United States
Department of
Agriculture
Forest Service
Pacific Northwest
Research Station
Research Note
PNW-RN-525
March 1998

Examples of Mortality and Reduced Annual Increments of White Fir Induced by Drought, Insects, and Disease at Different Stand Densities

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Abstract

A white fir (*Abies concolor* (Gord. & Glend.) Lindl.) levels-of-growing-stock study testing four density levels (20, 30, 40, and 50 percent of the normal stand density index value of 560) was established in spring 1983. The study was installed in four widely separated blocks in the Deschutes and Fremont National Forests. Annual increments were slightly lower than expected for the first period (1983-85) and much lower than expected during the second period (1986-90). Mortality between 1991 and 1995 destroyed the study. A general drought prevailed over the study areas from the late 1970s to the mid 1990s. Mortality on block 1 in the Deschutes National Forest was attributed to root rot (*Armillaria ostoyea* (Romagnesi) Herink) and western spruce budworm (*Choristoneura occidentalis* Freeman). Mortality on blocks 2, 3, and 4 was attributed to fir engraver beetles (*Scolytus ventralis* LeConte). Results raise doubts about maintaining stands with a large component of white fir on these sites over a long period. Managed stands on these sites should have a strong ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) component and should be managed by using ponderosa pine stocking curves.

Keywords: White fir, stand density, mortality, periodic annual increments, fir engraver, Modoc budworm, root rot, western spruce budworm.

Introduction

A levels-of-growing-stock (LOGS) study in white fir (*Abies concolor* (Gord. & Glend.) Lindl.) was established in 1982 to investigate growth, yield, and mortality at low stand densities. At the time of establishment, little density-related mortality was expected. Suppressed trees were removed in the initial thinning and the study was to be repeatedly thinned. Mortality due to agents other than suppression in even-aged white fir stands had not been shown to be related to stand density. Although Ferrell (1978) reported that trees with dawn xylem pressure potentials of -20 bars or less (greater negative values) are susceptible to fir engraver beetles (*Scolytus ventralis* LeConte), it was not until later that Ferrell and others (1993a, 1993b) demonstrated a positive correlation between susceptibility to these beetles and stand basal area. Stocking level curves for commercially sized trees (Cochran 1982b), therefore, suggested managing stand densities between 50 and 75 percent of normal density (the equivalent of between 33 and 50 percent of maximum density). This range of stand densities would eliminate the development of a suppressed tree class while causing only a moderate reduction in gross cubic volume growth (Cochran and Oliver 1988). This study, which included densities between 20 and 50 percent of normal, was destroyed by heavy mortality between 1990 and 1995. The relation of mortality and certain periodic annual increments (PAIs) to stand density for this short-lived study are presented here. The PAIs examined are those for survivor diameters, survivor heights, gross and net basal area, and gross and net cubic volume.

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Methods of Study

Design and Study Areas

Four growing stocking levels (GSLs) (20, 30, 40, and 50 percent of normal density) were employed in a randomized complete block design. These levels are equivalent to stand density index (SDI) values of 112, 168, 224, and 280. The SDI values were determined from,

$$SDI = (TPA)(QMD/10)^{1.73},$$

where TPA is the number of live trees per acre and QMD is the quadratic mean diameter. An exponent of 1.73, instead of 1.605 as proposed by Reineke (1933), was used because -1.73 was the slope of a least squares fit of $\log_e$TPA as a function of $\log_e$QMD for 56 fully stocked sample plots east of the Cascade Range in Oregon and Washington (Cochran 1982b).

Each stocking level was randomly assigned within blocks to a 0.4-acre plot with an additional 33-foot buffer strip. Four blocks, each with four plots, were installed in Oregon in fall 1982. Block 1 is in the Deschutes National Forest and blocks 2, 3, and 4 are in the Fremont National Forest (table 1). Elevations range from 4,500 to 5,900 feet, average slopes range from 17 to 37 percent, aspects differ, and average annual precipitation ranges from 16 to 31 inches (table 1). Soils on block 1 are Typic Xerothents developing on ash mixed with basalt fragments. Soils on block 2 are Typic Xerothents developing on Mazama ash mixed with residual basalt. Soils on block 3 are Typic Xerothents on three of the plots, and one plot (GSL 40) is on a Typic Durothent developing on rhyolitic breccia. Block 4 has residual soils (Typic Argixerolls) developing from basalt and colluvium. A grand fir (*Abies grandis* (Dougl.) Lindl.)-white fir species complex is recognized in the central Oregon Cascade Range (Zobel 1973). Many of the trees on block 1 and some of the trees on blocks 2, 3, and 4 display characteristics of both species.

Each block was installed in even-aged stands, 40 acres or less in size, precommercially thinned several years earlier to a 10-foot spacing for block 1 and a 14-foot spacing for blocks 2, 3, and 4. Age at breast height in fall 1982 was 56, 67, 65, and 80 years for blocks 1 through 4, respectively. Corresponding site index values (Cochran 1979) were 79, 64, 57, and 50 feet. The site index values of Cochran (1979) are determined from the tallest five trees per acre (two tallest trees on a 0.4-acre plot) and their breast high age. The index age is 50 years. Site index values of blocks 2, 3, and 4 may be low because of past top damage from Modoc budworm (*Choristoneura viridis* Freeman). Stem analysis of white fir trees in the Fremont National Forest for development of height growth and site index curves (Cochran 1979) indicated that height growth of many trees had been reduced in the past, presumably by Modoc budworm (Dolf 1980).

Plots and buffer strips were thinned to assigned levels in fall 1982 and thinned again to assigned levels in fall 1985. Rethinning to assigned levels was originally planned for 10-year intervals. Initially, however, some of the plots randomly picked for the highest GSL did not meet the required density and, also, there were several ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) trees on these plots. After 3 years of rapid diameter growth, the highest density plots attained or exceeded SDIs of 280 for three of the four blocks so all plots were rethinned in fall 1985 to remove more of the ponderosa pine. Removal of most of the pine reduced the highest GSL below the assigned stocking level, but it was thought that density levels of these plots would rapidly increase and assigned levels could easily be retained after the next thinning in 10 years. After each thinning, thinning slash was lopped and scattered over the plots and buffer strips.

The four blocks or locations are viewed as distinct populations, so results strictly apply only to the four locations. These four blocks probably represent a much larger area in central and south-central Oregon.

Measurements

A pretreatment plot inventory was taken by measuring the diameters at breast height (d.b.h.) of each tree on the 16 experimental units. Diameters and heights (H) of all trees were measured after the initial thinning (fall 1982), before the second thinning (fall 1985), 5 years after the second thinning (fall 1990), and 10 years after the second thinning (fall 1995). Heights were measured with optical dendrometers. Each time heights were measured, five trees on each thinned plot were measured with dendrometers so stem volume inside bark could be determined by using a modification of Grosenbaugh's (1964) STX program with Cochran's (1976, 1982a) method of estimating inside bark values along the bole. Selection of the trees measured for volume with dendrometers was made by first constructing a frequency distribution by 2-inch diameter classes after the initial thinning. Trees were then selected at random from each diameter class so that the complete range of diameter classes would be equally represented. If one of these trees died, the live plot tree closest in diameter at the previous measurement was selected as a replacement. Coefficients for the cubic volume (V) and board-foot volume (V1) equations (Schumacher and Hall 1933),

$$\log_e V = a + b[\log_e(\text{d.b.h.})] + c(\log_e H),$$

and

$$\log_e V1 = a_1 + b_1[\log_e(\text{d.b.h.})] + c_1(\log_e H),$$

were determined for each block at each time of measurement by using data for the 20 trees in each block for which volumes were determined from dendrometer measurements. These equations were then used to determine volumes for individual plot trees on each block at that time. A few scattered ponderosa pine existed on some of the plots. Volumes for the ponderosa pine were determined by using the above equations with the same coefficients for all blocks. The coefficients were obtained by measuring four ponderosa pine in each block for volume and forming a separate set of pine volume equations for each time of measurement. Heights to tip always were measured, and cubic volumes always included stump and tip, even though some of the tips on block 1 may have been dead toward the end of the study.

One 3-year (1983-85) and two 5-year measurement periods (1986-90 and 1991-95) exist for the study. Periodic annual increments (PAI, growth during each period divided by the number of growing seasons in the period) were calculated for survivor diameters and heights as well as gross and net basal area and cubic volume. In calculating gross and net cubic volume PAIs, no attempt was made to estimate volume of tops that might be dead. Volumes were calculated by assuming all tops of living trees were live. Observations for mortality consist of trees that died on each plot during each period (16 plots observed for 3 periods, or 48 observations). Percent mortality (mortality during each period divided by live tree values at the start of the period multiplied by 100) was calculated for trees per acre, basal area, and cubic volume. Ratios of dead:live tree diameter (QMD of trees that died during a period divided by the QMD of all live trees at the start of the period) also were determined.

Defoliation became severe on block 1 as the study progressed (Sheehan 1996). Current and cumulative percentage of defoliation (to the nearest 10-percent class) by crown thirds and bare top as a percentage of total tree height were estimated for each tree on the plots in this block in fall 1992 (USDA 1991).

Analyses

Repeated measures (split-plot in time) or standard analyses of variance (SAS Institute 1988) were used to test the following hypotheses: (1) There was no difference in mortality by block, GSL, or period; (2) there were no differences in survivor PAIs for QMD or average height by block, GSL, or period; (3) there were no differences in gross and net PAIs of basal area or cubic volume by block, GSL, or period; and (4) there was no difference in the ratio (QMD of mortality during period)/(QMD of live trees at start of period) for period 3. Because there were four GSL levels, a third-degree polynomial can be used to describe the relation between response and GSL. Linear, quadratic, and cubic or lack-of-fit effects were, therefore, tested by using orthogonal polynomial methods. Treatment average SDI values for GSLs 20, 30, 40, and 50 were 119, 175, 232, and 270 at the start of the three growth periods. These average values were used in determining the coefficients for these tests (Bliss 1970). Extreme mortality rates, which increased over time, produced a heterogeneity of variance situation that could not be corrected; thus the probability levels for tests of significance are potentially biased and error variances are not characteristic of treatment means for any particular periods. In spite of this problem, the above analyses were still run. The outcomes are obvious, and the conclusions could probably have been made without these analyses, but the added support is believed helpful.

Results

Before the initial thinning, the plots on block 1 had an average of 461 TPA and 270 square feet per acre of basal area. Plots on blocks 2, 3, and 4 had an average of 223 TPA and 145 square feet per acre of basal area. After the initial thinning, QMDs ranged from 9.2 to 13.7 inches, average heights ranged from 38.2 to 70.4 feet, basal areas ranged from 62 to 152 square feet per acre, cubic volumes ranged from 1,014 to 4,365 cubic feet per acre, and board-foot volumes per acre ranged from 3,281 to 20,351 (table 2). All four stands appeared healthy, and examination of past radial growth of sections at breast height from some of the trees thinned in 1982 showed no evidence of serious basal area growth loss in the past.

Mortality and Defoliation

Mortality occurred on 4 of the 16 plots during the first period (spring 1983-fall 1985), 8 plots during the second period (1986-90), and all plots during the third period (1991-95) (table 3). Cubic volume lost during period 3 ranged from 5.2 to 81.8 percent of the live volume at the start of the period (table 4). The TPA, basal area, and cubic volume of dead trees varied significantly ($p \leq 0.10$) with block or location, as well as period, and increased linearly ($p \leq 0.10$) with increasing GSL. The slope of these mortality-GSL relations varied with period as shown by the significance ($p \leq 0.10$) of the linear term of the period-by-GSL interaction (table 5). The cubic volume lost during the third period seems to be linearly related to the cubic volume at the start of the period for blocks 2, 3, and 4 (fig. 1). Analyses of mortality expressed as percentages produces the same results except no components of the period-by-GSL interaction were significant. Trees that died were about the same size as the trees that lived. For the third period, the ratio (QMD of mortality)/(QMD of live trees at the start of period) was 0.98, 1.02, 0.95, and 0.98 for GSLs 20 through 50, respectively. This ratio did not vary significantly ($p \leq 0.10$) with block or GSL (statistics not shown).

Each dead tree was examined. Mortality in block 1 was attributed to a combination of root rot (*Armillaria ostoyea* (Romagnesi) Herink) and western spruce budworm (*Choristoneura occidentalis* Freeman). All dead trees in block 1 showed evidence of being infected with root rot. Mortality in blocks 2, 3, and 4 was attributed to fir engraver beetles. Only two of the dead trees on these blocks (both on block 4) displayed evidence of armillaria root rot.

Minor defoliation from Modoc budworm occurred on blocks 2, 3, and 4. Spruce budworm was first noticed in the area containing block 1 in 1985 and defoliation increased in intensity during the following years. By fall 1992, defoliation of current year's growth was 90 percent or greater for all crown thirds on all plot trees. Cumulative defoliation averaged greater than 80 percent for the top crown third, 70 percent for the middle crown third, and 60 percent for the lower crown third. Bare tops averaged from 8 to 17 percent of total tree height for the four GSLs (table 6).

Periodic Annual Increments

All PAIs except net cubic volume PAI differed ($p \leq 0.10$) with block or location (tables 7 and 8). Survivor PAIs for QMDs were similar for all blocks during the first period (1983-85), but for periods 2 (1986-90) and 3 (1991-95), these PAIs were lowest for block 1 (table 8). Survivor height PAIs in block 1 went from an average of 0.5 foot per year in the first period to less than 0.1 foot per year in the next two periods (table 8). Survivor height PAIs for blocks 2 through 4 averaged 0.4 or 0.5 foot per year during periods 2 and 3. Survivor QMD and height PAIs decreased linearly ($p \leq 0.10$) with increasing GSL (table 7, figs. 2 and 3). Gross and net PAIs for basal area and gross PAIs for volume changed linearly ($p \leq 0.10$) with GSL (table 7, figs. 4 and 5). Significant ($p \leq 0.10$) differences in net cubic volume PAIs with block (location) or GSL were not detected owing, probably, to an inflated error term. All PAIs differed ($p \leq 0.10$) with period (table 7). Slopes of all PAI-GSL relations except those for survivor heights changed with period, thereby resulting in significance ($p \leq 0.10$) of the linear component of the period-by-GSL interaction term (table 7). Slopes for the gross cubic volume PAI-GSL relation were negative during the last period (1991-95) for blocks 2 and 4 (data not shown) and slopes for the net cubic volume PAI-GSL relation were negative for all blocks during the last period (fig. 6). Net PAIs for basal area and volume for all blocks were negative for period 3 (table 7).

General observations in the study areas and at other locations indicated that high mortality rates were not confined to the study plots. Many white fir trees died in central and south-central Oregon during the 1985-95 period.

Discussion and Conclusions

A general drought began in 1976, and annual precipitation was below normal for several years of the study (table 9). This drought probably was responsible for some of the reduction in PAIs in the second and third periods of the study. Defoliation by spruce budworm severely reduced growth rates, particularly height growth in block 1 during periods 2 and 3. Root rot mortality in block 1 began during period 2 and was severe during period 3. Attempts to separate growth losses due to the three agents—drought, budworms, and root rot—by using dendrochronology procedures (Swetnam and others 1985) were not made. The combined effect of the three agents on mortality and PAIs was severe. A relation between mortality (tables 3 and 4) or budworm damage (table 6) and GSL is not evident for block 1. Overall, the increase in both mortality rates and gross cubic volume PAIs with increasing GSLs resulted in a nondetectable difference in net cubic volume PAI with GSL (table 7).

Modoc budworm is endemic across much of the Fremont National Forest (the locations of blocks 2, 3, and 4) and caused some defoliation in these study areas. Fir engraver beetles were responsible for the mortality on these blocks while drought, and to a lesser degree, defoliation were responsible for reductions in survivor diameter and height PAIs. Mortality from fir engraver beetles appeared to increase with increasing stand densities and was above acceptable levels even at the lowest stand density (20 percent of the density considered normal for white fir).

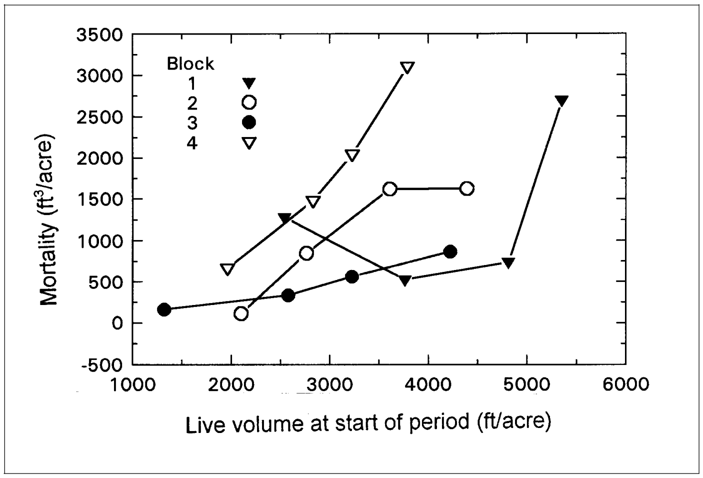

Figure 1—Cubic volume mortality during period 3 (1991-95) as a function of live cubic volume at the start of the period.

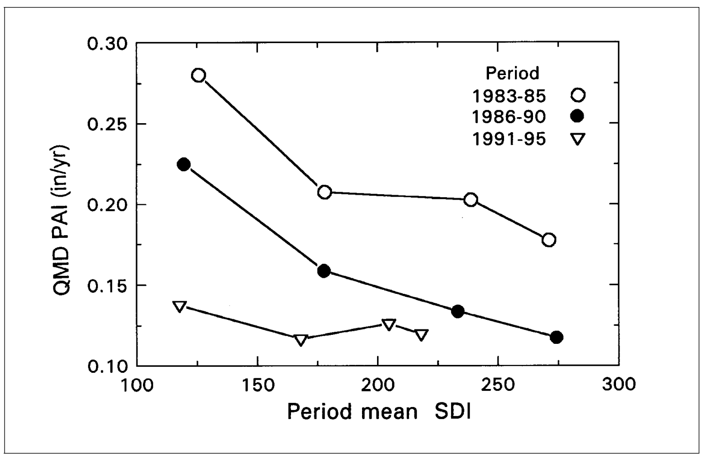

Figure 2—Survivor PAIS for quadratic mean diameter (QMD) as a function of period mean SDI for live trees. Plottted points are treatment means.

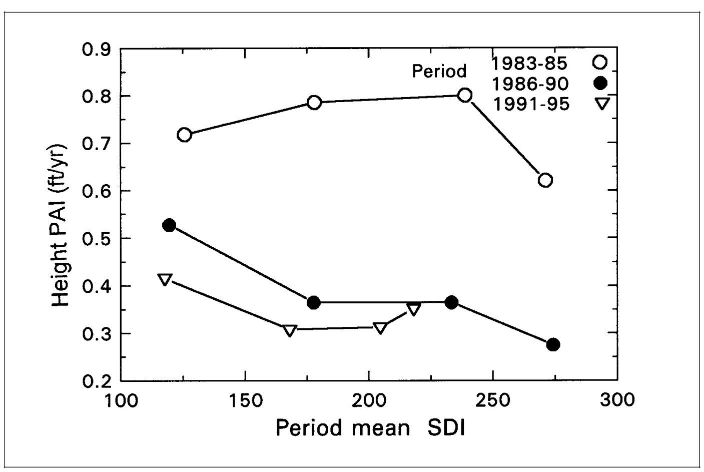

Figure 3—Survivor PAIs for average height as a function of period mean SDI for live trees. Plotted points are treatment means.

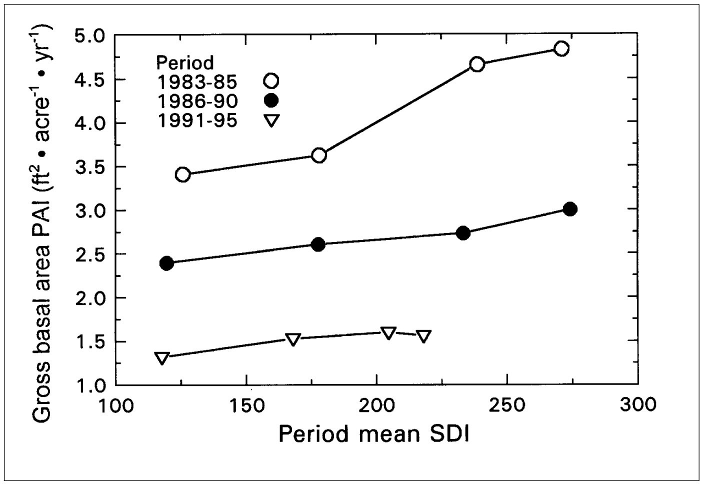

Figure 4—Gross basal area PAIs as a function of period mean SDI for live trees. Plotted points are treatment means.

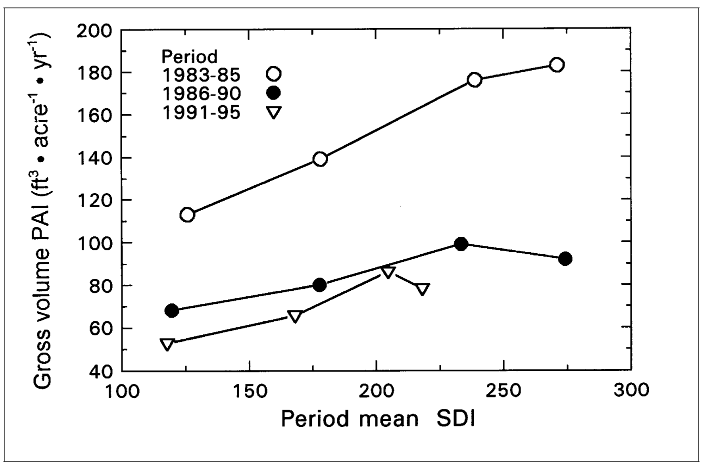

Figure 5—Gross cubic volume PAIs as a function of period mean SDI for live trees. Plotted points are treatment means.

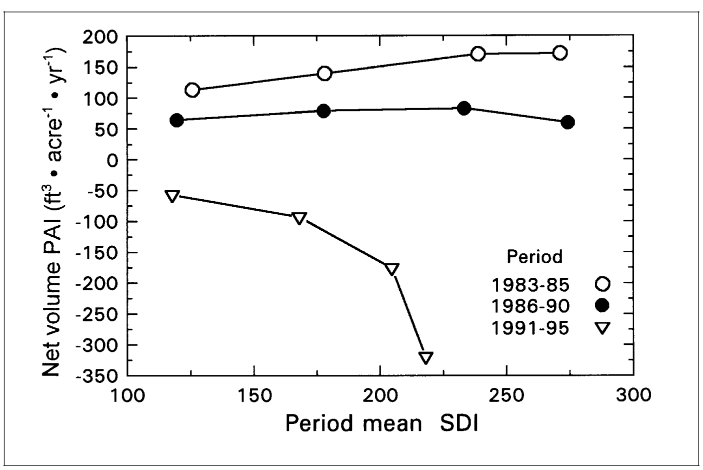

Figure 6—Net cubic volume PAIs as a function of period mean SDI for live trees. Plotted points are treatment means.

Schultz[1] used an isohyetal map of mean annual precipitation (Rantz 1969) and observations of white fir mortality, due mostly to fir engraver, to rate the risk of this mortality for the Modoc National Forest, California. He proposed four risk levels based on annual precipitation:

Risk	Mean annual precipitation
	Inches
Low	40 or more
Medium	30 to 40
High	25 to 30
Extreme	20 to 25

Only block 1 with 31 inches of annual precipitation would have a medium risk rating in this system; block 2 (16 inches of annual precipitation) would have an even higher than extreme rating, block 3 (20 inches of annual precipitation) would be rated as extreme, and block 4 (28 inches of annual precipitation) would be given a high risk rating.

Healthy stands of white fir grow very rapidly, produce a dense crown cover, and are visually pleasing. These results, however, raise doubts about growing white fir stands on sites with mean annual precipitation rates below 32 inches even if stand densities are kept very low. The four widely scattered stands represented in this study apparently grew well for more than 60 years and reached commercial size before severe mortality occurred. Where significant amounts of white fir are present, managers need the ability to manipulate stand composition to minimize mortality. Future stands on similar sites should have a large component of ponderosa pine and should be managed by using ponderosa pine stocking guides (Cochran and others 1994). These density levels would allow the individual fir trees, intermingled with pine, to reach commercial size at fairly young ages. If drought, disease outbreaks, or severe insect infestations occur, the white fir could be removed, leaving ponderosa pine on the site. Ponderosa pine quickly responds to new growing space even at old ages and would quickly take advantage of the available site resources. Ferrell (1978) reports that trees under high moisture stress (-20 bars dawn xylem pressure or higher negative pressures) for protracted summer periods are more susceptible to successful fir engraver attacks than are trees under less stress. If prolonged droughts are forecast, removal of most of the white fir on drier sites may be advisable. This would prevent the buildup of fir engraver populations that could migrate to moist sites and inflict heavy damage where, historically, white fir has survived dry periods.

Acknowledgments

Bruce Hostetler, entomologist, USDA Forest Service, Pacific Northwest Region, and Andris Eglitis, entomologist, USDA Forest Service, Area IV, estimated defoliation and top damage on block 1 of this study in fall 1992. Andris Eglitis also examined each dead tree on all blocks in fall 1995.

[1] Schultz, David E. 1994. Evaluation of white fir mortality on Big Valley RD. Forest Pest Management report NE94-2 to Forest Supervisor, Modoc National Forest. 6 p. plus maps. On file with: U.S. Department of Agriculture, Forest Service, Lassen National Forest, Susanville, CA 96130.

Metric Equivalents

1 inch = 2.54 centimeters

1 foot = 0.3048 meter

1 mile = 1.609 kilometers

1 acre = 0.4047 hectare

1 tree per acre = 2.47 trees per hectare

1 square foot = 0.09290 square meter

1 square foot per acre = 0.2296 square meter per hectare

1 cubic foot per acre = 0.06997 cubic meter per hectare

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Appendix

Table 1—Latitude, longitude, elevation, slope, aspect, and annual precipitation for the 4 blocks, white fir study, central and south-central Oregon

Block	North latitude	West longitude	Elevation	Average slope	Aspect	Average annual precipitation[a]
			Feet	*Percent*		*Inches*
1	44°44’	121°37’	4,500	17	East	31
2	42°23’	120°26’	5,900	37	Northeast	16
3	42°19’	120°35’	5,900	26	Southeast	20
4	42°03’	120°45’	5,860	25	Northwest	28

[a] Estimated from Franklin and Dyrness (1988, p. 39) for block 1 and from Rantz (1969) for blocks 2, 3, and 4.

Table 2—Stand characteristics (per acre basis) of live trees at the beginning of the study, before and after the 2d thinning, fall 1990, and fall 1995, white fir study, central and south-central Oregon

Block	GSL	Basal area	SDI	Number of trees	Average spacing	Quadratic mean diameter	Average height	Volume[a]	
		Ft^2			*Feet*	*Inches*	*Feet*	*Ft*^{3}	*Bd. ft.*
				Spring 1983 after initial thinning					
1	20	66.5	116	85	22.9	12.0	70.4	2,141	10,532
	30	93.6	164	128	18.4	11.6	69.0	3,029	14,781
	40	130.0	233	202	14.7	10.8	69.2	4,205	19,909
	50	139.6	250	215	14.2	10.9	67.2	4,365	20,351
2	20	65.1	115	93	21.6	11.4	57.8	1,478	7,628
	30	93.2	170	170	16.0	10.0	53.9	2,118	8,635
	40	125.0	224	195	14.9	10.8	56.4	2,909	13,443
	50	143.2	255	212	14.3	11.1	58.1	3,425	16,377
3	20	61.9	116	135	18.0	9.2	38.2	1,014	3,281
	30	99.9	174	128	18.4	12.0	54.5	2,129	10,226
	40	138.8	236	145	17.3	13.2	63.6	3,382	19,394
	50	152.5	277	250	13.2	10.6	49.3	3,066	13,119
4	20	73.8	124	72	24.6	13.7	59.5	1,754	8,431
	30	97.2	169	120	19.1	12.2	58.3	2,204	11,433
	40	125.8	223	178	15.6	11.4	58.5	3,035	14,353
	50	147.0	264	233	13.7	10.8	53.2	3,057	14,019
				Fall 1985 before 2d thinning					
1	20	78.0	133	85	22.9	13.0	72.6	2,574	12,743
	30	105.5	183	128	18.4	12.3	70.4	3,514	17,278
	40	143.2	254	202	14.7	11.4	70.9	4,807	22,673
	50	159.2	270	215	14.2	11.4	68.6	4,913	22,967
2	20	76.5	133	93	21.6	12.3	59.9	1,897	9,406
	30	106.4	191	170	16.0	10.7	55.8	2,502	10,844
	40	140.2	248	195	14.9	11.5	58.3	3,411	15,824
	50	160.4	281	212	14.3	11.8	60.9	4,080	19,719
3	20	71.9	133	135	18.0	9.9	39.6	1,238	4,300
	30	109.9	189	128	18.4	12.6	56.6	2,526	11,811
	40	152.4	255	142	17.3	14.0	67.4	4,080	22,713
	50	152.0	289	245	13.2	11.0	50.6	3,423	14,845
4	20	81.7	136	72	24.6	14.4	61.3	2,032	9,767
	30	105.1	181	120	19.1	12.7	62.1	2,606	13,293
	40	136.4	238	175	15.6	12.0	61.2	3,296	16,468
	50	159.4	284	232	13.7	11.2	55.2	3,555	16,382
				Spring 1986 after 2d thinning					
1	20	66.4	112	68	25.3	13.4	74.7	2,230	11,222
	30	97.2	168	110	19.9	12.8	72.4	3,288	16,368
	40	133.7	233	168	16.1	12.1	72.7	4,277	20,802
	50	153.0	270	215	14.2	11.4	68.6	4,913	22,967
2	20	64.9	112	75	24.1	12.6	61.7	1,633	8,284
	30	95.0	169	140	17.6	11.2	57.7	2,267	10,290
	40	127.6	223	165	16.2	11.9	60.2	3,134	14,690
	50	153.2	267	195	14.9	12.0	61.9	3,941	19,064
3	20	60.2	110	108	20.1	10.1	40.9	1,063	3,781
	30	98.9	168	105	20.4	13.1	58.7	2,311	10,996
	40	135.1	223	115	19.5	14.7	69.3	3,653	20,436
	50	149.8	265	210	14.4	11.4	52.1	3,239	14,350
4	20	66.9	110	55	28.1	14.9	63.4	1,700	8,264
	30	63.6	168	108	20.1	12.9	63.6	2,486	12,796
	40	129.0	224	160	16.5	12.2	62.4	3,146	15,797
	50	154.9	275	223	14.0	11.3	55.8	3,477	16,150

Table 2–Stand characteristics (per acre basis) of live trees at the beginning of the study, before and after the 2d thinning, fall 1990, and fall 1995, white fir study, central and south-central Oregon (continued)

Block	GSL	Basal area	SDI	Number of trees	Average spacing	Quadratic mean diameter	Average height	Volume[a]	
		Ft^2			*Feet*	*Inches*	*Feet*	*Ft*^{3}	*Bd. ft.*
					Fall 1990				
1	20	65.0	124	65	25.9	14.5	74.9	2,539	12,533
	30	111.0	187	110	19.9	13.6	73.2	3,763	18,457
	40	141.0	243	168	16.1	12.4	73.1	4,813	23,230
	50	160.0	280	208	14.5	11.9	68.9	5,350	24,259
2	20	78.2	132	75	24.1	13.9	65.5	2,097	10,927
	30	109.2	190	138	17.8	12.1	61.2	2,760	12,916
	40	141.7	244	165	16.2	12.6	62.0	3,606	17,428
	50	164.0	282	185	15.3	12.8	64.2	4,391	21,547
3	20	73.2	130	108	20.1	11.2	43.9	1,322	5,238
	30	110.1	185	105	20.4	13.9	60.8	2,578	12,897
	40	153.1	249	115	19.5	15.6	72.5	4,223	24,474
	50	150.0	261	188	15.2	11.4	54.1	3,227	14,927
4	20	77.2	125	55	28.1	16.0	66.5	1,960	10,107
	30	110.2	186	108	20.1	13.7	64.7	2,829	15,168
	40	131.3	226	148	17.2	12.8	64.0	3,227	16,568
	50	167.8	293	218	14.1	11.9	57.4	3,787	18,289
					Fall 1995				
1	20	39.3	64	30	38.1	15.5	75.2	1,413	6,446
	30	100.6	168	92	21.8	14.1	74.2	3,679	16,954
	40	125.6	214	135	18.0	13.1	74.7	4,662	21,228
	50	88.8	152	100	20.9	11.9	72.3	3,267	14,495
2	20	85.1	140	70	24.9	14.9	69.3	2,408	12,718
	30	86.7	149	100	20.9	12.6	63.0	2,212	10,531
	40	92.2	156	95	21.4	13.3	63.4	2,373	11,565
	50	104.5	177	108	20.0	13.4	65.3	2,826	14,255
3	20	75.1	131	95	21.4	12.0	46.5	1,377	5,748
	30	106.8	176	90	22.0	14.8	62.6	2,577	12,930
	40	132.0	211	88	22.2	16.6	75.1	3,899	22,354
	50	134.4	231	153	16.8	12.7	55.7	2,970	14,058
4	20	58.7	94	40	33.0	16.4	66.9	1,563	7,784
	30	60.4	101	58	27.4	13.9	65.4	1,587	8,268
	40	55.1	93	55	28.1	13.6	65.7	1,404	7,160
	50	39.0	67	45	31.1	12.6	60.2	943	7,933

[a] Total cubic-foot volume—entire stem, inside bark, all trees; Scribner board-foot volume—trees 8.0-inch diameter at breast height and larger to a 5-inch top diameter inside bark.

Table 3—Motality (per acre basis) for the 3 periods, white fir study, central and south-central Oregon

Block	GSL	Basal area	Number of trees	Quadratic mean diameter	Average height	Volume[a]	
		Ft^2		*Inches*	*Feet*	*Ft*^{3}	*Bd. ft.*
			Period 1 (spring 1983-fall 1985)				
1	20	—	—	—	—	—	—
	30	—	—	—	—	—	—
	40	—	—	—	—	—	—
	50	1	5	8.0	60.4	56	58
2	20	—	—	—	—	—	—
	30	—	—	—	—	—	—
	40	—	—	—	—	—	—
	50	—	—	—	—	—	—
3	20	—	—	—	—	—	—
	30	—	—	—	—	—	—
	40	2.3	5	9.1	49.9	46	24
	50	3.7	5	11.7	54.1	74	138
4	20	—	—	—	—	—	—
	30	—	—	—	—	—	—
	40	1.0	2	8.9	56.4	23	46
	50	—	—	—	—	—	—
			Period 2 (fall 1985-fall 1990)				
1	20	2.1	2	12.3	76.8	72	360
	30	—	—	—	—	—	—
	40	—	—	—	—	—	—
	50	6.8	8	12.9	71.7	230	1,252
2	20	—	—	—	—	—	—
	30	1.1	2	8.8	51.3	24	94
	40	1.4	2	10.2	52.7	31	127
	50	5.3	10	9.8	55.5	90	2,091
3	20	—	—	—	—	—	—
	30	—	—	—	—	—	—
	40	—	—	—	—	—	—
	50	15.2	23	11.1	52.2	323	1,468
4	20	—	—	—	—	—	—
	30	—	—	—	—	—	—
	40	11.5	12	13.0	67.0	293	1,558
	50	2.3	5	9.2	50.7	44	190
			Period 3 (fall 1990-fall 1995)				
1	20	34.8	35	13.5	73.4	1,275	5,710
	30	14.4	18	14.4	69.6	525	2,240
	40	19.7	32	10.5	69.6	736	3,040
	50	74.7	108	11.3	66.3	2,693	10,386
2	20	4.5	5	12.9	61.1	110	510
	30	32.5	38	12.6	63.6	848	4,091
	40	61.3	70	12.7	63.3	1,616	7,903
	50	71.8	78	13.0	65.9	1,624	9,733
3	20	8.6	12	11.2	46.7	162	656
	30	14.3	15	13.2	59.2	335	1,622
	40	31.7	28	14.5	68.6	865	4,672
	50	25.9	35	11.6	54.9	561	2,548
4	20	24.4	15	17.3	70.6	664	3,367
	30	55.2	50	14.2	65.7	1,475	7,910
	40	81.6	93	12.7	65.7	2,040	10,382
	50	133.5	173	11.9	57.2	3,098	14,505

[a] Total cubic-foot volume—entire stem, inside bark, all trees; Scribner board-foot volume—trees 8.0-inch diameter at breast height and larger to a 5-inch top diameter inside bark.

Table 4—Percentage of mortality[a] for periods 1, 2, and 3 where mortality occurred, white fir study, central and south-central Oregon

Block	GSL	Trees per acre	Basal area	Volume	
				Ft³	*Bd. ft.*
		Period 1			
1	50	2.3	0.7	1.3	0.3
3	40	3.4	1.7	.1	.2
	50	1.5	1.6	1.6	.6
4	40	1.1	.8	.8	.3
		Period 2			
1	20	2.4	2.7	2.8	2.8
	50	4.2	3.7	4.7	5.5
2	30	1.2	1.0	1.0	.9
	40	1.0	1.0	.9	.8
	50	4.7	3.3	2.2	10.6
3	50	9.4	10.0	9.4	9.9
4	40	6.9	8.4	8.9	9.5
	50	2.2	1.4	1.2	1.2
		Period 3			
1	20	53.8	53.5	50.2	45.6
	30	16.4	13.0	14.0	12.1
	40	19.0	14.0	15.3	13.1
	50	51.9	46.7	50.3	42.8
2	20	6.7	5.8	5.2	4.7
	30	27.5	29.8	30.7	31.7
	40	42.4	43.3	44.8	45.3
	50	42.2	43.8	37.0	45.2
3	20	11.1	11.7	12.2	12.5
	30	14.3	13.0	13.0	12.6
	40	24.3	20.7	20.5	19.1
	50	18.6	17.3	17.4	17.1
4	20	27.3	31.6	33.9	33.3
	30	46.3	50.1	52.1	52.1
	40	62.8	62.1	63.2	62.7
	50	79.4	79.6	81.8	79.3

[a] Percentage of mortality = 100 (mortality during period/live TPA, basal area, or volume at start of period).

Table 5—Probability of higher F-values for the analyses of variance of mortality, white fir study, central and south-central Oregon

		Actual values			Percent		
Source	Df [a]	Trees per acre	Basal area	Cubic volume	Trees per acre	Basal area	Cubic volume
Block	3	0.0718	0.0250	0.0566	0.0756	0.0349	0.0362
GSL:							
Linear	1	.0005	.0008	.0024	.0276	.0262	.0445
Quadratic	1	.1044	.1740	.2330	.3340	.3408	.3977
Cubic	1	.6213	.7433	.8545	.8998	.9455	.9999
Error	9						
Period (P)	2	.0001	.0001	.0001	.0001	.0001	.0001
P x GSL:							
Linear	2	.0011	.0035	.0042	.1275	.1579	.2284
Quadratic	2	.4372	.6302	.6176	.7508	.7986	.8348
Cubic	2	.8988	.9500	.9741	.9943	.9898	.9957
Error	24						
Error mean square:							
Whole plot		225.7523	128.33	111182.35	92.8286	81.92	92.5714
Subplot		430.2951	292.42	190845.38	143.9415	152.58	167.8387

[a] Df = degrees of freedom.

Table 6—Percentage of cumulative defoliation (averages of estimates to the nearest 10 percent crown class) by crown thirds and the amount of bare top as a percentage of total tree height in fall 1992 on block 1, white fir study, central Oregon

	Crown defoliation			Bare
GSL	Top 1/3	Mid 1/3	Lower 1/3	top
	- - - - - - - - - - *Percent* - - - - - - - - - -			
20	88	76	75	14
30	87	70	58	17
40	96	77	64	8
50	84	74	64	10

Table 7—Probability of higher F-values for the analyses of variance of PAIs for basal area and cubic volume, white fir study, central and south-central Oregon

		Survivor		Basal area		Cubic volume	
Source	Df [a]	QMD	Height	Gross	Net	Gross	Net
Block	3	0.0138	0.0004	0.0007	0.0069	0.0941	0.1763
GSL:							
Linear	1	.0004	.0489	.0010	.0020	.0167	.6713
Quadratic	1	.1319	.8776	.8757	.1616	.5977	.2726
Cubic	1	.2457	.3308	.5433	.6527	.5033	.2163
Error	9						
Period (P)	2	.0001	.0001	.0001	.0001	.0001	.0001
P x GSL:							
Linear	2	.0658	.5403	.0349	.0029	.0300	.0605
Quadratic	2	.8903	.2756	.8268	.6150	.9478	.6564
Cubic	2	.9169	.9107	.5513	.9609	.9971	.2376
Error	24						
Error mean square:							
Whole plot		.0018	.0183	.1921	4.77	1549.56	34,496.93
Subplot		.0019	.0308	.2860	13.01	377.66	26,359.28

[a] Df = degrees of freedom.

Table 8—Block average PAIs for each period, white fir study, central and south-central Oregon

Block	Period 1, 1983-85	Period 2, 1986-90	Period 3, 1991-95
	Survivor QMD PAIs		
	Inches per year		
1	0.2	0.1	0.0
2	.2	.2	.2
3	.2	.2	.1
4	.2	.2	.2
	Survivor height PAIs		
	Feet per year		
1	0.5	0.1	0.1
2	.7	.5	.5
3	.8	.5	.4
4	.9	.4	.4
	Gross basal area PAIs		
	$Ft^2 \cdot acre^{-1} \cdot yr^{-1}$		
1	4.3	2.3	0.6
2	4.8	3.0	2.2
3	4.1	2.9	2.1
4	3.3	2.6	1.1
	Net basal area PAIs		
	$Ft^2 \cdot acre^{-1} \cdot yr^{-1}$		
1	4.2	1.8	-6.6
2	4.8	2.6	-6.3
3	3.6	2.1	-1.9
4	3.3	1.9	-13.7
	Gross cubic volume PAIs		
	$Ft^2 \cdot acre^{-1} \cdot yr^{-1}$		
1	176.9	101.3	89.2
2	163.5	101.2	75.0
3	150.1	70.3	69.9
4	120.2	66.6	48.6
	Net cubic volume PAIs		
	$Ft^2 \cdot acre^{-1} \cdot yr^{-1}$		
1	172.3	86.2	-172.3
2	163.3	94.0	-134.9
3	140.0	54.2	-26.3
4	118.3	51.7	-315.2

Table 9–Annual precipitation[a] at Lakeview,[b] Oregon, and Sisters,[c] Oregon, for 1976 through 1995

Year	Lakeview	Sisters	Year	Lakeview	Sisters
	- - *Inches* - -			- - *Inches* - -	
1976	11.1	11.0	1986	M[d]	M[d]
1977	11.7	12.7	1987	M[d]	M[d]
1978	12.4	12.8	1988	13.1	11.5
1979	16.0	11.7	1989	10.4	11.4
1980	13.9	M[d]	1990	11.5	12.6
1981	22.1	22.3	1991	12.6	13.5
1982	15.0	17.0	1992	13.7	14.9
1983	20.1	19.2	1993	17.0	15.5
1984	13.6	18.2	1994	12.3	9.1
1985	11.6	M[d]	1995	M[d]	M[d]

[a] Data obtained from the National Climatic Data Center, Federal Building, Asheville, NC 28801-5001. Average annual precipitation is 14.4 inches at both locations.

[b] Distances and azimuths of blocks 2, 3, and 4 from Lakeview are, respectively, 15 miles and 330 degrees, 15 miles and 305 degrees, and 23 miles and 246 degrees.

[c] Block 1 is 21 miles from Sisters at an azimuth of 335 degrees.

[d] M = missing values.

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