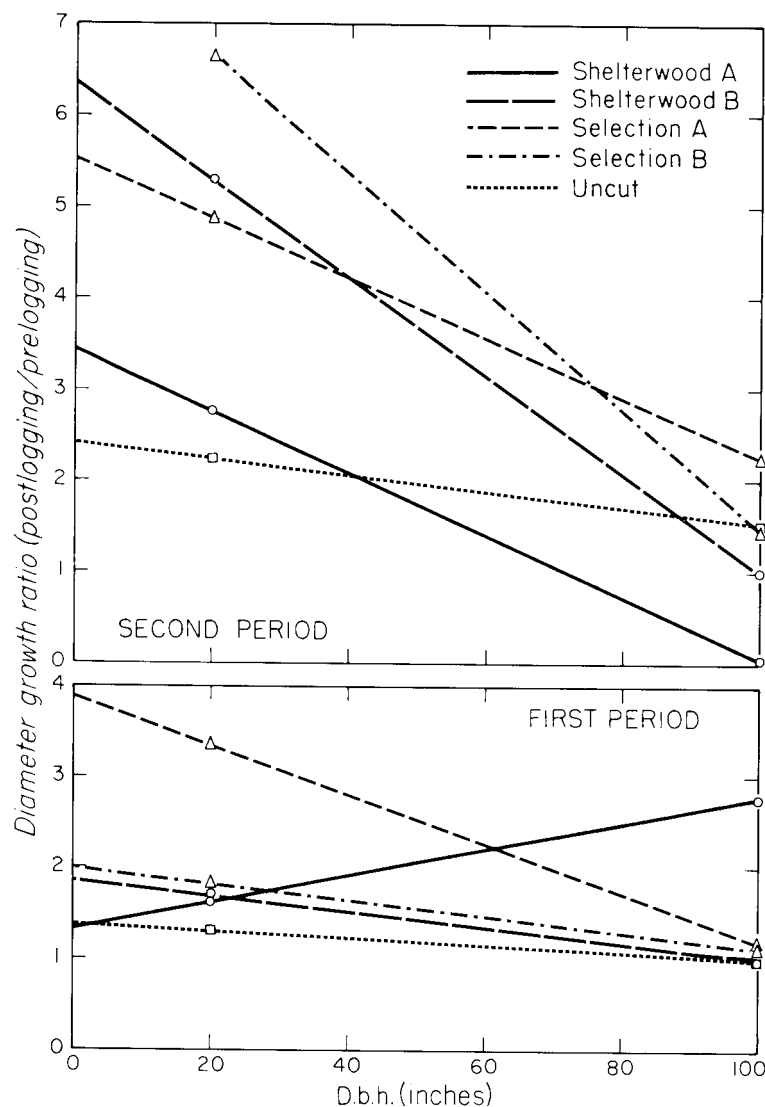


Figure 3—Relative diameter increase in redwood for postlogging periods was affected by initial diameter (correlation: r^{**} = 1 percent level; r^* = 5 percent level; r N. S. = not significant).

Diameter growth ratio, i.e., that annual growth for the first period after logging divided by annual growth for the immediate 10-year period before, is a relative measure of diameter increment. I analyzed its relationship to crown index ratio. On three of four cuttings, there was a positive regression for growth ratio to increase as crown index ratio increased. For diameter growth to increase in direct proportion to an increase in crown area was an expected relationship. The data on only one regression, however, were significantly correlated. When crown index ratio was used as an independent variable in a multiple regression analysis of diameter growth ratio, the correlation coefficient was surprisingly small. Since little of the variation in diameter increment could be explained by the combination of variables including crown index ratio, I concluded that crown index estimates in old-growth redwood stands are not useful as tree variables.

Growth Ratio and Growing Stock—Diameter growth in a stand after cutting should be affected by competition from the growing stock; in this study the basal area of this growing stock was used to express this competition. Two linear regressions were calculated for each cutting and for the uncut stand—one for each of the two periods after cutting.

Data from the two shelterwood cuttings show that slopes of regressions were positive the first period, i.e. an accelerated growth was evident with the larger reserved basal area. Slopes for the second period were negative. Data from the two selection cuttings and for two periods shows that only one slope was negative. For both periods on the uncut stand the regression slopes were positive—opposite to the expected. From these results I concluded that basal area of the reserved growing stock is a weak variable for estimating the trend of diameter growth after cutting. Further testing of basal area in the multiple regression analysis with crown index ratio led to the same conclusion: basal area of the reserve stand was not a useful variable for estimating diameter increment of the reserved trees.

Diameter Growth Ratio and Diameter—The initial diameter of reserved trees was a satisfactory variable for explaining diameter growth in the stand after cutting. For diameters less than 100 inches d.b.h., accelerated growth occurred on three cuttings and on the uncut stand. (fig. 3). The rate, as expected, decreased as diameter increased in all except shelterwood A; this relationship seemed to be atypical. In shelterwood A, the rate increased as diameter increased, but the correlation coefficient, unlike the coefficients for the other regressions, was not significant. On the uncut stand the height of the regression line above the 1.0 growth-ratio ordinate axis would indicate a climatic effect; therefore, the release effects of cutting are mainly the differences between the regressions for the cuttings and the uncut stand (fig. 3).

During the second growth period of about 5 years (10 years after cutting) the levels of growth rates based on the first 10 years before logging were considerably higher than those compared to the first period (fig. 3). Since the relative growth in the uncut stand also was about double that in the previous period, we can assume that favorable climate accounted for some of the increase of the cuttings. Nevertheless, on the selection cuttings A and B and shelterwood B cutting there were substantial gains, after adjustment for climate, over the previous period. Half of the shelterwood A had been cut after the first study period, and too few trees were left on the remainder to yield a significant regression.

The regressions and their correlation coefficients on the same three cuttings in both growth periods showed similarity. Therefore, I considered it proper to combine all of the data on the cutover stands into a linear regression equation for growth prediction:

$$Y = 4.009 - 0.026X; r = 0.329$$

in which Y = diameter growth ratio for a 10-year period, X = initial d.b.h. (inches), and the correlation coefficient is highly significant at the 0.01 level.

DISCUSSION AND CONCLUSIONS

In the conversion of old-growth redwood stands to younger managed stands, the regeneration cutting options are to strive for even-aged stands by clearcutting and shelterwood cutting (also seed-tree cutting), or for uneven-aged stands by selection cutting. Among

the many factors to evaluate as advantages or disadvantages for a particular method are growth and mortality on reserved growing stock and development of new growing stock from regeneration. The measurements in uncut stands provide a baseline for compari-

son with cut stands, and resource information for estimating growth in old-growth stands that are being held for future harvesting.

The results document that tractor logging mortality is heavy, is related to the volume or level of cut, and is especially destructive of small trees. Therefore, if heavy partial harvests are made, such as shelterwood and selection cuttings, specific procedures should be followed to save the smaller trees.

A manager will ordinarily view the growth on the reserved shelterwood growing stock somewhat differently from that on selection cuttings. If he uses the shelterwood method, he first wants regeneration over the entire harvested area. The growing stock is retained for seed production, protection to the seedlings, and short-term growth gain. But the future stand yield will be based on the new even-aged stand. On selection cuttings, however, regeneration is mainly required in openings, and the reserved growing stock should optimally produce wood increment during the rather long conversion period to an uneven-aged stand, in which the oldest trees will eventually be the chosen rotation age. On clearcuttings the principal growth is accumulated on the new young stand.

Selection cuttings in old-growth redwood, however, as judged from these results, are not likely to produce initially a volume of wood commensurate with the site potential. Although a hurricane was the cause of greatly increased windfall in our cuttings, the expected heavy mortality usually results in negative net basal area and cubic volume growth for sawtimber. If this killed timber can be salvaged then gross growth may appear to be favorable. But increment on surviving trees will be low—considering the square feet of basal area and cubic volume of growing stock. Prospective growth rates of from 0.2 to 0.8 percent indicate the over-all poor response.

And because initial poletimber growing stock may be minimal in old-growth stands, expected immediate net growth likewise will be small. But if healthy young sawtimber, poletimber, and saplings are present they should be protected because they are a valuable addition to the new young growing stock.

After a few years, on selection cuttings, the sapling component, which will be mainly from new reproduction, is the future hope for growth. These trees are the source of ingrowth into poletimber plus increment on sapling ingrowth. The level of growth, how-

ever, appears to be potentially consistently less than for the other cuttings.

The short-term growth gain of sawtimber trees on shelterwood cuttings will ordinarily be low in proportion to growing stock and site quality because of mortality and tree response. In these old-growth stands, diameter and age are strongly correlated. The smaller younger trees, on the average, respond well to additional growing space and generally provide the most increment during the regeneration and conversion period. Fritz (1951) also found that percent increase of small trees left after cutting in old-growth redwood was large. These smaller trees, however, are usually inadequate seed producers for natural regeneration (Boe 1968); therefore, some larger trees will need to be reserved for this purpose. Hence the reserved sawtimber should be viewed essentially for seed production and minimal growth.

As on selection cuttings, not much growth can be expected from poletimber on shelterwood cuttings because there are usually relatively few of these trees, and mortality can be high. Individual trees respond very well to the ample growing space, but the greatest potential for net growth ordinarily is new reproduction.

Saplings that develop from the expected good regeneration on shelterwood cuttings provide the growing stock for potential best growth. I expect that the first few periods of net basal area and cubic volume growth probably always will be better than on selection cuttings, but growth will be generally less than on clearcuttings. When the shelterwood overstory is removed, an effort to limit damage to the reproduction and to assure restocking of any nonstocked areas is essential.

Where complete utilization of sawtimber is possible, small clearcuttings appear to be a good method, considering only effect on growth, for converting to younger managed stands. Unless there are young, healthy saplings and pole timber in the stand, which it may not be possible to save anyway, an entirely new stand must be started. This can be done successfully by natural regeneration, or if needed, by seeding and planting. By the end of 10 years, net basal area growth will easily surpass that on either the selection or shelterwood cutting—essentially because of mortality on the latter two. And increment on surviving trees and ingrowth will approach that on selection and shelterwood cuttings and likely surpass it in another 10 years.

APPLICATION

A linear regression for the combined two growth periods based on initial diameter can be useful for reliably predicting growth. This approach can be applied to similar stands on good sites elsewhere. To use the equation: (1) multiply the prelog 10-year diameter growth for a size class by the computed growth ratio to get the predicted postlog 10-year growth; (2) add this result to the previous diameter to provide the new diameter for each class; (3) arrange these re-

sults in table form with columns for present and projected basal areas and cubic volumes. For short time periods, bark growth is ignored.

By use of basal area tables and local cubic volume tables, both the prelog and postlog stands may then be computed. The difference between these two is the increment on the surviving trees. It is best to estimate mortality for each stand to adjust increment to get net growth.

LITERATURE CITED

Boe, Kenneth N.

1965. **Windfall after experimental cuttings in old-growth redwood.** Proc., Soc. of Amer. For. 1965:59-63, illus.

Boe, Kenneth N.

1968. **Cone production, seed dispersal, germination in old-growth redwood cut and uncut stands.** USDA Forest Serv. Res. Note PSW-184, 7 p., illus. Pacific Southwest Forest and Range Exp. Stn., Berkeley, Calif.

Fritz, Emanuel.

1951. **Some principles governing the growing of redwood crops.** J. For. 49:263-266.

Person, Hubert L.

1942. **Increment of residual redwoods.** J. For. 40:926-929, illus.

Show, S. B.

1932. **Timber growing and logging practice in the coast redwood region of California.** U.S. Dep. Agric. Tech. Bull. 283, 22 p., illus.



The Forest Service of the U.S. Department of Agriculture

- . . . Conducts forest and range research at more than 75 locations from Puerto Rico to Alaska and Hawaii.
- . . . Participates with all State forestry agencies in cooperative programs to protect and improve the Nation's 395 million acres of State, local, and private forest lands.
- . . . Manages and protects the 187-million-acre National Forest System for sustained yield of its many products and services.

The Pacific Southwest Forest and Range Experiment Station

represents the research branch of the Forest Service in California and Hawaii.

Boe, Kenneth N.

1974. **Growth and mortality after regeneration cuttings in old-growth redwood.** USDA Forest Serv. Res. Paper PSW-104. 13 p., illus. Pacific Southwest Forest and Range Exp. Stn., Berkeley, Calif.

To convert old-growth redwood (*Sequoia sempervirens*) to younger managed stands, three types of regeneration cuttings are being tried at the Redwood Experimental Forest, northern California: clearcutting, shelterwood, and selection cutting. Logging mortality was heavy for all tree sizes and greatest where the heaviest cuts were made. The large size of a negative net growth of sawtimber on selection cuttings is attributed to mortality during a 10-year postlogging period. Net growth was slightly negative on shelterwood cuttings. By the end of the 10 years, basal area growth for saplings on all cuttings was significant. Because of well-stocked reproduction, growth is expected to accelerate—especially on clearcuttings and to a lesser extent on shelterwood cuttings.

Oxford: 174.7 *Sequoia sempervirens*: 221.2:228

Retrieval Terms: *Sequoia sempervirens*; regeneration cuttings; stand development; logging damage; mortality.

Boe, Kenneth N.

1974. **Growth and mortality after regeneration cuttings in old-growth redwood.** USDA Forest Serv. Res. Paper PSW-104. 13 p., illus. Pacific Southwest Forest and Range Exp. Stn., Berkeley, Calif.

To convert old-growth redwood (*Sequoia sempervirens*) to younger managed stands, three types of regeneration cuttings are being tried at the Redwood Experimental Forest, northern California: clearcutting, shelterwood, and selection cutting. Logging mortality was heavy for all tree sizes and greatest where the heaviest cuts were made. The large size of a negative net growth of sawtimber on selection cuttings is attributed to mortality during a 10-year postlogging period. Net growth was slightly negative on shelterwood cuttings. By the end of the 10 years, basal area growth for saplings on all cuttings was significant. Because of well-stocked reproduction, growth is expected to accelerate—especially on clearcuttings and to a lesser extent on shelterwood cuttings.

Oxford: 174.7 *Sequoia sempervirens*: 221.2:228

Retrieval Terms: *Sequoia sempervirens*; regeneration cuttings; stand development; logging damage; mortality.

Boe, Kenneth N.

1974. **Growth and mortality after regeneration cuttings in old-growth redwood.** USDA Forest Serv. Res. Paper PSW-104. 13 p., illus. Pacific Southwest Forest and Range Exp. Stn., Berkeley, Calif.

To convert old-growth redwood (*Sequoia sempervirens*) to younger managed stands, three types of regeneration cuttings are being tried at the Redwood Experimental Forest, northern California: clearcutting, shelterwood, and selection cutting. Logging mortality was heavy for all tree sizes and greatest where the heaviest cuts were made. The large size of a negative net growth of sawtimber on selection cuttings is attributed to mortality during a 10-year postlogging period. Net growth was slightly negative on shelterwood cuttings. By the end of the 10 years, basal area growth for saplings on all cuttings was significant. Because of well-stocked reproduction, growth is expected to accelerate—especially on clearcuttings and to a lesser extent on shelterwood cuttings.

Oxford: 174.7 *Sequoia sempervirens*: 221.2: 228

Retrieval Terms: *Sequoia sempervirens*; regeneration cuttings; stand development; logging damage; mortality.

Boe, Kenneth N.

1974. **Growth and mortality after regeneration cuttings in old-growth redwood.** USDA Forest Serv. Res. Paper PSW-104. 13 p., illus. Pacific Southwest Forest and Range Exp. Stn., Berkeley, Calif.

To convert old-growth redwood (*Sequoia sempervirens*) to younger managed stands, three types of regeneration cuttings are being tried at the Redwood Experimental Forest, northern California: clearcutting, shelterwood, and selection cutting. Logging mortality was heavy for all tree sizes and greatest where the heaviest cuts were made. The large size of a negative net growth of sawtimber on selection cuttings is attributed to mortality during a 10-year postlogging period. Net growth was slightly negative on shelterwood cuttings. By the end of the 10 years, basal area growth for saplings on all cuttings was significant. Because of well-stocked reproduction, growth is expected to accelerate—especially on clearcuttings and to a lesser extent on shelterwood cuttings.

Oxford: 174.7 *Sequoia sempervirens*: 221.2: 228

Retrieval Terms: *Sequoia sempervirens*; regeneration cuttings; stand development; logging damage; mortality.