Estimating the Fuel Moisture Content of Indicator Sticks from Selected Weather Variables

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Contents

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THEODORE G. STOREY has specialized in forest fire research since shortly after joining the Forest Service at Berkeley, Calif., in 1949. In 1955 he transferred to the Southeastern Station, Asheville, N.C. He worked at the Forest Fire Laboratory in Macon, Ga., for 3 years before returning to the Pacific Southwest Station in 1962. The field work for the study reported in this paper was done while he was at the Macon laboratory. Storey is a forestry graduate of the University of California (1948). Since 1963 he has been assigned to the Pacific Southwest Station's Forest Fire Laboratory at Riverside, Calif.

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Every day during the fire season some 2,250 trained observers take certain measurements of the existing fire danger at selected points in forested areas throughout the United States. More than 2,000 of these observers carefully weigh specially prepared fuel moisture indicator sticks and record their moisture content. These measurements are important in assessing fire danger because they represent the relative dryness of fire-carrying fuels in the forest area—a factor that is directly related to the ignition and spread of fire.

When exposed under actual or simulated typical forest conditions, the sticks reveal the effects in one simple measurement of all weather variables affecting moisture content, such as precipitation, humidity, temperature, evaporation, solar radiation, and wind. Basswood slats ⅛ by 2⅜ by 18 inches are used at fire danger stations in the East and South, where fine fuels predominate (Nelson 1955b). In the West and Northwest, where fuels are of larger diameter, ½- by 19-inch ponderosa pine dowels are used (Hardy, *et al.* 1955).

Although sticks are satisfactory, there are problems associated with their use. They require lengthy processing, including, for slats, preweathering and calibration (Hardy 1953; Nelson 1955); they must be replaced twice a year, and they must be exposed on a special support. Screen shading, used to simulate natural shading, must be changed in spring and in fall. A special scale and shelter for weighing the sticks must be provided.

In the South the requirement for changing from six-screen shading over the slats in the summer to one-screen in the winter is questionable. Pine trees lose very few needles in winter, and the shade they cast changes very little throughout the year. Also, the change from one screen to six screens in spring may be too abrupt, resulting in too sudden an apparent increase in fine fuel moisture content and decrease in fire danger. In fall, the reverse sometimes happens. One amount of screen shading yearlong seems more reasonable.

If the moisture content of the sticks could be estimated accurately from the weather variables controlling their moisture content, weather instruments could be substituted for sticks at fire-danger stations. Stick moisture content under one or more amounts of shading could be determined from suitable graphs or tables. Meteorologists could predict the pertinent weather variables as well as stick moisture. Furthermore, fire danger ratings could be computed currently or for historical periods in areas where weather records are available but where no fire danger stations exist.

Information on shading and radiation effects on stick moisture content should be particularly pertinent to the national fire danger study (Keetch 1959). The estimating equations for slat moisture content described in this paper are the basis for the fine-fuel moisture tables in the national fire danger rating system, developed by the U.S. Forest Service for Service-wide use.

For several years fire weather forecasters in the East have used various tables to estimate the moisture content of basswood slats from psychrometric variables (Hood).[1] These estimates are used for short-term forecasts. None of these tables has proved completely satisfactory, probably because each was based on uncontrolled data. And no indication of statistical accuracy is given.

The present study was planned to (a) develop a more accurate system for estimating slat moisture content, (b) to devise a system for estimating dowel moisture content, and (c) determine whether one amount of screen shading for slats could be used yearlong in the South. This paper reports the results of work on the first two goals. Work on the third objective was not completed because the development of a national fire danger rating system appeared imminent (Keetch 1959).

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[1] Hood, F. C. *Indicated average moisture content of thin basswood slats in relation to temperature on sticks and dewpoint temperature.* 1954. (Unpublished report on file at U.S. Weather Bureau, Asheville, N.C.)

Study Procedure

Sticks were exposed unshaded and under artificial shade in the form of one, three, four, and six layers of 14-by 18-mesh aluminum wire window screen. Each amount of shading was replicated three times. The 15 frames were spaced 5 feet apart, forming a rectangular block with the number of screens randomized within the block (fig. 1).

Each frame included a set of three slats, a set of four dowels, a single slat, and a single dowel exposed side-by-side on a standard fuel moisture slat support (fig. 2). A weathering study was conducted concurrently with the main study to determine weathering correction factors to apply to sticks.

Surface temperature of the single sticks was measured by a mercury-in-glass thermometer attached to the stick and by a thermocouple imbedded within the stick. The thermometers were read directly, and the thermocouples remotely with a potentiometer. Other weather variables measured included dry bulb (air) temperature, wet bulb temperature, relative humidity, and maximum and minimum temperatures (at 4½ feet above the ground in a thermoscreen), wind speed and direction (at 15 feet above ground), precipitation, solar radiation, and current weather. Temperature, humidity, solar radiation, and precipitation were recorded automatically on strip charts.

The sticks were weighed and weather readings were taken at 2 p.m. daily from May 1959 through April 1960. One day a week readings were taken at 8 a.m., 10 a.m., 12 noon, 2 p.m., and 4 p.m. No readings were taken while rain was falling or when the moisture content of the basswood slats exceeded 50 percent. Sticks in the study were changed after six months' exposure to conform to standard practice at fire danger stations (Nelson 1955). The old sticks were oven-dried and weighed to determine their weight loss.

Sticks in the weathering study were dried and weighed every 2 weeks to determine their weight loss and to obtain corrections for application to test sticks. A daily average correction was computed and applied to the weight of the test sticks for each day in the 2-week period.

Moisture Relations in Wood

The sorption curve of moisture content over relative humidity for wood is characteristically S-shaped (Stamm 1952). For a given relative humidity, the equilibrium moisture content is higher when equilibrium is approached by desorption than when it is approached by adsorption (Masson and Richards 1906). This phenomenon is known as sorption hysteresis.

Seborg (1937) showed that the hysteresis ratio obtained by dividing the adsorption by the desorption moisture content is almost constant over most of the range of relative humidities. At 0- and 100-percent humidities, the hysteresis ratio is near unity.

The area bounded by the hysteresis loop represents an area of equilibrium (Urquhart and Eckersall 1930). At any point in this area, equilibrium moisture content may occur depending on preliminary and conditioning treatments of the material. The maximum hysteresis effect is only obtained when working under very carefully controlled conditions.

Investigators, each working under controlled laboratory conditions, differ as to the effect of specimen size on hysteresis. Stamm and Loughborough (1935) found that hysteresis was essentially eliminated when working with large specimens. On the other hand, Sergovskii (1951), found that hysteresis increased as specimen size increased, up to pieces 0.31 inches thick, after which it remained fairly constant. Schniewind (1956) concluded that whatever influence thickness may have, it was very slight.

Drying Rate and Timelag

Time is required for wood to come to equilibrium within a given set of conditions. When drying, a sample of wood will approach equilibrium moisture content at a rate that decreases exponentially with time. Byram[2] called this rate a timelag. It is the time required for a wood sample in an atmosphere of constant temperature and humidity to lose about 63 percent of the moisture it would lose if left there for an infinite time (until it reached equilibrium). For any given material, timelag interval depends only on the size and temperature of the specimen.

[2] Byram, G. M. *An analysis of the drying process in forest fuel material.* 1963. (Unpublished manuscript on file at Southeastern Forest Expt. Sta., Forest Fire Lab., U.S. Forest Serv., Macon, Ga.)

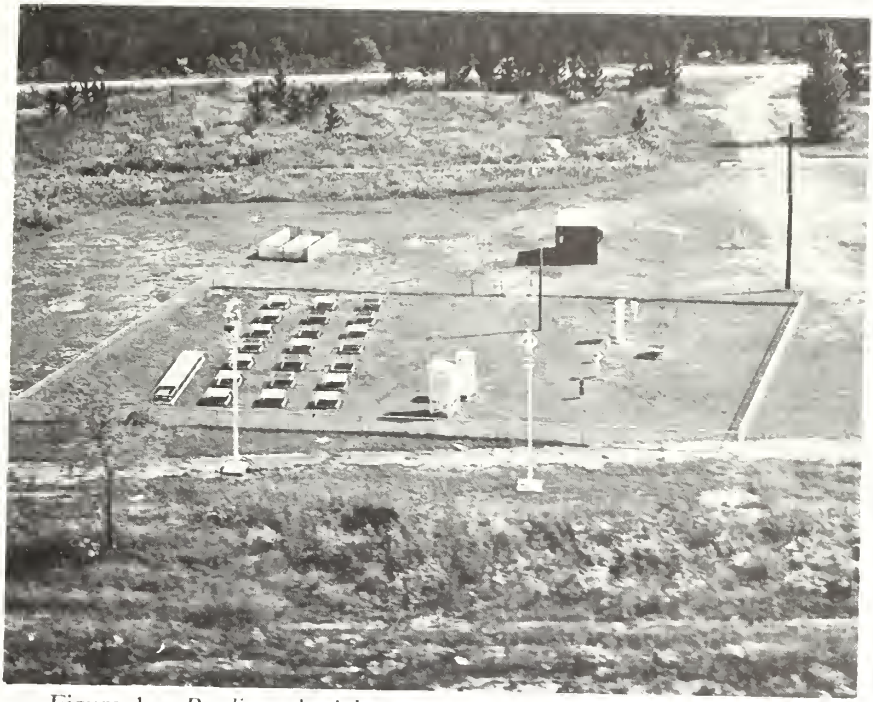

Figure 1.—*Replicated stick exposures are shown at left inside the enclosure. The long frame at the extreme left held the weathering study sticks and screens. Instruments for recording the weather variables occupied the rest of the enclosure. The stick weighing shelter is shown at top right.*

Figure 2.—*Sticks exposed under no screens were placed on supports. The tube leading into the ground carried the thermocouple lead-in wires to the potentiometer in the weighing shelter. Sticks were also exposed under one, three, four, and six layers of screen.*

At an air temperature of 80° F. under full shade the timelag interval is about 1.4 hours for basswood slats and about 5 hours for ½-inch pine dowels. Under the shading of one layer of screen these intervals drop to about 1 hour and 3 hours, respectively.

Moisture Content of Wood in Service

Wood in service, such as fuel moisture sticks exposed outdoors, is seldom at exact equilibrium because neither the humidity nor temperature of the air remain constant for long. Direct or reflected solar radiation may raise the surface temperature of the sticks above the temperature of the surrounding air, reducing the stick moisture content below what would be indicated based on air temperature and relative humidity (Byram and Jemison 1943; Jemison 1935). Wind, if present, may cool the sticks (Byram 1940). Rain falling directly on the sticks may increase their moisture content greatly. However, because the timelag interval of slats is short, their moisture content probably is very nearly in balance with the surrounding weather conditions most of the time on drying days, particularly at the customary 2 p.m. reading time at fire danger stations. Air temperature usually is near the daily maximum and relative humidity near the daily minimum about then. Although dowels have a longer timelag than slats do, there would appear to be enough daylight hours before 2 p.m. on most rainless days for dowels to come to some degree of balance with the surrounding weather conditions.

Analysis and Results

There were 208 days with usable data covering a wide range of stick moisture content and weather conditions (tables 1 and 2). Of the 24 weather variables determined from the weather factors measured, 17 were functions of weather factors observed during preceding time intervals of various lengths; these variables were intended to reflect the cumulative effect of the antecedent weather on stick moisture.

Slats

Sorting Out the Variables

In a preliminary analysis, we studied 10 weather variables: ST, DBT, DPT, WBD, $(DPD)^2$, RH, T_x–T_m, W, AR_2, and AH_S.

Coefficients of determination for 2 p.m. slat moisture content under one-screen and six-screen shading were computed for all possible combinations of the 10 independent variables. Data for the period May to September were used. The strongest single variables and strongest two-, three-, four-, and five-variable combinations were determined by inspection (table 3). As a result, the weather variables T_x–T_m, W, AR_2, and AH_S were eliminated. $(DPD)^2$ was correlated with AR_2, the solar radiation variable. The two variables were equally usable in the analysis, but $(DPD)^2$ proved easier to determine in practice.

Coefficients of determination were also calculated for slat moisture content under zero, three, and four screens using all possible combinations of the six independent variables selected above. The strongest single variables and combinations of variables up to three were determined by inspection (table 3). Many combinations were of limited value for prediction because certain variables were alternate expressions of the same factor; for example, DPT, RH, and WBD all reflected humidity.

One of the three best three-variable combinations was DBT, DPT, and $(DPD)^2$. This combination can be put into the form of a two-way table for ease of use because the third variable is the square of the difference of the first and second variables. A statistical analysis showed that there was a significant gain in information by adding successively DPT and $(DPD)^2$ to DBT. Adding successively a fourth and a fifth variable increased R^2 by slight but significant amounts. However, four- and five-variable equations are cumbersome to use. A three-variable equation is about the practical limit.

Regression equations containing the three strongest independent variables were computed from the 91 data using the model:

$$Y = a + b_1x_1 + b_2x_2 + b_3x_3$$

Table 1.--*Range in moisture content and surface temperature of fuel moisture indicator sticks (Basis: 208 data of readings at 2 p.m.)*

MOISTURE CONTENT

Screens (number)	Slats			Dowels		
	Symbol	Range	Average	Symbol	Range	Average
		- - - - *Percent* - - - -			- - - - *Percent* - - - -	
0	SM_0	2.4 to 20.3	6.0	DM_0	6.6 to 31.5	12.1
1	SM_1	3.1 to 20.6	6.8	DM_1	7.0 to 34.6	12.4
3	SM_3	3.8 to 20.8	8.0	DM_3	7.2 to 45.0	13.0
4	SM_4	3.9 to 27.0	8.5	DM_4	6.9 to 41.1	13.1
6	SM_6	4.4 to 22.8	8.7	DM_6	7.4 to 29.0	12.6
SURFACE TEMPERATURE (BY THERMOCOUPLE)						
		- - - *Degree F.* - - -			- - - *Degree F.* - - -	
0	ST_0	51 to 126	89.2	DT_0	44 to 116	85.7
1	ST_1	44 to 120	85.4	DT_1	44 to 115	82.2
3	ST_3	42 to 116	81.1	DT_3	41 to 112	79.4
4	ST_4	40 to 112	79.7	DT_4	40 to 109	78.7
6	ST_6	41 to 110	79.5	DT_6	41 to 109	78.2

which, Y is SM_0, SM_1, SM_3, SM_4, or SM_6; a, b_1, , and b_3 are regression coefficients; x_1 is DBT, is DPT, and x_3 is $(DPD)^2$.

Similar equations were computed from the 117 ata for the period October 1959 to May 1960. his is the normal one-screen season at 8-Type e danger stations during which hardwood trees e without leaves.

vo Seasons' Data Combined

An analysis of variance test applied to the two asons' data showed that the seasons did not ffer significantly. The two sets of data were comned and a new set of equations of the same rve form based on 208 data were computed.

lecting the Proper Curve Form

An improved curve form for the basic threeriable equation was determined by a series of atistical tests and graphic comparisons. Plotting siduals from the computed equations showed at SM, the dependent variables, should be in log form ($\log_e SM$).

The third independent variable $(DPD)^2$ also as transformed to the log form ($\log_e DPD$). rves computed from equations containing the nsformed variables better fitted published equirium curves for wood (Forest Prods. Lab. 1955; hniewind 1956) (fig. 3). Because their timelag interval is short[3] slats will reach equilibrium moisture content rather rapidly. It might be expected, therefore, that the computed prediction curves and equilibrium curves would be similar.

Use of the transformed variables resulted in the following regression model:

$$\log_e Y = a + b_1(X_1) + b_2(X_2) + b_3 \log_e(X_3)$$

in which Y is SM_0, SM_1, SM_3, SM_4, or SM_6; a, b_1, b_2, and b_3 are regression coefficients; X_1 is DBT, X_2 is DPT, and X_3 is DPD.

Values for the regression coefficients, coefficients of determination, and confidence limits calculated using this model were computed (table 4), and selected solutions of the equations were plotted (figs. 4, 5).

A similar analysis of 127 data from a well-run fire danger station in Connecticut afforded an independent check of the estimating equation for slat moisture content under one screen. The two equations were nearly identical. The coefficient of determination was slightly smaller, and the standard error of estimate slightly larger for the check equation—probably because the slats were not as carefully selected and precisely weighed as in the present study.

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[3] See footnote 2.

Table 2.--*Ranges in values of weather factors (Basis: 208 data of readings at 2 p.m.)*

Weather factors	Symbol[1]	Units	Range	Average
Dry bulb (air) temp.	D.B.T.	°F.	38 to 101	74.5
Dew point temp.	D.P.T.	°F.	11 to 76	51.8
Wet bulb depression	W.B.D.	°F.	1 to 63	13.8
Dew point depression	D.P.D.	°F.	4 to 47	23.4
Relative humidity	R.H.	Pct.	16 to 87	44.8
Maximum temp.-minimum temp.	T_x-T_m	°F.	10 to 45	27.2
Wind speed (15 ft.)	W	m.p.h.	1.0 to 15.0	6.5
Antecedent solar radiation	AR_1	gm.cal./cm.^{2}	12 to 78	50.4
Antecedent solar radiation	AR_2	gm.cal./cm.^{2}	24 to 188	104.0
Antecedent solar radiation	AR_8	gm.cal./cm.^{2}	--	--
Antecedent relative humidity	AH_4	Pct.-hrs./20	2 to 15	9.5
Antecedent relative humidity	AH_8	Pct.-hrs./20	2 to 26	12.1
Antecedent relative humidity	AH_{24}	Pct.-hrs./20	--	--
Antecedent relative humidity	AH_{48}	Pct.-hrs./20	--	--
Antecedent relative humidity	AH_{72}	Pct.-hrs./20	--	--
Antecedent time at saturation	AS_8	hours	0 to 6	1.6
Antecedent time at saturation	AS_{24}	hours	0 to 20	7.7
Antecedent time at saturation	AS_{48}	hours	--	--
Antecedent time at saturation	AS_{72}	hours	--	--
Antecedent precipitation	AP_4	inches	0 to 0.20	0.001
Antecedent precipitation	AP_8	inches	0 to 1.05	0.007
Antecedent precipitation	AP_{16}	inches	--	--
Antecedent precipitation	AP_{24}	inches	--	--
Antecedent precipitation	AP_{48}	inches	--	--

[1] Numbers in subscript are the number of hours the variable was accumulated.

Dowels

A somewhat similar analysis was made of the 208 dowel data with the two seasons combined. We examined 10 weather variables: DT, DBT, DPT, RH, W, AR_2, AR_3, AH_8, AH_{24}, and AS_{24} (table 1). More antecedent weather variables were included than in the slat analysis because the time-lag interval is longer for dowels.[4] Weather conditions the preceding night or preceding night and day would be expected to influence dowel moisture content the following day.

Coefficients of determination for $\log_e$ (dowel moisture content) under zero-, one-, three-, four-, and six-screen shading were computed for all possible combinations of the 10 independent variables. The strongest single variables and the strongest two-, three-, four-, and five-variable combinations were determined by inspection (table 5).

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[4] See footnote 2.

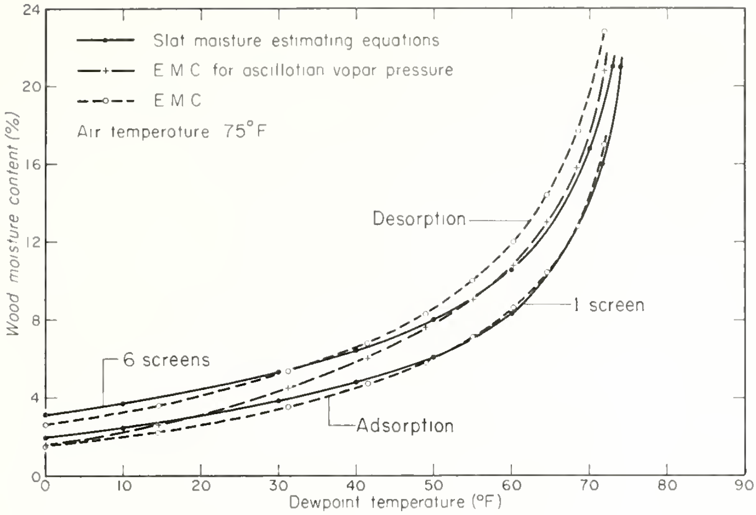

Figure 3.—*Computed estimating curves for slat moisture content plotted on curves of equilibrium moisture content (E.M.C.) for wood (Schniewind 1956) and for oscillation vapor pressure (Forest Products Lab. 1955). The six-screen shading was most similar to shading indoors where the E.M.C. studies were conducted.*

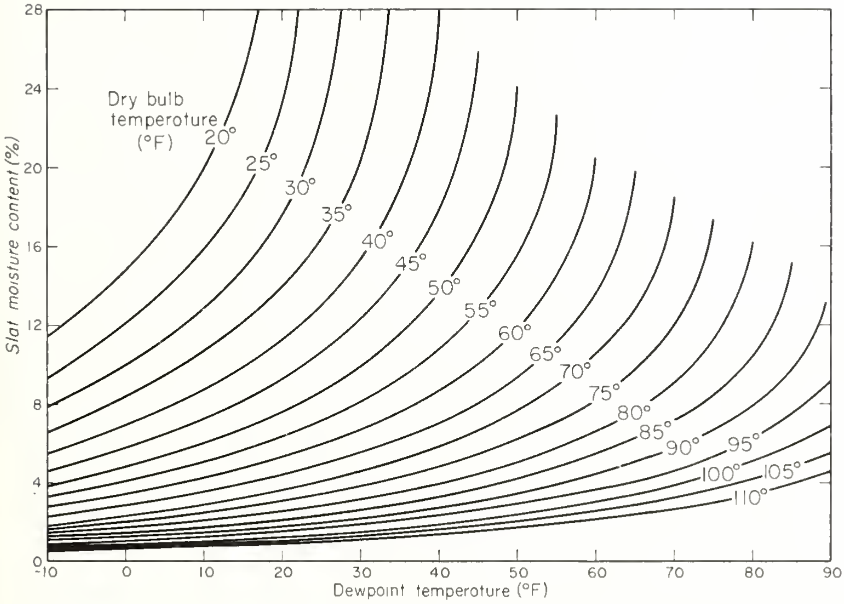

Figure 4.—*Computed curves for estimating slat moisture content under one-screen shading from psychrometric variables.*

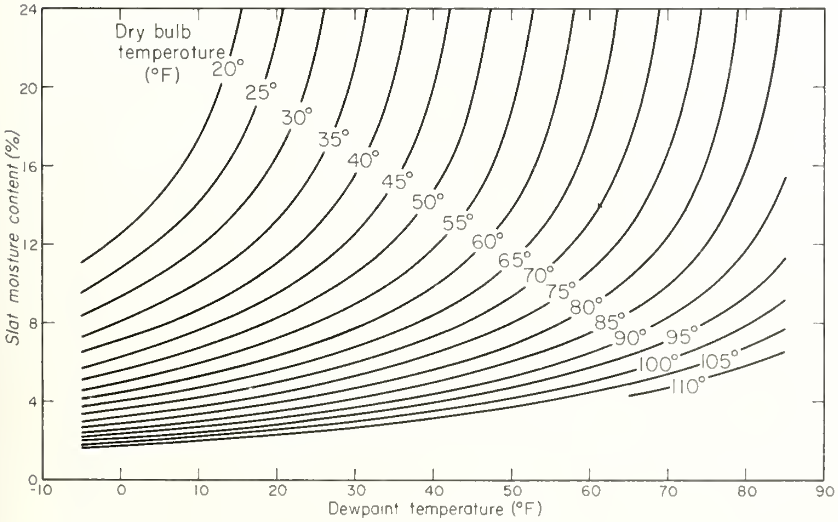

Figure 5.—*Computed curves for estimating slat moisture content under six-screen shading from psychrometric variables.*

Table 3.--*Best single variables and combinations of variables for predicting slat moisture content (Basis: 91 data, May to September 1959)*

Variables in combination	Coefficients of determination (R^2)				
	0-screen	1-screen	3-screen	4-screen	6-screen
1:					
RH	0.677	0.796	0.729	0.647	0.711
WBD	.658	.752	.659	.576	.648
$(DPD)^2$	.517	.595	.518	.453	.536
2:					
ST, RH	.717	.852	.749	.659	.734
DBT, RH	.727	.821	.731	.647	.711
DBT, DPT	.691	.769	.665	.581	.659
3:					
ST, RH, $(DPD)^2$	.728	.871	.790	.701	.754
DBT, RH, $(DPD)^2$	.745	.848	.771	.687	.730
DBT, DPT, $(DPD)^2$	.740	.846	.774	.687	.734
4:					
ST, RH, $(DPD)^2$, AH_8	--	.877	--	--	.760
ST, RH, $(DPD)^2$, W	--	.874	--	--	.761
DBT, DPT, $(DPD)^2$, AH_8	--	.855	--	--	.743
5:					
ST, RH, $(DPD)^2$, AH_8, W	--	.877	--	--	.766
DBT, RH, $(DPD)^2$, AH_8, W	--	.853	--	--	.740
DBT, DPT, $(DPD)^2$, AH_8, W	--	.855	--	--	.745

Table 4.--*Regression equation constants, coefficients of determination (R^2), and confidence limits for estimating slat moisture content (SM) (Basis: 208 data for the period May 1959 through April 1960)*

Screens (number)	Regression coefficients					Confidence limits at 95-percent level[1]
	a	b_1	b_2	b_3	R^2	
						Percent[2]
0	4.41028	-0.020188	0.005152	-0.45707	0.816	- 73.9 +135.2
1	3.84924	- .032019	.018703	- .17361	.830	- 76.7 +130.4
3	4.14172	- .016778	.008291	- .40801	.810	- 77.9 +128.4
4	4.05962	- .017926	.010626	- .37790	.777	- 76.1 +131.3
6	3.81922	- .017253	.011504	- .31695	.792	- 79.1 +126.5

[1] For individual (single) estimates of slat moisture content at the mean value of the independent variable (tables 1 and 2).

[2] Of predicted slat moisture.

Table 5.--*Best single variables and combinations of variables for predicting dowel moisture content (DM) (Basis: 208 data)*

Variables in combination	Coefficients of determination (R^2)				
	0-screen	1-screen	3-screen	4-screen	6-screen
1:					
AR_2	0.311	0.309	0.287	0.280	0.319
AS_{24}	.344	.301	.211	.190	.212
DBT	.289	.255	.181	.158	.178
2:					
DT, AS_{24}	.569	.576	.528	.550	.637
DBT, AH_8	.617	.601	.561	.575	.630
DBT, DPT	.556	.548	.498	.522	.604
3:					
DT, AH_{24}, AS_{24}	.678	.685	.655	.676	.754
DBT, DPT, AH_{24}	.673	.672	.641	.665	.737
DT, DPT, AH_{24}	.672	.671	.638	.654	.642
4:					
DT, AR_8, AH_{24}, AS_{24}	.685	.695	.665	.687	.770
DBT, DPT, AH_{24}, AR_8	.684	.685	.655	.679	.755
DBT, DPT, AH_{24}, AS_{24}	.681	.682	.649	.674	.757
5:					
DT, RH, AR_8, AH_{24}, AS_{24}	.693	.703	.673	.696	.774
DT, W, AR_8, AH_{24}, AS_{24}	.691	.703	.660	.685	.773
DBT, DPT, AH_{24}, AS_{24}, AR_8	.690	.694	.669	.692	.770
All	.722	.724	.691	.710	.786

Table 6.--*Test of gain in precision of estimating dowel moisture content (DM) by adding variables to the estimating equation, 1-screen and 6-screen shading (Basis: 208 data)*

Variables	One-screen			Six-screen		
	F[1]	R^2	Confidence limits (95 percent) level[2]	F[1]	R^2	Confidence limits (95 percent) level[2]
			Percent[3]			*Percent*[3]
$\log_e DM = f(DBT)$	--	0.255	--	--	0.178	--
$\log_e DM = f(DBT, DPT)$	133**	.548	- 68.9 +145.3	220**	.604	- 77.8 +128.6
$\log_e DM = f(DBT, DPT, AH_{24})$	78**	.672	- 73.2 +136.4	103**	.737	- 81.4 +122.9
$\log_e DM = f(DBT, DPT, AH_{24}, AS_{24})$	6*	.680	- 73.1 +137.0	17**	.757	- 82.1 +121.9
$\log_e DM = f(DBT, DPT, AH_{24}, AS_{24}, AR_8)$	8**	.694	- 73.4 +136.2	11**	.770	- 82.4 +121.4
$\log_e DM = f(\text{all } 10)$	--	.724	--	--	.786	--

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[1] F = test for significant gain in information due to adding variables; ** highly significant; * significant.

[2] For individual (single) estimates of dowel moisture content at the mean value of the independent variable (tables 1 and 2).

[3] Of predicted dowel moisture.

Table 7. --*Regression equation constants, coefficients of determination* (R^2), *and confidence limits for estimating dowel moisture content (DM) (Basis: 208 data)*

Screens (number)	Regression coefficients					Confidence limits at 95-percent level[1]
	a	b_1	b_2	b_3	R^2	
						Percent[2]
0	3.49477	-0.026340	0.014771	0.021947	.673	- 74.4 +134.2
1	3.45754	- .025716	.015048	.021968	.672	- 73.2 +136.4
3	3.38792	- .024364	.015228	.023089	.641	- 72.4 +138.5
4	3.35229	- .023875	.015715	.021814	.665	- 72.0 +138.8
6	3.20931	- .020265	.013633	.016372	.737	- 81.4 +122.9

[1] For individual (single) estimates of dowel moisture content at the mean value of the independent variable (tables 1 and 2).

[2] Of predicted dowel moisture.

Table 8.--*Comparative errors of determining slat moisture content by equation and by weighing at fire danger stations*

Screens (number)	Slat moisture content	Error by equation[1]	Error in field practice due to --				Total[6]
			Calibration[2]	Weathering[3]	Scale[4]	Natural variation[5]	
			- - - - *Percent* - - - -				
1	3.1	(>±0.83)	±0.5	±0.8	±0.2	±0.5	1.09
	6.8	±1.82	± .5	± .8	± .2	± .5	1.09
	20.6	(>±5.52)	± .5	± .8	±1.0	± .5	1.46
6	4.4	(>±1.04)	± .5	± .8	± .2	± .5	1.09
	8.7	±2.06	± .5	± .8	±1.0	± .5	1.46
	22.8	(>±5.40)	± .5	± .8	±1.0	± .5	1.46

[1] Based on an average of the confidence limits at 95-percent level (table 4) and for individual (single) estimates of slat moisture content at the mean values of the independent variables (tables 1 and 2).

[2] Allowable variation in processing slats.

[3] Due to the average weathering correction used in field practice.

[4] Due to reading errors and variation between scales used in weighing.

[5] Due to timelag differences resulting primarily from differences in thickness of slats.

[6] Probable error $= \sqrt{\Sigma[(\text{individual sources of error})^2]}$.

The most promising three-variable combination was DBT, DPT, and AH_{24}. A statistical analysis of the one-screen and six-screen dowel moisture data showed that there was a significant gain in information by adding successively DPT, AH_{24}, AS_{24}, and AR_s to DBT (table 6). However, adding more than two variables had little practical benefit since R^2's were increased only slightly. The small gain in precision of estimating dowel moisture content probably would not be worth the effort to measure AS_{24} and AR_s in field practice.

Regression equations containing the best three variables were computed (table 7) and portions plotted (fig. 6), as follows:

$$\log_e Y = a + b_1(X_1) + b_2(X_2) + b_3\log_e(X_3)$$

in which Y is DM_0, DM_1, DM_3, DM_4, or DM_6; a, b_1, b_2, and b_3 are regression coefficients; X_1 is DBT, X_2 is DPT, and X_3 is AH_{24}.

By holding the third independent variable (AH_{24}) constant, it is possible to demonstrate the equations by a two-dimensional plot (fig. 6). However, a three-dimensional block diagram would be needed to demonstrate the exact relationships between all three independent variables and dowel moisture content.

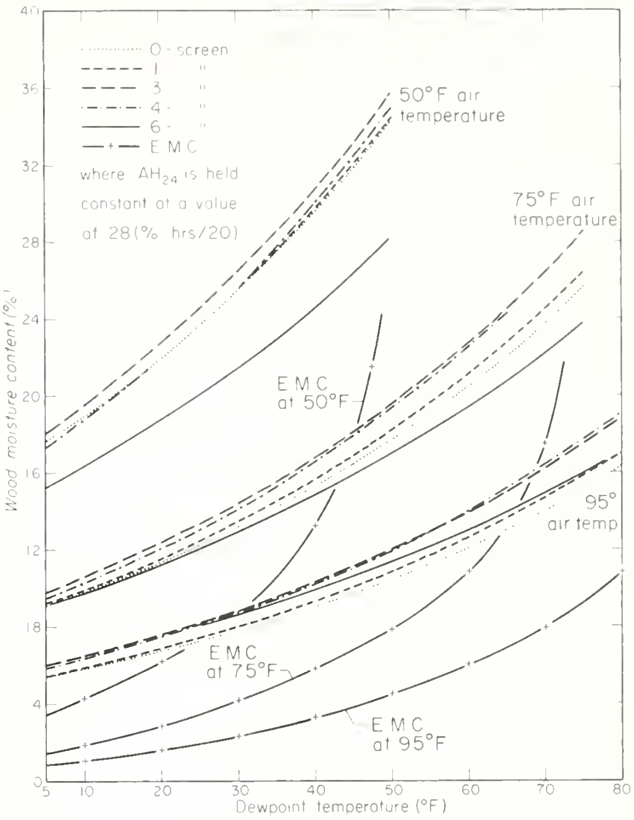

Figure 6.—*Computed curves for estimating dowel moisture content under zero-, one-, three-, four-, and six-screen shading from psychrometric variables. Equilibrium moisture content curves (E.M.C.) for wood (Forests Products Lab. 1955) are plotted for comparison.*

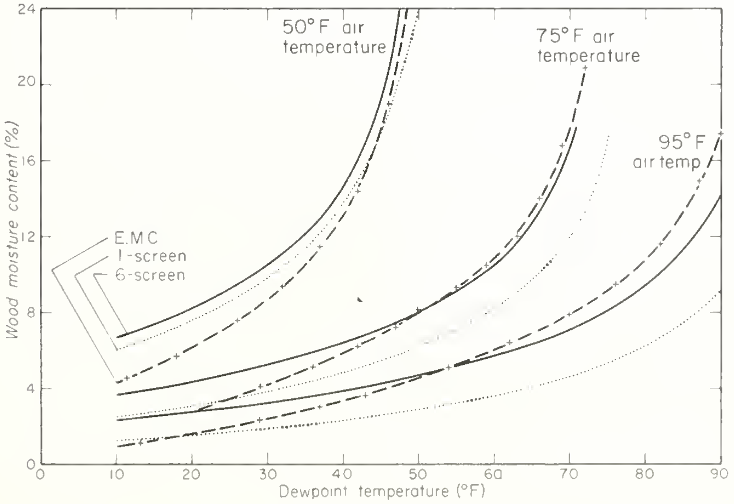

Figure 7.—*Computed slat moisture estimating curves plotted on curves of equilibrium moisture content (E.M.C.) for wood (Forest Products Lab. 1955) for three air temperatures.*

Discussion

Slat Moisture Content

Dewpoint temperature was selected over relative humidity to express humidity in the final equation, although the two variables showed to equal advantage in the analysis (table 3). This choice was made primarily for the benefit of fire weather forecasters who usually prefer to work with dewpoint. However, for those who prefer to use relative humidity or wet bulb depression, the conversion is easily made. It can be done most easily from computed plotting values or graphs of the final equation with the aid of a psychrometric slide rule or tables. Stations that ordinarily take only wet and dry bulb readings would find a tabular form of the equation with wet bulb depression and dry bulb temperature as entries easiest to use. Tables or graphs should be equally accurate in any of the three forms.

Solar radiation has a marked influence on slat moisture content, primarily through surface heating. Less than full shading allows a certain amount of radiation to reach the slats and raise their surface temperature above air temperature (tables 1 and 2). This effect lowers the humidity immediately above the slats and reduces the slat moisture content. The amount that slat moisture content is reduced compared to fully shaded sticks depends on the air temperature and the amount of screen shading (tables 1 and 2, figs. 3 and 7). The reduction is greatest at high temperatures and no shading.

The effect of radiation shading is partially responsible for observed differences between computed slat moisture content and equilibrium moisture content (E.M.C.) for wood (fig. 7). However, timelag is also a factor. The higher the air temperature, the shorter the timelag interval, and the lower the moisture content of slats compared to equilibrium—other things being equal.

The accuracy of estimating slat moisture content by equation, for mean values of the independent variables, approaches that of actual measurement at fire danger stations (table 8). Accuracy of estimation decreases as values of the independent variables depart from their means. The equations are most accurate at low slat moisture content and least accurate at high moisture content. In fire danger measurement work it is considerably more important to be able to estimate stick moisture content accurately in the critical low moisture range, that is, below about 8 percent.

Dowel Moisture Content

The percent of moisture content in dowels can be estimated more closely by equation than that in slats (tables 4 and 7). This is largely because the moisture content of dowels averages from 1½ to 2 times as high as that of slats for similar conditions of weather and shading (table 1).

Solar radiation has at least as much influence on dowel moisture content as on slats as indicated by the spacing between curves for different amounts of screen shading (figs. 6 and 7). As with slats the effect of radiation decreases as temperature and humidity decrease.

At some temperature above 95° F. the curves for zero, one, three, four, and six screens began to reverse order (fig. 6). The slat curves did not show this tendency (fig. 7). At 95° F. the six-screen curve was positioned between the one- and the three-screen curves. At 75° F. the six-screen curve was in the lowest position and the three- and four-screen curve had just reversed order. This tendency continued at lower air temperatures and was most pronounced at higher dewpoint temperatures.

One possible explanation of this phenomenon is on the basis of dew effects and drying rates. Less dew forms at night on shaded dowels than on dowels in the open. However, shaded dowels may be able to retain more of their acquired moisture the next day because they are protected from evaporative effects of the sun. By 2 p.m. the dowels in the open will have lost nearly all of the moisture picked up during the night. On the other hand, unless the day is very hot and bright, the shaded dowels ordinarily will not have lost by 2 p.m. any appreciable portion of the relatively small quantity of moisture they acquired during the night. Dowels dry slowly as is indicated by their long timelag interval, and the interval lengthens rapidly as air temperature decreases. This characteristic probably explains why the reversal becomes more pronounced at low air temperatures. The fact that days with low air temperature usually are shorter, with fewer drying hours before 2 p.m., undoubtedly contributes to this effect.

The reversal is less pronounced at low dewpoint temperatures, probably because less dew is formed at night following days with low dewpoint temperature.

Slats probably pick up relatively more moisture from dew at night than dowels. However, they ordinarily will lose most of it by 2 p.m. the next day because the timelag interval for slats is only about one-fifth as long as for dowels.

Computed moisture content curves for dowels paralleled E.M.C. curves for wood fairly well at high air temperatures, although there was considerable separation (fig. 6). The separation was much greater at low air temperatures, and the computed curves were much flatter than E.M.C. curves.

Summary and Conclusions

Weather factors affecting the 2 p.m. moisture content of two types of fuel moisture indicator sticks exposed under five different amounts of screen shading were studied near Macon, Georgia. Replicated sets of basswood slats and ponderosa pine dowels were exposed under zero, one, three, four, and six layers of aluminum window screen in a randomized block design for 1 year (rainy days were excluded).

Of the 24 weather variables considered in initial trials, 10 showing the most promise were evaluated in detailed multiple regression solutions for each type of indicator stick and amount of shading. All possible combinations of the 10 weather variables were analyzed jointly with stick moisture content.

The resulting equations proved fairly good predicting equations for both slats and dowels. They indicated that for mean values of the independent variables, slat moisture content could be determined with approximately equal precision by equation in the critical low moisture content range or by weighing at fire danger stations. But equations were considerably less accurate than field practice in the high moisture content range. For ease of use the predicting equations can be put into the form of a simple two-way table. This is possible because the third independent variable, dewpoint depression, is composed of the first and second variables, dry bulb temperatures, and dewpoint temperature. Relative humidity or dry bulb depression can be substituted for dewpoint temperature since the three are alternate expressions of humidity.

The percent of dowel moisture content could be determined with slightly greater precision by equation than percent of slat moisture content. Numerically, however, the dowel equations were less precise because dowels averaged one and a half to two times more moisture content than slats for similar weather conditions. Dry bulb temperature, dewpoint temperature, and average relative humidity during the 24-hour period preceding the 2 p.m. reading proved to be significant gauges of dowel moisture content. The variable "antecedent relative humidity" reflected the relatively long timelag interval of dowels. None of the antecedent weather variables was significant in the slat analysis because slats dry rapidly and have short timelag intervals. Three-way tables are required to express the predicting equations for dowel moisture content in tabular form. These are more cumbersome to use in practice than the two-way tables for slats. In addition, humidity must be determined periodically in order to compute the antecedent humidity variable.

Other findings included a close agreement between slat moisture under six screens and equilibrium moisture content for wood at moderate air temperatures and dewpoints; slat moisture under six screens underruns equilibrium moisture content at high temperatures and dewpoints, and overruns equilibrium moisture content at low dewpoints regardless of air temperature; dowel moisture curves parallel equilibrium moisture content curves with considerable separation at very high air temperatures, but the two types of curves resemble one another very little at other air temperatures.

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The Pacific Basin Market for Wood Products for Military Support Activities

John D. Zinnikas

U. S. FOREST SERVICE RESEARCH PAPER PSW-27 1966

Pacific Southwest Forest and Range
Experiment Station - Berkeley, California
Forest Service - U. S. Department of Agriculture

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Military activities of the United States exert an important influence on the economy of the Pacific Basin. Hawaii is the operational center for the defense of the entire Pacific area. As a result nearly 18 percent of the population of the State consists of military personnel and their dependents. Defense expenditures total around $400 million annually.

Logistical requirements of the military forces in the Pacific Basin include many supporting materials—among them large quantities of lumber and other wood products. Because Hawaii is the operational center of Pacific military activity and is, locationally, the hub of the Pacific area, the State is in an advantageous geographical position to provide some of the wood product needs of the military forces.

The use of wood products in support of military activity can be an important market for Hawaii-produced lumber and other wood products. This paper reports on a study of the consumption of lumber and other wood products used in support of military operations in the Pacific Basin. It defines the military market for wood in the Pacific Basin; reports the size of this market, by species and product; and describes the conditions necessary for entry into this market by individual firms.

In this paper, the Pacific Basin is defined to include the west coast of North America, all islands in the Pacific Ocean, and the east coast of Asia. The Pacific Basin is subdivided into three separate market areas: (a) the state of Hawaii, (b) the west coast of North America, and (c) all other Pacific Island land areas bordering the Pacific Ocean. The data reported in this paper were classified according to these three market areas.

What is the Market?

The military use of lumber and other wood products can be divided into two main parts. The first is military construction, including housing for military personnel and their dependents. This market is satisfied through the use of private contractors. Although the materials used in construction must meet or exceed set military specifications, the sources of supply, species used, and other decisions are made by these private contractors and sub-contractors. These contractors purchase lumber and other materials either from local vendors or from United States mainland sources. Volume estimates of this market are difficult to determine. An indication of its importance is the dollar value of military housing. The publication, *Military Construction Program,*[1] issued by the Department of the Army, lists the current working estimate of new housing at nearly 33 million in the Pacific Basin.

The second major demand for lumber and other wood products by the armed forces is in military support activities. For example, wood is used in transporting military personnel and equipment and in maintaining existing bases of operation. Information concerning wood used in military support is somewhat easier to obtain because all purchases are made through two regional procurement sub-offices of the U.S. Defense Construction Supply Center.

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[1] Directorate of Military Construction, Office of the Chief of Engineers, Department of the Army, Washington, D.C. Sec. D. 1964.

Size of Market

In 1963 slightly more than 113 million board feet of lumber were used in military support activity in the Pacific Basin (tables 1, 2). This volume dropped to 86 million board feet in 1964. Plywood and veneer consumed by the military services totaled 14 million square feet (surface measure) in 1963 and almost 18 million square feet in 1964. Military activities also required sizable quantities of a wide variety of other wood products, such as ties, crossarms, poles, and a multitude of other items made from both hardwoods and softwoods.

In the Hawaii market, 3.3 million board feet of lumber were used in military support activity in 1964, most of which was softwood lumber. Hardwood consumption was only 141,000 board feet in 1963 and 52,000 board feet in 1964. There were a number of miscellaneous wood items, such as poles, ties, etc., used for maintenance.

The other two markets overshadowed Hawaii in almost every category, with the "other Pacific" market the volume leader. In hardwood lumber alone, the level of consumption in the other Pacific market was twice that of Hawaii's total annual production of all wood products. Much of this consumption was in products that could have been produced in Hawaii from species of wood currently being produced; e.g., crossarms from *E. robusta* in Hawaii.

The appendix to this report shows in greater detail the breakdown, by commodities, of wood products consumed by the armed forces. Distinction is made between green and dry lumber, by individual species and species groupings. During 1964, the consumption of dry hardwood lumber was almost four times greater than that of green hardwood lumber.

The oaks as a species group were most important from the standpoint of volume used. However, it cannot be said that oak is the dominant species, for certain military procurement requirements preclude a breakdown, by species. Procurement office regulations allow a supplying firm to fill its contract with several species as long as they meet or exceed set military specifications. Thus, the term "species group" indicates that the military will accept an order containing a variety of species. This "species group" concept applies to both hardwoods and softwoods.

Particular orders may specify certain species only. An example of a species group would be No. 2 construction boards. An order for this grade of lumber can be filled by a variety of species including aspen, magnolia, and soft maple, at the option of the supplying firm.

Entry into the Military Support Market

Procurement of lumber and wood products needed for military support activities is the responsibility of the U.S. Defense Construction Supply Center, Columbus, Ohio. The actual procurement is handled by its two regional suboffices: one at Atlanta, Georgia, and the other at Portland, Oregon. The Atlanta suboffice purchases most of the hardwood products used by the military forces. Both suboffices purchase softwood lumber. Purchase responsibility is determined by both type of raw material (species) and by destination point.

The first step for producers in Hawaii to enter the military market is to get Hawaii-grown species accepted by the armed forces. For instance, the acceptable "species group" for hardwood construction board, utility board, and dimension admit such varieties as aspen, poplar, soft elm, and soft maple. If Hawaii-grown hardwoods can be included in this grouping, then island firms can enter this market.

The second step to entering this market involves the individual supplier firms, who must see that they are placed on the bidders' mailing list of the two procurement suboffices. These offices will provide the necessary forms upon request. Lists will be furnished of the types of materials purchased by each suboffice and of the bidding procedure. Firms on the bidding list will be contacted when purchases are to be made and will be asked to submit bids. If Hawaii-based firms can successfully enter this market, they will have a locational advantage for all shipments to the "other Pacific" area. From the State's viewpoint, the "other Pacific" market for lumber is quite significant even though it is dwarfed by the size of the softwood

Table 1.--*The military market for lumber and wood products in the Pacific Basin, 1963*[1]

Item	Hawaii	West Coast	Other Pacific	Total
	Thousand board feet			
Lumber:				
Softwood	3,299	30,271	76,935	110,505
Hardwood	141	174	2,202	2,517
	Thousand sq. ft. surface measure			
Plywood and veneer:				
Softwood	688	6,973	6,265	13,926
Hardwood	--	105	127	232
	Linear feet			
Molding	123,137	42,939	6,000	172,076
Batten strip	7,000	--	--	7,000
	Each			
Ties	600	129,187	9,500	139,287
Crossarms	123	290	10,892	11,305
Piles	899	401	1,320	2,620
Line construction poles	189	663	7,229	8,081
Wood poles	70	120	11,155	11,345
Doors	--	174	3,753	3,927

[1] Source: Regional Procurement Suboffices, U.S. Defense Construction Supply Center, Atlanta, Georgia, and Portland, Oregon.

Table 2.--*The military market for lumber and wood products in the Pacific Basin, 1964*[1]

Item	Hawaii	West Coast	Other Pacific	Total
	Thousand board feet			
Lumber:				
Softwood	3,276	25,005	55,165	83,446
Hardwood	52	216	1,797	2,065
	Thousand sq. ft. surface measure			
Plywood and veneer:				
Softwood	1,201	9,455	6,742	17,398
Hardwood	--	62	71	133
	Linear feet			
Molding	107,150	109,148	7,794	224,092
Batten strip	20,000	--	--	20,000
	Each			
Ties	5,700	285,627		291,327
Crossarms	84	700	3,294	4,078
Piles	250	1,330	845	2,425
Line construction poles	90	285	1,770	2,145
Wood poles	181	456	8,759	9,396
Doors	--	261	957	1,218

[1] Source: Regional Procurement Suboffices, U.S. Defense Construction Supply Center, Atlanta, Georgia, and Portland, Oregon.

lumber consumption in the Pacific. Hardwood consumption has been around 2 million board feet annually, or more than twice the Island's current production of all wood products. If Hawaii-grown hardwoods can gain acceptance in the species group, then Hawaii firms should be able to compete with mainland suppliers for the hardwood lumber market in other areas of the Pacific.

Summary and Conclusions

Military support activities in Hawaii use between 50 and 150 thousand board feet of lumber annually for which locally grown and produced hardwood lumber might be used. In addition, the "other Pacific" market uses about 2 million board feet of hardwood lumber annually, making it the largest of the three submarkets in the Pacific Basin.

The Pacific Basin can be an important market for the timber products industry in Hawaii because of the locational advantage it has compared to mainland producers. However, the composition of this market is mainly of softwood species, while the State currently is producing mostly hardwoods.

Future demand of the military market is clouded by uncertainty which precludes the accurate planning of a forestry program to provide for this market. Changes in world conditions may alter the national defense picture affecting military activity and thus, the use of lumber and wood products. However, for the foreseeable future, the Pacific Basin—with Hawaii as the operational center—will continue to be vitally important to national security.

Appendix

Table 3.--*Military shipments of hardwood lumber and wood products to the Pacific Basin, by species, species group, and grade, 1963*

Species or species group	Hawaii		West Coast		Other Pacific		Total	
	Green	Dry	Green	Dry	Green	Dry	Green	Dry
	Thousand board feet							
White oak	--	14	--	4	--	24	--	42
Mixed oak	--	--	--	--	386	75	386	75
Maple	--	24	--	16	1	2	1	42
Ash	1	3	--	3	--	10	1	16
Mahogany	--	11	--	--	--	--	--	11
Birch	--	--	--	1	--	1	--	2
Walnut	--	--	--	2	--	--	--	2
Miscellaneous hardwoods	--	--	--	--	--	16	--	16
Nos. 2 and 3 construction boards	--	73	37	20	219	842	256	935
Nos. 1, 2 and common dimension	--	--	9	--	139	67	148	67
Flooring	--	15	--	--	--	182	--	197
Unspecified mahogany	--	--	--	--	--	--	--	--
Miscellaneous grades	--	--	59	5	32	200	91	205
Planks, beams, and stringers	--	--	--	18	--	6	--	24
Total	1	140	105	69	777	1,425	883	1,634

Table 4.--*Military shipments of hardwood lumber and wood products to the Pacific Basin, by species, species group, and grade, 1964*

Species or species group	Hawaii		West Coast		Other Pacific		Total	
	Green	Dry	Green	Dry	Green	Dry	Green	Dry
	Thousand board feet							
White oak	7	7	14	9	38	35	59	51
Mixed oak	--	1	11	3	12	24	23	28
Maple	--	20	--	17	--	2	--	39
Ash	--	5	--	22	--	1	--	28
Mahogany	--	--	--	--	--	8	--	8
Birch	--	--	--	1	--	6	--	7
Walnut	--	--	--	1	--	--	--	1
Miscellaneous hardwoods	--	--	--	--	--	--	--	--
Nos. 2 and 3 construction boards	--	--	--	16	148	819	148	835
Nos. 1, 2, and common dimension	12	--	12	--	124	265	148	265
Flooring	--	--	--	13	--	224	--	237
Unspecified mahogany	--	--	--	21	--	3	--	24
Miscellaneous grades	--	--	66	9	--	72	66	81
Planks, beams, and stringers	--	--	--	1	1	--	1	1
Total	19	33	103	113	323	1,459	445	1,605

Table 5.--*Military shipments of hardwood plywood to the Pacific Basin, by species, 1963-64*

Hardwood	Hawaii		West Coast		Other Pacific		Total	
	1963	1964	1963	1964	1963	1964	1963	1964
	Thousand board feet (surface measure)							
Mahogany	--	--	3	4	3	5	6	9
Yellow poplar	--	--	--	--	32	5	32	5
Birch or maple	--	--	2	11	38	53	40	64
Gum	--	--	--	--	30	7	30	7
Oak	--	--	--	--	24	--	24	--
Pecan hickory	--	--	25	47	--	--	25	47
Douglas-fir and western hardwoods	--	--	--	--	--	1	--	1
Veneer paper overlaid	--	--	75	--	--	--	75	--
Total	--	--	105	62	127	71	232	133

Table 6.--*Military shipments of softwood lumber to Hawaii, 1963-64*

Lumber product	Year	
	1963	1964
	Thousand board feet	
Boards	1,183	1,390
Shop lumber	3	8
Dimension lumber	1,591	1,221
Timbers	300	154
Flooring	33	13
Beams and stringers	117	--
Planking	9	10
Shiplap	10	--
Miscellaneous	53	480
Total	3,299	3,276

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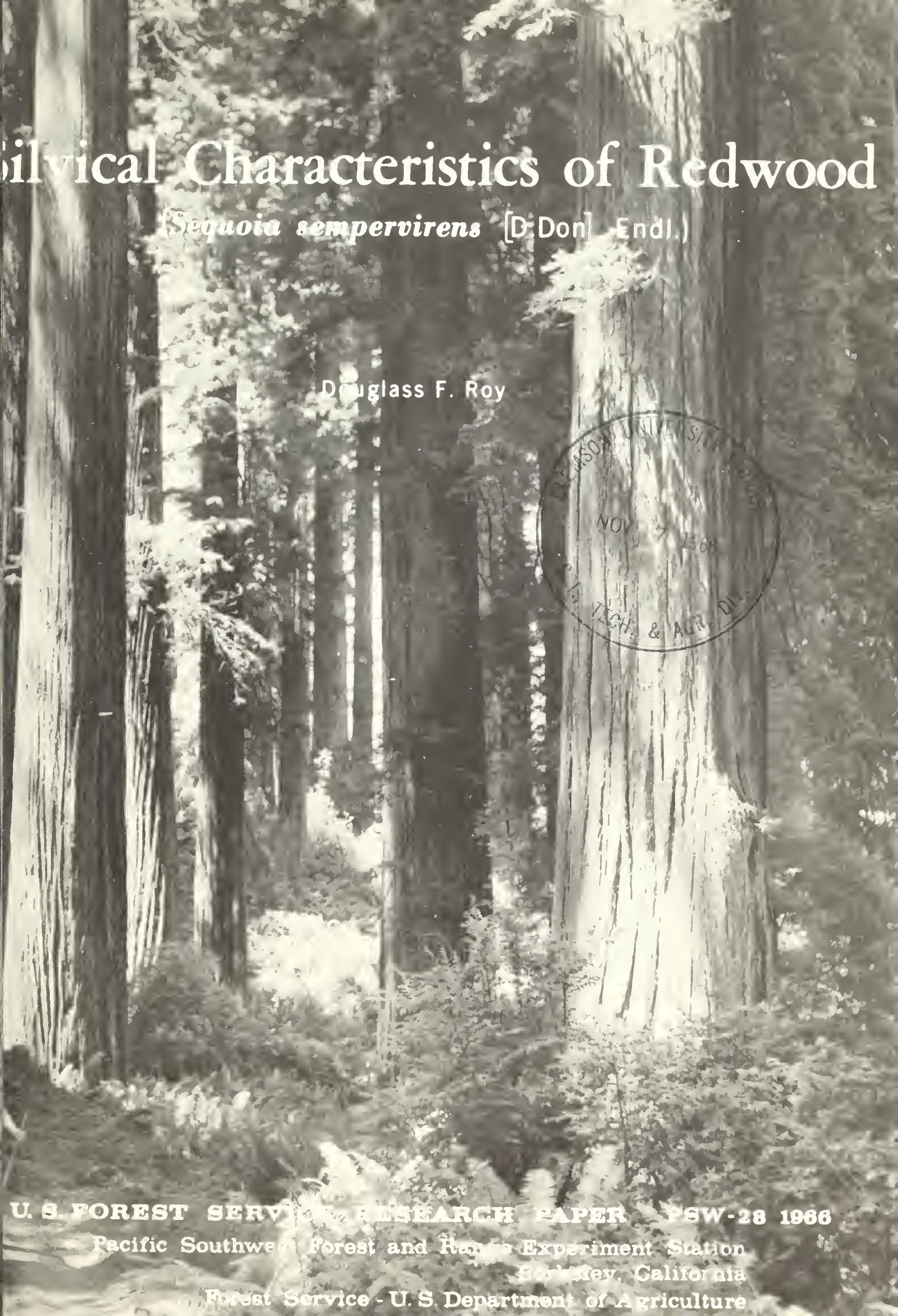

Silvical Characteristics of Redwood

(*Sequoia sempervirens* [D. Don] Endl.)

Douglass F. Roy

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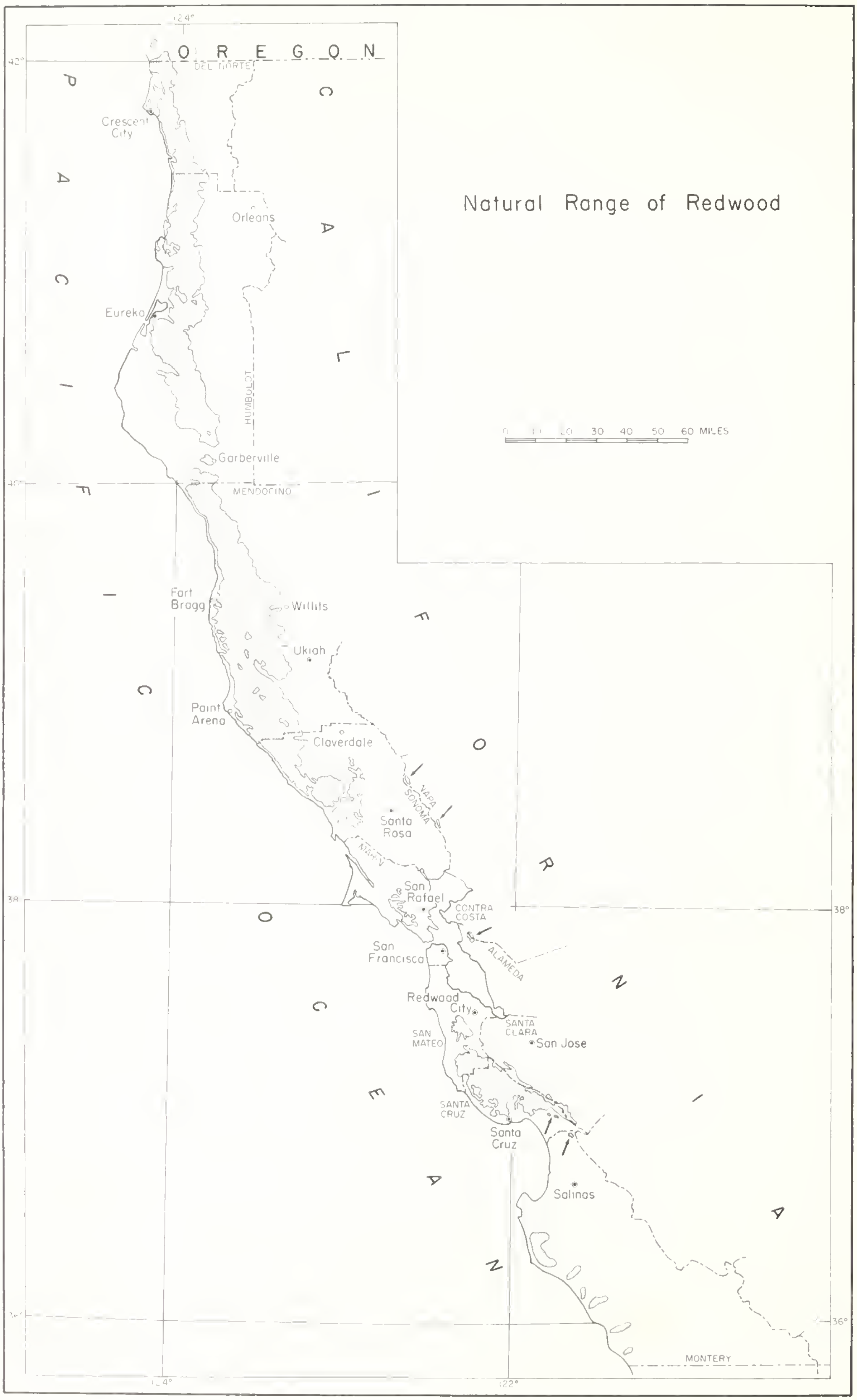

Figure 1.—*The natural range of redwood.*

The first record of redwood (*Sequoia sempervirens* [D. Don] Endl.) was written by Fray Juan Crespi on Tuesday, October 10, 1769, in his diary of the Don Gaspar de Portola Expedition. On that day the expedition traveled northwestward from a camp on the Pajaro River, now the boundary between Santa Cruz and Monterey Counties, into low hills, well forested with very high trees of a red color. No one recognized these trees so they were named redwood (palo colorado) from their color.

Archibald Menzies, surgeon and botanist with the Vancouver Expedition, is credited with the botanical discovery of redwood. He probably saw this tree at one or more points on the California coast in 1792 or 1793, but his collection is dated 1794 (Jepson 1923).

Stephen Endlicher, the noted Hungarian botanist, named the genus and the species in 1847. Although he did not explain the origin of the generic name, it seems certain that it honors the Cherokee Indian, Sequoyah, or George Guess. Sequoyah was talented, active, and prominent in working for his tribe, and is best known for developing an 83-character syllabic alphabet for the Cherokees (Jepson 1910; Save-The-Redwoods League 1935).

The natural range of redwood extends southward from two groves on the Checto River in the extreme southwest corner of Oregon to Salmon Creek Canyon in the Santa Lucia Mountains of southern Monterey County, California. This redwood belt is an irregular, narrow coastal strip about 450 miles long and 5 to 35 miles wide.[1] It has a transverse break along the headwaters of the Mattole River in southern Humboldt County. And south of Sonoma County, redwoods are found in detached and irregular areas (fig. 1).

Habitat Conditions

Climatic

The mild climate of the redwood region with its equable temperatures can be classed broadly as superhumid or humid (Thornthwaite 1941). Mean annual temperatures vary between 50° and 60° F. Differences between mean annual maximum and mean annual minimum temperatures range from 10° to 15° F. for coastal points to 30° F. for the eastern edge of the redwood type. Temperatures rarely fall below 15° F. or climb above 100° F. The frost-free period lasts from 6 to 11 months (Person 1937; U. S. Forest Service 1908).

Annual precipitation varies between 25 and 122 inches and falls mostly as winter rain, although the highest ridges sometimes are covered with snow. The distribution of precipitation at Scotia, Humboldt County, by seasons is: winter, 55 percent; spring, 23 percent; summer, 2 percent; and autumn, 20 percent. Generally, January is the wettest month, and August is the driest (Martin and Kincer 1934).

The frequent summer fogs which blanket the redwood region seem to be more important to redwood than the amount of precipitation. Fog decreases water loss from evaporation and transpiration and adds to the soil moisture supply to some degree. The relationship between redwood and fog seems intimate because the natural range of this tree is limited to the regions where heavy summer fogs from the ocean provide a humid atmosphere (Cooper 1917).

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[1] By Forest Survey definition, which classifies a forest stand as redwood type if redwood trees comprise 20 percent of the stand, including hardwood and conifer cover, the commercial forest land area in redwood type totals 1.6 million acres.

Edaphic

The parent rock material of the redwood region is largely massive marine sandstone formed in the Tertiary and upper Mesozoic periods. Considerable shale and lesser amounts of Mesozoic limestones and Franciscan slates, cherts, limestones, and sandstones also are represented, and schists are fairly common in some localities (Person 1937).

Soils vary from thin rocky loams on some of the steepest slopes to deep sandy loams on flats and benches. Sometimes clays are close to the surface and clay loams replace the more typical loams and sandy loams. One characteristic soil is moderately deep sandy loam containing a variable admixture of fine to coarse rocky material, usually sandstone, with a clayey subsoil (Person 1937).

Productive soils for redwood are the Hugo, Josephine, Melbourne, Empire, Sites, and Larabee series, and associated alluvial soils. The residual soils of high site quality have been derived from either consolidated or soft sedimentary rocks. They are light grayish brown or light reddish brown to brown in color, and are moderately to strongly acid (Gardner 1960; Roy 1957). Redwood tolerates a soil pH between 5.0 (acid) and 7.5 (alkaline), with 6.5 as the optimum (Zinke 1964). Soil textures grade through loam, sandy loam, fine sandy loam, silt loam, to clay loam (Gardner 1960; Roy 1957).

Limits of redwood forests sometimes are determined by soil types. For example, redwood does not grow on soils having high amounts of magnesium and sodium (Zinke 1964).

Fertility of soils under redwood stands has been studied by measuring the replaceable calcium concentration, expressed in equivalents, present in a square meter to a depth of 30 cm. This measure indicates fertility best because it separates nutritional properties from other environmental effects. Equivalents ranged from 4 to over 80, with 63 appearing to be optimum (Waring and Major 1964).

Excess nitrate formation has been found under mature redwoods bearing symptomatic silvery-gray foliage. A nitrate deficit was observed under chlorotic young-growth stands. Here, nitrification was blocked, probably because too many microorganisms were produced in the abundant organic matter resulting from timber harvesting (Florence 1965).

Basal area of redwood stands, used as an index of stand development, has been related to the lowest amount of soil moisture available during the year. This minimum available moisture, expressed as a percentage of storage capacity, ranged between 18 and 86, with 62 correlated with maximum basal area (Waring and Major 1964).

Physiographic

Redwood stands are largely confined to coastal topography between latitude 35° 41′ N. and 42° 09′ N. Much of the land configuration is characterized by irregular ridges oriented northwest to southeast with deep, narrow valleys between (Poli and Baker 1954). Consequently, the principal streams drain to the northwest.

Although this mountainous area is still developing by fold-faulting (Hinds 1952), the topography is characteristic of early maturity in the fluvial erosion cycle. Much of the terrain is rough, steep, and extremely dissected both by major streams and smaller drainages (Roy 1957). In spite of the rugged terrain, the total relief is small for a mountainous country. Only occasional peaks reach elevations of 4,000 to 4,500 feet above sea level.

Redwoods grow from sea level to about 3,000 feet (Jepson 1910), but most are found between 100 and 2,500 feet (Person 1937). The best stands have developed on the flats and benches along the larger streams, on moist coastal plains, river deltas, moderate westerly slopes, and valleys opening toward the sea. Some of the flats and benches support pure redwood stands of almost unbelievable volumes (Person 1937).

Although the main bodies of redwood are close to the ocean, redwood does not tolerate ocean winds. And considerable evidence suggests that it is sensitive to ocean salts carried inland during storms (Jepson 1923). Where redwoods grow close to the coast line, they are either protected from wind by other species such as Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) and Sitka spruce (*Picea sitchensis* [Bong.] Carr.), or by the landform (Zinke 1964).[2] The slopes, canyons, or valley floors where redwoods grow, are at least moderately sheltered from the direct impact of ocean gales, protecting the trees from shearing

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[2] Daniel, T(heodore) W. *The comparative transpiration rates of several western conifers under controlled conditions.* 1942. (Unpublished doctor's thesis on file at Univ. Calif., Berkeley.)

by the wind. Usually redwoods do not grow on hillsides squarely facing the sea (Jepson 1923).

As elevation, dryness, and slope increase, redwoods become smaller and give away to other species. In the north, redwoods clothe the eastern sides of watersheds (U. S. Forest Service 1908). In the southern part of their range, redwoods are restricted to western or northern exposures. And at the extreme southern extension they are restricted almost entirely to the bottoms of narrow canyons which cut through the steep foothills that abut the ocean. Trees near the mouths of these canyons often are exposed to onshore winds and frequently have flat tops which are dead on the windward side. This effect has been attributed to the tree's inability to replace moisture lost through desiccation by the winds (Haasis 1933).

Biotic

Redwood grows within the Transition life zone (Grinnell 1935; Merriam 1898). Appropriately, this area has been called the Redwood Transition Zone to differentiate it from the Sierran Transition at higher altitudes (Jepson 1923; Person 1937). Most redwoods are within the redwood forest cover type, but a few along the eastern edge of the range grow in the Pacific Douglas-fir type. Changes from the well-defined redwood type to another are typically sharp and distinct (Society of American Foresters 1954).

Pure stands of redwood are found only on some of the best sites, usually the moist river flats and gentle slopes below 1,000 feet. Although redwood is usually a dominant tree in mature stands throughout its range, it generally is mixed with other conifers and broad-leaved trees. Douglas-fir is the most important associate. It is well distributed throughout most of the redwood type. Other conifers are more limited in distribution within the type. Important species on the coastal side of the redwood type are grand fir (*Abies grandis* [Dougl.] Lindl.) and western hemlock (*Tsuga heterophylla* [Raf.] Sarg.) northward from northern Sonoma County, and Sitka spruce northward from the vicinity of Humboldt Bay.

Conifers occurring less commonly with redwood are:

- Port-Orford-cedar (*Chamaecyparis lawsoniana* [A. Murr.] Parl.)
- Pacific yew (*Taxus brevifolia* Nutt.)
- Western redcedar (*Thuja plicata* Donn)
- California torreya (*Torreya californica* Torr.).

Some conifers associated with redwood under atypical situations are:

- Gowen cypress (*Cupressus goveniana* Gord.)
- Knobcone pine (*Pinus attenuata* Lemm.)
- Lodgepole pine (*P. contorta* Dougl.)
- Sugar pine (*P. lambertiana* Dougl.)
- Bishop pine (*P. muricata* D. Don).

Of the hardwoods in the redwood type, the two most abundant and generally distributed are:

- Tanoak (*Lithocarpus densiflorus* [Hook. and Arn.] Rehd.)
- Pacific madrone (*Arbutus menziesii* Pursh).

Other hardwoods found in the redwood type are:

- Vine maple (*Acer circinatum* Pursh)
- Bigleaf maple (*Acer macrophyllum* Pursh)
- Red alder (*Alnus rubra* Bong.)
- Golden chinkapin (*Castanopsis chrysophylla* [Dougl.] A. DC.)
- Oregon ash (*Fraxinus latifolia* Benth.)
- Pacific waxmyrtle (*Myrica californica* Cham.)
- Oregon white oak (*Quercus garryana* Dougl.)
- Cascara sagrada (*Rhamnus purshiana* DC.)
- Willows (*Salix* L. spp.)
- California laurel (*Umbellularia californica* [Hook. & Arn.] Nutt.).

Shrubs which are redwood associates are:

- Lady bloom (*Ceanothus parryi* Trel.)
- Blueblossom (*Ceanothus thyrsiflorus* Eschsch.)
- Creek dogwood (*Cornus* x *californica* C. A. Meyer)
- California hazel (*Corylus cornuta* var. *californica* [A. D C.] Sharp)
- Salal (*Gaultheria shallon* Pursh)
- Pacific rhododendron (*Rhododendron macrophyllum* D. Don)
- Western azalea (*Rhododendron occidentale* Gray)
- Poisonoak (*Rhus diversiloba* T. & G.)
- Wood rose (*Rosa gymnocarpa* Nutt.)
- Thimbleberry (*Rubus parviflorus* Nutt.)
- Salmonberry (*Rubus spectabilis* Pursh)
- California blackberry (*Rubus vitifolius* C. & S.)
- California huckleberry (*Vaccinium ovatum* Pursh)
- Red bilberry (*Vaccinium parvifolium* Sm.).

A variety of herbs, many restricted to the redwood type, are found on the redwood forest floor. They include (Jepson 1935; Person 1937):

- Deerfoot vanillaleaf (*Achlys triphylla* [Sm.] DC.)
- Western baneberry (*Actaea spicata* L. var. *arguta* Torr.)
- Glade anemone (*Anemone deltoidea* Hook.)
- Wild ginger (*Asarum caudatum* Lindl.)
- Longleaf mahonia (*Berberis nervosa* Pursh)
- Clintonia (*Clintonia andrewsiana* Torr.)
- Milkmaids (*Dentaria integrifolia* var. *californica* [Nutt.] Jepson)
- Bleeding heart (*Dicentra formosa* [Andr.] DC.)
- Fairy lantern (*Disporum smithii* [Hook.] Piper)
- California alum root (*Heuchera micrantha* Dougl.)
- Western water leaf (*Hydrophyllum tenuipes* Hel. var. *viride* Jepson)

Oregon coltsfoot (*Maianthemum bifolium* DC. *kamtschaticum* [Gmel.] Jepson)
Monkey-flower (*Mimulus dentatus* Nutt.)
Indian lettuce (*Montia parvifolia* [Moq.] Greene)
Redwood sorrel (*Oxalis oregana* Nutt.)
Sweet coltsfoot (*Petasites palmata* [Ait.] Gray)
White-veined shin-leaf (*Pirola picta* Sm.)
Saxifrage (*Saxifraga* L. spp.)
Slinkpod (*Scoliopus bigelovii* Torr.)
Fat solomon (*Smilacina amplexicaulis* Nutt.)
Slim solomon (*Smilacina sessilifolia* Nutt.)
Fringe cups (*Tellima grandiflora* [Pursh] Dougl.)
Sugar-scoop (*Tiarella unifoliata* Hook.)
Star flower (*Trientalis europaea* L. var. *latifolia* Torr.)
Coast trillium (*Trillium ovatum* Pursh)
Inside-out flower (*Vancouveria parviflora* Greene)
Pioneer's violet (*Viola glabella* Nutt.)
Western heart's ease (*Viola ocellata* T. & G.)
Evergreen violet (*Viola sempervirens* Greene).

Several shade-loving ferns are important components of the ground cover under redwood stands. Sword fern (*Polystichum munitum* Presl.) is by far the most common. Others are:

California maidenhair (*Adiantum emarginatum* Hook.)
Five-finger fern (*Adiantum pedatum* L.)
California wood fern (*Aspidium rigidum* Swz. var. *argutum* Eat.)
Common wood fern (*Aspidium spinulosum* [Mull.] Swz. var. *dilatatum* Hoffm.)
Lady fern (*Athyrium filixfoemina* L. var. *californicum* Butters)
Bladder fern (*Cystopteris fragilis* [L.] Bernh.)
Gold fern (*Gymnogramme triangularis* Kaulf.)
Deer fern (*Lomaria* [*Blechnum*] *spicant* Desv.)
Licorice fern (*Polypodium volgare* L. var. *occidentale* Hook.)
Chain fern (*Woodwardia radicans* Sm.).

Bracken (*Pteris* [*Pteridium*] *aquilina* L. var. *lanuginosa* [Bory] Hook.) may be abundant on openly wooded hill slopes (Jepson 1935).

One grass is mentioned as a ground cover species in redwood stands. It is California vanilla grass (*Torresia macrophylla* [Thurb.] Hitchc.).

After redwood stands are logged, some of the less tolerant or sprouting plants increase greatly in abundance at the expense of the nonsprouting or tolerant species. The greatest change in flora of cutover sites, however, is caused by the invasion of many species found rarely, if at all, in the virgin forest (Person 1937).[3]

Life History

Seeding Habits

Flowering and Fruiting

The blooming period of redwood varies between late November and early March, although flowering usually is over by the end of January (Metcalf 1924; Sargent 1922; U. S. Forest Service 1948).

Weather conditions during flowering may directly affect seed quality. If flowers open during a continuous rainy period, pollen is washed from the pollen strobili. Little pollen may reach the conelets. Dry periods during flowering permit optimum dispersal of pollen and help produce seed crops of high viability.[4]

Redwood cones, which are terminal, ovoid, and ½-inch to 1⅛-inches long, mature in the autumn following flowering (Metcalf 1924) and begin to open in early September to the latter part of December (Collingwood and Brush 1955; Geiger 1926; Green 1933). Although cones persist for several months, they open and begin to shed seed soon after ripening.

Seed Production

Redwoods generally produce abundant seed almost every year, although the seed production pattern of redwood varies by individual trees and locations (Fritz 1958; Harlow and Harrar 1950; Show 1932; U. S. Forest Service 1948). Even trees in the intermediate crown-class frequently produce seed crops (Fritz 1951b). The minimum age for good seed-bearing is 20 years, but the optimum is from 60 to 100 years (U. S. Forest Service 1948).

One study showed that seed viability increased with the age of parent trees. The maximum was reached when trees were older than 250 years; seeds produced by trees less than 20 years old generally were less than 1 percent viable; but seeds

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[3] See appendix for information concerning plant species found on cutover redwood lands.

[4] Lott, Hugh Carlin. *The productivity and viability of redwood* (SEQUOIA SEMPERVIRENS) *seed*. 1923. (Unpublished master's thesis on file at Univ. Calif., Berkeley.)

from trees over 1,200 years were sterile or did not exceed 3 percent in viability[5] (Metcalf 1924).

Many exceptions to redwood's general seed production pattern have been noted. A cone, for example, was found on a tree 3 years old and 12 inches tall ([Merriam] 1927). Seedlings 7 years old (Metcalf 1924) and 9 years old, and 11-year-old trees grown from cuttings have produced cones (Hein 1934). Very young redwood sprouts also produce cones (Fritz 1929a; [Merriam] 1927). In one case 5-year-old sprouts produced seed which were 8 percent sound by cutting test and 4.5 percent viable.[6] Cones produced by sprouts less than 10 years old generally contain few seed.[7]

"Fire-columns" (see section on vegetative reproduction) produce few cones during the first 4 years following the fire which caused them. About half the fire-columns bear cones in the fifth year, however, and almost all produce cones by the seventh or eighth year.[8]

Some redwoods apparently never produce seed (Fritz 1951b). An unsubstantiated opinion suggests that cone production by redwoods is determined by permanent features of the root environment, and that no cones are produced in some areas unless induced by impairment of the root system by some kind of ground disturbance (Muelder and Hansen 1961).

Redwood cones are relatively free of pests. Some cones, however, are badly deformed by larvae of a lepidopterous insect.[9] The roundheaded borer (*Phymatodes nitidus* Lec.) is found frequently in cones (Keen 1952). And the redwood chickaree (*Sciurus douglasii mollipilosus* [Audubon & Bechman]) steals a few seeds by cutting cones.

A redwood cone has 15 to 20 scales, and each scale produces 2 to 5 seeds (U. S. Forest Service 1948). The number of seed per cone averages 60 (Metcalf 1924).

Cones number about 330 per pound (Metcalf 1924), and 100 pounds of cones yield about 11 pounds of seed (Metcalf 1924; U. S. Forest Service 1948). The number of seed per pound averages 123,000 and ranges between 59,000 and 300,000. The average seed size within redwood's natural range may increase from south to north (U. S. Forest Service 1948).

Seeds are mature when cones turn color from green to greenish yellow, or when the cone scales separate slightly (Metcalf 1924). Specific gravity of the seed does not indicate seed maturity or quality. Seeds of lower specific gravity often are more viable than seeds of higher density. Soundness in one seed lot did vary significantly with seed size. Seeds passing 12, 10, and 8 mesh screens were 2, 8, and 15 percent sound, respectively.[10]

Germinative capacity of redwood seed varies from 1 to 36 percent and averages 10 percent (U. S. Forest Service 1948). Seed viability may vary widely from tree to tree. Fritz (1951b) reported that one tree 8 feet in diameter and about 300 feet tall was heavily laden with cones, but the seeds were too poor in quality to collect; other trees, some as young as 20 years, produced seed with germinative capacities over 40 percent.

Poor average germination often is caused by the high percentage of empty seed rather than by dormancy (U. S. Forest Service 1948). Germination-cutting-test ratios varied from 65 to 95 percent and averaged 71 percent.[11] When obviously empty seed are removed, germination may be as high as 79 percent (Boe 1961). Seeds from seven sources recently were photographed by X-rays. The distribution of seeds in categories were: empty or tannin filled, 58 to 97 percent; seeds with embryos damaged by fungi, 0 to 11 percent; and sound seed, 1 to 32 percent (Hansen and Muelder 1963).

Redwood seed does not seem to store well. One seed-lot was stored successfully for 3 years, but lost its viability completely after 5 years (Schubert 1952).

Seed Dissemination

Redwood cones dry readily under conditions of low humidity and quickly release their seeds with slight shaking. But weather conditions at cone ripening usually are unfavorable for rapid drying. Therefore, seed dispersal may be spread over periods varying considerably in length, depending upon the dryness of the site. Significant factors include altitude and exposure.

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[5] Lott, H. C. *Op. cit.*, footnote 4.

[6] Lott, H. C. *Op. cit.*, footnote 4.

[7] Person, Hubert L. and Hallin, William. *Possibilities in the regeneration of redwood cut-over lands.* 79 pp., illus. 1939 (Unpublished report on file at Pacific SW. Forest & Range Exp. Sta.,U.S. Forest Serv., Berkeley, Calif.)

[8] Person and Hallin. *Op. cit.*, footnote 7.

[9] Lott, H. C. *Op cit.*, footnote 4.

[10] Lott, H. C. *Op cit.*, footnote 4.

[11] Lott, H. C. *Op cit.*, footnote 4.

At the other extreme, rains also may hasten seed dissemination. One observor found in many instances "that redwood seeds remain in the open cones until a drenching rain soaks the tannic crystals (in the cones) and dissolves them."[12]

Seed dissemination during the winter months seems characteristic of redwood in the northern stands. More than four-fifths of the sound seed counted in one study was shed during December and January (Boe 1961).

Redwood seeds are small and light, but lack efficient wings to slow them in falling. Therefore, redwood seeds fall at rates between 4.9 and 20.5 feet per second, averaging 8.6 feet. These rates are faster than for most other forest seed and limit seed dispersal considerably[13] (Siggins 1933).

Timbered edges of clearcut units have effective seeding distances of only 200 feet uphill and 400 feet downhill under average redwood stand conditions (Person and Hallin 1942). A clearcutting in Del Norte County received sound seeds in proportion to the number of trees in the border and the distance from them (Boe 1961). A margin of 12 trees produced 2 million seeds per acre; a margin of 20 trees produced 3 million. At the center of the clearcutting, 400 feet from timbered edges, the seed fall was only 196,000 per acre. About 8 percent of the seed falling at the timbered edges was sound, but only 4.4 percent was sound at the center. Under these conditions, areas 500 to 600 feet from timbered margins will not receive enough sound seed for prompt regeneration.

The largest clearcut units, therefore, should be nearly round or square and not much larger than 20 acres until larger experimental cuttings have been studied.

In partially cut stands in Mendocino and Humboldt Counties, the minimum number of seed trees needed to provide acceptable stocking varied from 4 per acre on north slopes, with favorable ground conditions, to 8, or more, for south exposures (Person and Hallin 1942). In Del Norte County more than 1.4 million sound seeds per acre fell under a shelterwood stand of 3 seed trees per acre, and 4.4 million seeds fell in the selection cutting where 14 seed trees to the acre were reserved (Boe 1961).

Although rodents have been accused of finding and consuming redwood seed (Fritz 1950) they probably do not alter the effectiveness of redwood seed fall. The deer mouse (*Peromyscus maniculatus rubidus* Osgood), the most abundant small mammal found on cutover lands in Del Norte County, does not seem to seek redwood seed for food[14] (Boe 1961).

Vegetative Reproduction

Redwood has the potential for propagation by cuttings (Metcalf 1924), but no large scale attempts at this kind of reproduction have been reported. In one instance, cuttings from the tops of fast growing seedlings were nonchalantly pushed into forest nursery soil; these cuttings received no special treatment, but 40 percent developed new root systems (Fritz 1929a).

The ability of redwood to sprout at any season of the year within two or three weeks after logging is an outstanding characteristic possessed by no other commercial conifer.[15] Numerous and vigorous sprouts originate close to the stumps from adventitious buds on the large lateral roots. In one area, where the average stump diameter was 35 inches, the number of sprouts averaged 72 for each stump (Metcalf 1924), but stumps often are circled by more than 100 sprouts (Jepson 1910; Jepson 1923). Each sprout soon develops its own root system and competes with its neighbors. In a remarkably short time the dominant sprouts create circles of new trees around the old stumps.

Any individual redwood may have the ability to sprout abundantly, but this power is stronger on the better forest sites and may be influenced by the tree's size and age. One study[16] showed, for example, that 100 percent of the stumps under 30 inches in diameter sprouted. Only 82 percent of the stumps 50 to 70 inches in diameter, and 52 percent of those over 110 inches in diameter sprouted. In another study (Pacific SW. Forest &

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[12] Siggins, Howard William. *Dissemination by wind of seed of important conifers of California*. 1926. (Unpublished master's thesis on file at Univ. of Calif., Berkeley.)

[13] Siggins, H. W. *Op. cit.*, footnote 12.

[14] Patterson, David W. *Response of animal population to logging in the redwood forest region and an investigation into the possible utilization of redwood seeds* (SEQUOIA SEMPERVIRENS) *by animals on the area*. 1960. W. M. 125 Project. (Unpublished report on file at Humboldt State College, Arcata, Calif.)

[15] Two conifers associated with redwood also sprout from stumps. Sprouting is vigorous by California torreya but weak by Pacific yew (Jepson 1910).

[16] Personal correspondence with William E. Hallin, U.S. Forest Service, February 2, 1963.

Range Expt. Sta. [1963]), 62 percent of all redwood stumps sprouted. Eighty-one percent of the stumps less than 56 inches in diameter sprouted, but only 36 percent of the stumps over 126 inches produced sprouts.

Redwood stumps in northern Humboldt County were examined in another study. Trees providing these stumps varied in age from 250 to 1,500 years. Sprout development was most vigorous around stumps of trees 500 to 700 years old, and no sprouting was observed for stumps of 15 trees which were older than 1,200 years when cut.[17]

Early estimates of stocking from sprouts varied from 20 to 35 percent of full stocking (Fisher, van Schrenk and Hopkins 1903; Mason 1922). Later, these estimates were recognized as high (Metcalf 1924; Show 1932) because they apply only when the best quality pure redwood stands, found on alluvial benches, are logged. Redwood sprouts on typical cutover redwood land in Mendocino and Humboldt Counties stocked 8 percent of the milacres examined (Person and Hallin 1942).

Sprouting by redwood is not limited to root crowns. Sprouts often grow from the sides or tops of stumps. These are undesirable because, first, they must rely on conductive tissues of the parent stump, second, they are mechanically weak, and third, they are not as vigorous as root-crown sprouts. Root sprouts also are mentioned in published reports,[18] but foresters familiar with redwoods often question their importance, and, in some cases, their existence. A careful study showed that 76 percent of sprouting stumps produced the sprouts from the root crown, and 9 percent had root sprouts (Pacific SW. Forest & Range Exp. Sta. [1963]).

Redwood also can sprout along almost the entire length of its trunk. If the crown of a tree is destroyed by fire, mechanically damaged, or exposed to stronger light, numerous buds along the trunk are stimulated and produce new foliage. Trees in this condition are called "fire columns" because they have a typical appearance. Most of the trunk will be covered by feathery foliage 2 or 3 feet thick (Jepson 1910). Eventually, normal crowns develop again.

A redwood seedling begins to develop a burl around its stem slightly under the soil surface when about 6 months old. This burl soon produces many dormant buds, some of which will sprout if the seedling's top is injured (Cooper 1965). Even where fire has burned away the tops of trees in plantations less than 2 years old; most of the basal burls are uninjured and the seedlings sprout again (Mason 1924). Detailed examinations on separate burns showed that almost 90 percent of the redwood seedlings top-killed by fires sprouted (Person 1937).

Seedling Development

Establishment

Redwood seed generally is ready to germinate soon after it falls to the ground if seedbeds are moist and the weather is warm enough. As a rule, seed do not require pretreatment for germination. Occasionally, however, germination has been improved by stratification, indicating slight and variable seed dormancy (U. S. Forest Service 1948).

The period of germinative energy averages 35 days, but may vary by as much as 20 days between individual seedlots receiving the same treatment.[19] Under laboratory conditions one seed lot reached the peak of germination in 14 days, and only a few seed germinated after 23 days (Boe 1961).

Mineral soil is the best seedbed,[20] but seed will germinate readily in duff, on logs, in debris, or under other vegetation, and in either shade or full sunlight, provided that adequate soil moisture is available (Fritz 1950; Fritz 1958). Redwood seed germination is epigeous. Cotyledons generally number two, rarely three or four (Butts and Buchholz 1940; Hill and Fraine 1908).

New redwood seedlings require a greater supply of soil moisture for survival than that needed by seedlings of most of its associated trees. Therefore, the incidence of late spring and early fall rains can be critical survival factors (Fritz 1958).

Apparently, redwoods have no root hairs. Consequently, redwood roots do not seem to function efficiently in extracting soil moisture. This fact may limit natural distribution to sites where favorable water relations result from high rainfall, humid air, moist soil, or low summer temperatures, or from various combinations of these conditions (Cannon 1926).

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[17] Personal correspondence with Robert F. Powers, Humboldt State College, September 14, 1965.

[18] Mason 1922; Metcalf 1924; U. S. Forest Service 1908; Van Dersal 1938.

[19] Lott, H. C. *Op. cit.*, footnote 4.

[20] Fritz 1951b; Metcalf 1924; Pacific SW. Forest & Range Exp. Sta. (1963); Person and Hallin 1942; U. S. Forest Service 1948.

Redwood seems capable of extremely high transpiration rates. Therefore, long periods of relatively low humidity, with resulting evaporational stress, could prevent redwood from maintaining its internal vapor pressure and desiccate the foliage.[21]

Seedlings usually grow best on exposed mineral soil because there they need not compete with other vegetation (Fritz 1951b; Person and Hallin 1942). A broken soil surface that will help retain moisture during the first two dry seasons is another desirable seedbed condition (Fritz 1958). Partial shade during the first few months after germination also is beneficial (Metcalf 1924; Person and Hallin 1942).

Redwood seedlings on fully exposed soil can withstand considerable surface heat if their roots have reached an abundant permanent moisture supply. Otherwise, they die before soil surface temperatures reach 140° F. (Fritz 1958).

Light slash sometimes may be desirable (Fritz 1951b) because it provides shade, but areas where slash burning was classified as medium and heavy had 5 to 10 times as much reproduction as unburned or lightly burned cutover areas (Person and Hallin 1942).

A dense vegetative cover becomes reestablished rapidly on redwood cutover lands. Therefore, the first two years following logging and slash disposal are the most favorable for natural regeneration (Person and Hallin 1942). Redwood seedlings withstand the competition of fireweeds (*Erechtites* spp. and *Epilobium angustifolium*) which often solidly cover cutover lands (Fritz 1950). These tall herbs and others are erect but not bushy. They may serve as nurse plants by giving maximum protection from sun and wind with minimum competition for soil moisture.

Far better stocking of smaller seedlings is associated with tall herbs than with low herbs, ferns, and shrubs which become more abundant with time. Only a negligible amount of stocking is added by new seedlings after the first four years. The poorest stocking definitely is associated with grass.[22]

Seedling mortality is heaviest the first year and is caused by a variety of factors. Small redwood seedlings may die because moisture is deficient. This condition is most common on south slopes where natural stocking has been 24 percent less than on other aspects.[23] Frost heaving occurs infrequently, and rarely on other than north slopes (Fritz 1950).

Slugs, snails, birds, and rodents have been suspected of destroying redwood seedlings (Fritz 1950). But although slime trails of the large Columbian slug (*Ariolmax columbianus* [Gould]) may sometimes smother tiny redwood seedlings, neither this slug, nor the large shelled snail (*Monadenia fidelis* [Gray]), or birds, have been observed eating redwood seedlings. If any small mammals damage redwood seedlings, the meadow-mice (*Microtus* spp. Schrank) are the most likely culprits.[24]

Known destructive agents include brush rabbits (*Sylvilagus bachmani ubericolor* [Miller]), which eat the tops of young redwood seedlings, and Columbian black-tailed deer (*Odocoileus hemionus columbianus* [Richardson]) and cattle, which browse seedlings, particularly after they are about 1 foot high. And tall herbs, which may be desirable when green and standing, sometimes kill small seedlings by falling over to form a thick smothering mat (Fritz 1950).

Established redwood seedlings are scarce in undisturbed forests. Their absence has been attributed to root rot fungi in the A soil horizons (Muelder and Hansen 1961; Florence 1965).

Early Growth

In its early stages redwood sometimes grows rapidly in both height and diameter (Green 1933). Height growth of 18 inches in the first season is not unusual for seedlings (Fritz 1929a), but slower growth during the first 4 or 5 years is more common. Where seedlings numbered 900 to 2,100 per acre, annual height growth ranged between 2.5 and 14 inches (Cooper 1965). In one case planted redwoods were only 7, 12, and 35 inches tall at 1, 4, and 6 years after logging, respectively (Person 1937). Another study showed virtually all natural redwood seedlings to be less than 1 foot tall when 5 years old. In this instance grand fir and Douglas-fir were significantly taller at the same age.[25] Height growth of redwood usually accelerates when seedlings are 4 to 6 years old. Leaders of

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[21] Daniel, T. W. *Op. cit.*, footnote 2.

[22] Person and Hallin. *Op. cit.*, footnote 7.

[23] Person and Hallin. *Op. cit.*, footnote 7.

[24] Personal correspondence with Robert R. Talmadge, Willow Creek, California, March 7, 1964.

[25] Personal correspondence with William E. Hallin, U. S. Forest Service, October 26, 1965.

trees 4 to 10 years old frequently grow 2 to 6½ feet in a year (Harlow and Harrar 1950; Jepson 1910), and one tree grew 7.3 feet in a year (Cooper 1965).

Sprouts are commonly 24 to 36 inches high at the end of the first year, but often are taller (Fritz 1929a). They may be over 6 feet tall in a year (Fritz 1945). In one case a fire killed all sprouts around a stump. About 300 new sprouts appeared at once, and at the end of one growing season many reached 7 feet (Fritz 1929a). Sprouts grow more rapidly than seedlings because they obtain great nourishment from the parent trees' root systems. The initial impetus lasts many years.[26]

Root growth by seedlings is best in loose soil. A 1-year-old tree may have roots only 3 inches deep in compacted soils, but more than 12 inches deep and abundantly branched in loosened soils (Fritz 1950).

A diurnal temperature variation is not required for maximum growth of redwood seedlings (Hellmers and Sundahl 1959). But with diurnal temperature variations, redwood seedlings grew tallest when the day temperature was 66° F. and the night temperature was 59° F. Increased temperatures, either day or night, decreased growth, and a decrease in night temperature from 59° F. to 52° F. restricted growth markedly (Hellmers 1964). Roots developed best in the laboratory when the soil temperature was 64° F. compared to temperatures of 46° F. and 82° F. (Hellmers 1961).

Juvenile growth of redwood is best in full sunlight, but redwood seedlings can endure heavy shade, although growth may be slow (Fritz 1950). Redwood has a remarkably efficient system for photosynthesis. Seedlings of this species grew vigorously in much weaker light than 12 other tree species tested by Bates and Roeser (1928). For example, redwoods increased their size 8.8 times in 10 percent of full sunlight in a 9-month period. This was more than twice the growth of any other species. For appreciable growth Engelmann spruce (*Picea engelmannii* Parry) and Douglas-fir require as much light as redwood, and pines, as a group, require three to four times as much.

Seasonal Growth

Information on seasonal growth of redwood is almost nonexistent. Limited measurements of radial growth of redwood in Mendocino County at points 4, 9, and 20 miles from the coast showed no marked locational growth pattern differences. Radial growth began after mid-March, increased to a maximum in late May, and then declined at a fairly uniform rate to a minimum at the end of September. Growth was negligible from October 1 to March 15 (Bawcom, Hubbell, and Burns 1961).

One report (Cooper 1965) indicates that redwoods 6 months to 40 years old began height growth in Del Norte and Humboldt Counties between January 1 and 18, even when night temperatures dropped below the frost point. Height growth generally ended by mid-July but sometimes continued another 2 months.

Sapling Stage to Maturity

Growth and Yield

Besides growing in a special habitat, the redwood itself is unique—it is long-lived, grows taller than any other tree in the world, and is exceeded in bulk only by the giant sequoia (*Sequoia gigantea* [Lindl.] Decne.) of the Sierra Nevada.

In age, redwoods are mature at 400 or 500 years (Jepson 1910; Jepson 1923; U. S. Forest Service 1908). The oldest tree so far found by actual growth ring counts is just under 2,200 years (Fritz 1957).

Virgin redwood forests sometimes are incorrectly called even-aged and over-mature, when, in fact, there is no other forest in the world that can match many redwood stands in range of ages and mixture of vigorously growing and decadent trees. For example, when ages of trees on a 30-acre tract typical of Humboldt County were determined, all ages were represented. The oldest was 1,380 years (at stump height), and the runner-up was 1,246. Not counting more than 1,000 trees under 12 inches in diameter, the trees were distributed by broad age classes as follows (Fritz 1929b):

Age, years:	*Number*	*Percent*
0–200	696	55
201–400	197	16
401–600	183	15
601–800	105	8
801–1,000	65	5
Over 1,000	17	1
	1,263	100

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[26] Barnes, John Scott. *Redwood growth studies: I. The relative volume production of sprouts and seedlings in second growth. II. The height growth of young redwood in mixture. III. A site classification for virgin stands.* 1924. (Unpublished master's thesis on file at Univ. Calif., Berkeley.)

Redwood probably is best known for its great size although the average redwood is smaller than many persons realize. Trees larger than 12 inches in diameter, measured on the 30-acre tract mentioned above and classed by diameters, fell approximately into these divisions: 12 to 30 inches, 50 percent; 31 to 60 inches, 32 percent; 61 inches and larger, 18 percent. Redwoods 12 to 16 feet in diameter, found scattered over the entire range, are considered large. A few trees 20 feet in diameter, or slightly larger, at a point 5 feet above the ground have been found, but these are rare (Fritz 1929a; Fritz 1957).

Redwoods taller than 200 feet are common, and many trees growing on the alluvial benches, where the soil is deep and moist, are taller than 300 feet. The three tallest trees of record grow in Redwood Creek Grove, about 7 miles southeast of Orick, Humboldt County. They measure 367.8, 367.4, and 364.3 feet, respectively (Zahl 1964).

The largest diameters and heights are not necessarily found in the same trees. The "Founders' Tree" is 352.6 feet tall, but only 12 feet 7 inches in diameter at breast height. The greatest volume of wood in any standing tree may be contained by the "Giant" at Rockefeller Grove on Bull Creek Flat. This tree is 356.5 feet tall and 16.5 feet in diameter.

One tree in the Maple Creek drainage, Humboldt County, was over 20 feet in diameter, 5 feet above the ground, and 308 feet tall. It had such slight taper that it was still more than 12 feet in diameter 230 feet above the ground. Its merchantable volume scaled 361,366 board feet by the Spaulding log rule, enough to build 22 average houses.[27] Another tree is supposed to have tallied 480,000 board feet from the saw,[28] but this record is unconfirmed.

Large trees and dense stocking combine to produce high yields. More than 81 percent of the commercial redwood forest land is classified as highly productive, and only 2 percent is poor for growing trees. Individual acres yielding more than 100,000 board feet of sawtimber are common, even on slopes (Collingwood and Brush 1955; Fritz 1929a). Recent cuttings in Del Norte County (Boe [1960]; Boe 1963), on units of 13 acres and larger, produced gross volumes ranging from 95,000 to 280,000 board feet (Scribner) per acre. Defect in logs hauled was about 12 percent, and about 40,000 board feet of cull logs and broken wood were left on the ground. The number of merchantable trees varied from 29 to 46 per acre, and tree sizes were from 14 to 198 inches in diameter.

Flats along rivers have yielded more than 1,000,000 board feet per acre in scaled logs.[29] One acre is reported to have contained 2,500,000 board feet, yielding 1,500,000 board feet of cut lumber (Anon. 1902; Jepson 1910; Peattie 1953). This report is not documented.

Performance of young-growth redwood is, in its own way, often as spectacular as the dimensions and yields of old growth. Dominant young-growth trees on good sites are 100 to 150 feet tall at 50 years, and 165 to 220 feet at 100 years (Boe [1960]). Height growth is most rapid up to the 35th year (Lindquist and Palley 1961).

Diameter growth of individual young trees can be rapid or very slow. In dense stands where competition for light and soil moisture is severe, annual radial increment is commonly as small as one-thirtieth-inch. Occasionally there are 100 rings per inch. At the other extreme, under ideal conditions, radial growth can be as great as 1 inch a year. One redwood growing with little competition reached 84 inches in diameter in 108 years (Fritz 1957).

The yield of young-growth redwoods stands at 100 years is expected to range from 56,000 board feet per acre on low sites to 358,000 board feet on high sites. Much of the acreage now under management will grow 2,400 board feet per acre per year (Lindquist and Palley 1963).

Hallin (1934) reported an exceptional case, in which the annual growth of a 260-year-old stand had averaged 2,987 board feet per acre. Growth had been much faster during the first 150 years, however; ring counts showed it probably was between 3,500 and 4,000 board feet per acre. At 260 years the dominant trees were 37 to 80 inches in diameter, averaging 50.6 inches, and their heights averaged 256 feet. The largest tree was 80 inches in diameter at breast height, and 270 feet tall.

Natural pruning in young redwood stands often is not good. Although live crowns may be limited to no more than the upper third of the trunk, dead limbs are persistent. Stubs, although decayed, may remain over 50 years. In old growth, some branch

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[27] Fritz 1929a; Fritz 1930; Fritz 1957; Tiemann 1935.

[28] Anon. 1902; Harlow and Harrar 1950; Jepson 1910; Peattie 1953; Preston 1948.

[29] Browne 1914; Fritz 1929a; Fritz 1930; Fritz 1957; U. S. Forest Service 1908.

stubs have been found which affected the quality of the timber produced over a 200-year period (Fritz 1951b; Fritz 1958). But trees in the intermediate crown class often prune well naturally (Fritz 1958). Some trees in a heavily stocked stand had clean trunks for 75 to 100 feet at 85 years (Fritz 1945).

Reaction to Competition

When 55 foresters ranked redwood in a scale of five broad tolerance classes, all of them placed it in either the highest or second highest class—40 percent called redwood "very tolerant," and 60 percent judged it "tolerant" (Baker 1949).

Redwood stands are dense. The average well stocked acre supports nearly 1,000 stems at 20 years, including 500 dominant and codominant trees. At 60 years redwood has a basal area of 486 square feet on the best sites (Bruce 1923). Close stocking is desirable because the relatively high tolerance to shade permits an acre to support a large number of dominant and codominant trees.[30]

Redwoods can endure suppression almost indefinitely. Small suppressed trees often grow so slowly that 40 growth rings are required to produce an inch of radius; and a 10-inch tree might be well over 100 years old (Fritz 1938).

Small trees may be suppressed for over 400 years but still maintain a remarkable capacity to accelerate growth rates when released, if they are not injured seriously during logging or slash-burning operations (Fritz 1940; Merrill 1953b). A 12-inch tree, 160 years old, about 100 feet tall and over-topped by a 300-foot-high stand containing about 165,000 board feet per acre, increased its annual growth rate from less than 1 percent to almost 20 percent for the first 10 years after the overstory was removed (Fritz 1951b). Other small trees, with only one-fifteenth-inch growth rings, increased annual radial growth to one-third inch after partial cutting (Fritz 1929a).

Large trees also are capable of accelerating growth when released from competition with their neighbors. A 1,000-year-old tree, for example, increased its radial growth from 30 rings to 6 rings per inch when it was only partially freed from competition by cutting on a highway right-of-way (Fritz 1951b).

The redwood forest is a climax type. When growing with other species redwood is always a dominant tree.

Principal Enemies

Fire is redwood's worst enemy throughout life. Young stands can be destroyed outright by a single ground fire (U. S. Forest Service 1908). Fires are especially damaging to trees less than 20 years old because the thin bark of young trees does not protect them. Also, more flammable litter lies on the ground, and the microclimate is drier than under old-growth forests (Fritz 1932).

Old-growth redwood stands show evidence of three or more severe fires each century (Fritz 1957). In many cases fires may only reduce the thickness of the protective bark—ground fires often cause the basal bark to be thinner on one side of the tree, and thinner than bark higher up the tree (Kimmey and Hornibrook 1952). In other cases fires injure the cambium and wood. Rots enter through these basal fire wounds, destroy heartwood, and prepare better fuel for the next fire. The combination of recurring fires and advancing decay produce large basal cavities called "goose pens" (Fritz 1932). In extreme cases mature trees may be so weakened mechanically that they fall (Fritz and Bonar 1931).

Redwood has no tree killing diseases, but heart rots cause extensive cull. In extreme cases rot may extend from the center of the tree to within 8 inches of the bark, and for the full length of the bole (Fritz 1957).

Two principal fungi attack redwood heartwood. They enter trees through fire scars, logging wounds, broken tops, or other wounds which expose the heartwood. Most common heart rot in the southern part of redwood's range is a brown cubical rot caused by *Poria sequoiae* Bonar; a white ring rot caused by *Poria albipellucida* Baxter is most important farther north (Kimmey and Hornibrook 1952). Other decay fungi have been identified in redwood, but they have caused negligible volume losses[31] (Kimmey and Lightle 1955).

Only one disease which is a potential killer is known. This is a twig and branch canker (*Coryneum* sp.) which has been observed on sprouts and plantation trees of seedling and sapling size. This canker, which girdles small stems and branches, could become damaging in plantations.[32]

Several insects are found on redwood, but none causes significant damage (Essig 1926; Keen

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[30] Person and Hallin. *Op cit.*, footnote 7.

[31] Forest Disease Research, Host Index File. U. S. Forest Serv. Pacific SW. Forest & Range Exp. Sta., Berkeley, Calif.

[32] Personal correspondence with Willis W. Wagener, U. S. Forest Service, Feb. 19, 1963.

1952). These include the redwood scale (*Cryptaspidiotus shastae* Cole.) which sometimes becomes abundant, the redwood mealy-bug (*Pseudococcus sequoiae* Cole.), and the cypress mealy-bug (*Pseudococcus ryani* Coz.). A flatheaded twig borer and girdler, *Anthaxia aeneogaster* Cast., mines the bark and outer wood, and may kill small trees or branches. The redwood barkbeetle (*Phloesinus sequoiae* Hopk.) mines the inner bark of injured, dying, or dead trees. Larvae of the twig borer (*Phloesinus cristatus* Lec.) work under the bark of twigs and limbs of declining or dead redwoods. And sequoia pitch moths (*Vespamima sequoiae* Hy. Edw.) mine the cambium of redwood branches and boles.

The dusky-footed wood rat (*Neotoma fuscipes fuscipes* Baird) is one of the most harmful factors limiting the survival of planted trees on old cutover land. Fortunately, rodent damage usually is not severe on newly logged land (Person 1937). Wood rats also attack sprouts occasionally, but usually cause little damage to these larger trees (Fritz 1951a).

The California gray squirrel (*Sciurus griseus griseus* Ord.) sometimes causes considerable damage in local areas by stripping bark from large saplings or from the thin-barked upper crowns of larger young trees (Fritz 1950). When sprouts are damaged this way, they may lose all their foliage on the side facing the mother stump. Discontinuous growth rings are a common result of this kind of loss. Although normal growth increments are produced on the side of the stem facing away from the stump, the inner side may remain dormant for a number of years (Fritz and Averell 1924).

Bark stripping by the American black bear (*Euarctos americanus americanus* [Pallas]) has become serious in some parts of the redwood region (Fritz 1951a). Bears rip wide strips of bark from the tree, frequently from the top to the ground, from April to August. The bears then scrape the juicy sapwood with their teeth. Many trees are girdled (Merrill 1953a). Trees 10 to 30 years old and 6 to 10 inches in diameter are damaged most (Glover and Hansen 1952).

Young redwoods are easily injured by frost, especially in the spring. Sometimes they are killed (Dallimore 1931; Fritz 1958).

Redwood also is easily damaged by strong winds. When exposed to prevailing winds, redwoods generally have deformed leaders and height growth is slow. Associated species often provide enough protection so that redwoods grow normally in mixed stands on sites where it would be deformed if growing alone (Metcalf 1924).

Redwoods have no tap roots, but lateral roots are large and wide-spreading (Fritz 1929a; U. S. Forest Service 1908). Small trees have better than average windfirmness (Fritz 1958), and large redwoods are windfirm under most conditions (McCollum 1957; U. S. Forest Service 1908).

From a study in Del Norte County, Boe ([1960]; 1966) concluded that a combination of wet soil and strong winds is necessary for significant windfall damage, and consequently windfall is caused by only few of the many winter storms. Uprooting accounted for 80 percent of the redwood windfall in this study. Other destroyed trees were broken, but rot was not an important factor. Winds from the southeast-southwest sector caused the damage. In partial cuttings the smaller codominant and intermediate trees were most frequently blown down. Windfall was least in shelterwood cuttings where vigorous codominant trees were chosen for the reserve stand. In clearcuttings, the leeward margins were most damaged by wind.

Special Features

A prominent special feature of the redwood is its production of burls from which beautifully figured table tops, veneers, bowls, and other turned products are cut. These burls are found on any part of the trunk and in sizes varying from an inch to many feet in diameter. Even young seedlings produce burls that encircle the stems just below the ground line. If these seedlings are killed back by frost, drought, or fire, they generally sprout from the small burls (Cannon 1926; Fritz 1929a).

In old growth, burls 5 to 6 feet in diameter are common, and some, even larger, completely encircle a tree. The longest recorded (Fritz 1928) was 60 feet, and the largest was a pyramidal basal burl measuring 75 feet in circumference at its base and containing 30,000 board feet of beautifully figured wood.

The cause of burls is unknown. They form from closely-spaced, persisting dormant buds which produce an intricate grain as growth rings are added each year. Burls on trees seldom produce shoots, but profuse sprouts grow from young burls after they are removed and placed with their cut surfaces in shallow water (Fritz 1928).

Another feature of redwood is its extremely tough and fibrous bark. The tree has been classed as thick-barked. Bark sometimes is as much as a foot thick, but usually is much less (Isenberg 1943). This bark must be removed before logs reach the head saws so that sawing uniform lumber will be possible (Fritz 1940). The bark contains no traces of oil or resin (Anon. 1902). It has been shredded and used for upholstering (Kellogg 1882) and for insulation. Both bark and wood contain tannin which has been used widely to control the viscosity of mud for oil-well drilling and to produce leather (Carr 1956).

On the alluvial flats where redwoods reach their maximum development, soils have been built up by deposits of sediment from successive floods. In one area the ground level had been raised 11 feet in 700 years (Fritz [1934]). In another, repeated flooding in the last 1,000 years has deposited nearly 30 feet of silt and gravel around the bases of many large redwood trees (Stone and Vasey 1962). Individual deposits have been as deep as 30 inches. Redwoods adapt themselves to the new ground levels by originating new and higher root systems (Fritz [1934]). That they respond to each deposit by stimulating diameter growth has been suggested (Univ. Calif. School Forestry 1960), but not proved.

Races and Hybrids

Foresters do not recognize races of redwoods, but the following varieties have been described (Dallimore and Jackson 1948):

var. *adpressa* Carriere
    Tips of shoots creamy white. Awl-like leaves.
var. *glauca* R. Smith
    Leaves ¼-inch long and glaucous.
var. *gracilis* Hort.
    Branchlets slender.
var. *pendula* Rovelli
    Branches pendulus.
var. *taxifolia* Hort.
    Leaves broader than in the type.

A Russian reports hybridization of redwood with giant sequoia (*Sequoia gigantea* [Lindl.] Decne.), baldcypress (*Taxodium distichum* [L.] Rich.), and Japanese cryptomeria (*Cryptomeria japonica* D. Don) (Yablokov 1960).

Stebbins (1948) proposed an interesting hypothesis concerning the origin of redwood (2n 66 chromosomes): that redwood originated as an allopolyploid from hybrids between an early Tertiary or Mesozoic species of *Metasequoia* S. Miki. and some probably extinct Taxodiaceous plant like the modern giant sequoia, taiwania (*Taiwania cryptomeriodes* Hyata), or Tasmanian cedars (*Athrotaxis* Don spp.).

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Appendix

Table 1.--*Plant species, other than trees, found on cutover redwood lands in Humboldt and Mendocino Counties, California*[1, 2]

TALL WOODY SHRUBS

Vegetation group and species (species above lines are listed in order of dominance)	Order of dominance within same group in virgin stands	↓
Ceanothus thyrsiflorus Eschsch.	blueblossom	7
Vaccinium ovatum Pursh	California huckleberry	2
Rhododendron macrophyllum D. Don	Pacific rhododendron	1
Salix L. spp.[3]	willows	10
Arctostaphylos columbiana Piper	hairy manzanita	14
Vaccinium parvifolium Sm.	red bilberry	3
Myrica californica Cham.[3]	Pacific bayberry or waxmyrtle	4
Corylus rostrata var. *californica* A. DC.	California hazel	5
Baccharis pilularis DC.	coyote brush	[4] E
Rhamnus purshiana DC.	cascara sagrada	8
Acer circinatum Pursh[3]	vine maple	
Ceanothus velutinus Dougl.	snowbrush	
Holodiscus discolor (Pursh) Maxim.	cream bush	
Ribes L. spp.	gooseberry and currant	
Sambucus glauca Nutt.	blue elderberry	
Sambucus callicarpa Greene	elderberry	
VINELIKE SHRUBS AND FERNS		
Gaultheria shallon Pursh	salal	1
Pteris (Pteridium) aquilina L. var. *lanuginosa* (Bory) Hook.	bracken	E
Polystichum munitum Presl.	sword fern	2
Rubus vitifolius C. & S.	California blackberry	5
Rubus parviflorus Nutt.	thimbleberry	3
Berberis nervosa Pursh	longleaf mahonia	6
Rhus diversiloba T. & G.	poisonoak	4
Rubus leucodermis Dougl.	western raspberry	9
Lonicera hispidula Dougl. var. *californica* Jepson	California honeysuckle	
Rosa californica C. & S.	Califirnia wild rose	
Rubus spectabilis Pursh	salmonberry	
Woodwardia radicans Sm.	chain fern	
TALL HERBS		
Erechtites prenanthoides DC.	Australian fireweed	E
Epilobium angustifolium L.	fireweed	E
Anaphalis margaritacea (L.) B. & H.	pearly everlasting	E
Erechtites arguta DC.	New Zealand fireweed	E
Iris douglasiana Herbert	mountain iris	1
Iris macrosiphon Torr.	ground iris	2
Lotus stipularis (Benth.) Greene var. *subglaber* Ottley	bird's-foot trefoil	11
Baccharis douglasii DC.	Douglas baccharis	E
Gnaphalium decurrens Ives var. *californicum* Gray	California everlasting	E
Cirsium arvense Scop.	Canada thistle	E

Footnoted at end of table.

Table 1.--*Plant species, other than trees, found on cutover redwood lands in Humboldt and Mendocino Counties, California*[1,2] (continued)

TALL HERBS, continued

Vegetation group and species (species above lines are listed in order of dominance)	Order of dominance within same group in virgin stands	↓
Sonchus asper L. and *Sonchus oleraceus* L.	prickly sow-thistle and common sow-thistle	E
Cirsium edule Nutt.	Indian thistle	E
Epilobium paniculatum T. & G.	paniculate fireweed	10
Achillea millefolium L. var. *lanulosa* Piper	common yarrow	
Adenocaulon bicolor Hook.	adenocaulon	
Aquilegia truncata F. & M.	columbine	
Chrysanthemum leucanthemum L.	ox-eye daisy	
Epilobium watsonii Barb. var. *franciscanum* (Barb.) Jeps.	fireweed	
Erigeron canadensis L.	horseweed	
Gnaphalium ramosissimum Nutt.	pink everlasting	
Madia madioides (Nutt.) Greene	woodland madia	
Madia sativa Molina	Chile tarweed	
Parentucellia viscosa (L.) Caruel	parentucellia	
Sidalcea malachroides Gray	checker	
Stachys chamissonis Benth.	hedge nettle	
Tellima grandiflora (Pursh) Dougl.	fringe cups	
LOW HERBS		
Whipplea modesta Torr.	western whipplea	11
Hypochoeris radicata L.	hairy cat's ear	E
Oxalis oregana Nutt.	redwood sorrel	1
Trientalis europaea L. var. *latifolia* Torr.	star flower	15
Crepis capillaris (L.) Wallr.	smooth hawksbeard	E
Viola sarmentosa Dougl.	wood violet	7
Medicago lupulina L.	nonesuch	E
Gnaphalium purpureum L.	purple cudweed	E
Medicago hispida Gaertn.	bur clover	E
Plantago lanceolata L.	ribwort	E
Asarum caudatum Lindl.	wild ginger	
Clintonia andrewsiana Torr.	clintonia	
Dicentra formosa (Andr.) DC.	bleeding heart	
Echinocystis oregana Cogn.	hill man-root	
Erodium moschatum L'Her.	white-stem filaree	
Galium L. spp.	bedstraw	
Hypochoeris glabra L.	smooth cat's ear	
Lotus L. spp.	bird's-foot trefoil	
Montia perfoliata (Donn) Howell	miner's lettuce	
Montia sibirica (L.) Howell	Indian lettuce	
Myosotis sylvatica Hoffm.	forgetmenot	
Polygala californica Nutt.	milkwort	
Rumex acetosella L.	sheep sorrel	
Smilacina amplexicaulis Nutt.	fat Solomon	
Smilacina sessilifolia Nutt.	slim Solomon	

Footnoted at end of table.

Table 1.--*Plant species, other than trees, found on cutover redwood lands in Humboldt and Mendocino Counties, California*[1,2] (continued)

Vegetation group and species (species above lines are listed in order of dominance)	Order of dominance within same group in virgin stands	↓
	LOW HERBS, continued	
Trifolium pratense L.	red clover	
Trillium ovatum Pursh	coast trillium	
Vancouveria hexandra (Hook.) Morr. & Dec.	vancouveria	
Vancouveria parviflora Greene	inside-out flower	
	ANNUAL GRASSES	
Lolium temulentum L.	darnel	E
Aira caryophyllea L.	silver hairgrass	E
Festuca megalura Nutt.	foxtail fescue	E
Bromus mollis L.	soft chess	E
Festuca rubra L.	red fescue	E
Bromus rigidus Roth.	ripgut grass	E
Polypogon monspeliensis (L.) Desf.	rabbitfoot grass	E
	PERENNIAL GRASSES	
Holcus lanatus L.	velvet grass	E
Dactylis glomerata L.	orchard grass	E
Deschampsia elongata (Hook.) Benth.	slender hairgrass	E
Hierochloe occidentalis Buckl.	California sweetgrass	1
Festuca occidentalis Hook.	western fescue	E
Festuca L. spp.	fescues	E
Bromus vulgaris (Hook.) Shear	brome	E
Melica L. spp.	melicgrass	E
	SEMI-AQUATICS	
	mosses	
Equisetum L. spp.	horsetails	
Juncus L. spp.	rushes	
Carex L. spp.	sedges	
Luzula DC. spp.	woodrushes	

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[1] Person, Hubert L., and Hallin, William. Possibilities in the regeneration of redwood cut-over lands. 1939. (Unpublished report on file at Pacific SW. Forest & Range Exp. Sta., U.S. Forest Service, Berkeley, Calif.)

[2] Basis: 7,082 milacre quadrats surveyed in 1932.

[3] Trees listed as shrubs because their environmental effect is shrublike.

[4] Species marked E are found only on cutover areas, not in virgin stands. They are either exotics or invaders from adjacent types.

Table 2.--*Species important in virgin redwood stands but not common on cutover lands in Humboldt and Mendocino Counties, California*[1, 2]

SHRUBS	
Cornus nuttallii Audubon	Pacific dogwood
Physocarpus capitatus (Pursh) Kuntze	ninebark
Sambucus callicarpa Greene	elderberry
Symphoricarpos albus (L.) Blake	snow berry
FERNS	
Adiantum pedatum L.	five-finger fern
Lomaria (Blechnum) spicant Desv.	deer fern
TALL HERBS	
Actaea spicata L. var. *arguta* Torr.	baneberry
Lysichiton kamtschatcense (L.) Schott	skunk cabbage
Petasites palmata (Ait.) Gray	sweet coltsfoot
Phacelia bolanderi Gray	phacelia
LOW HERBS	
Achlys triphylla (Sm.) DC.	deerfoot vanillaleaf
Disporum hookeri (Torr.) Britt.	fairy bells
Disporum smithii (Hook.) Piper	fairy lantern
Lilium L. spp.	lilies
Maianthemum bifolium DC. *kamtschaticum* (Gmel.) Jepson	Oregon coltsfoot
Mimulus dentatus Nutt.	monkey-flower
Scoliopus bigelovii Torr.	slinkpod
Streptopus amplexifolius (L.) DC.	liver-berry

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[1] Person, Hubert L., and Hallin, William. Possibilities in the regeneration of redwood cut-over lands. 1939. (Unpublished report on file at Pacific SW. Forest & Range Exp. Sta., U.S. Forest Serv., Berkeley, Calif.)

[2] Basis: 7,082 milacre quadrats surveyed in 1932.

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The Phenology and Growth Habits of Pines in Hawaii

Ronald M. Lanner

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Contents

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The Author

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Trees taken from their natural habitats and grown in another climate often develop in ways that cannot accurately be predicted. Foresters must understand this behavior if they are to make sound decisions in planting and managing these introduced species.

Over the years many pine species have been planted in Hawaii—both as ornamentals and as a potential source of locally grown softwoods. Even casual observers have noticed unusual behavior among some of these introduced species.

Pines in temperate regions undergo a regular annual growth cycle. They grow most actively in spring, stop growing in summer, and remain dormant throughout fall and winter.[1] Even most tropical pines come from areas where a pronounced dry season imparts seasonability to the climate, although winter temperatures may be mild.

This paper reports on a study of how the coordinated seasonal cycle of growth and flowering has been influenced by the climatic conditions that pine species encounter in Hawaii. The study sought to define the unusual behavior among some species in terms of the interaction between the species and their new environment. In some cases, this goal was met. But much more research needs to be done before the effects of environmental conditions in Hawaii on introduced species are fully understood.

Climate of Hawaii

Three characteristics of the Hawaiian climate are of major importance to studies of plant response: (a) the comparatively slight change in daylength—a consequence of low altitude (19 to 22° N.); (b) mild temperatures except at high elevations—owing to the Islands' oceanic position within the tropics; and (c) generally high rainfall—owing to the orographic effects of mountains on moisture laden air brought in by the northeast tradewinds. Most of the sample data given below are from Blumenstock (1961).

The small variation in daylength is a striking feature (fig. 1). At 20° latitude the longest day is only 13.3 hours and the shortest 11 hours—a difference of only 2.3 hours.

Temperatures at low and middle elevations are not only mild but equable (table 1). Both mean temperatures and extremes show little variability. Thus at Hawaii Volcanoes National Park, on the sland of Hawaii, the lowest temperature ever recorded in the coldest month (January) was 40° F.; the lowest in the warmest month (September) was 51° F. The highest temperatures ever recorded for these months were 73° F. and 80° F., respectively. Records of the U.S. Weather Bureau show that the annual mean temperature for a typical year for Kulani Camp, Hawaii, was 55.3° F. And temperature extremes for a 5-year period there (1958–1962) ranged from 31 to 78° F. The highest temperature ever recorded in the entire State was 100° F., at Pahala, Island of Hawaii; the lowest, 18° F., near the summit of Mauna Kea, an extinct volcano that rises almost 14,000 feet above the sea.

Rainfall varies enormously. At low and middle elevations on the islands of Hawaii, Kauai, Maui, and Oahu, rainfall is heavy enough to support a rain-forest community on the windward (north and east) sides. But above the temperature inversion layer (usually present at 4,000–7,000 feet) and at leeward locations are some very dry areas. Rainfall in the State is somewhat seasonal in distribution, the winter months (October–April) being wetter than the summer months (May–September). This difference is less pronounced in high-rainfall areas, where rainfall may vary greatly from year to year.

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[1] The term "dormancy" is used in the sense proposed by Doorenbos (cited by Romberger 1963) as a "general erm for all instances in which a tissue predisposed to elongate does not do so."

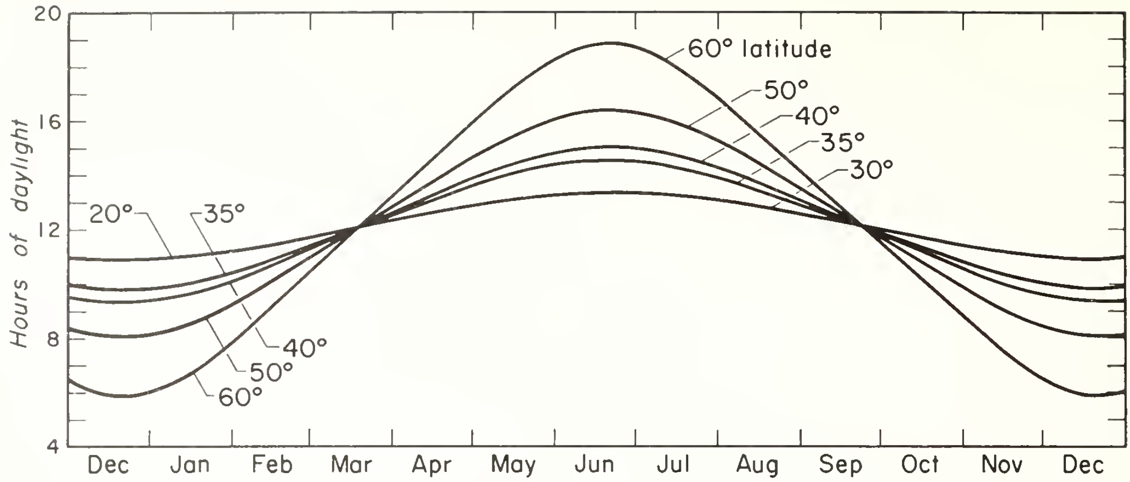

Figure 1.—*Change in length of day at different latitudes. Civil twilight was excluded.*

Table 1.--*Temperature data for seven selected stations in Hawaii*[1]

Station	Elevation	Mean January temperature	Mean August temperature	Mean temperature range
	Feet		*Degrees F.*	
Hilo, Hawaii	40	71	76	5
Olaa, Hawaii	280	70	75	5
Mountain View, Hawaii	1,530	65	70	5
Hawaii Volcanoes National Park, Hawaii	3,971	58	64	6
Kulani Camp, Hawaii	5,190	53	58	5
Haleakala, Maui	7,030	52	58	6
Mauna Loa Observatory, Hawaii	11,150	39	47	8

[1] Haleakala data from Britten (1962); all other data from Blumenstock (1961).

Methods

More than 200 observations were made of trees of 25 species (tables 2, 3). Sometimes only young trees were seen, so there was no opportunity to obtain flowering data. Because some trees or stands were difficult to reach, they were visited only once or at insufficient intervals to gather critical information.

Vegetative shoots were considered active if they showed evidence of elongation at the base of the bud, or if the needles on the current shoot increment showed a distinct gradient in length. They are considered dormant if the buds were enclosed within scales and if the youngest needles were full-sized. Normally it can be inferred that pine shoots are elongating if pollen is being shed, but in Hawaii this is not always true. In some species male cones mature irregularly, and pollen may continue to fly for several months after shoots have become

Table 2.--*Natural range and minimum probable displacement of species studied*

Common name[1]	Scientific name[1]	Natural range	Minimum probable displacement
			Degrees of latitude
Aleppo pine	*Pinus halepensis* Mill.	Mediterranean region	20
Caribbean pine	*P. caribaea* Morelet	West Indies and Central America	3
Chihuahua pine	*P. leiophylla* Schiede & Deppe	Mexico and Southwestern United States	0
Chir pine	*P. roxburghii* Sarg.	Himalaya Mountains	9
Coulter pine[2]	*P. coulteri* D. Don	Central California to Baja California	14
Eastern white pine	*P. strobus* L.	Eastern United States and Canada	20
Jack pine	*P. banksiana* Lamb.	Northeastern United States and Canada	25
Japanese black pine	*P. thunbergiana* Franco	Japan, Korea	10
Jeffrey pine	*P. jeffreyi* Grev. & Balf.	Baja California to Oregon	15
Khasi pine	*P. insularis* Endl.	Southeast Asia, Philippines	2
Knobcone pine	*P. attenuata* Lemm.	Baja California to Oregon	15
Loblolly pine	*P. taeda* L.	Southeastern United States	10
Lodgepole pine[2]	*P. contorta* Dougl.	Western North America	15
Longleaf pine	*P. palustris* Mill.	Southeastern United States	10
Maritime pine[2]	*P. pinaster* Ait.	Mediterranean region	20
Masson pine[2]	*P. massoniana* Lamb.	Southeastern China	3
Mexican weeping pine[2]	*P. patula* Schiede & Deppe	Mexico	0
Mexican white pine	*P. ayacahuite* Ehrenb.	Mexico	0
Monterey pine[2]	*P. radiata* D. Don	California	15
Montezuma pine	*P. montezumae* Lamb.	Mexico	0
Ponderosa pine	*P. ponderosa* Laws.	Western North America	15
Scotch pine[2]	*P. sylvestris* L.	Europe and Asia	25
Shortleaf pine	*P. echinata* Mill.	Southeastern United States	10
Slash pine	*P. elliottii* Engelm.	Southeastern United States	9
West Indian pine	*P. occidentalis* Sw.	Haiti (known source)	0

[1] Nomenclature here and elsewhere in this paper follows that given by Critchfield and Little (1966).

[2] Regenerates naturally in Hawaii.

dormant. High humidity for prolonged periods may delay drying of male cones and hinders the normal shedding of pollen. Therefore it was usually necessary to examine vegetative and sexual shoots independently.

Reproductive structures were studied in greater detail following a classification based on that used at the Institute of Forest Genetics, Placerville, California (Cumming and Righter 1948). Male cones were classed on their progress toward anthesis: (a) enclosed in buds, (b) not yet flying, (c) starting, (d) flying, (e) mostly shed, or (f) all shed; and female cones according to their stage of development: (a) buds large, (b) buds opening, (c) scales partly open, (d) scales fully open, (e) scales partly closed, (f) closed, or (g) conelet enlarging.

In collating the data for summarization, some interpolation has been necessary to reconstruct the annual cycles for selected species. But the observations were detailed enough to prevent serious error. Most of the observations were made in 1962–64, though a few data collected by R. G. Skolmen, of the Pacific Southwest Station in 1961, are included.

Table 3.--*Location of study trees*

Locale	Island	Elevation	Rainfall
		Feet	*Inches*
Hakalau	Hawaii	1,000	200
Haleakala Plot 1	Maui	6,500	50
Haleakala Plot 2 (Hosmer Grove)	Maui	6,800	104
Haleakala Plot 3	Maui	8,000	60
Hilo	Hawaii	50-400	150
Kamuela	Hawaii	2,600	29
Kamuela (Puu Ohu)	Hawaii	3,300	40
Keanakolu	Hawaii	5,300	110
Keawiwai	Hawaii	4,000	100
Keawiwai	Hawaii	6,000	50
Kokee	Kauai	3,000	100
Kulani Camp	Hawaii	5,200	98
Mauna Kea	Hawaii	9,000	26
Olinda Nursery	Maui	3,600	54
Pohakuloa	Hawaii	6,400	16
Poli Poli Spring	Maui	6,500	40
Puu Kihe	Hawaii	7,800	45
Puu Laau	Hawaii	7,500	20
Taro patch, Stainback Highway	Hawaii	3,600	150
Volcano	Hawaii	3,700	80
Waiakea Arboretum	Hawaii	800	200

Annual Growth Cycle

Major findings on the annual growth cycle of pines are summarized in table 4 and shown graphically in figure 2. The discussion that follows focuses on the species observed most often.

Findings for Selected Species

Mexican weeping pine.—At Olinda many spontaneous seedlings were found. Pollen-shedding was observed in December, January, February, March,

Table 4.--*Summary of phenological data on annual growth cycle of pines in Hawaii*[1]

Species	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Aleppo pine			a									
Caribbean pine	a	da	a		a				a		d	
Chihuahua pine	d				a							
Chir pine			ma		a							
Coulter pine	dm				ma	am						
Eastern white pine	d	m				a						
ack pine	mf[2]	m[2]				m[2]						
apanese black pine	mf[2]		mad[2]	maf	a	mf[2]		md[2]	d	mad[2]	m[2]	
effrey pine	d				ma	am		d				
hasi pine		a		a	a						ad	
nobcone pine	ma				a				d			
oblolly pine	dmaf		maf	a	a	a	m		ad		d	
odgepole pine				dmaf				mf				
ongleaf pine	d	a	a								d	
aritime pine	dm	amf	madf	a	ma				m		d	d
asson pine	dmfa	m			a				d			
exican weeping pine	fma	ma	maf	maf	maf				d		d	ma
exican white pine	d		a									d
onterey pine	fam[3]	fam[3]	fam[3]	fam[3]	fam[3]	af[3]	fa[3]	fam[3]	a	a	fam[3]	am[3]
ontezuma pine	d		da									
onderosa pine	d					m					m	
cotch pine	dm[2]	m[2]	da	fam		mf[2]		m[2]				
hortleaf pine	da	a		m	fa						d	
lash pine	d	m	amf		a				d			dm
est Indian pine	d		a									

a = vegetative shoots active
d = shoots dormant
f = female flowering
n = male flowering
Flowering data (male) excluded from tabulation in text.
Flowering data (both sexes) excluded from tabulation in text.

pril, and May. Pollen-receptive conelets were en in January, March, and May.

Vegetative shoots became visibly active in Dember or January and grew until about Septemr, several whorls of branches extending during is period. During the short dormant period many ees had, in their upper crowns, shoots that had ongated up to 3 feet without having extended eir needles. These shoots appear similar to what have termed "bare overwintering shoots" in knobne pine (Lanner 1963), where they were assoated with a bi-modal growth pattern. Similar oots, though much shorter ones, have been deribed for jack pine (Rudolph 1964) and, in uth Africa, for loblolly and Mexican weeping nes (Norskov-Lauritsen 1963).

Maritime pine.—One of the most commonly planted pines in Hawaii, maritime pine appeared to be quite normal in growth and form. It produces many cones, and the cones of both sexes are sychronized. Natural regeneration was noted at Olinda, Maui.

There were six reports of pollen-shedding for January and February, one for March, one for May, and one report for September. Conelets in the pollen-receptive stage were seen in February and March at Kulani Camp.

Dormant shoots were recorded in November, December, January, and March. The plantation with shoots dormant in March was considerably younger than the others. Except for the single case of pollen-shedding in September, maritime pine

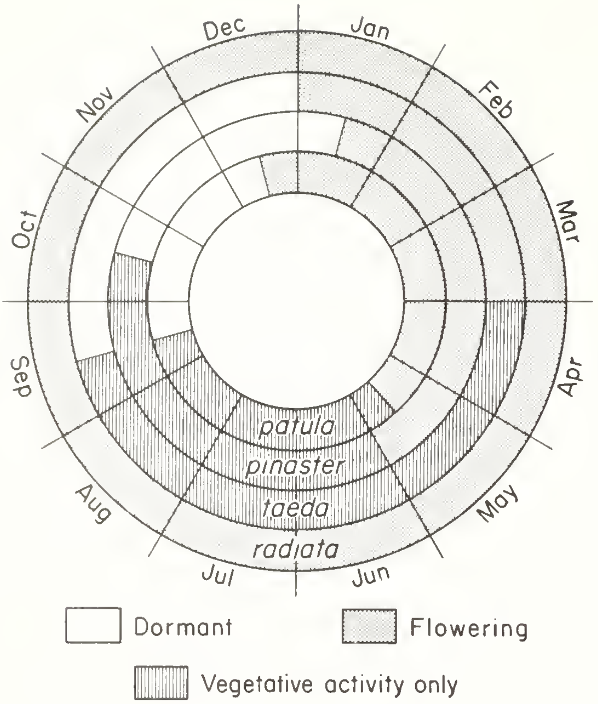

Figure 2.—*Calendar of phenological events in four species of pine in Hawaii.*

has been found to observe a regular seasonal cycle of growth and dormancy even where rainfall is about 100 inches annually (Kulani Camp).

Loblolly pine.—Periodic visits to a loblolly pine plantation at Olinda made it possible to view the same trees throughout an entire growth cycle. The trees were then in their fourth year (third year in plantation) and just starting to flower. Unfortunately, as with many of the trees reported upon in this paper, the seed source of this plantation is unknown, but phenologically the plantation was quite uniform.

Growth started in early January and both anthesis and the emergence of conelets occurred during this month. Shoot elongation continued, several whorls being produced, until September, when most trees became dormant. But in other trees the newly organized terminal bud elongated and became a lammas shoot or summer shoot (Shaw 1914). At the Waiakea Arboretum, where temperatures are milder and rainfall higher (Richmond 1963), the same vegetative cycle seemed to hold, but at Kamuela an isolated tree flowered heavily in July as well as in January. In a plantation above Kamuela (Puu Ohu), shedding male cones and pollen-receptive conelets were found in March.

Monterey pine.—Among a population of Monterey pines, most of the trees grow episodically, but some can grow continuously under suitable site conditions. This species is unusual in having no defined dormant season. Because of their bizarre appearance and their physiological and genetic significance, continuously growing trees are described elsewhere in this paper. Trees that grow episodically—and they are in the majority—do not all turn dormant at the same time of the year. Inspection of plantations of this species at any time of year will disclose shoots, vegetative buds, and male and female cones in several stages of development. And dormant and active shoots can be found side by side on a single tree. It appears that in Hawaii as in Australia (Jacobs 1937) the higher the order of a branch the more likely it is to form a resting bud.

Pollen-shedding was noted in January, February, March, April, May, August, November, and December, when there were male cones in earlier stages of development that probably shed pollen during the remaining months. Thus, pollen-shedding in Monterey pine may be considered a year-round affair.

Female cones at or near the receptive stage were observed in February, March, August, and November. Other cones probably reached this stage in April, July, October, and December. Conelets, like male cones, therefore can appear at any time. Within a period of several months, we saw branches on which five whorls of conelets were produced.

Synchrony of pollen-shedding and conelet receptivity was observed at Puu Kihe, Kulani Camp, and Pohakuloa. Natural regeneration has become established at Puu Kihe, where 809 pounds of cones yielded 9½ pounds of cleaned seed which germinated at the rate of 92 percent.[2]

Cyclic Pattern of Growth

The most significant finding in this study was that, except for Monterey pine, all species investigated in adequate detail showed a cyclic pattern of growth and dormancy. Most sites on which these trees were growing, and perhaps all of them, had climates mild enough to permit growth at any time. Yet the pines still showed the episodic growth pattern that characterizes their behavior at their places of origin.

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[2] Personal correspondence with Masa Takaoka, Hawaii Forestry Division, March 18, 1964.

Romberger (1963) has pointed out that even in tropical woody plants episodic growth is the usual condition, with alternating periods of rapid elongation and little or no elongation. This condition is true even of the tropical evergreen species near Singapore, only 1° N. of the equator, and in a tropical rain forest environment where variations in climate are of far less amplitude than in Hawaii (Koriba 1958).

Equally significant was the near synchrony of the various species of pine—the regularity of dormant, flowering, and growing periods that permitted us to delineate seasons in Hawaii in terms of pine response. Thus we may say that, in general, pines stop growing in September and resume growing in December, January, or February.

Seasonality of Flowering

Flowering is also seasonal, though some of the data obscure this pattern. To discern seasonal pattern, it is first necessary to exclude Monterey pine because of its unique capability of flowering throughout the year. Pollen-shedding data for jack, Scotch, and Japanese black pines that were not undergoing an obvious grand period flush must also be excluded because of the effects of high humidity. Female flowering data for these three species are included in this analysis because the opening of female buds is probably far less affected by humid conditions than is the release of pollen. The seasonal distribution of pine flowering in Hawaii is as follows:

	Species	
	With pollen-receptive female cones	Shedding pollen
	- - - (number) - - -	
Month:		
January	5	6
February	1	5
March	4	5
April	6	5
May	2	2
June	2	1
July	0	1
August	1	1
September	0	1
October	0	0
November	0	1
December	0	2

Several other facts must be considered regarding seasonality of flowering. First it must be admitted that too few observations were made during the months of July, August, October, and December. Had more time been spent in the field during those months, perhaps more flowering would have been seen. On the other hand, several observations of flowering late in the year are probably of little value in offsetting the strongly seasonal trend. For example, the records of pollen-shedding for June and for November refer to a single ponderosa pine at Hosmer Grove, Maui. There were no other data for this species, and this tree may be atypical. The July pollen-shedding record was for a single loblolly pine—this tree also flowered in January as have a large number of others of this species. The September record for maritime pine is another case in which one tree deviated from the behavior of many other trees of the same species.

There are precedents for flowering patterns that are other than strictly vernal. For example, Gregg pine (*P. greggii* Engelm.), a close relative to Mexican weeping pine, flowers regularly in June and November at Placerville, California.[3] Hodgson (1963) reports that Mexican weeping pine has two distinct flowering seasons in Southern Rhodesia. The major flowering season for male and female cones is between July and November at this southern hemisphere location, but between January and March female flowering recurs.

Mirov (1962) reported that pollen is shed twice a year—during January–February and July–August—in plantations (elevation 4,900 ft.) of Merkus pine (*P. merkusii* Jungh. & De Vries) in Java. Near sea level, plantation records showed that pollen and conelets were produced year round. Chalmers (1962) reported that in Trinidad, Caribbean pine of British Honduras origin produces pollen in every month, but mostly during November–January. This latter period was the only time when he saw emerging conelets.

In humid environments dates of anthesis can be misleading, because of lags in the opening of the pollen sacs. However, dates of flowering in Hawaii have been compared with dates for the various species in their native areas, or where such information was not readily available, in California (table 5). Of the 12 species seen flowering in Hawaii (excluding the jack, Japanese black, Monterey, and Scotch pines), in eight there is some degree of overlap, in two species flowering in Hawaii is no more than 2 months early, and in 2 species flowering in Hawaii is no more than 3 months early. So the Hawaiian environment

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[3] Personal correspondence with W. B. Critchfield, U.S. Forest Service, March 20, 1964.

usually deflects flowering periods either not at all or by only a few months; and when pines flower at the "wrong" time they are usually early. Magnitude of the deflection of flowering time and latitudinal displacement of the species are not related. These results are consistent with Mirov's observation (1956) that pines are neither long-day nor short-day plants.

Cone Anomalies

Anomalies, or abnormalities, in the position and structure of the reproductive structures of *Pinus* have received attention from botanists and foresters for many years. Recent interest in tree improvement has shown the need for more detailed information on the entire process of flowering, and especially the physiological mechanisms underlying the initiation and development of cone pri-

Table 5.--*Pine flowering dates in Hawaii compared with other records*

Species	Hawaii flowering date	Flowering date outside Hawaii	Location	Reference
Chir[1]	March	Feb., March, April	India[2]	Troup 1921
Coulter	January	April, May, June	California[2]	Duffield 1953
Eastern white	February	May, June	Canada[2]	Canada Dep. Forestry 1963
Knobcone	January	March, April	California[2]	Duffield 1953
Loblolly[1]	Jan., March, July[3]	Feb., March, April	North Carolina to Texas[2]	Dorman and Barber 1956
Lodgepole[1]	April-May, July, August	April, May, June	California[2]	Duffield 1953
		May, June, July	Alberta, Canada[2]	Smithers 1962
Maritime[1]	Jan., Feb., March, May September[4]	April	California	Duffield 1953
Masson	Jan., Feb.	April	California	Duffield 1953
Mexican weeping[1]	Jan., Feb., March, April, May, Dec.	March, April	California	Duffield 1953
Ponderosa[1]	June, Nov.[5]	April, May, June	California[2]	Duffield 1953
		May, June	Canada[2]	Canada Dep. Forestry 1963
Shortleaf	April, May	March, April May	North Carolina to Texas[2]	Dorman and Barber 1956
Slash[1]	Dec., Feb., March	Jan., Feb.	South Carolina to Texas[2]	Dorman and Barber 1956

[1] Indicates that flowering periods in Hawaii and elsewhere overlap.

[2] Trees growing within the natural range.

[3] Record for July based on single tree; others included numerous trees at each of two locations.

[4] Record for September based on single tree; others included several trees at three locations.

[5] Both records based on a single tree.

Figure 3.—*Cone clusters of Japanese black pine, Puu Kihe, Hawaii.*

mordia. This interest, in turn, has focused attention on anomalies because studies of the abnormal often shed light on the normal.

Normal Cone Development

Female cones are the ontogenetic equivalents of branches (long shoots). They originate from buds that occur in whorls just below the apex of a terminal bud, as do vegetative branches. After emerging from its cover of bud scales, the tiny conelet parts its scales, exposing to view the axis on which the scales are spirally arranged. At this point the conelet is said to be pollen-receptive, for this is when pollination takes place. After pollination the scales close and the conelet enlarges somewhat. Next spring the cone increases in size until it matures in late summer or fall.

Male cones are the ontogenetic equivalents of needle bundles (dwarf shoots). They emerge from small buds located below the zone of needle bundles on an elongating branch. They then elongate, and the pollen sacs along their axes split open, releasing the pollen. After pollen-shedding the male cones dry up and wither.

Types of Anomalies

Position Anomalies

In position anomalies, organs are found on parts of the tree where they do not usually occur.

Female cones in the needled zone is a condition known in German literature as Zapfensucht, or "cone disease." The cones appear in positions normally occupied by needle bundles and are sometimes clustered in great numbers (Black 1961; Debazac 1963; Fielding 1960; Gal'pern 1956; Neubauer 1960). In Hawaii this condition was observed on a Maritime pine and a Masson pine, several times on Mexican weeping and lodgepole pines, and many times on Japanese black pine, where it is so common as to have become the "normal" mode of growth for this species—at least in the high elevation plantings on Haleakala and Mauna Kea (fig. 3).

Every cone in such a cluster occupies a position that would otherwise bear a fascicle of needles, and every cone that develops at a whorl occupies what would otherwise be the position of a branch. When both types of cones are produced in great profusion (fig. 4) an abnormal pagoda-like crown is formed.

In Japanese black pine the clustered cones may be found at the base of the needled tract, at the top of it, or within the tract of foliage. They may occur in dense masses, or be interspersed singly among needle bundles. Most of them fail to attain normal size because of severe crowding.

It is interesting that position anomalies are so much more common in Japanese black pine than in the other species in Hawaii. As Mergen (1963) has pointed out, many of the recent reports of sex transformation have pertained to this species. According to Black (1961), Jackson has reported

Figure 4. — *Japanese black pine "pagodas" at Puu Kihe, Hawaii. Heavy coning prevents formation of a normal crown.*

Figure 5. — *Needles emerging from the portion of the stem bearing male cones. Mexican weeping pine, Kulani Camp, March 1964.*

"cone disease" of this species in Britain, and Gal'pern (1956) in southern Russia.

Male cones mixed with needles is a condition common in Mexican weeping pine, where strobili may be found intermingled with needle bundles in predominantly needled zones, or needles in the zone of strobili (fig. 5).

Pseudo-terminal cones. — Female conelets in *Pinus* normally emerge from buds arranged in whorls below the apex of a terminal bud. There are, however, reports of "terminal cones" (Doak 1935, Fielding 1960), that is, cones actually borne at the tip of a shoot. Such a configuration renders the growth of the cone-bearing shoot determinate, in contrast to its normal indeterminate nature (Sinnott 1960). That is, the shoot can no longer extend its axis, for it is capped with a soon-to-be-dead structure instead of a living vegetative bud. Masters (1890, p. 309) attributed the apparently terminal position of cones to arrested development of the terminal bud and assumption of dominance by the cone.

At Olinda, Maui, N. H. Cheatham and I found three wildlings of Masson pine, each of which had its leader surmounted by what appeared to be a terminal cone in the pollen-receptive stage (fig. 6). Two of these were descaled and found not to be terminal at all. In each case the cone was a lateral appendage. The terminal bud was very small and still tightly enclosed within its scales. Apparently the terminal bud had not elongated after the cone emerged, and as a result of its superior vigor the cone had achieved dominance. The weak terminal bud would probably have remained inhibited and eventually aborted. These observations agree with those of Masters (1890).

A pseudo-terminal cone of Masson pine has been deposited in the herbarium of the Institute of Forest Genetics, Placerville, California.

Developmental Anomalies

The timing of development of reproductive organs is modified in developmental anomalies.

Late pollen-shed.—In several individuals of Mexican weeping pine, and in the single knobcone pine available for study, there were male cones on the previous years' shoots that were just reaching anthesis. Presumably these were year-old

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Figure 6. — *Apparent terminal cone of Masson pine, Olinda, Maui, February 1964.*

cones that had developed very slowly. This delay of one year in the maturation of male cones seems analogous to delay in needle maturation of Mexican weeping pine noted earlier in this paper and in knobcone pine (Lanner 1963).

Overlapping development of male cones.—Pollen-shed is normally a short-term affair. For example, Sarvas (1962) found that in most years pollen from Scotch pine was shed during a 5- to 10-day period. In Hawaii, however, male cones on the same branch may mature during a much longer period. Within a cluster of male cones all stages of development may be found, from tightly closed buds to totally shed-out male cones. Nor does maturation always proceed systematically upwards or downwards along the shoot (Fielding 1957). Instead, male cones in several stages may be intermingled along the shoot axis. The period of pollen-shedding is thus prolonged far beyond even the 19 days recorded for Monterey pine in Australia (Fielding 1957). This overlapping development of male cones has been commonly observed in Monterey, Scotch, Japanese black, and jack pines. It should not be confused with the delay in shedding from matured strobili though it is often associated with it.

Differential development within male cones.—On one tree each of ponderosa pine and loblolly pine, male cones have been found in which the distal half was shedding or shed out while the proximal half was not yet ready to shed. In the ponderosa pine, too little material was available to establish the frequency of this pattern. But in the loblolly pine, which was flowering heavily, nearly all the male cones had developed in this way.

Structural Anomalies

In structural anomalies, the morphology of an organ is altered.

Bisexual cones of Japanese black pine have been found at the Hosmer Grove, Haleakala, and at Puu Kihe. The upper portion was female, the lower portion male in every case. Similar bisexual cones were found on Mexican weeping pine at Keanakolu and Puu Kihe, where they occurred within cone clusters in the male-cone zone.

Club-shaped male cones.—A slash pine at Kaaweiki, Kauai, had male cones that were swollen to twice the normal diameter in the upper two-thirds of their length. Dissection revealed no sign of insect attack or other internal damage.

A recent tendency has been to view anomalies as evidence of physiological disturbances in introduced species (Zobel 1952; Black 1961). It is true that most reports of such anomalies deal with introduced species, but this may be due to the closer attention that these species receive.

Crown Form

A pine normally tends to produce a pryamidal crown until, at an advanced age, the leader loses dominance and the crown flattens. Any radical departure from the pyramidal shape that is not due to mechanical damage or pathological factors is considered abnormal for the purpose of this paper.

Larson (1962) has suggested a unifying concept of the influence of the crown on wood quality—mainly as to wood specific gravity and the annual ring. He points out that wood quality is influenced by environmental factors, not as independent agents, but as controllers or modifiers of growth within the crown. For example, latewood information is associated with the cessation of growth in the terminal shoot. If the environment is modified so that terminal growth is prolonged during the period of earlywood formation, then latewood formation will be delayed. In this case, the activity of the shoot is an intermediary between the environmental factor and the structure of the wood. If the same environmental modification was used too late or too early to influence shoot growth suitably, it would not have the same effect on wood quality. Larson's concept is useful in solving some of the problems of pine growth in the tropics because it permits the observer to make inferences regarding wood quality based on simple phenological observations.

Influence on Annual Ring

In light of Larson's concept (1962) the annual ring is seen to be a manifestation of changing growth conditions in the crown. When shoot activity ceases and the tree becomes dormant, a band of latewood is laid down by the cambium. Thus, we would expect the pines that exhibit an annual growth cycle in Hawaii, including a period of dormancy, to produce truly annual rings. Except for the occurrence of false rings (and these are formed in pines in their natural habitats as well) this generalization appears valid. Ring counts on trees of known age have disclosed annual rings in ponderosa, Jeffrey, Coulter, slash, and loblolly pines. And Skolmen (1963) has reported annual rings in maritime pine. Normal-looking rings were seen in a Scotch pine, but the age of this tree, a naturally seeded one, was not known independently. All of these pines go dormant in Hawaii.

Japanese black pine appears to form a false ring about every other year on the average. The phenology of this species is not yet satisfactorily understood. Though it flushes in spring and becomes dormant in winter, its behavior during the growing season is erratic.

Monterey pine is difficult to interpret. Continuous-growing individuals of this species form practically no latewood, so ring counting is impossible. In other trees bearing no evidence of continuous growth, the latewood may or may not be well enough defined to demarcate rings. In some cases broad zones of latewood contrast but little in color with earlywood. The situation here is probably similar to that described by Oppenheimer in Aleppo pine under conditions of mild weather that permit recurrent growth flushes (Studhalter et al. 1963).

Morphology of the Shoot

Normalcy of crown form implies not only a certain phenological course of development and a specified anatomical organization of the woody tissue but a well-defined pattern of shoot morphology as well (Debazac 1963; Doak 1935). A new vegetative branch that has just elongated and become dormant is organized in a particular fashion. At the base is a series of closely-knit scars. They show the points of attachment of the bud scales that enclosed the branch when it was an unextended bud. Further along the branch is a needle-less zone, or sterile-scale zone. Beyond this zone is the needled portion of the branch, which is surmounted by a whorl of lateral buds and a terminal bud. When these buds extend, the same pattern will be repeated on the branches they produce—bud-scale scars, sterile-scale zone, needled zone. On so-called "multinodal" shoots there are intermediate branch whorls, but just above the whorls is the usual sterile-scale zone. Bud-scale scars are found only at the base of the first shoot increment (Jacobs 1937).

If normal growth of pines is understood from the three points of view—phenological, anatomical, and morphological—it is possible to gain some insight into the nature of abnormal forms.

Branchless Pines or Foxtails

Numerous reports of branchless or nearly branchless trees among pines planted in tropical and sub-tropical areas, chiefly Africa and Latin America (table 6), have cropped up in recent years. Such trees are called foxtails—a term coined by Lloyd (1914). Except for the reports by Lloyd and by Kummerow (1962) there have been no serious efforts to describe such trees, so it is necessary to describe here in some detail a typical foxtail of Monterey pine.

Monterey Pine

Morphological Features

This Monterey pine foxtail was planted at Kulani Camp, Hawaii, in August 1958 and cut in March 1964. It was then 22 feet tall, and had several whorls of branches or branch scars between the base and 3.5 feet above ground (figs. 7, 12).

The shoot.—The terminal shoot had no branch scars or lateral buds over its entire 18.5-foot unbranched length. The only sterile-scale zone was just above the branch whorl at the base of the foxtail. Thus, most of the shoot consisted entirely of the elongated internodes[4] between dwarf shoots. The foxtail bore about 3,200 needle fascicles between the basal sterile-scale zone and a point several inches below the tip. The shoot tapered very gradually as it was only 3 inches in diameter at the stump.

Along a 4-foot section of the trunk starting 2 feet above the ground, nearly all of the needle fascicles had proliferated (fig. 8), giving that portion of the stem the bearded appearance remarked upon by Lloyd (1914) and Kummerow (1962). Most of the branches arising in this way were only a few inches long, but occasionally branches up to 3 feet long have been encountered. In one case such a branch was found bearing male cones.

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[4] "Internode" is used in the strict botanical sense to refer to the portion of a stem between the points of attachment of successive lateral appendages, not the space between branch whorls. In this case it is the portion of the shoot between successive needle bundles.

Table 6.--*Reports of branchless pines or long leaders*

Species	Location	Length of branchless stem (feet)	Reference
Canary Island pine (*P. canariensis* C. Smith)	Kenya, Nyasaland, Tanganyika	--	Anonymous 1962
Caribbean pine	Argentina	--	Golfari 1963[1]
	British Honduras	up to 10	Anonymous 1962
	Kenya, Tanganyika	--	Anonymous 1962
	Northern Rhodesia	up to 35	Anonymous 1962
	Trinidad and Tobago	20	Streets 1962
	Transvaal, Zululand	up to 50	Poynton 1957
	Hawaii	12	ff. this paper
Chihuahua pine	Kenya	--	Anonymous 1962
Chir pine	Kenya, Nyasaland	--	Anonymous 1962
Khasi pine	Kenya, Northern Rhodesia, Tanganyika	--	Anonymous 1962
	Nyasaland	--	Anonymous 1962
	Hawaii	9	ff. this paper
Longleaf pine	British Honduras	--	Anonymous 1962
	Hawaii	42	Skolmen 1963[1]
	New Zealand, Southern Rhodesia	--	Streets 1962
Masson pine	Kenya	--	Anonymous 1962
Merkus pine (*P. merkusii* Jungh. & de Vriese)	Northern Rhodesia	--	Anonymous 1962
	Vietnam[2]	[3]10	Gaussen 1960[1]
Mexican pinyon (*P. cembroides* Zucc.)	Arizona[2]	4	Phillips 1911[1]
Mexican weeping pine	Nyasaland	--	Anonymous 1962
Michoacan pine (*P. michoacana* Martinez)	Northern Rhodesia	--	Anonymous 1962
Monterey pine	Australia	up to 17	Fielding 1960[1]
	Brazil	--	Golfari 1963
	California[2]	--	Lloyd 1914[1]
	Colombia, Peru	up to 22	Kummerow 1962[1]
	Hawaii	up to 19	ff. this paper
	Kenya	up to 20	Anonymous 1962
	New Zealand	up to 20	Streets 1962
	Nyasaland, Tanganyika	--	Anonymous 1962
	California[2]	15.8	Institute of Forest Genetics 1933[1]
	California[2], Australia and New Zealand	12	Scott 1960
Montezuma pine	Northern Rhodesia	--	Anonymous 1962
	Tanganyika	up to 8	Anonymous 1962
Pseudostrobus pine (*P. pseudostrobus* Lindl.)	Nyasaland	--	Anonymous 1962
Slash pine	Fiji, Kenya, Mauritius, Nyasaland, Tanganyika	--	Anonymous 1962
	Florida[2] (var. densa Little and Dorman)	--	Little and Dorman 1954[1]
Tropical pine (*P. tropicalis* Morelet)	Isle of Pines[2]	[3]10	Little and Dorman 1954[1]
West Indian pine	Kenya	--	Anonymous 1962

[1] Appropriately illustrated.

[2] Trees were growing within natural range.

[3] Estimated from photograph.

Figure 7.—*Monterey pine foxtail at Kulani Camp, Hawaii. The tree, 5½ years after planting, was 22 ft. tall, with 18½ ft. of unbranched leader.*

Figure 8. — *Proliferated dwarf shoots on a Monterey pine foxtail give it a characteristic appearance.*

The spacing of needle fascicles along the foxtail was regular. In normal annual shoot increments of pines (Bannister 1962; Debazac 1963), grapevines (Gard 1900), eucalypts (Carr and Carr 1959), *Ribes* (Haskell and Wills 1963), and several other genera (Büsgen and Münch 1929), the distance between nodes varies systematically. At the base of the shoot, internodes are short, in the middle they are longer, and at the distal end they again shorten. But if the distances between lines of phyllotaxy intersecting a hypothetical orthostichy on the woody portion of a foxtail are plotted, the result is a nearly straight line (fig. 9).

The branches.—All but the uppermost whorl included fine wire-like branches that were probably already present when the seedling was planted or that elongated soon after. The uppermost whorl had the only strong branches on the tree, but the longest of these was only 5 feet long. Each branch of the upper whorl had at its base a zone of sterile scales, then a short portion along which the dwarf shoots had proliferated, and finally a needled portion. Some branches were further ramified, but several were unbranched in the manner of the foxtail itself.

The terminal bud.—In contrast to the conventional pine bud the terminal bud of a foxtail consisted only of primary leaves subtending needle fascicles. The needles decrease in length as the summit is approached. Despite the lack of sterile bud scales the terminal bud was brown due to the

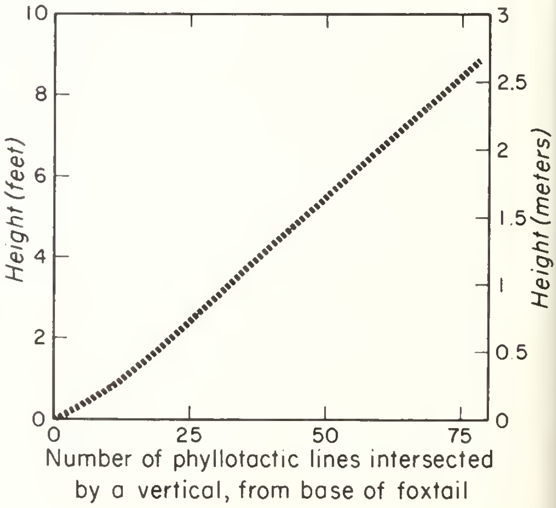


Figure 9.—*Cumulative distance, by lines of phyllotaxy, along the woody portion of a Monterey pine foxtail. Starting point is 3 ft. above highest branch whorl.*

overlapping primary leaves (fig. 10). The foxtail bud is analogous to the central portion of a conventional pine bud during the period of shoot elongation, but it looks the same all year round. It has no grand period flush so there is never a long, bare, limber shoot at the top of the leader.

The needles.—The needles of foxtails attain lengths much greater than is encountered in this species' natural range in California. According to Forde (1964) needles of Monterey pine population samples ranged from 7 to 18 cm. in length. Sample means varied from 11 to 15 cm. A typical foxtail from Kulani, however, had needles ranging in length from 14.5 to 23 cm., and the mean length of 100 needles was 20.0 cm. These were in fascicles of 3, 4, and 5. On the limbs of the foxtail-bearing trees, needles are of normal size; especially if these branches are themselves branched. The short branches arising through proliferation of dwarf shoots also carry needles of normal dimensions.

Wood anatomy.—Several foxtails were cut and their wood examined. The sections examined ranged from 2 to 5 inches in diameter and were at least 5 years old—yet not a single definite ring was visible (fig. 11).

The wood specimen shown in figure 11 was studied with a stereomicroscope at 100x. The smoothed transverse section was projected by a camera lucida on squared paper, and the number of tracheids in a radial file that occupied successive squares were counted. A total of 1,727 tracheids were counted along a composite radius extending from just outside the pith to the cambium. Viewed in the camera lucida, there were 6 to 9 tracheids along the side of each square. Taking the tracheids along each square as a single sample, mean tracheid diameter varied from 29 to 43 micra. The standard deviation of 218 samples was 0.36; the coefficient of variation was 0.045.

These extremely low values attest to the striking uniformity of tracheid diameter within foxtail wood formed during 5½ years. None of the tracheids seen had the tangential flattening of typical latewood cells, nor was there any discernible rhythm in tracheid diameter.

It is true that within the "juvenile core" of some pines the latewood zone is very narrow (Larson 1962), but in Monterey pine grown in California the annual rings are distinctly visible all the way to the pith (fig. 12). So the lack of latewood bands in the foxtails cannot be attributed to juvenile core characteristics. Actually, the wood of the ju-

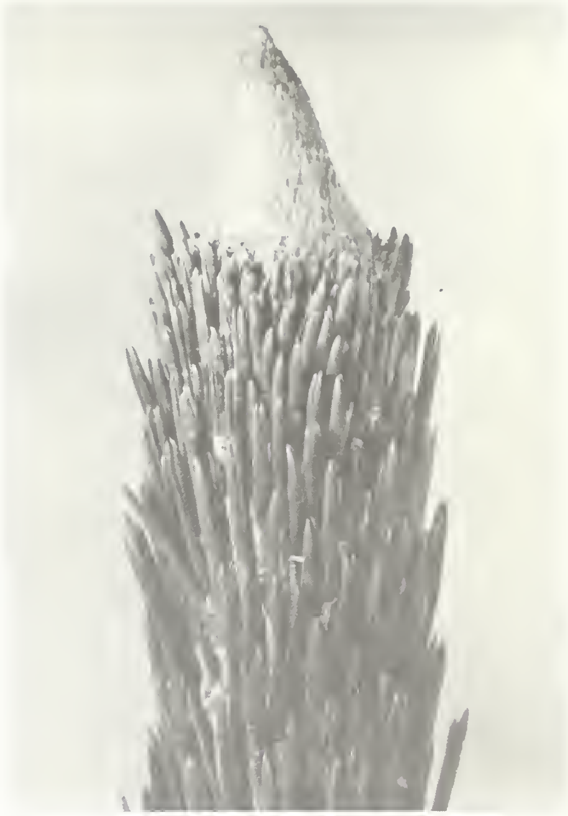


Figure 10.—*Tip of a Monterey pine foxtail showing the continuous series of scales subtending needle fascicles, and the absence of sterile bud scales. This tip was photographed in March, but appears the same all through the year while growth is continuous.*

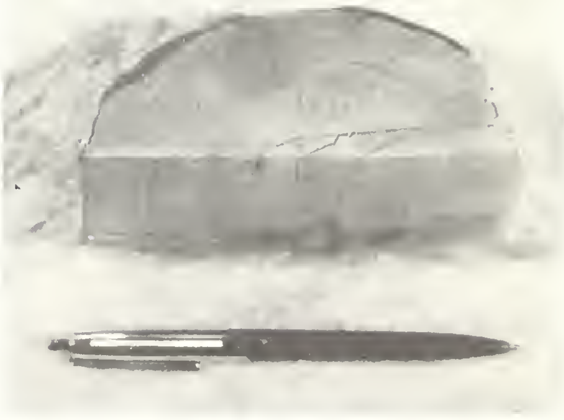
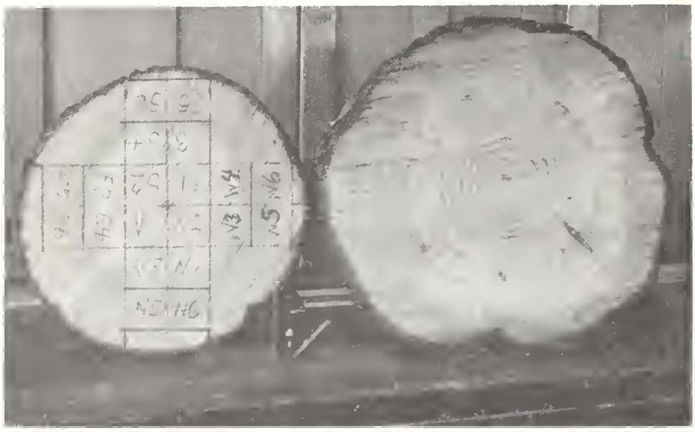


Figure 11.—*An example of foxtail wood.*



← Figure 12. — *Monterey pine from its native California habitat.*

venile core is merely wood that has developed within the influence of an active crown (Larson 1962) and is a less extreme example of crown influence than is foxtail wood.

Pith.—In several foxtails the pith was succulent within the entire needled portion of the shoot—as much as 16 feet down from the tip—and green over most of this length (fig. 13).

Evidence of Continuous Growth

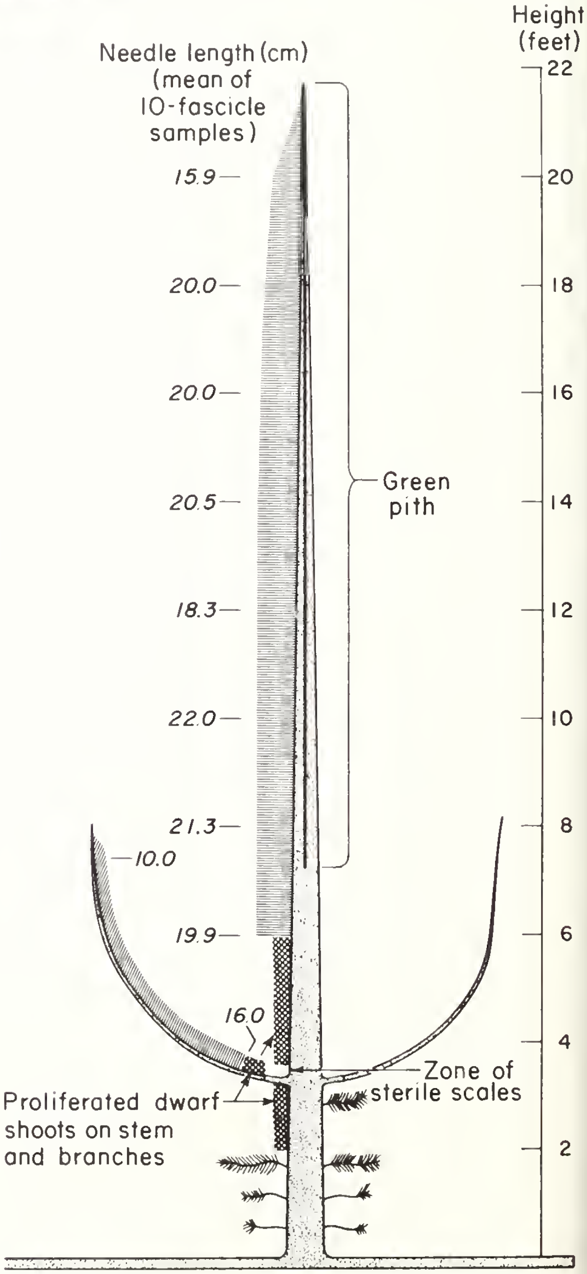
According to Shreve (1924) Monterey pine elongates slightly during the winter even in its native habitat. But this is not continuous growth as defined by Romberger (1963) and as understood here.

The evidence for continuous growth is all indirect, but in light of its consistency it is compelling nevertheless. In discussing implications of episodic growth, Romberger (1963, p. 76) reported that:

> "If growth is to be continuous, development of primordia must be controlled so that scales are not formed or do not accumulate. In addition meristematic activity must persist in the subapical region. Continuous growth requires a delicate balance between initiation and development of primordia and elongation of internodes."

This passage describes precisely the conditions in a foxtail. During the period when foxtails are growing, no bud scales are produced, nor are sterile scales or lateral long shoots. The absence of these is evidence that a foxtail is branchless because *branch primordia have not been formed.* These structures have not been formed because the tree is in a "morphogenetical steady state," so to speak, and produces primary leaves subtending dwarf shoot primordia and only dwarf shoot primordia for a period far in excess of a normal season's growth. How long this condition can persist is not known, but some foxtails at Kulani Camp have

↓ Figure 13.—*Diagrammatic representation of a Monterey pine foxtail.*



almost certainly not produced any axillary structures, except dwarf shoots for 6 years. It should be evident that foxtails satisfy Romberger's first criterion in not forming or accumulating scales.

Does meristematic activity persist? There are several reasons for believing it does. The appearance of the shoot tip is suggestive (fig. 10). Throughout the year, needles of all sizes and stages of development may be found. The shoot tip itself is made up of tightly packed needles still within their unbroken sheaths. Below these are needles penetrating the sheaths and needles free of their sheaths and gradually increasing in size until an abnormal length is attained. The progressive increase in needle size, culminating in proliferation of the interfoliar bud, also suggests continuous growth.

The significance of succulent and green pith is not entirely clear. According to Esau (1953) mature pith is normally devoid of chlorophyll.

Coordination of Growth Activities

The extension of shoots, formation of early and latewood, initiation of primordia, emergence of cones, elongation of needles—each of these events takes place at a particular time relative to the occurrence of the others. They normally occur in specific relation to the calendar—there is a time of year (season) for these activities. The pattern in Monterey pine foxtails is obscured by their bizarre appearance, but nevertheless, these trees are in a certain stage of growth. And the several activities in these foxtails are in synchrony with each other if not with the calendar.

Figure 14 shows the nature of this internal coordination. The curve is the S-shaped height-growth curve obtained by measuring a normal shoot periodically during the growing season and plotting its total height at each time. Such a curve exemplifies normal episodic growth. Stages I, II, and III represent the slow start of elongation, the grand period of height growth, and the onset of dormancy. In the accompanying chart three growth activities are correlated in time with these stages of shoot growth. The cited data pertain to other species of *Pinus;* no such studies having been made of Monterey pine.[5] If we hypothesize that the apical meristem of a foxtail remains in the late stage II condition, the continued production of dwarf shoots, the laying down of earlywood, and the sustained growth of the needles can be put into a meaningful context. Under this hypothesis, the growth rate of a foxtail could be expected to be rather steady without a typical grand period flush: this condition is indicated by the dashed line tangent to the S-shaped curve. Field observations of foxtails at Kulani during every month of the year were consistent with this expectation. A consequence of the steady growth rate of foxtails was the absence of stem kinks caused by leader flop (Jacobs 1938), and the temporary collapse of long, limber, top-heavy leaders. Sinuous curves were common but these were probably due to wind pressure.

Environmental Factors

Only two reports in the literature give enough details to make it certain that they concern foxtails. Kummerow (1962) described Monterey pine foxtails planted in the Andes of Colombia and Peru.

Lloyd (1914) reported on a Monterey pine foxtail growing in a yard at Carmel, California.

The Colombian and Peruvian plantations reported on by Kummerow were 5–8° from the equator and the Chilean seed source was at 33° S. latitude. Although he included the possibilities of mutation or injury by insects or pathogens, Kummerow thought photoperiod was responsible for the development of foxtails. The Chilean plantation is in a strongly seasonal climate, with a marked dry season; the Colombian and Peruvian plantations grew in areas of relatively little seasonal change. Thus he reasoned that photoperiod rather than seasonal change would act as a growth control factor.

The foxtails described by Lloyd grew close to a cesspool. Several other trees with proliferating dwarf shoots grew near springs. Lloyd suggested that abundance of water and possibly nitrogen was responsible for the proliferation of dwarf shoots and the branchless stem. Lloyd was uncertain whether branchlessness was due to abortion of buds or failure to initiate branch primordia. Neither Lloyd nor Kummerow attributed foxtails to continuous growth. Lloyd's report of foxtailing at about 36° N. under conditions of abundant soil moisture appears to conflict with Kummerow's interpretation.

Foxtailing can be readily understood if it is rec-

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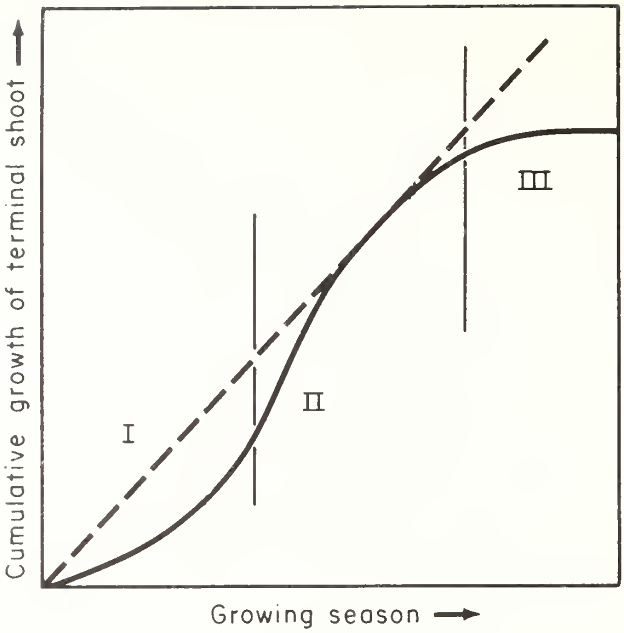
[5] The timing of needle primordium initiation in *P. resinosa* differs from that of *P. ponderosa* and *P. lambertiana* (Duff and Nolan 1958). Until comparative studies in the genus clarify the variation in the morphogenetic sequence, it seems useful to retain the generalized model used here.



	Stage of Terminal Shoot Activity		
	I	II	III
Primordia being initiated at apex: *P. ponderosa* and *P. lambertiana* (Sacher 1954)	Sterile scales	Dwarf shoots	Lateral long shoots and bud scales
Type of wood formed (Larson 1962)	Earlywood	Earlywood	Latewood
Stage of needle activity: *P. resinosa* (Kienholz 1934)	Not yet elongating	Growth starting, rapidly reaching a peak	Growth slowing

Figure 14.—*Generalized model showing relationship of growth activities in pines and the annual growth cycle.*

ognized as the result of continuous growth. Of special importance is the fact that foxtailing occurs only in some trees, and that it probably does not persist in any of them for the life of the tree. Thus, the factors that permit continuous growth are not permanent but transient. In the locations where Monterey pine foxtails have been studied, photoperiod of course follows the same pattern every year. Temperatures vary but little from year to year, and are seldom low enough to stop growth for more than a few hours at a time. Rainfall, however, can vary considerably both within and between years, at any location.

The role of abundant rainfall in sustaining continuous growth is made apparent by comparing growth and rainfall data for two Monterey pine plantations in which foxtailing has been observed. These plantations were established within 3 months of each other—the Kulani stand in August, and the Olinda stand in November 1958.

The Olinda Plantation.—The Olinda stand was inspected and measured about 3 years after planting by N. H. Cheatham, of the Hawaii Forestry Division, Kahului, Maui. At that time at least 18 percent of the stand (spacing plot 33) was noted as unbranched above stump height and at least 11 feet tall. During this period of foxtailing mean monthly rainfall was 4.36 inches; the longest drought was a 7-month period when mean monthly rainfall was 1.77 inches. For the purpose of this report "drought" months are those in which rainfall was less than 4 inches (table 7).

When I inspected this plantation in January 964, I found that all of the original 29 foxtails ad branched. During this period of branching, nean monthly rainfall (for 27 months) had delined to 3.53 inches. But there had been an 8-nonth drought during which monthly rainfall veraged only 0.85 inches. For the 62 months lapsed since planting mean monthly rainfall was .99 inches.

The Kulani Plantation.—In January 1964 this stand contained about 20 percent foxtails. In the 65 months after planting, the most severe drought was a 3-month period when monthly rainfall averaged 1.33 inches—far less severe than either of the Olinda droughts. Monthly rainfall for the entire period averaged 7.82 inches, almost twice that at Olinda (table 8).

This comparison supports the hypothesis that an

Table 7.--*Rainfall at Olinda, Maui, during the early years of a Monterey pine plantation in which foxtails were common in October 1961 but absent in January 1964*

Month	1958	1959		1960	1961	1962		1963
	Inches							
January	--	17.87		1.08	5.83	2.03		7.13
February	--	8.55		15.50	9.13	2.70		2.62
March	--	1.16		5.23	.09	4.01		4.92
April	--	5.90		3.12	10.58	.05		9.85
May	--	2.53		3.17	3.18	1.51		9.12
June	--	.06	drought	1.56	1.67	.17	drought	2.55
July	--	1.73		1.22	1.42	.30		2.89
August	--	2.87		.72	1.65	.87		3.03
September	--	2.23		1.79	.75	1.23		5.08
October	-	.39		.81	5.11	.24		3.48
November	3.60	11.16		4.91	8.20	2.41		4.52
December	7.31	9.99		3.78	2.32	6.53		2.54
Total	10.91	64.44		42.89	49.93	22.05		57.73
	Period of foxtailing				Period of branching			

Table 8.--*Rainfall at Kulani Camp, Hawaii, during the early years of a stand in which foxtails were still common at the end of the period*

Month	1958	1959	1960	1961	1962	1963
	Inches					
January	--	17.57	15.10	1.46	1.00	3.13
February	--	14.95	11.37	17.14	3.59	2.01
March	--	5.57	9.48	6.62	7.54	17.07
April	--	8.11	15.11	5.43	3.29	41.35
May	--	6.47	6.75	4.15	5.06	13.07
June	--	1.33	3.24	2.17	[1] .32	7.07
July	--	5.56	2.48	4.13	[1] 2.09	12.83
August	16.55	11.35	9.04	4.47	[1] 1.58	4.35
September	3.44	4.16	5.66	3.95	5.48	5.04
October	8.02	3.26	3.65	14.44	3.35	3.42
November	10.91	14.42	16.05	17.80	3.74	5.37
December	2.41	13.70	2.56	20.95	5.07	.50
Total	41.33	106.45	100.49	102.71	42.11	115.21

[1] Drought.

abundance of rainfall permitted certain trees to grow continuously. Such growth was arrested by drought which induced the formation of a terminal bud complete with long-shoot primordia. In terms of the scheme in figure 14, while rainfall was abundant, the foxtail leader remained in stage II; moisture stress induced the shoot to enter stage III.

Further support to the hypothesis is lent by measurements of tree 29 at Olinda. Assuming a steady rate of growth between the times this tree was measured in 1961 and 1964 it appears that its single whorl of branches emerged about May 1963. Allowing several months for the elongation of previously formed internodes between formation and unfolding of the lateral long shoots, it seems likely that the long-shoot primordia were formed in response to the drought of April–November 1962.

The importance of abundant moisture in permitting continuous growth is also suggested by Scott's (1960) comment that very long leaders ". . . 12 feet or more, with no side branches" were common among Monterey pines planted in warm parts of California and irrigated. Earlier, Chamberlain (1935) had written that near Jalapa, Mexico (Tabasco State) trees growing in forests "wet throughout the year" had no well-defined annual rings. But individuals of the same species just a few miles away, where there were alternating wet and dry seasons, showed clear growth rings.

Monterey pine is notorious for its great genetic variability (Fielding 1953, 1960; Syrach Larsen 1956) despite its restricted natural range. Fielding (1960) has demonstrated genetic variation in the number of whorls per annual shoot increment. He has shown that while most trees produce several whorls per year some produce only one whorl per year. Perhaps the so-called "uninodal" trees are the ones that produce foxtails. Such a tree would have fewer opportunities to make lateral branch primordia instead of short-shoot primordia. Environmental conditions (droughts) necessary to bring about this changeover would have to occur more often than in the case of multinodal trees in order to favor branching. In the strongly multinodal trees the opportunity to respond to a drought would occur more often and would be more likely to coincide with one.

Figure 15.—*Strongly multinodal Monterey pine at Kulani Camp, Hawaii.*

At Kulani Camp after almost 6 years in plantation many trees were still unbranched. The other trees showed the full range of branching habit from foxtails that had just put on the first whorl since seedling days to trees averaging more than two whorls per year (fig. 15). Unfortunately, little time was devoted to the study of these more nearly normal trees. The presence of branches shows that the leaders of these trees do not grow continuously in the sense that the foxtails do, but some of the limbs may grow continuously for several years before producing branches of the second order (fig. 15). During this period the branch tips are similar to the tip shown in figure 13. An increment core from the base of such a tree was similar to those from foxtails in lacking latewood. Perhaps the formation of latewood is inhibited by continuous growth anywhere in the crown. Further study is needed to clarify this point.

Silvicultural Considerations

Should foxtails be regarded as desirable forms or as poor ones? At present this question cannot be answered, as evidenced by confusion in the minds of foresters of many countries (Anonymous 1962). The few small plantations of Monterey pine in Hawaii have not been subjected to silvicultural treatment or study. Present planting plans in Hawaii do not indicate any great enlargement of ie acreage of pines so this is not a matter of nportance there. But the likelihood that Monterey ine will be planted in other areas of the world nder similar environmental conditions lends in- erest to this question.

It is true that spectacular lengths of clear stem an be obtained. But these may be associated with rger and steeper-angled branches if it is the so- alled "uninodal" trees that tend to form foxtails Fielding 1960). The fact that only earlywood is roduced during the foxtail period would seem to gue against retaining such trees in the stand. eight measurements at Olinda showed that 3 ars after planting the average height of the en- re stand of 158 trees was 12.4 feet while the erage height of the 29 foxtails in that stand was 2.3 feet, an insignificant difference. Breast-height ameter averaged 2.0 inches for the entire stand id 1.9 inches for the current foxtails, again an significant difference. Stem crooks are common nong foxtails, but as explained above, they may ot be serious. Perhaps further crooks result from avy branching above a long foxtail that has ased continuous growth. The silviculturist would ve to make his own determination under his own cal conditions if he were managing plantations which foxtailing is rampant.

Most of the Monterey pines seen in these studies ere less than 10 years old. And it was in the unger stands that foxtails were most apparent. ithout exception the foxtails had whorls of anches on the lower portion of the trunk in po- ions that indicate those branches were either present when the trees were planted or elongated shortly afterwards. No signs of foxtailing were seen in Monterey pines in the nursery. Therefore selection for or against continuous growth cannot be accomplished in the nursery unless the seedlings are permitted to remain at least 2 years.

Foxtails of Other Species

Foxtails were also found in a small plantation of Khasi pines at the Waiakea Arboretum. These trees were examined in April 1964, about 4 years after planting (Richmond 1963). Several showed evidence of continuous leader growth and others had continuously growing laterals.

The buds of these trees are similar in appearance to those of Monterey pine foxtails and the shoot is similar in structure (fig. 16) but lacks proliferated dwarf shoots.

At Olinda, Maui, several foxtails were observed in a plantation of 7-year-old Caribbean pine of Honduran origin. A review of published photographs leads me to conclude that foxtails develop on Merkus pine in Vietnam (Gaussen 1960) and on Carbbean pine in Argentina (Golfari 1963).

The term "foxtail" has been used indiscriminately in the British Commonwealth (Anonymous 1962). This practice is also true of several zoomorphic terms in New Zealand and what is called "furry fishing rod" in Kenya. I suggest that the term foxtail be used only for trees in which long-sustained continuous growth has prevented branches from forming.

"False Foxtails"

Some branchless trees do not develop from orphogenetically continuous growth, but rather rough the abortion of lateral branch buds. To stinguish these trees, I suggest calling them 'alse foxtails." By applying some of the same orphological, anatomical, and phenological cri- tria that aided in understanding foxtails, the na- tre of false foxtails has also been resolved.

The following description is a composite of veral slash and longleaf pines growing on a va- ty of sites in Hawaii.

Morphology

Shoot.—The terminal shoot bears the alternat- g series of bud scale scars, sterile scales, and varf shoots found on a normal stem. At the base of each sterile-scale zone is usually a whorl of lateral buds that are much reduced in size and still dormant if not aborted (fig. 17). In the Waiakea Arboretum, 10 lateral buds were recovered from three whorls of a branchless 4-year-old slash pine. Eight of these were merely empty shells consisting of bud scales whose contents had withered; the other two were still alive but dormant and small.

Terminal bud is normal in all respects. During the winter it is enclosed in sterile bud scales and in spring it undergoes a typical grand-period flush.

Needles.—In several cases needles from false foxtails have been measured and found to fall within the range of normal length for the species.

Wood anatomy.—Increment cores have been taken from a false foxtail of longleaf pine of

Figure 16.—*Foxtail of Khasi pine* (P. insularis) *at Waiakea Arboretum, April 1964.*

Figure 17.—*A false foxtail of* Pinus palustris *at Waiakea Arboretum, November 8, 1963. The exposed portion of the stem is covered with sterile scales which have never borne needle fascicles. At the base of this zone is a whorl of aborted buds and branches, one of which is visible in silhouette on the right side.*

←

Figure 18.—*False foxtail of* P. palustris, *Keanakolu. Hawaii.*

nown age. The number of distinct latewood bands orresponded closely with the age of the tree, uggesting truly annual growth.

Cyclic or episodic growth.—The differences beween the two types of branchless trees are indiated by the presence of bud scales, sterile-scale ones, lateral buds on the stem, zonation of the vood, normal needle length. and phenological data n the species in which false foxtails have been bserved.

False foxtails result not from the absence of ateral buds, but from failure of the buds to elonate. They grow cyclically, not continuously.

Causes

Despite the failure of lateral buds to elongate, he branchless leaders themselves are entirely noral in their morphology and development. Diamter growth is retarded, but this is to be expected ecause the only foliage available to carry on hotosynthesis is that borne on the leader. The eedles live for only a few years so as the tree rows the amount of foliage diminishes in relation o the surface area of cambium it must support. ven though diameter growth becomes progresively less, it is remarkable that these trees can ve as long as they do—up to 30 years in the case f the longleaf pine at Keanakolu (fig. 18).

Examination of published photographs shows hat some of the branchless trees reported in the terature are false foxtails. These include Mexican pinyon (Phillips 1911) and South Florida slash pine (Little and Dorman 1954). In the southeastern United States, there are occasional longleaf, slash, and loblolly pines in which the lateral branches have failed to develop.[6] These and other branchless southern pines grown abroad (Anonymous 1962; Poynton 1957; Streets 1962) also are probably false foxtails, as this group of pines seems especially prone to this growth habit. The tropical pine illustrated in the bulletin by Little and Dorman (1954, p. 25) is probably a false foxtail judging from the appearance of its terminal bud. And most of the "foxtails" mentioned in the Forestry Newsletter (Anonymous 1962) are probably false foxtails too, as most of them are reported from regions with a pronounced dry season that would not permit continuous growth.

False foxtails therefore result from the wholesale inhibition, dormancy, or abortion of lateral buds. The growth habit is most obvious in trees where this happens year after year, but there may be trees that "miss" a whorl only occasionally. Such trees might be of interest to tree breeders and would also seem to be helpful in the study of bud inhibition and suppression. The presence of dormant buds in the whorls of pines is of course well-known (Stone and Stone 1943). And perhaps the false foxtail results merely from an intensification of whatever factors cause them.

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[6] Personal correspondence with Keith W. Dorman, U.S. Forest Service, July 1, 1963.

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ome Characteristics of the Three-Dimensional Structure of Santa Ana Winds

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U. S. FOREST SERVICE RESEARCH PAPER PSW- 30

Pacific Southwest
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Foreword

In March 1962 a contract was made between e Office of Civil Defense, now in the Office of ecretary of the Army, and the Department of griculture, Forest Service, Pacific Southwest Fort and Range Experiment Station, to carry out a udy of critical fire weather patterns and their retionship to synoptic patterns and to topography. he general objective of this study was to determine, region by region, the major synoptic scale eather patterns creating conditions under which rge area ignition would result in high intensity, st spreading fires; to determine the frequency of currence of these patterns and aids for predictg their occurrence; and to analyze and measure ajor topo- and mesoscale weather patterns creatg critical fire weather in selected target areas.

The first two parts of this objective were deribed in two previous reports "Synoptic weather pes associated with critical fire weather" (Schroer et al. 1964) and "Critical fire weather patrns—their frequency and levels of fire danger" Hull, O'Dell, and Schroeder 1966). Two other ief reports, "Probability of effective post-attack e fighting in wildlands" (Chandler and Schroer 1965) and "Monthly fire behavior patterns" Schroeder and Chandler 1966) have indicated ways in which data from this study can be reoriented for application to specific problems.

The mesoscale fire-weather pattern selected for investigation was the Santa Ana wind of southern California. Similar foehn-type winds affect many areas of the mountainous West. One previous report, "Surface wind patterns in the Los Angeles Basin during 'Santa Ana' conditions" (Edinger, Helvey, and Baumhefner 1964) presents the results of an analysis of 7 years of Santa Ana wind situations in both statistical terms and in streamline presentations of individual situations. A second report, "The structure of thermal convection in the lower atmosphere" (Myrup 1965) deals with the more general and basic problem of the way in which heat introduced at the bottom of the atmosphere is carried upward and thus modifies air masses.

This report describes the measurement of the three-dimensional wind flow and temperature structure in the lower atmosphere during Santa Ana conditions. Although the study of Santa Ana wind flow is by no means complete, this is the final report for the Office of Civil Defense under the present contract. Forest Service plans call for further field studies of the structure and variations of Santa Ana wind flow.

The work reported in this paper was performed by the Forest Service, U. S. Department of Agriculture, for the Office of Civil Defense, Office of the Secretary of the Army, through the U. S. Naval Radiological Defense Laboratory, San Francisco, California, under Contract OCD-PS-65-27 (Subtask 2535A)

Acknowledgments

The field portion of this study required the participation of other projects and agencies. Richard M. Ogden and Donald V. Lust, of the U. S. Weather Bureau, and William Innes, of the California Division of Forestry, assisted in field observations. Further observations were made by personnel from the Pacific Southwest Forest and Range Experiment Station's Forest Fire Laboratory in Riverside, Calif. The Weather Bureau staffs at San Diego, Santa Monica, and Las Vegas took extra rawinsonde observations for the study, as did the U. S. Navy at the Pacific Missile Range. Dr. J. G. Edinger, the University of California at Los Angeles, obtained pilot balloon observations in the Los Angeles basin. Meteorology Research Inc., of Altadena, Calif., obtained—under contract—aircraft and radar observations. Personnel at Edwards Air Force Base, Cuddeback Lake Naval Test Site, and 29 Palms Marine Corps Station in California provided data routinely taken but not normally available. We also appreciate the National Meteorological Center data and analyses provided by the Los Alamitos Naval Air Station. The Los Angeles and Riverside Air Pollution Control Districts provided data from their special networks. The California Division of Forestry aided by securing permission from private and public landowners to set up the field equipment.

Contents

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MARK J. SCHROEDER is responsible for forest meteorology studies at this Station. Native of Edgar, Wisconsin, he was graduated from Wisconsin State University (1936) and did graduate work in meteorology at the University of Chicago. He has been on assignment to the Station from the U. S. Weather Bureau since 1955, and headquartered at the forest fire laboratory since 1963.

Fire behavior is affected by many meteorological elements. The two most influential elements are wind speed and relative humidity. During foehn activity, the lee slopes of mountain ranges experience both high winds and low humidity. When winds up to 50 meters per second combine with relative humidity of 5 percent, fire danger reaches a critical stage. In southern California, the foehn is known locally as the Santa Ana. Together with the low relative humidities, it produces the most extreme fire danger found anywhere in the world.

The synoptic features producing Santa Ana winds are reasonably well understood and can be forecast. But their mesoscale and smaller characteristics produced by mountain waves are less well understood. The behavior of large wildland fires is affected by variations in the mesoscale Santa Ana of such features as foehn islands, surfacing, and intensity of outflow. These characteristics would similarly affect mass fires resulting from nuclear attacks.

The purpose of this study was to determine the three-dimensional structure of the Santa Ana so that the mesoscale morphological behavior could be understood. Data were collected during two cases of Santa Ana winds—each 48 hours long—in December 1963 and January 1964. This paper describes the procedures and results of the study, and suggests implications as well as recommendations for future research.

Early Studies

The major portion of research on foehn winds has been done in the Inn Valley of Austria. The foehn phenomena of descending air, adiabatic warming (Defant 1951; Godske et al. 1957), and low humidities along a mountain slope and the adjacent valleys have been partially understood since the 1800's. Hann (1866) proposed the thermodynamic explanation of the warming as a release of latent heat on the windward side and adiabatic warming on the leeward side of a mountain range during the descent.

Ficker and Rudder (1943) summarized the large scale aspects of foehn occurrence. Their explanation is that pressure must be low on the lee side of the mountain range. If the air current is cold, it piles up to the top of the range and spills over. The descending air is warmed adiabatically and shows the foehn characteristics only after the adiabatic modification has changed the cold air characteristics to such an extent that it is warmer and dryer than the air it is replacing. If the air flow is warm, it assumes foehn characteristics much higher on the lee slope. In general, the factors determining the foehn type are the synoptic situation, the orientation of the mountain range, and the air mass properties.

Four factors—mechanism of descent, foehn islands, surfacing along the lee slope, and the diurnal fluctuations—have been identified as related to a mountain wave phenomenon (Gutman and Tebuev 1961; Holmboe and Klieforth 1954; Lyra 1943).

The Santa Ana wind of southern California was first identified as foehn flow by Carpenter and Gorthwaite (1914). The *Riverside Daily Press* of December 24 and 30, 1901, suggested that the air was warmed adiabatically. The synoptic aspects of Santa Ana winds (Sergius 1952) require an anticyclone in the Great Basin and a surface low pressure trough off the California coast. Because the Great Basin anticyclone has a cold core, gradient flow at the ridge top associated with the resultant upper Low is nearly perpendicular to the San Gabriel and San Bernardino Mountain ranges. This is an ideal situation for the development of lee waves (Colson 1952). Because the anticyclone in the Great Basin is more often cold than warm, most of the Santa Ana winds are of the cold type described by Flicker and Rudder (1943). During early fall, however, the warm type is often observed.

Analysis of theoretical work on lee waves yields the following factors that influence the amplitude of the waves (Corby and Wallington 1956):

1. Amplitude will increase if the wind speed increases with increasing height, or the stability decreases with increasing height. The amplitude is more responsive to the wind profile than to the stability.

2. Largest amplitude waves occur when the critical conditions for airstream characteristics for wave formation are just barely reached.

3. Adiabatic mixing near the ground decreases the amplitude.

4. Large amplitude waves are more likely in airstreams having a shallow layer of great stability rather than a deep layer of moderate stability. Foldvik and Wurtele (1964) suggested that the stable layer is a result of and not an *a priori* condition for wave formation. Corby and Wallington (1956) also indicated that the wave-length is increased by adiabatic mixing near the ground.

Meso and local analysis of the Santa Ana has been somewhat neglected; only papers by Sergius (1952) and Edinger, Helvey, and Baumhefner (1964) describe the climatology of the surface winds, temperatures, and humidities associated with the Santa Ana. The salient features of these studies are:

1. A wind shadow perpendicular to the flow is cast by the mountain range. This shadow is so effective that a sea breeze or pseudo-sea breeze pervades the shore every day.

2. The sea breeze or pseudo-sea breeze is characterized by low humidities and is probably foehn air that has been over the ocean only a short time.

3. The areas of strong winds are well defined. The strongest winds blow out of the passes, particularly on the flanks of the San Gabriel range, and occasionally have preferred channels on the plain, such as along the Santa Ana River bed.

4. Humidities are found to be low (less than 20 percent) throughout southern California during a Santa Ana, with a slight tendency to be as high as 30 percent in the mountain top areas.

5. Fuel moisture tends to have minimum values in sheltered and semi-sheltered areas and maximum values at high elevations and along the axes of the strongest winds. In a case study, Fosberg (1965) found that the descending flow was complicated by the interaction with the mountain and valley winds.

The line along which the Santa Ana separates from the mountain, the spotty descent—both in time and in space—the interaction with more local winds—such as mountain and valley winds and the sea breeze—and the spectrum of lee waves produced by the complex nature of the mountains are difficult to determine from surface data.

If the Santa Ana separates from the mountain at a high elevation, only the normal thermal winds are found at lower elevations on the lee side. The behavior of wildfires occurring under such conditions is controlled by the local winds. If, however, the Santa Ana surfaces and scours out the lee canyons, a fire can be carried down slope and into heavily populated areas. This wind action occurred in such California fires as the Malibu fires in 1956, the Bel Air fire of 1961, and the Coyote fire in 1964, when many expensive homes were destroyed.

The major objective of the work reported in this paper was to determine the three-dimensional structure of the Santa Ana winds from analyses of wind, temperature, and moisture fields. To determine this structure, such characteristics as the areal extent, spatial variations, and relation to the synoptic pattern were examined. The influence of the mountains and the basic wind and thermal structure also had to be separated in order to determine which wave characteristics were due to the mountains and which were due to the static stability and the wind profile. To further describe the Santa Ana we had to answer such questions as: 1. Are foehn islands strongly related to both the downwind topography and to the wave characteristics or does topography play a dominant role? 2. What is the life history of the Santa Ana? 3. Does the sea breeze penetrate as a cool marine surge during the decay stage of the Santa Ana? Condensation is not involved in the Santa Ana to any appreciable degree, yet in the European foehn, condensation is quite important. 4. What difference does the lack of release of latent heat produce in the Santa Ana?

Procedures

Field Study

The area selected for study covers the Los Angeles Basin, the San Bernardino Valley, and the mountains to the north and east. Our principal effort was in the latter two areas.

Originally, 20 recording weather stations were installed to obtain surface weather information (fig. 1). Considerable difficulty was encountered in keeping the stations operating so that data acquisition was not complete. For this reason, only 10 stations were installed for the second case study. The sites were selected to provide area coverage

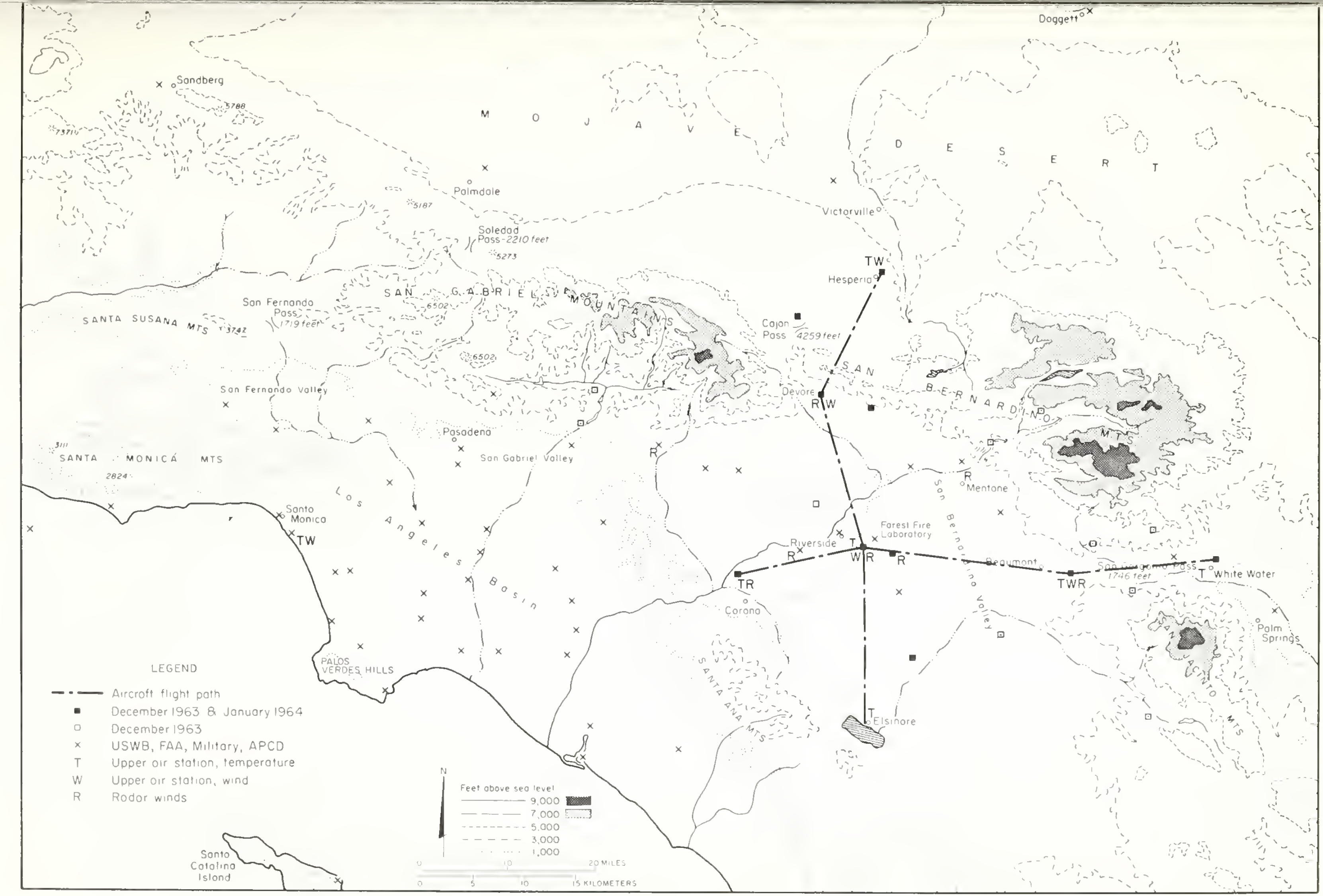


Figure 1.—*Map of southern California showing major topographic features, station locations, and aircraft flight paths.*

and data for cross sections through Cajon Pass and San Gorgonio Pass. Surface observations included wind speed and direction, and dry- and wet-bulb temperature. Surface pressure readings were made at some stations, but the measurements were not accurate enough to be useful in the analysis.

The recording stations were placed in their sites well in advance of the study periods. Participating personnel remained on call until a Santa Ana situation was forecast. On the basis of the forecast, all personnel were then sent into the field to take upper-air observations. Observations were continued until the Santa Ana winds showed signs of diminishing. In each of the two cases the study period lasted 2 days.

Double-theodolite winds aloft observations were made at 3-hour intervals—0100, 0400, etc.—at Devore, Hesperia, and Beaumont. Thirty-gram balloons were used with a free lift giving a normal ascension rate of 180 meters per minute. Runs were ended after 18 minutes.

Radiosonde observations were taken at the Forest Fire Laboratory at Riverside, California, to coincide with upper-air wind observations, except for 0100 P.s.t. observations. Standard procedures were used.

Meteorology Research, Inc., operated an M-33 tracking radar on Box Springs Mountain and tracked aluminum foil targets attached to balloons. At Riverside a target was attached to the radiosonde train, and wind profiles were obtained by tracking. Wind profiles were also obtained by tracking targets on 30-gram balloons released from Corona (December 1963 case), and near Riverside Airport (January 1964 case) as soon after the 3-hour observation time as possible, and from the Forest Fire Laboratory at 0100 P.s.t. when a radiosonde was not released.

Trajectory balloons with targets were released for radar tracking at Devore, Beaumont, Mentone, and Cable. Two balloons were attached to a single target. One was filled with a free lift of 3 grams and the other was given a free lift of 30 grams, but a slow leak was provided by punching a hole in the neck. The object was to allow the two balloons to rise to about 300 m. and then have them take off on a constant altitude course. In practice the balloons and targets usually ascended at a slow rate. The release times of the trajectory targets were coordinated with the radar to fit into the radar schedule. Releases were about 0200 and 1400 from Cable; about 0500 and 1700 from Devore; about 0800 and 2000 from Mentone; and about 1100 and 2300 from Beaumont.

The radar provided a graphical track of the balloon target, giving its position in terms of range, azimuth, and height. By measuring the track between 1-minute plots, it was possible to deduce the direction and speed of the wind at balloon level.

Although winds aloft information was obtained from most of the balloon releases, considerable gaps in the winds aloft record occurred because radar could not distinguish between return from the balloon target and ground clutter. Balloon releases made far from the radar were difficult to acquire since the widening of the radar beam width with distance allowed for more interfering returns to mask the target. At close-in points, when the balloon could be sighted visually at release, the target could be tracked optically until it rose above the ground clutter. The radar could then be locked on it. This generally occurred at about 500–600 m. above the surface.

In general the trajectory balloons failed, chiefly because (a) it was virtually impossible to fly the balloons at a given level, and (b) whenever the balloons were flying at altitudes close to the surface, they were lost in the ground clutter.

We tried to obtain wind information at aircraft level by using radar to track the airplane's path as it flew past the radar site. The plan was to derive the wind vector by solving the wind triangle. From the aircraft the true air speed and heading were obtained, while the radar track provided the true course and ground speed. The difference between these two sets of readings would be the wind affecting the airplane. Unfortunately the first priority requirement of tracking balloons almost fully occupied the radar so that little time remained for extensive experiments with this technique.

Aircraft observations were made by Meteorology Research, Inc., in a twin-engined Piper Apache instrumented to record pressure, temperature, humidity, turbulence, compass reading, and true air speed. The aircraft was based at Cable. The flight pattern consisted of a sounding from near the surface to 3100 m. at Corona, a traverse at that altitude eastward through San Gorgonio Pass to Whitewater, descent to near the surface at Whitewater, a low-level traverse westward to Beaumont, and sounding to 3100 m. at Beaumont. The aircraft then proceeded to Hesperia, descended near the surface, then proceeded southward through Cajon Pass at an intermediate elevation to near

Lake Elsinore. There, it made a sounding to 3100 m., and then returned to Cable.

Flights were started about 0200, 0800, 1400, and 2000 P.s.t. Each flight took 3 hours so that he originally-planned, additional probings of the mountain wave crest could not be conducted withn the scheduled flight-time limitations. However, data acquired in the course of the various soundngs and the traverses between sounding points did provide a partial picture of the extent of the wave phenomenon associated with these Santa Ana winds.

Data Reduction

Surface Data

The surface data were recorded on Esterline Angus milliameter strip chart recorders. A programer was used to cycle through the various ensor signals. The charts were read and data ecorded manually using calibration scales.

Upper-air Data

Theodolite readings for the pilot balloon obervations were placed on punchcards along with ther pertinent data. Computations were made by lectronic computers. Besides the horizontal wind peeds and direction, the computer program proided the vertical component by subtracting the ormal vertical displacement from the measured isplacement. The program also computed the orth-south and east-west components of the wind. n this study the components along the cross secons through Cajon Pass and through San Goronio Pass were desired. These components were ear enough to north-south and east-west, respecvely, so that it was not necessary to rotate the oordinate system.

Data for significant levels on the radiosonde run vere also placed on punchcards and the computaons were made by computers.

adar Wind Data

Data were obtained from the original radar lot of the targets. These data were plotted on a eries of upper-air charts (in 305-m. intervals, om 1000 to 3100 m.) at the geographical locaons of the observational points as determined om the radar.

ircraft Data

The various data obtained during the aircraft oundings and traverses were plotted against height above mean sea level). The soundings were identified with the point on the ground over which the aircraft circled during the course of the sounding. Data from aircraft traverses were plotted on cross sections—the data points corresponding to the actual points on the aircraft's flight path.

Air temperature, obtained in degrees Celsius, was later converted into potential temperature in degrees absolute to put the data in a form convenient for the determination of vertical motion patterns in the airflow.

Subjective turbulence reports by the aircraft pilot were displayed on the cross sections.

Analysis

Analysis of the data collected during the two case studies was designed to accomplish two goals: (a) to obtain the three-dimensional structure in such a way that the physical processes could be understood; and (b) to obtain information on the interaction of the local outflow of foehn air and the synoptic patterns in such a way that the intensity of the foehn could be understood.

The analyses of surface and constant pressure charts, vorticity, and vertical motion by the National Meteorological Center were taken as a *prima facie* description of the structure of the atmosphere. Only when the data coverage was at least one order of magnitude greater per unit area, was the NMC analysis modified and then only in sub-synoptic scale detail.

The second analysis scale was at the mesoscale, covering the Southwestern United States. The analysis area can be described by lines running east and south from San Francisco and north and west from Yuma, Arizona. Horizontal analysis at this scale was at 50-mb. intervals from 1000 mb. to 500 mb. on constant pressure surfaces where geopotential height, vector winds, temperature and mixing ratio were analyzed. Isentropic analyses, at the 280° A, 290° A, and 300° A surfaces, of mixing ratio, pressure and vector wind were also performed. These three surfaces are in the outflow boundary layer, the transition layer and smoothed outflow, and gradient flow level. Vertical cross sections from the surface to 300 mb. were also analyzed from San Francisco to San Diego and from Las Vegas to San Nicolas Island (an offshore Navy station in the Gulf of Santa Catalina) to provide information on long-wave gravity flow. The time period between analyses at this scale was 6 hours, just half that of the synoptic scale. The base map at this scale was 1 to

3 million and included surface contours.

For the surface analyses a 1 to 250,000 base was used to obtain enough detail of the local outflow. Data analyzed at this scale were mixing ratio, vector wind in scalar form, and temperature reduced adiabatically to sea level. Vertical cross sections of vector wind, potential temperature, aircraft flights, radiosondes and subjective turbulence reports were analyzed in an east-west cross section from Whitewater to Corona and a north-south cross section from Hesperia to Elsinore. These cross sections had a 16.7 to 1 vertical exaggeration.

Results

The two cases, 10–12 December 1963 and 7–9 January 1965, are described in this section. Little attempt was made to draw or define common characteristics or to synthesize the data into a single descriptive model here, but a synthesis and model are given in the next section. All times reported in these two case studies are in Pacific Standard Time.

Case of 10-12 December 1963

The synoptic features of this case are typical of those encountered in the development of a Santa Ana (fig. 2). A high pressure area of maritime origin moved into the Great Basin from northwest Canada. Concurrently, the short-wave trough deepened until 1600 P.s.t., 11 December. The surface High and upper trough had reached their most intense stage and began to weaken, although the system remained quasi-stationary through the twelfth. A surface low pressure area over northern Mexico remained quasi-stationary throughout the Santa Ana, but by 2200 P.s.t. on the tenth, a surface trough began to develop parallel to the coast and out of the Mexico Low. This trough line was apparently associated with a weak front that had passed through southern California 2 days before and was now stationary. The surface Low offshore and the Great Basin High provided a 1.8×10^{-2} mb./km. pressure gradient between the Great Basin High and the offshore trough. The mountain ranges ringing southern California have a maximum elevation of near 3000 m. so the 700 mb. charts provide a good basis to examine the wave development criteria. The air was stable, temperature decreased 16° C. in 200 mb. Although no direct computation of Scorer's (1949) l^2 stability parameter was made, it is safe to say that l^2 decreased with height. This decrease is a necessary condition for the formation of lee waves, but the waves formed would not have a large amplitude. At higher levels, around 600 mb., where the flow is more nearly geostrophic, the flow was from the northwest and not the optimum condition for Santa Ana waves (fig. 17). In this respect, this case is not a perfect example of Santa Ana structure.

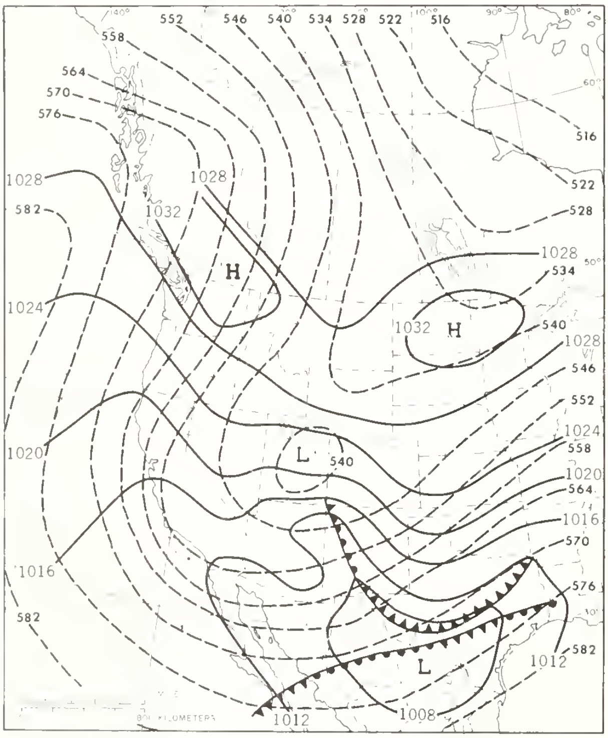


Figure 2.—*NMC analysis of synoptic features at 1600 P. s. t., 10 December 1963. Dashed lines are 500 mb. contours, solid lines are surface isobars.*

By the afternoon (1600 P.s.t.) of the eleventh, the flow had veered to north in the upper levels and northeast at 700 mb. The wind shear had decreased, but the shear of the perpendicular to the ridge had increased. And the conditions for large amplitude waves became more favorable. The period of optimum wave formation was short-lived as the vertical wind shear decreased by 0400 P.s.t. on the twelfth. In summary, this case developed more slowly than normal, maintained

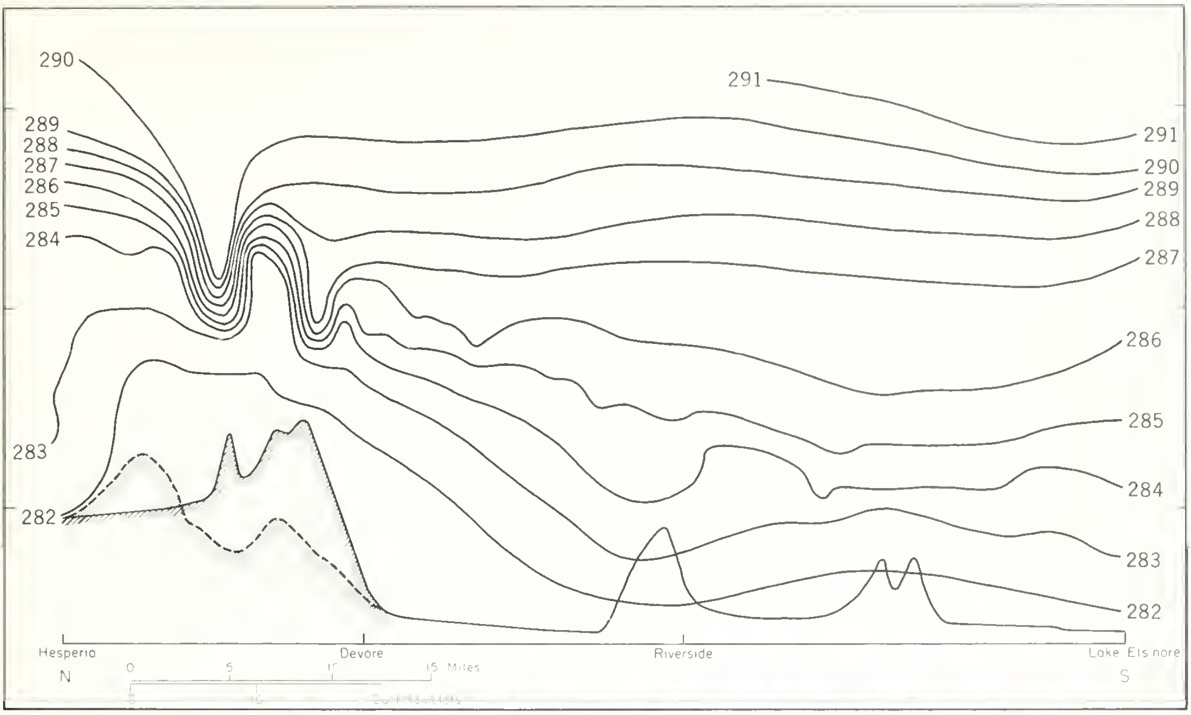


Figure 3.—*North-south potential temperature cross section. Hesperia to Elsinore 2159 P. s. t. to 2303 P. s. t., 11 December 1963. Short waves are dominant at this scale, the long wave is indicated by general downslope of isentropes to the lee of the mountains. Dotted terrain is through Cajon Pass. Hashed terrain is along flight path of aircraft 2 to 3 km. east of Cajon Pass.*

maximum intensity only for a short time, then dissipated in a near normal manner.

The detailed local features of the Santa Ana are best seen in the surface analysis of streamlines and the vertical cross sections of potential temperature. Several overwhelming features are clearly evident in the vertical cross sections (fig. 3). The first, and perhaps single most important feature of the Santa Ana, is the lee wave train set up downward from the mountains. The wave train sloped downward on a much longer wave, with apparently few or no wave lengths between the small waves set up by individual ridges and the large wave set up by the mountain range.

The outflow of the Santa Ana both in the mountains and on the plains appeared to be influenced most by the long waves (figs. 4–9). The term outflow, in general, refers to the easterly offshore flow observed in and immediately above the planetary boundary layer during a Santa Ana. Particular features, such as strong winds, foehn islands, eddies, etc., are not identified in detail by the term. The usefulness of this "outflow" concept comes from the fact that the driving force of the Santa Ana is in the free atmosphere rather than in the planetary boundary layer. The variability of the outflow in the mountains depended on the characteristics of both the long wave and the short waves. However, the outflow on the plain seemed to be nearly independent of the short waves. The Santa Ana outflow showed a strong dependence on local topographic features. The predominant paths of outflow in the mountains were through the major passes (Cajon, Soledad, and—to a secondary degree—San Gorgonio). Winds through the passes were strong (10 to 20 m. sec. $^{-1}$). Near the coast, even such minor obstructions as the Palos Verdes Hills in Los Angeles deflected the outflow (fig. 7).

North of the major range of mountains, the surface flow was southerly (figs. 4–7), suggesting an eddy with a horizontal axis and downward motion along the north slope.

Since true European foehn conditions of high temperature and low humidities were not observed in this case, the definition of foehn islands might be modified in such a way as to emphasize the areas of strong outflow that are observed as isolated cells. From this standpoint, the foehn islands occur primarily on the northern end of the Santa Ana Mountains (figs. 4, 5, 8) and are related primarily to elevation rather than to the lee waves.

The life history of this case showed an initial weak invasion of foehn air to the western portion of Los Angeles, where it was stopped by the sea breeze (fig. 4) at 1900 P.s.t., 10 December 1963. As the foehn became stronger, the sea breeze was rapidly pushed offshore. The offshore push was aided by the nocturnal cooling over the land (figs. 5, 6) throughout the night and morning. Until 1300 P.s.t., 11 December (fig. 9), there was no onshore flow, and the outflow behaved as in the general description given above. At 1300 P.s.t., 11 December 1963 (fig. 9), the sea breeze made a futile attempt to penetrate the coastline at Santa Monica and along the coast opposite the Santa Ana Mountains. By 1600 P.s.t., (fig. 10) the sea breeze had invaded a narrow strip all along the coast, but further offshore the winds were again easterly foehn flow. This feature, along with the moisture content of the onshore flow of 4 to 6 gm./kg. mixing ratio (compared to 1–3 gm./kg. in the unmodified foehn air) suggests that this is not a true sea breeze (when the normal moisture content is of the order of 10 gm./kg.), but foehn air that has had only a short trajectory over the sea. This return flow is probably from an eddy with a horizontal axis. In contrast, at 0100 P.s.t., 12 December 1963 (fig. 11), an eddy with a vertical axis was responsible for onshore flow. Since a sea breeze is not expected at this time of night, the flow is exclusively returning foehn flow. The onshore flow during the daytime is undoubtedly aided by the surface heating over the land. The decaying stages of the Santa Ana, from 0100 P.s.t., 12 December 1963 on (figs. 11, 12) showed a gradual weakening of offshore flow. Subsequently flow returned to normal.

The temperature field associated with the Santa Ana was dominated by descending air and adiabatic warming. This characteristic was evidenced by weak temperature and potential temperature gradients at the surface. Surface heating played a minor role—indicated by relatively small diurnal surface temperature changes during the Santa Ana period.

The mesoscale charts and cross sections indicate a strong tie between the local features and the synoptic features. Each set of meso maps showed a smooth transition from the large scale flow pattern observed at 500 and 700 mb. to the local outflow patterns observed in the detailed surface maps. The transition first became noticeable at 750 mb. when the mountains began to deflect the flow around their flanks and set up a mesoscale eddy on the leeward side (fig. 13). The eddy tilted out to sea and was apparently associated with a lee trough set up from the conservation of absolute vorticity. At 900 and 950 mb. (figs. 14, 15) the flow was similar to the surface flow in the Los Angeles Basin. One of the striking features of the transition layer is an apparent conversion of potential energy to kinetic energy immediately downwind of the San Gabriel Mountains. As the wind at ridge top level veered to the northeast, the transition layer dropped to near 800 mb. and the lee eddy became less pronounced (fig. 16). The major change in the trough appeared to be in the winds rather than the thermal field.

The dissipation stage of the Santa Ana appeared to have less coupling through the meso field than the forming and mature stages. The dissipation apparently resulted from a decreased pressure gradient brought on by the eastward migration of the synoptic features.

Isentropic analysis of the mesoscale features showed the interaction clearly. The airflow in the Santa Ana is nearly isentropic. At the transition level (fig. 17) (290A surface) the influence of the mountains was particularly noticeable. The airflow upstream closely followed that observed on constant pressure analysis. The flow was strongly deflected by the mountain barrier—a trough in the isentropic surface formed upstream, and a ridge formed to the lee of the mountain range. (Although the analysis on the isentropic surface is in terms of pressure, we refer to ridges and troughs in terms of height rather than pressure so as to be consistent with the terminology used on vertical cross sections of potential temperature.) A lower isentropic surface would show a ridge over the mountain range and a broad trough to the lee side because of the vertical shrinking of the air layer over the mountains and vertical stretching on the lee side (Haltiner and Martin p. 357, 1957).

As the Santa Ana approached dissipation stage the lee ridge became less pronounced (fig. 18). This change was reflected in the boundary layer outflow which also gradually weakened.

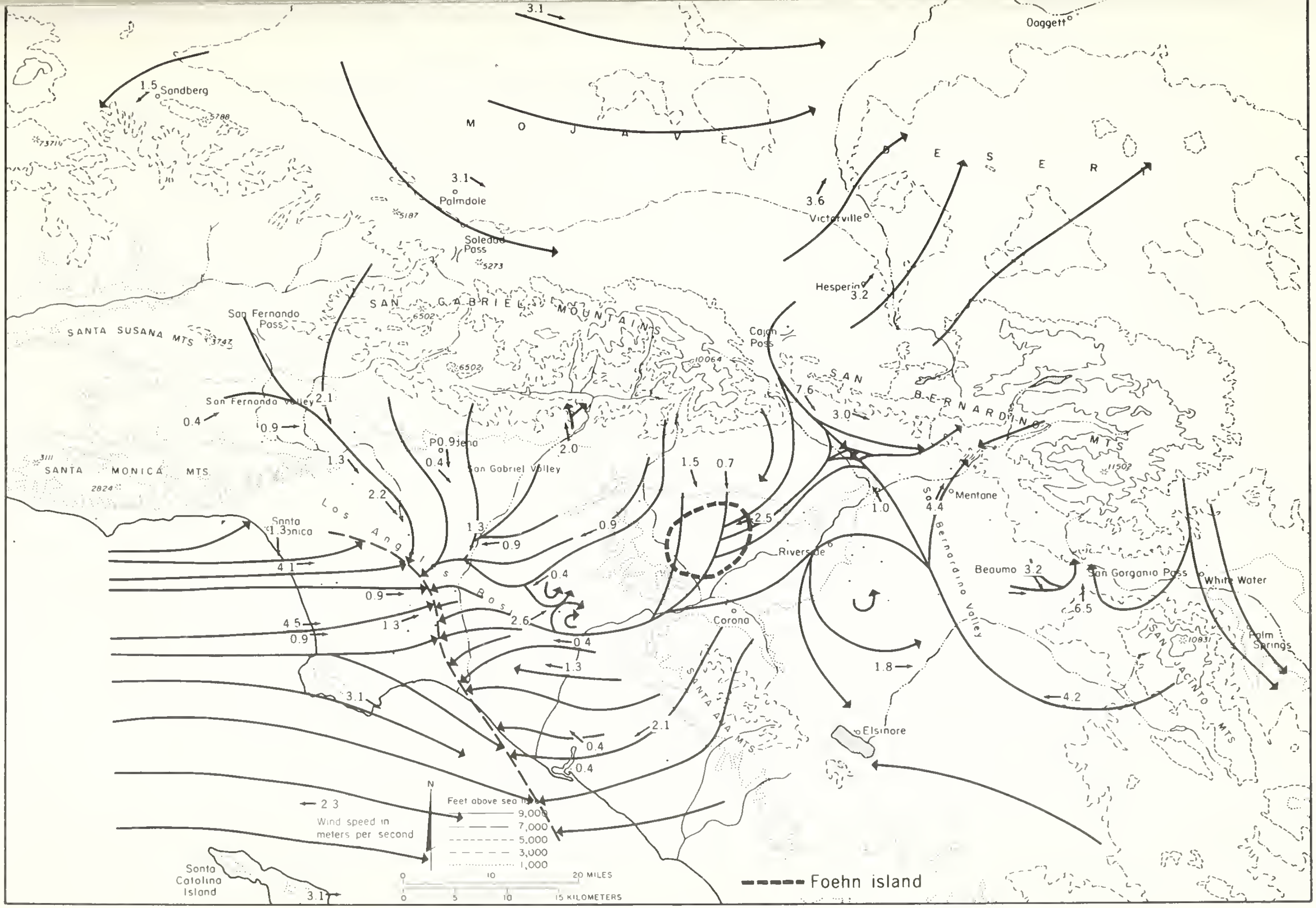


Figure 4.—*Surface streamlines 1900 P. s. t., 10 December 1963. Weak foehn flow is interacting with sea breeze.*

Figure 5.—*Surface streamlines 2200 P. s. t., 10 December 1963. Santa Ana is assisted by land breeze.*

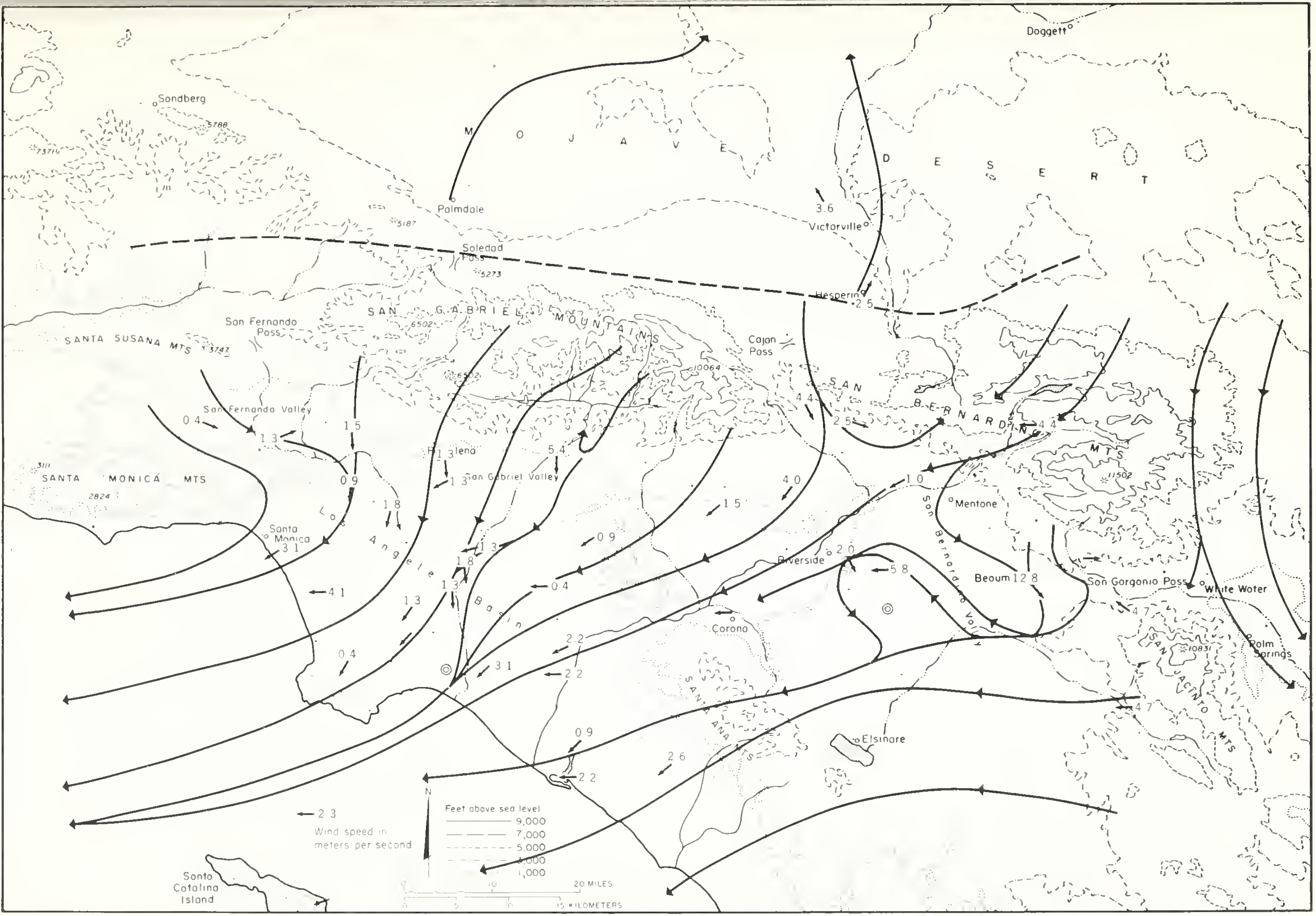


Figure 6.—*Surface streamlines 0100 P. s. t., 11 December 1963, showing general pattern of mature Santa Ana flow. Strongest outflow winds are through the passes. Strong winds may also occur near mountain peaks.*

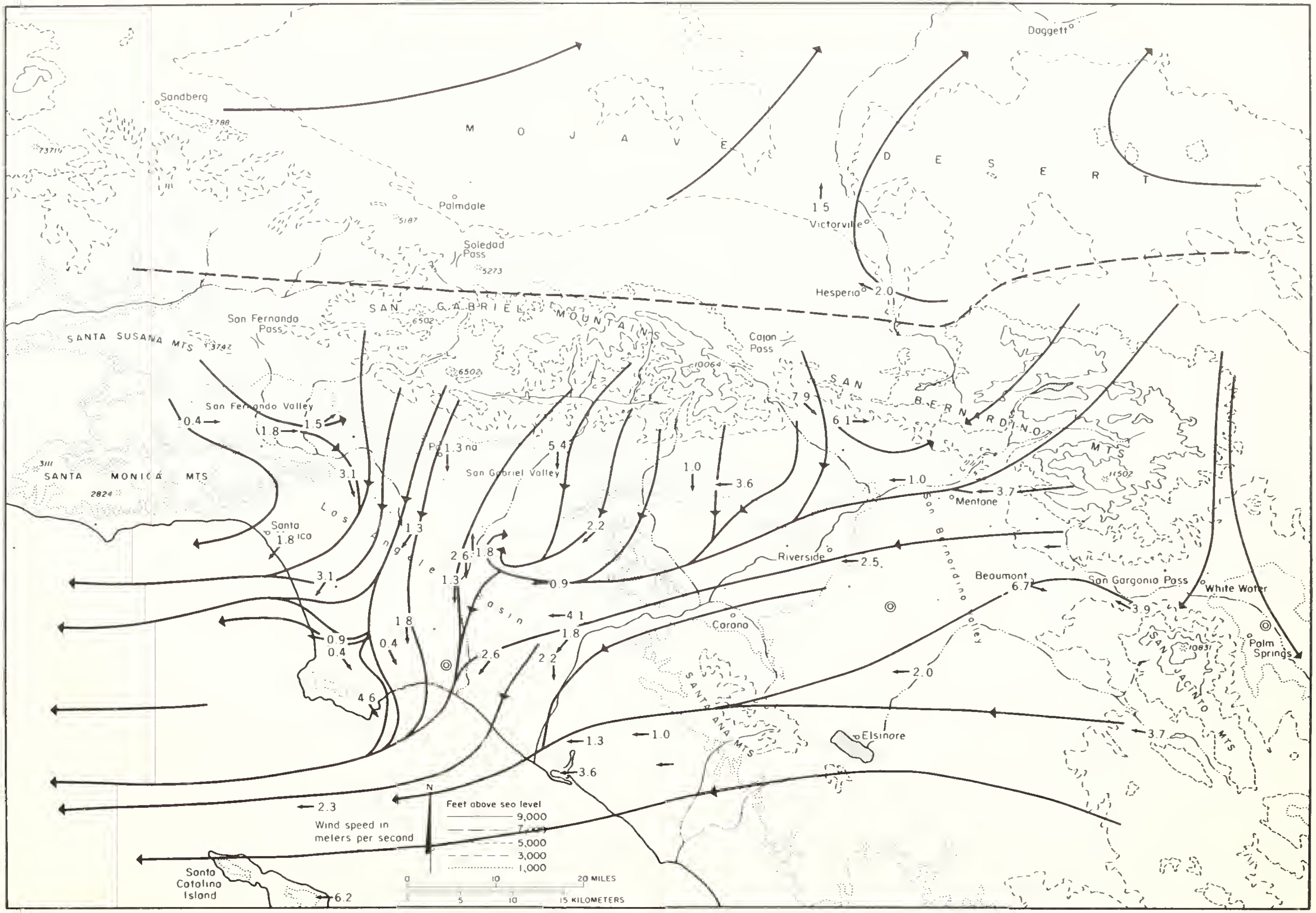


Figure 7.—*Surface streamlines 0700 P. s. t., 11 December 1963. Flow is deflected by Palos Verdes Hills.*

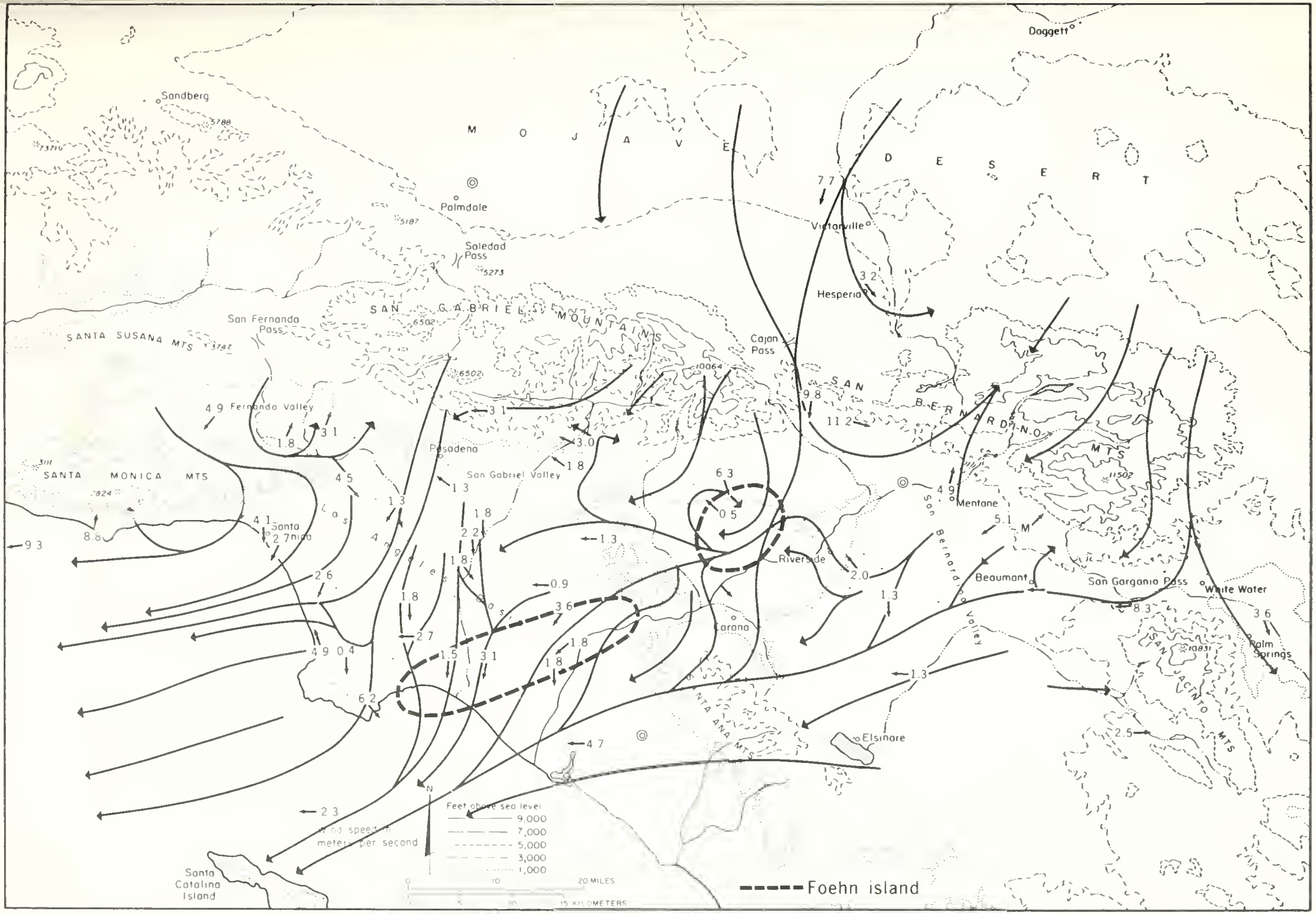


Figure 8.—*Surface streamlines 1000 P. s. t., 11 December 1963. Note foehn island on northern end of Santa Ana Mountains.*

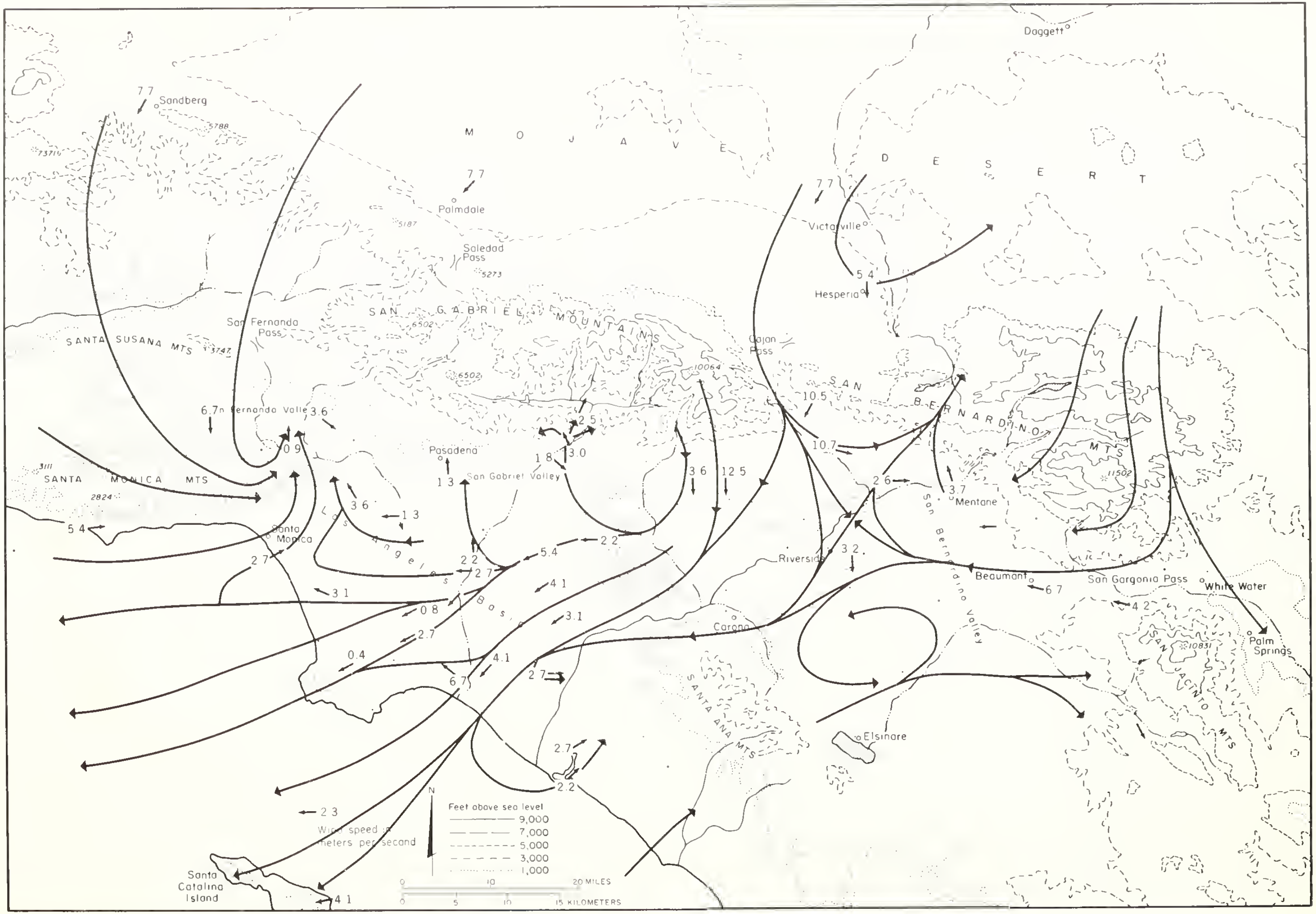


Figure 9.—*Surface streamlines 1300 P. s. t., 11 December 1963, showing beginning of delayed sea breeze along coast.*

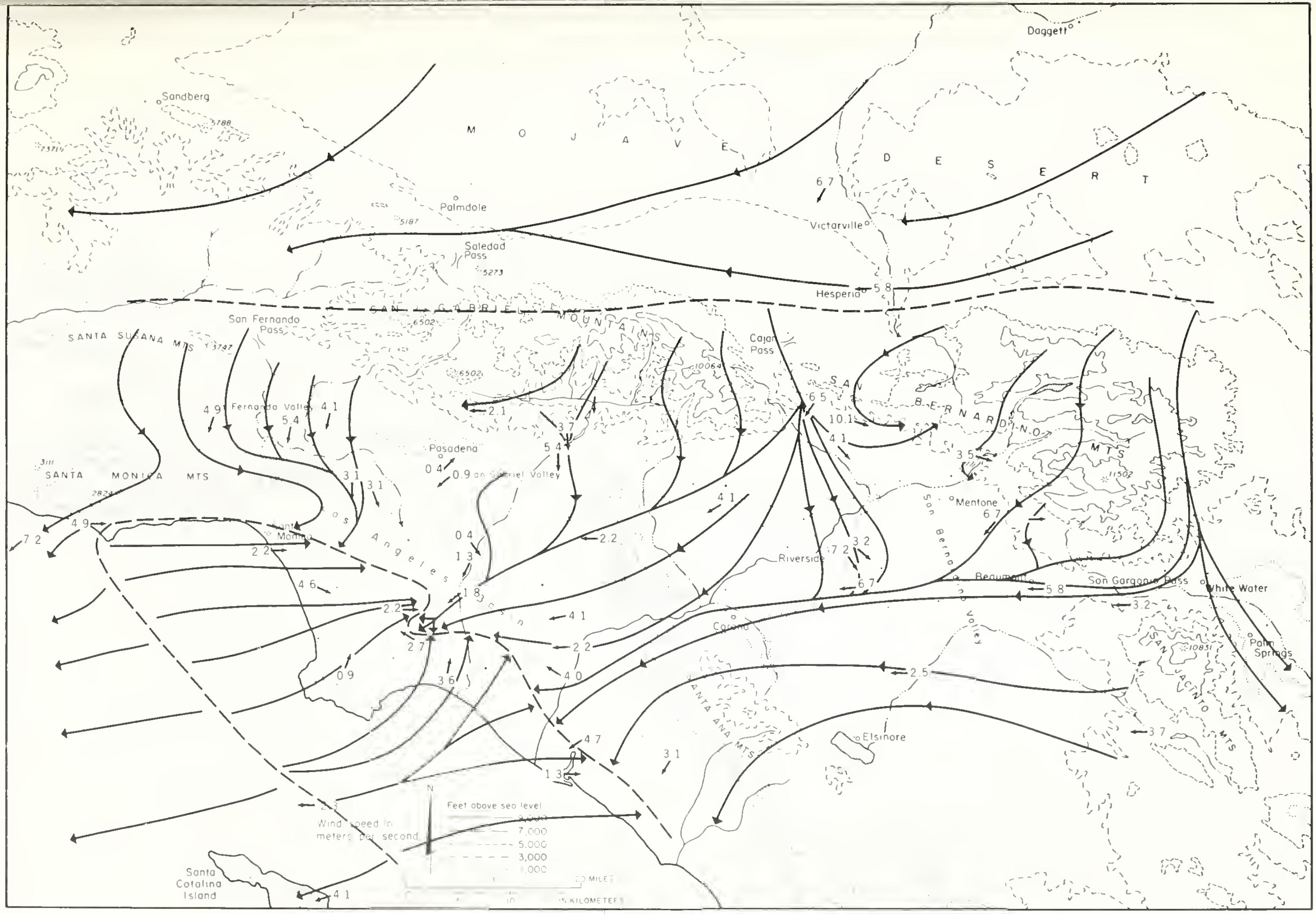


Figure 10.—*Surface streamlines 1600 P. s. t., 11 December 1963, showing extent of sea breeze penetration. Note easterly flow further offshore.*

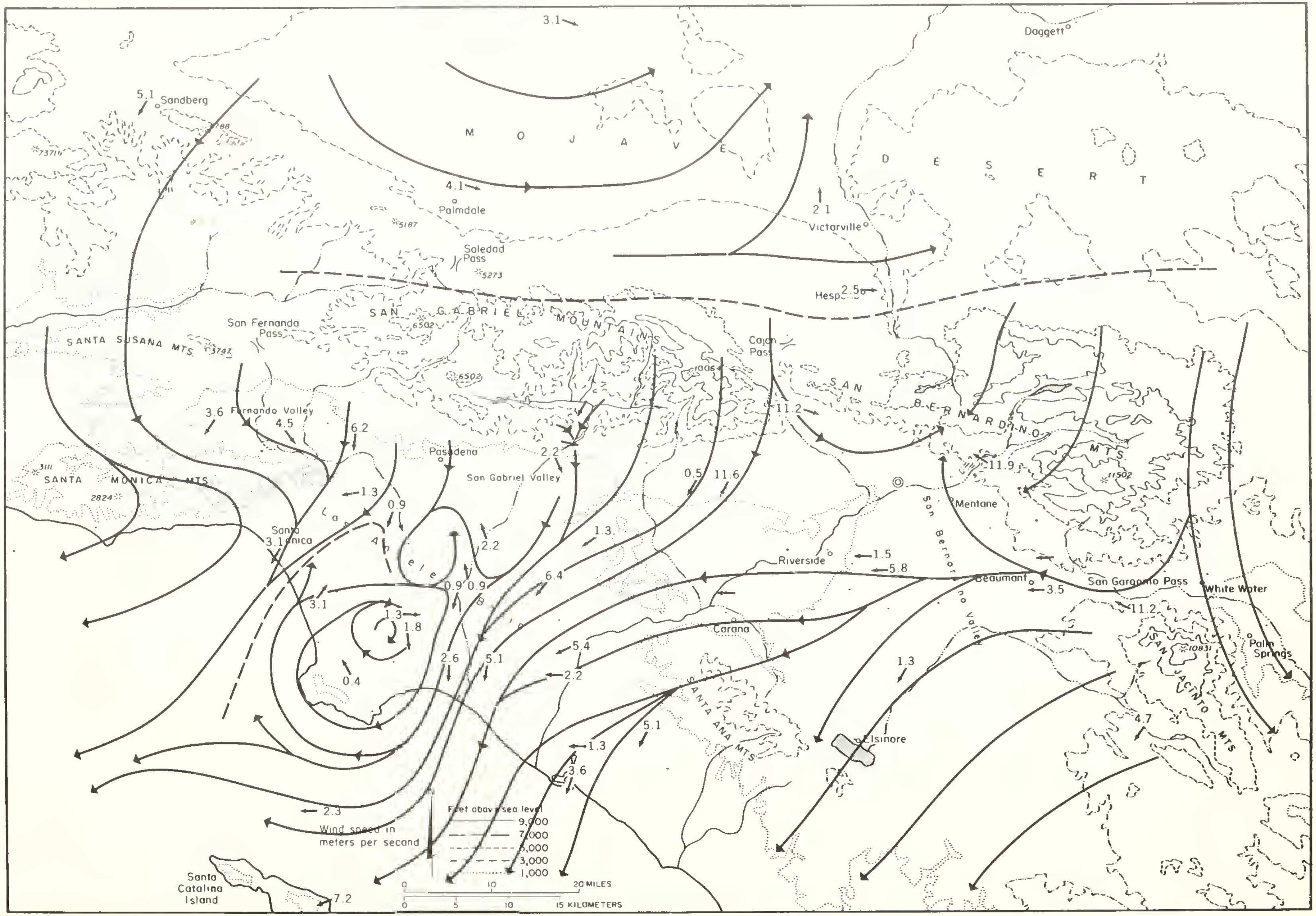


Figure 11.—*Surface streamlines 0100 P. s. t., 12 December 1963. Note onshore flow from eddy.*

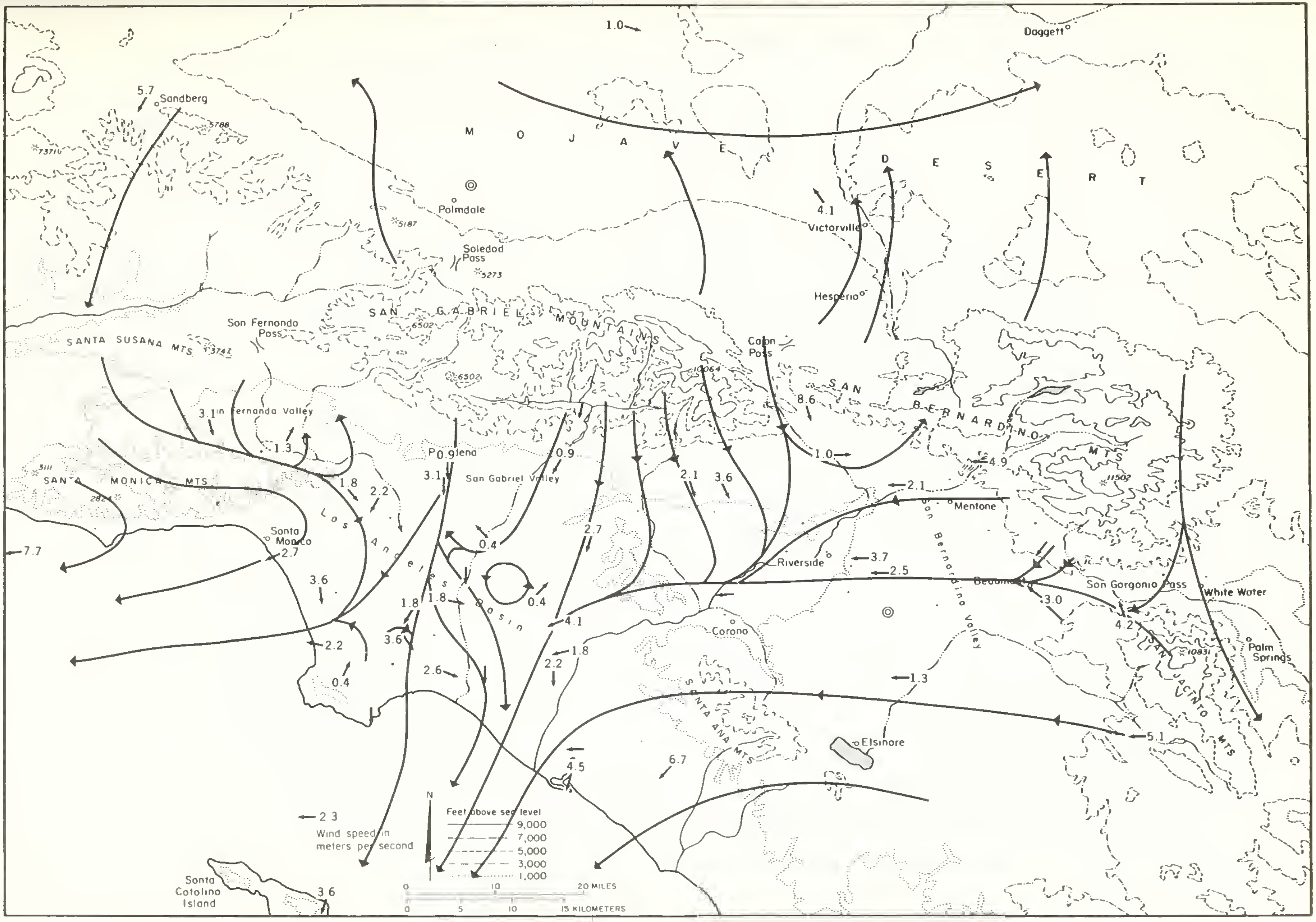


Figure 12.—*Surface streamlines 0700 P. s. t., 12 December 1963, showing decaying stage of Santa Ana.*

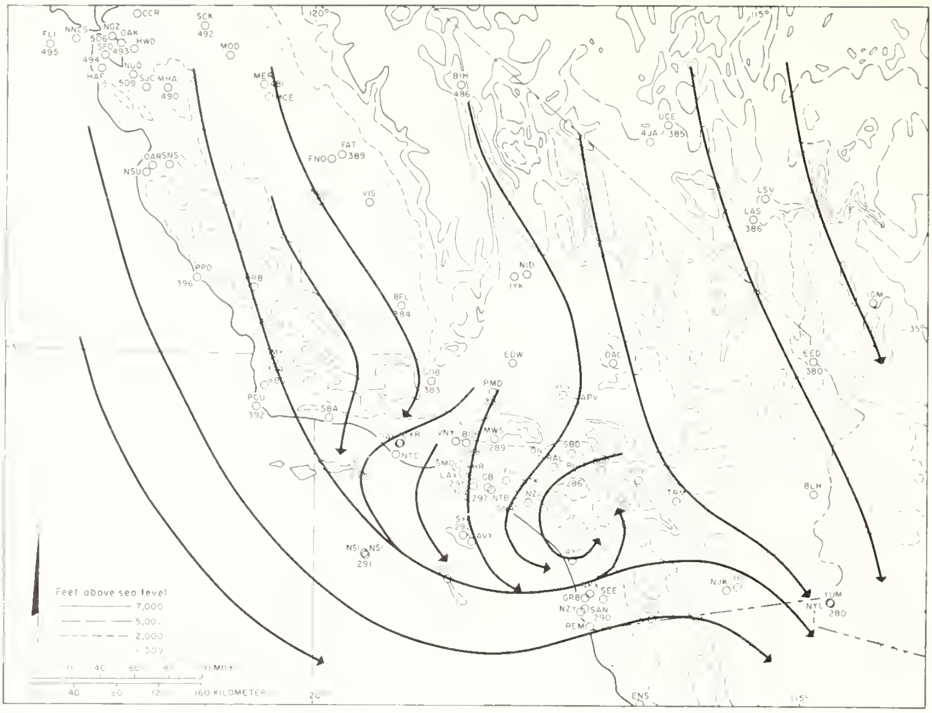


Figure 13.—*750 mb. streamlines 0400 P. s. t., 11 December 1963. Beginning of transition layer between local outflow and synoptic flow. Lee trough is pronounced.*

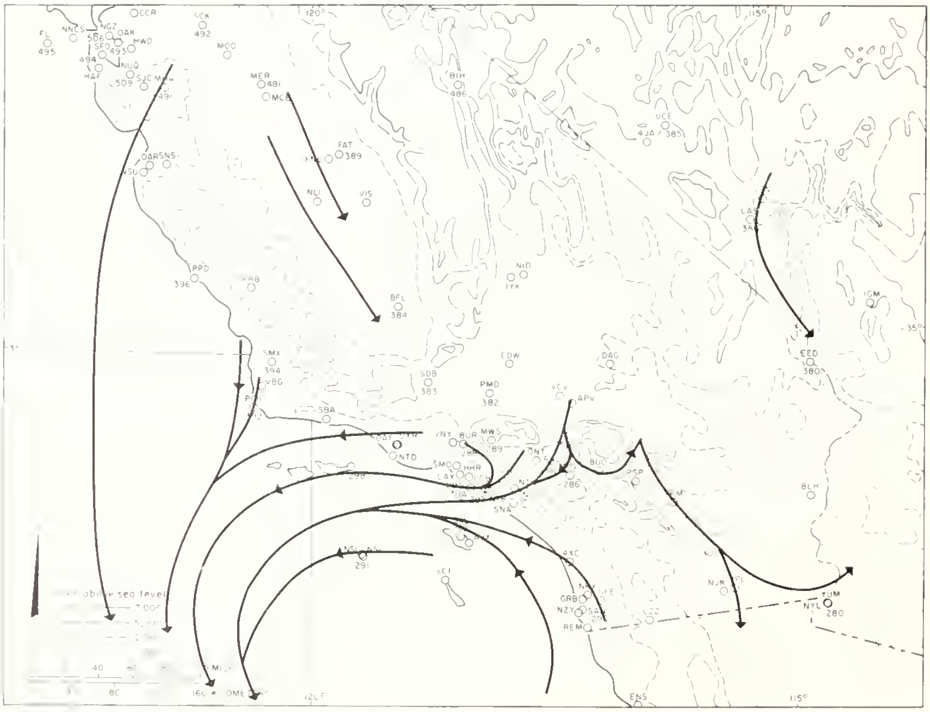


Figure 14.—*900 mb. streamlines 0400 P. s. t., 11 December 1963. This is the mid-level of planetary boundary layer and has appearance of smooth surface map.*

Figure 15.—*950 mb. streamlines 0400 P. s. t., 11 December 1963. Flow approximates that observed at the surface.*

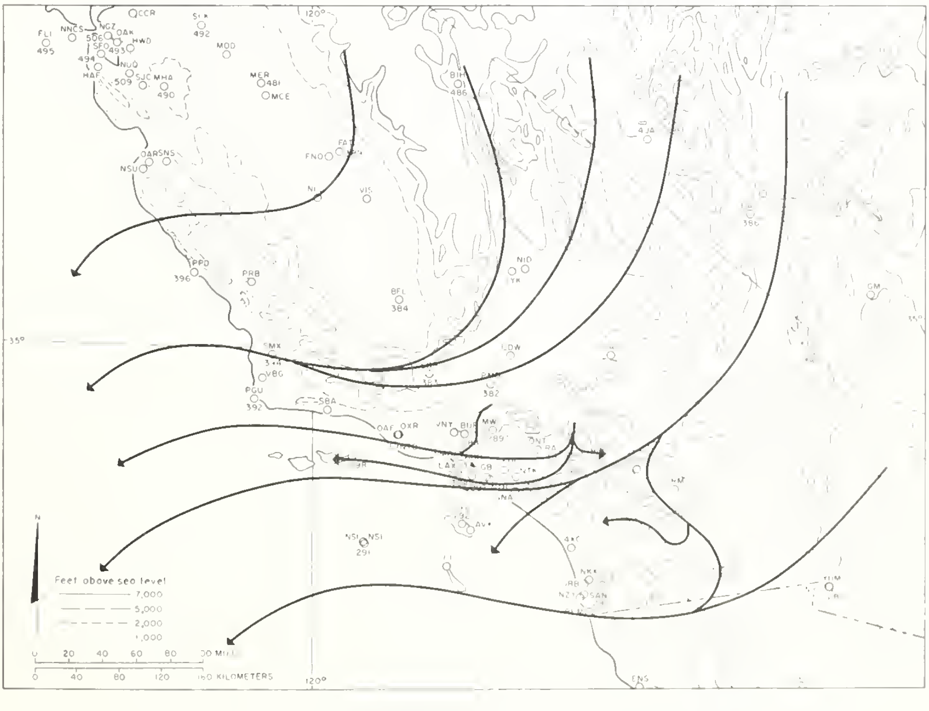


Figure 16.—*800 mb. streamlines 1000 P. s. t., 11 December 1963. The transition layer has lowered as gradient wind veered to northeast.*

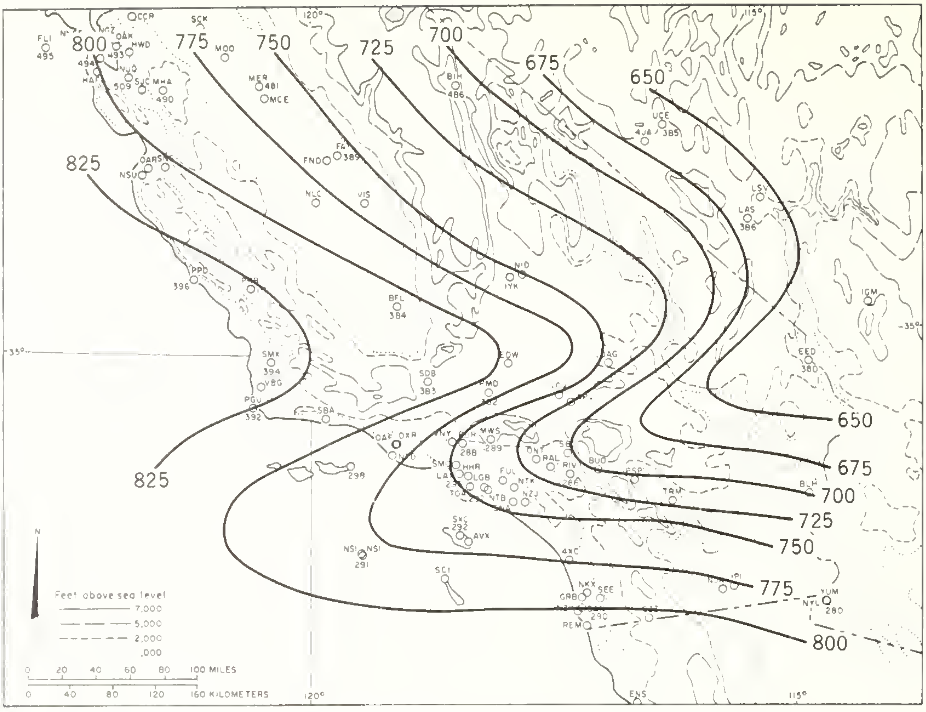


Figure 17.—*290A isentropic surface 0400 P. s. t., 11 December 1963. Flow is isentropic.*

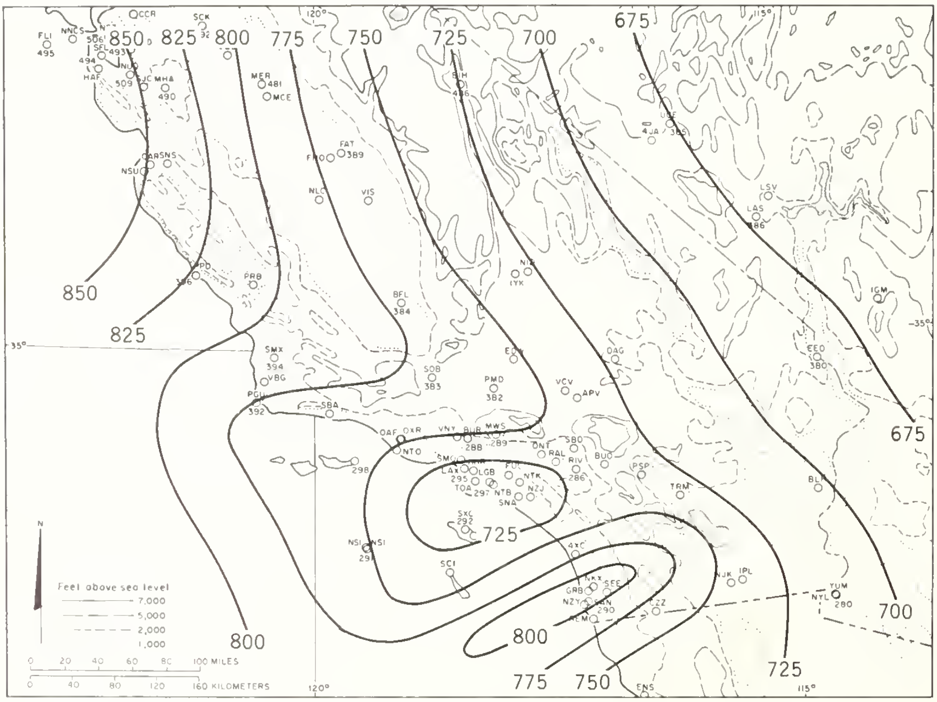


Figure 18.—*290A isentropic surface 1600 P. s. t., 11 December 1963. This is the dissipating stage of the Santa Ana.*

Case of 7-9 January 1964

The synoptic development of this case was similar to the December case. An anticyclone moved southward from northwest Canada into the Great Basin late on 7 January 1964 (fig. 19). A trough associated with a weak front extended along the coast (fig. 19) so that the pressure gradient was 1.4 x 10^{-2} mb./km. The Great Basin anticyclone remained quasi-stationary during the Santa Ana. From 700 mb. up, a small amplitude trough began to deepen so that the winds veered to near north at 700 mb. (fig. 20) and north-northwest from 500 mb. up at 1600 P.s.t., 7 January 1964 (fig. 19). As in the December case the winds increased as height increased, and the static stability was negative so that l^2 decreased above 700 mb. and the synoptic features indicated conditions favorable for the formation of mountain waves. The dissipation stage was brought on by two factors: (a) The surface front and trough migrated eastward decreasing the surface pressure gradient; and (b) a vigorous short-wave trough caused a small amplitude ridging along the west coast.

The detailed local analysis of this case showed nearly the same features as the December case (figs. 21–24). Cajon, Soledad, and San Gorgonio Passes showed the strongest outflow. The wind shadow in the lee of the San Gabriel Mountains was less noticeable during the early stages, but became pronounced toward the end. As in the December case, the pseudo-sea breeze was delayed until 1300 P.s.t. (fig. 23). The sea breeze penetrated only in the wind shadow and was somewhat stronger than the December case. The local upslope winds on the lee side of the San Gabriels assisted in this invasion of onshore winds (fig.

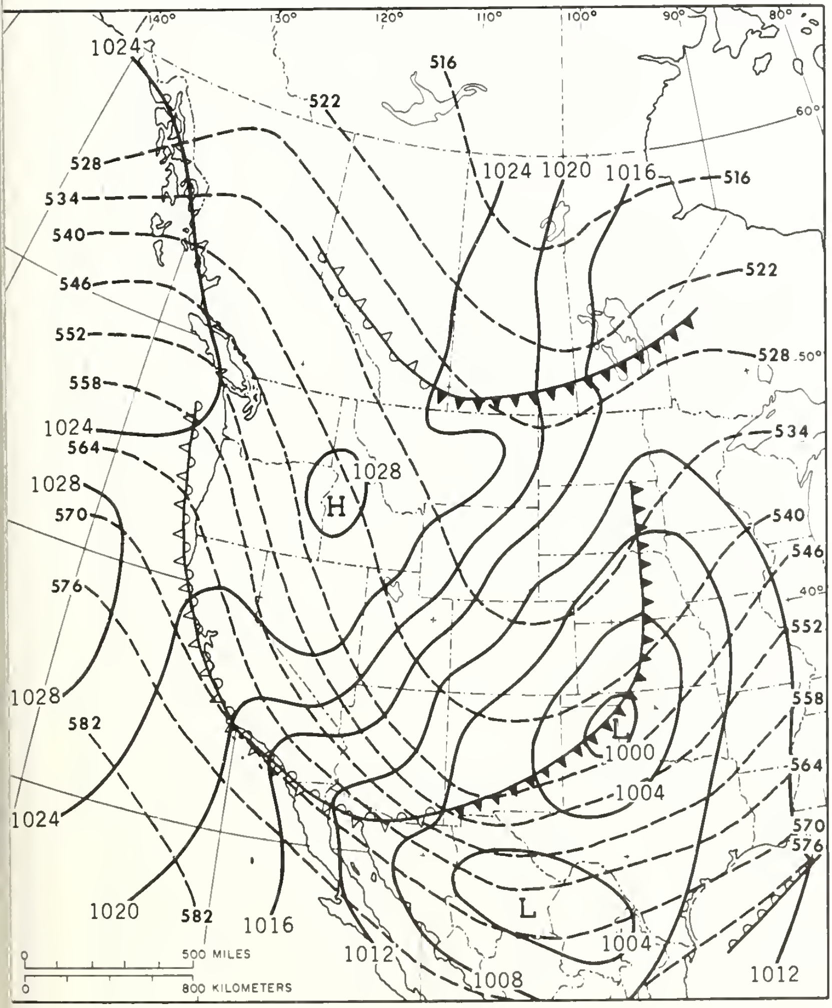


Figure 19. — *NMC analysis of 2200 P. s. t., 7 January 1964 surface features and 1600 P. s. t., 7 January 500 mb. synoptic features. Dashed lines are 500 mb. contours, solid lines are surface isobars.*

24). The outflow over the plain was about the same strength, but contained many more transient eddies from deflection around small obstacles and from convergence of different airstreams.

The local vertical cross section of wind and potential temperature illustrates the series of short waves downstream from the mountains and the long single wave of the lee trough (fig. 25). The importance of these two dominant wave lengths cannot be overemphasized. The short waves tended to behave as linear solutions; the long wave was produced by the conservation of potential vorticity. Again, as in the December case, the mesoscale analysis of constant pressure charts showed the tie between the synoptic features and the local outflow. The lee trough over the Los Angeles Basin was less pronounced in this case than during the December case (figs. 26–29). The mesoscale vertical cross section also showed the gradual weakening of this lee trough. The vertical displacement of the foehn air was on the order of 3 km. at the lower levels (below 700 mb.) and about 1.5 km. above that level (fig. 30), verifying the vertical stretching and conservation of potential absolute vorticity to form the mesoscale lee trough.

Since the small scale features and the synoptic scale pattern show a close relationship, this may account for the difference in intensity of Santa Anas. The differences between the two cases are slight, but there was some indication that the January case was somewhat less intense. The transition from large scale smooth flow to the gravity wave outflow was near 750 mb. for the entire case (fig. 26). The smooth transition was more marked, perhaps because the large scale flow was predominantly from the northwest. Only in the low levels was the flow perpendicular to the mountains.

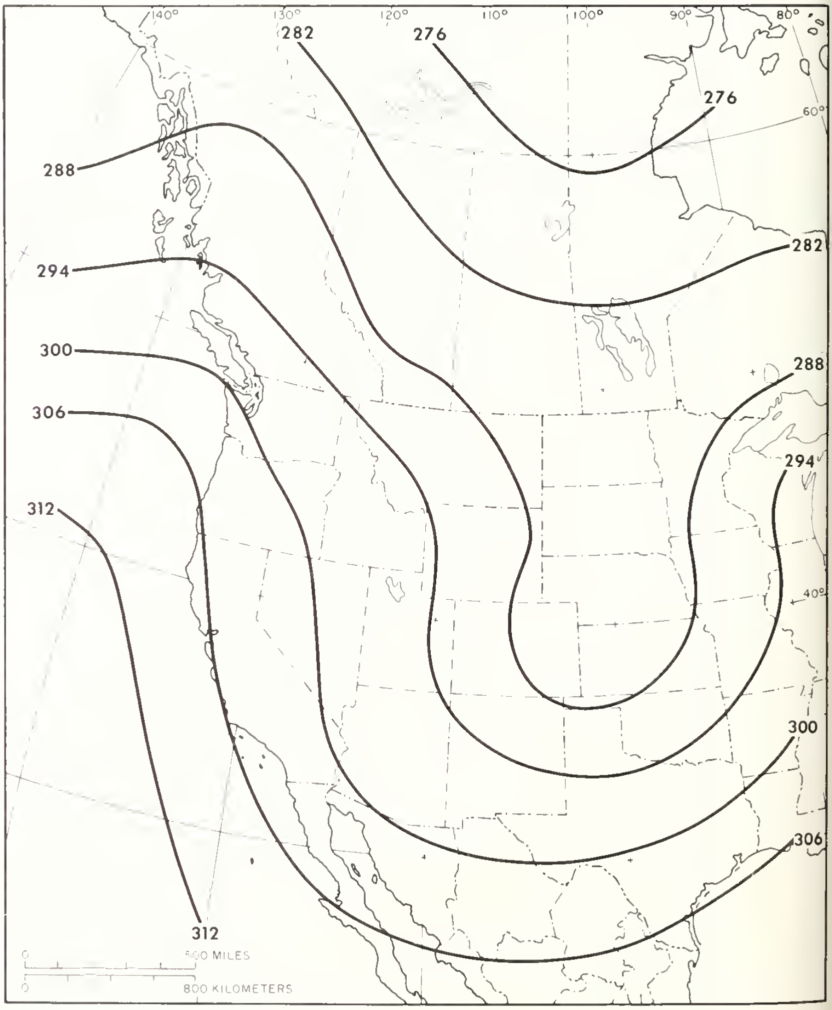


Figure 20.—*NMC analysis, 700 mb. chart for 1600 P. s. t., 7 January 1964, showing the beginning of Santa Ana synoptic conditions.*

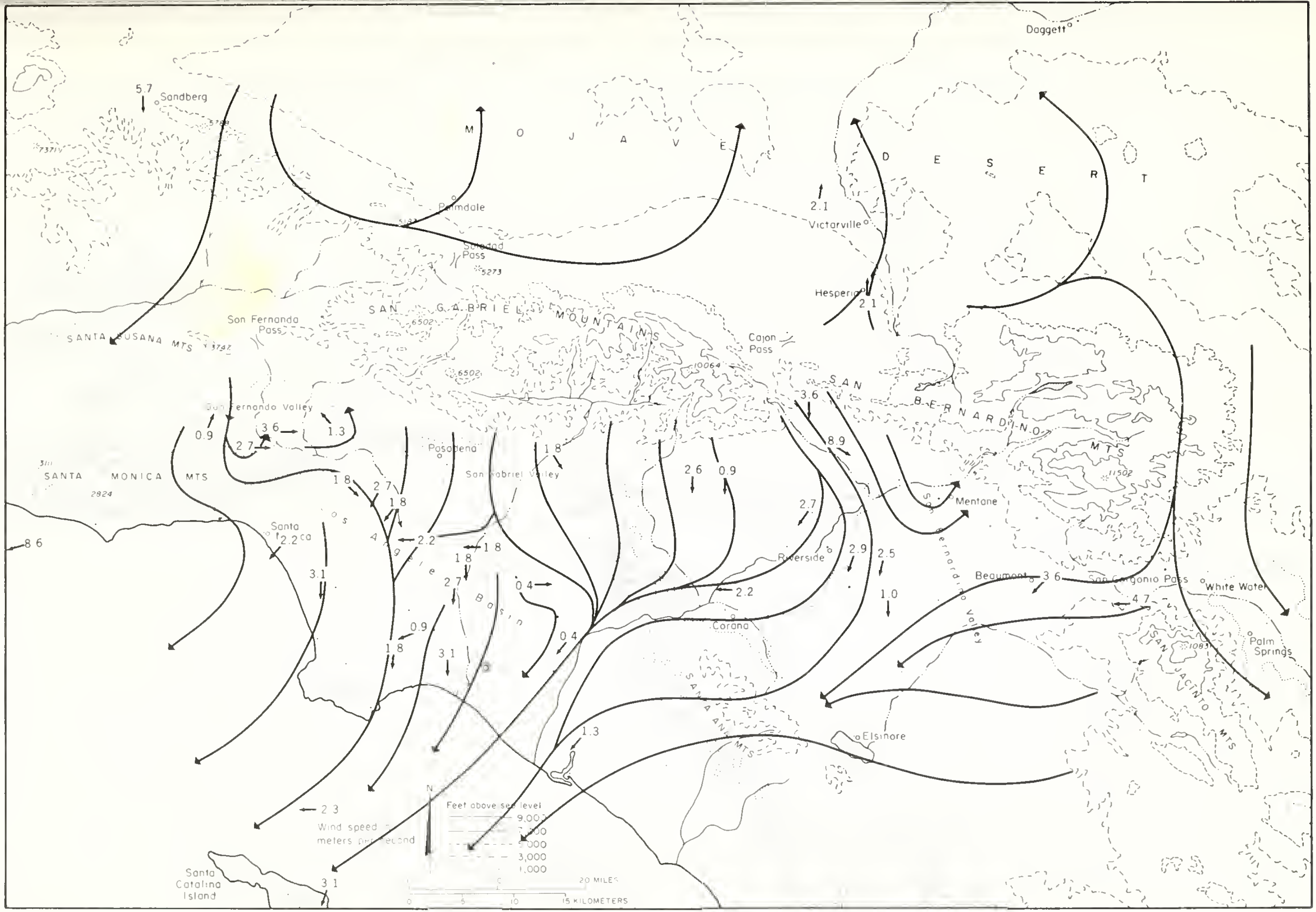


Figure 21.—*Surface streamlines 0100 P. s. t., 8 January 1964. Strongest flow is in the passes as in the December case.*

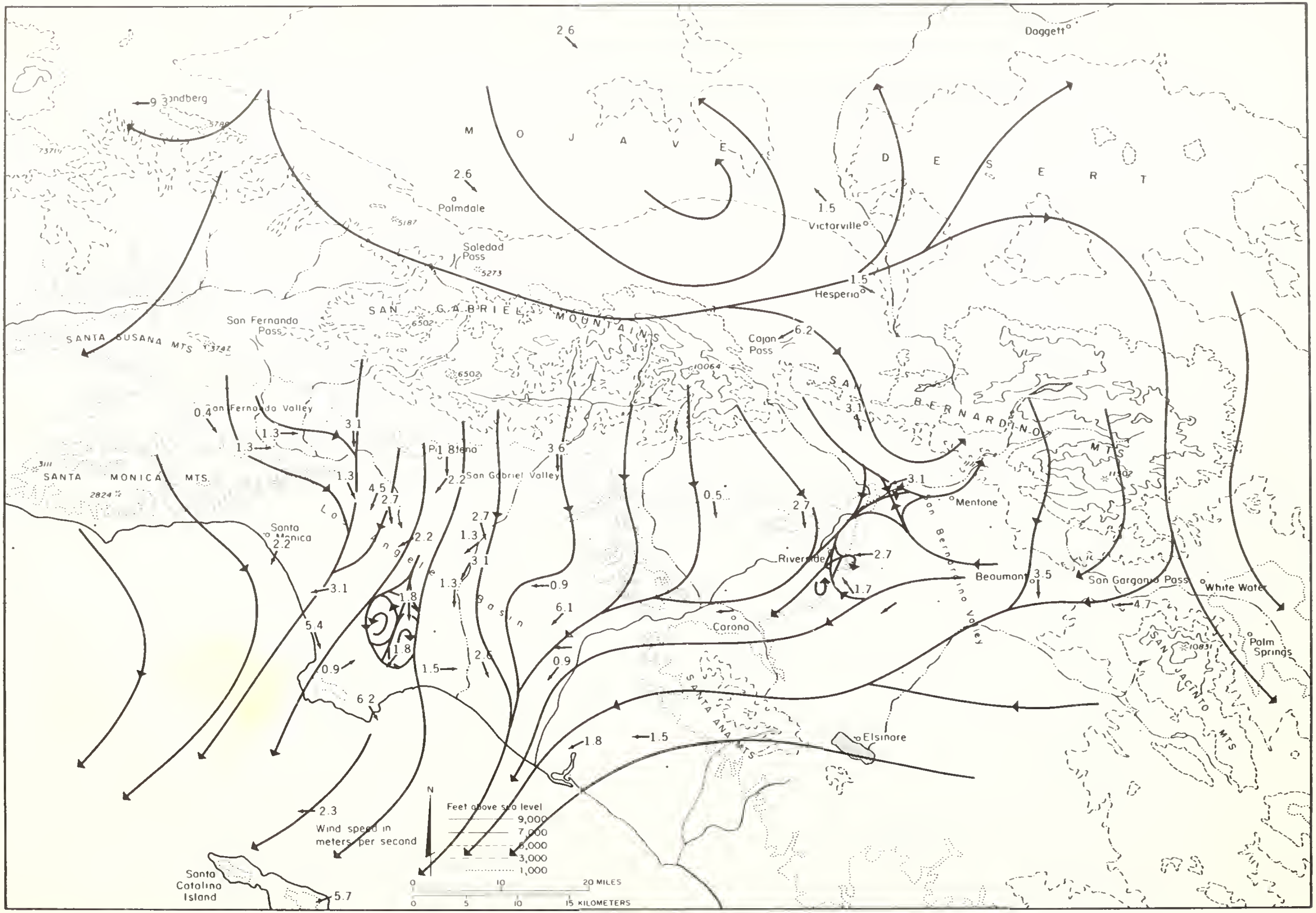


Figure 22.—*Surface streamlines 0700 P.s.t., 8 January 1964. Wind shadow is not pronounced at this time.*

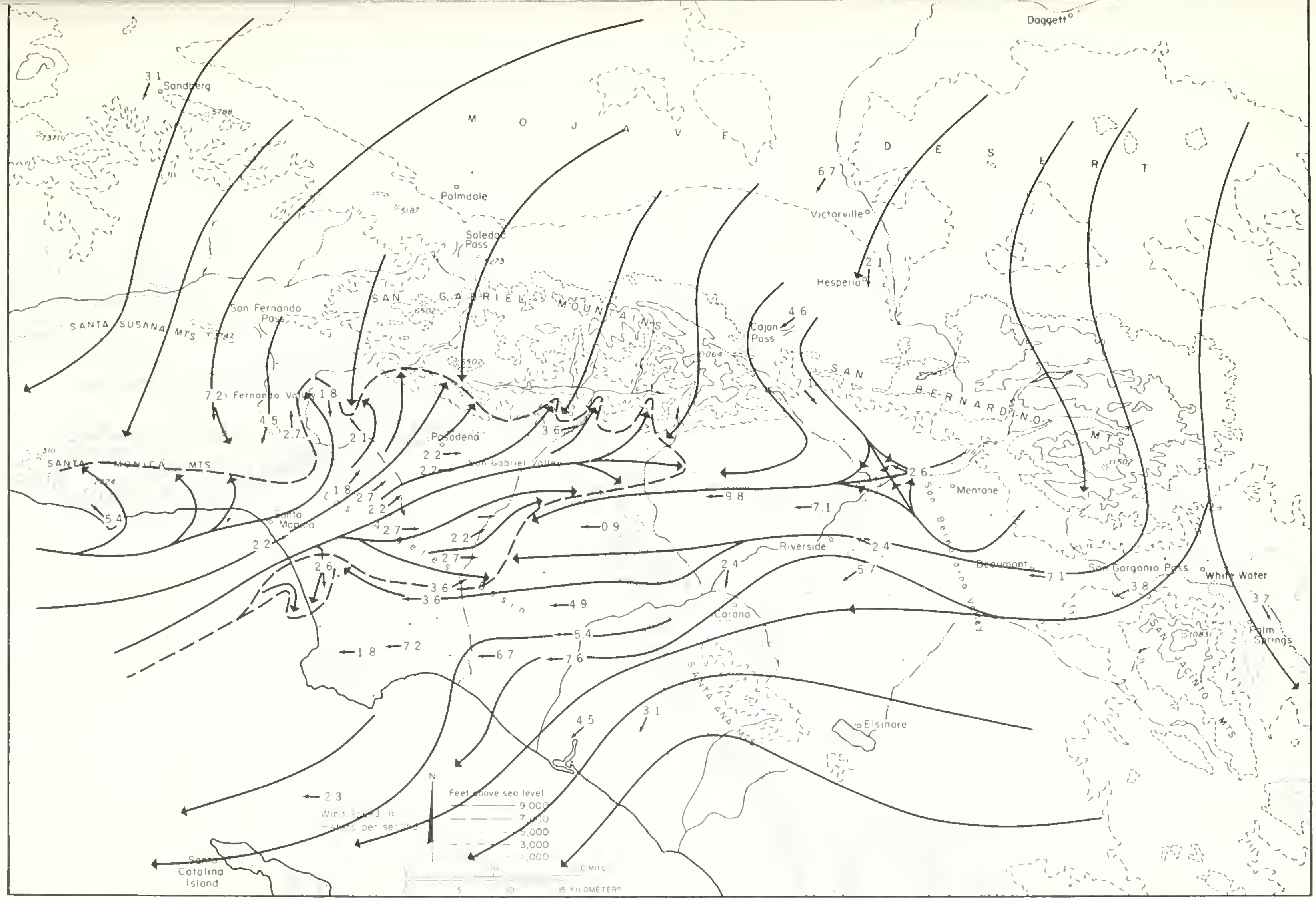


Figure 23.—*Surface streamlines 1300 P. s. t., 8 January 1964, showing the beginning of sea breeze penetration.*

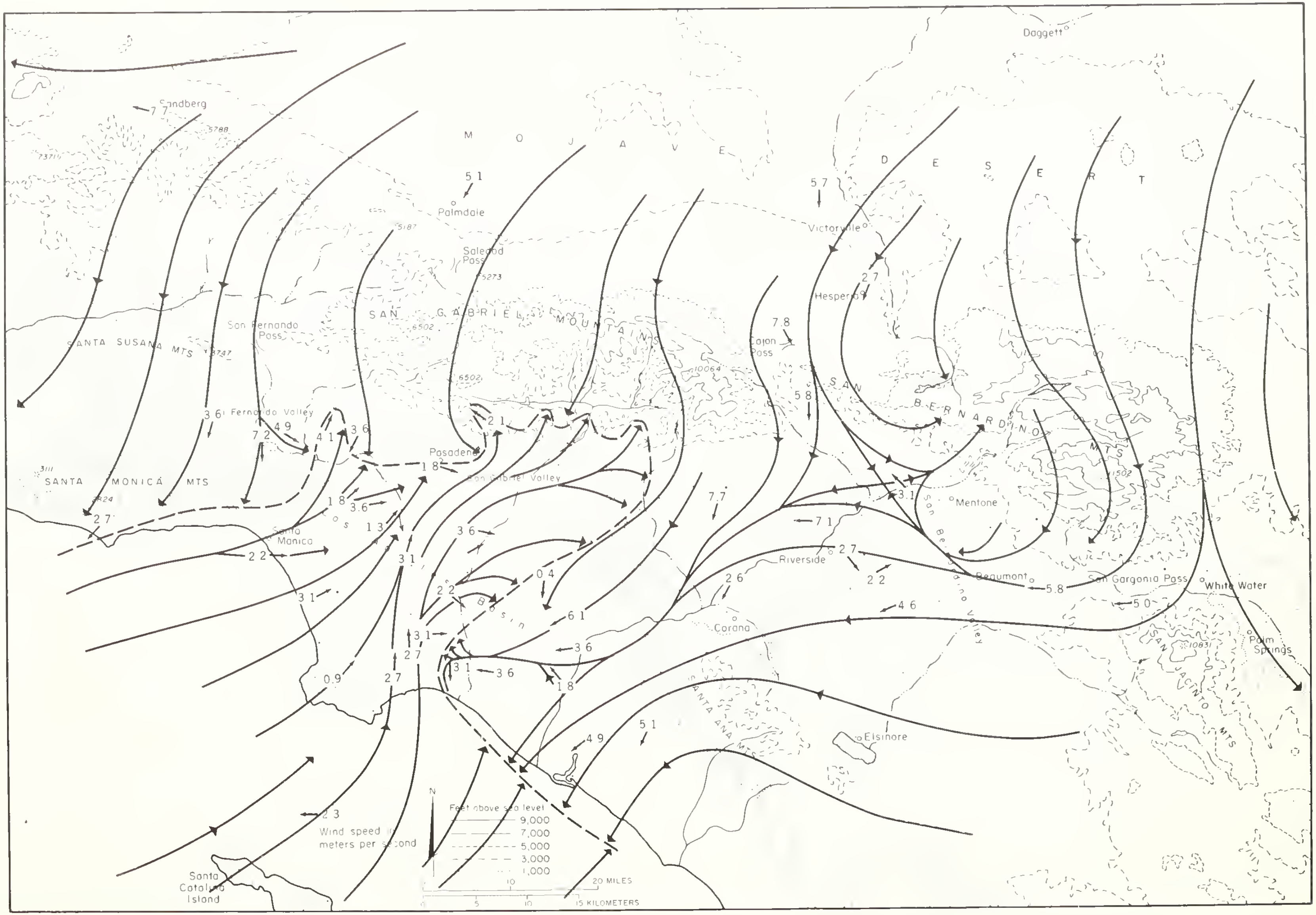


Figure 24.—*Surface streamlines 1600 P. s. t., 8 January 1964. Sea breeze has penetrated only in wind shadow of San Gabriel Mountains. The flow contains numerous small eddies.*

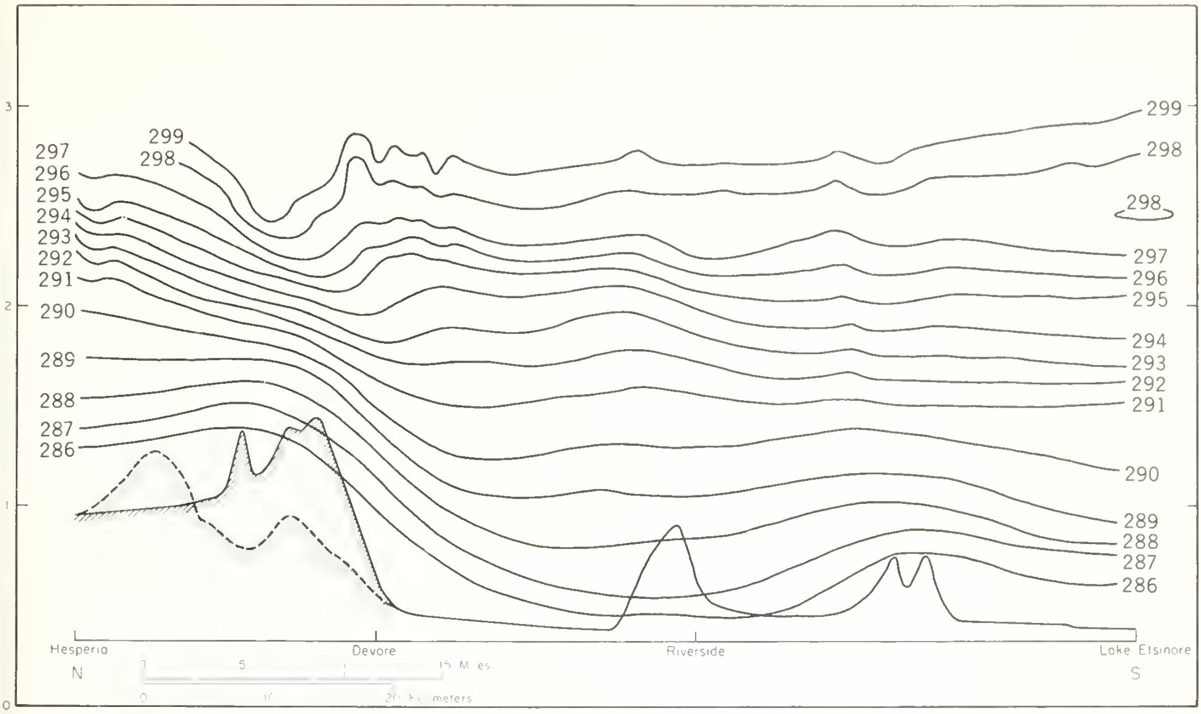


Figure 25.—*Vertical cross section of potential temperature Hesperia to Elsinore, 0420 to 0519 P. s. t., 8 January 1964. Bispectral wave pattern is strongly indicated. Dotted terrain is through Cajon Pass. Hashed terrain is along flight path of aircraft 2 to 3 km. east of Cajon Pass.*

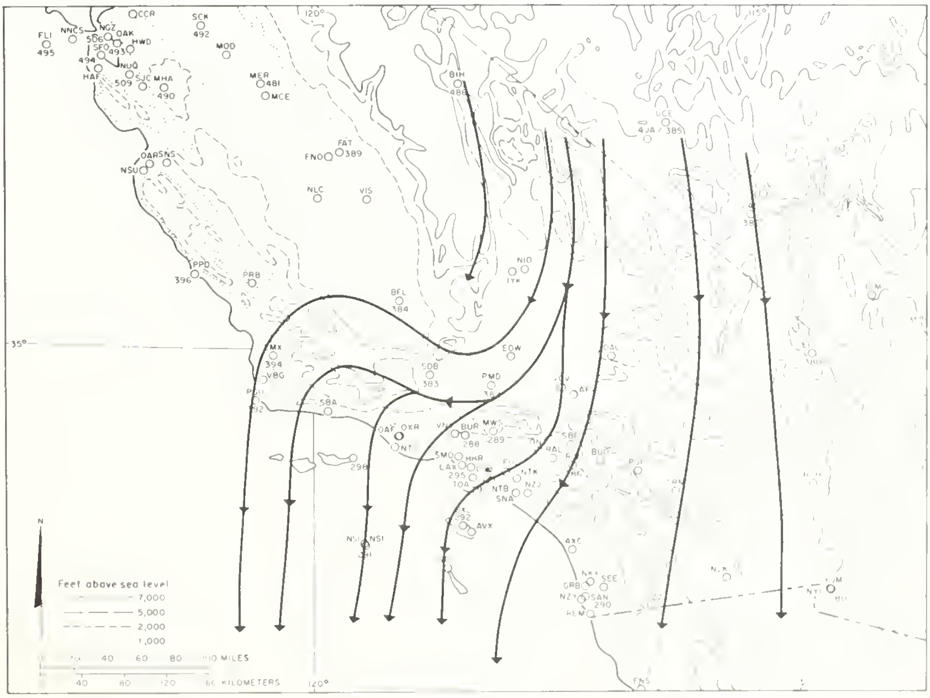


Figure 26.—*750 mb. streamlines 1000 P. s. t., 8 January 1964. This is the top of the transition layer for the entire case. Deflection around flank of mountain is evident. The lee trough is less pronounced than in the December case.*

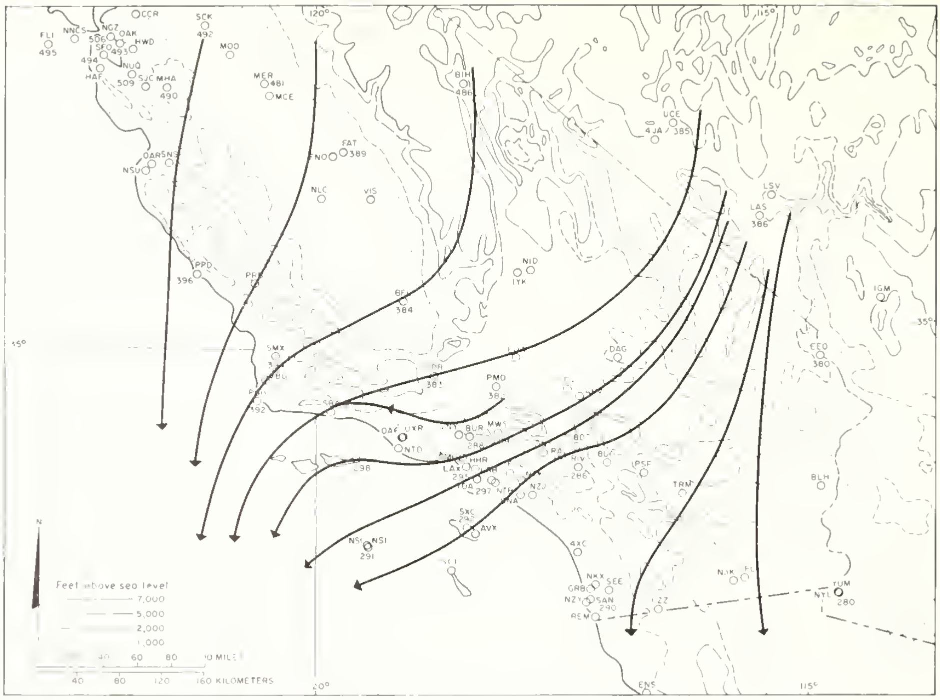


Figure 27.—*850 mb. streamlines 1000 P. s. t., 8 January 1964. There is only a slight hint of the lee trough.*

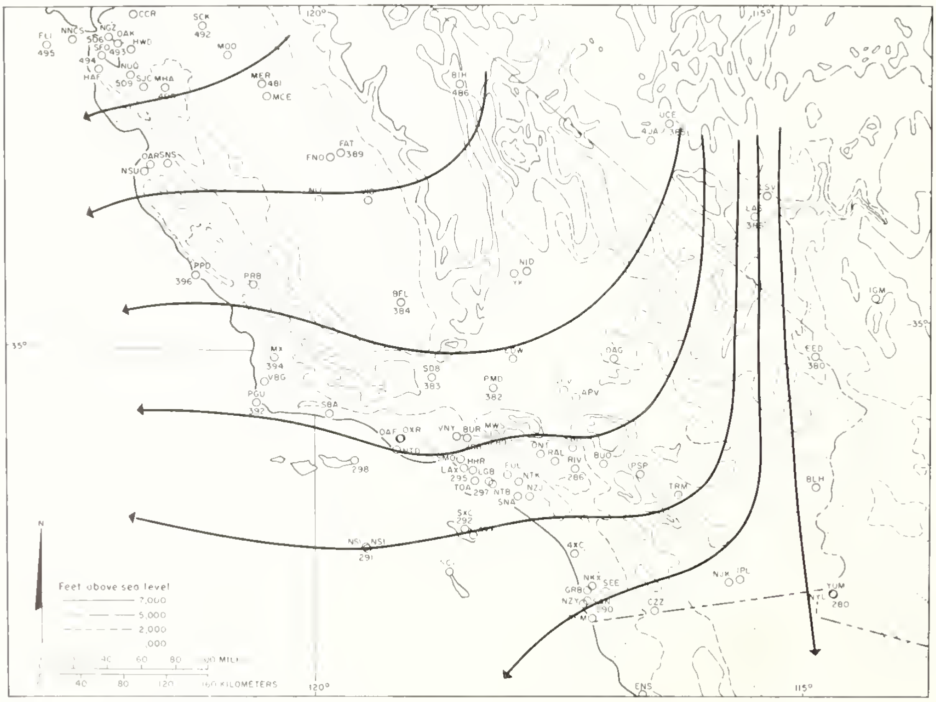


Figure 28.—*900 mb. streamlines 1000 P. s. t., 8 January 1964. Flow at this level approximates that observed at the surface.*

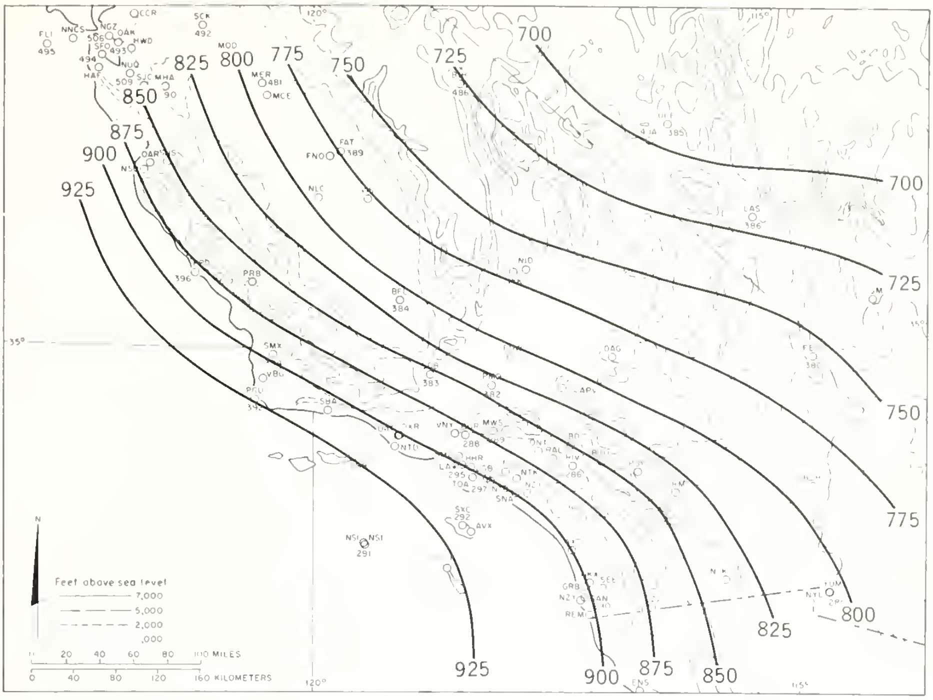


Figure 29.—*290A isentropic surface of 8 January 1964, 1000 P. s .t. Flow is nearly isentropic. Lee trough is not pronounced, supporting surface data to suggest a weak foehn.*

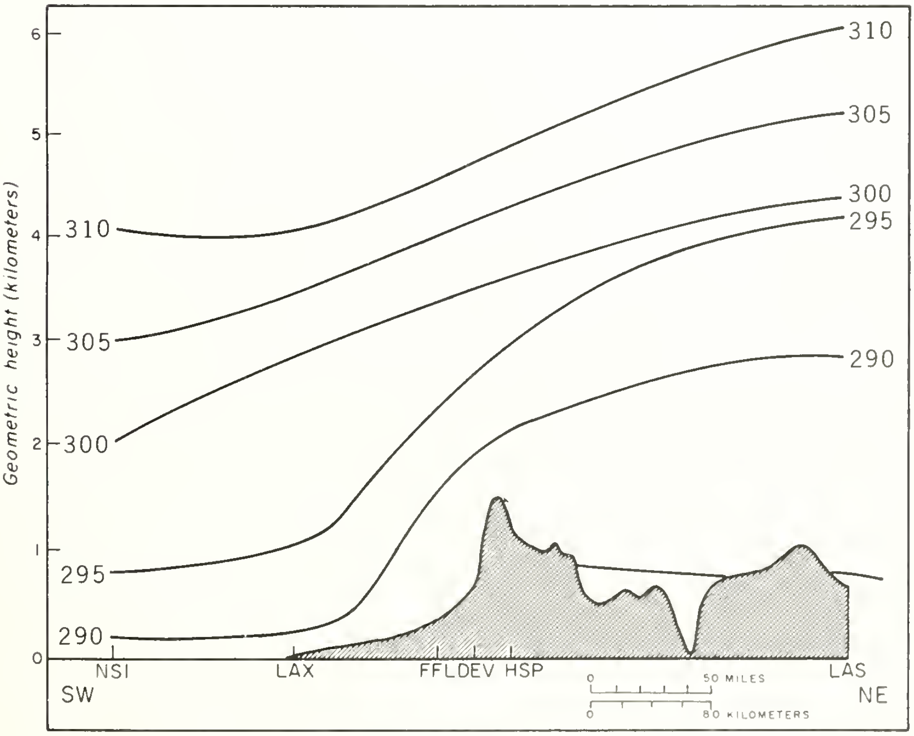


Figure 30.—*Vertical cross section of potential temperature Las Vegas to San Nicolas Island for 7 January 1964, 2200 P. s. t. Lee trough is well illustrated. Short waves have been smoothed out. Major source of outflow air is from the mid and upper troposphere.*

Implications

The simplest and perhaps most useful way to summarize the two case studies is to suggest a schematic structure of the Santa Ana (figs. 31–33). Apart from the synoptic patterns associated with the foehn flow, the most significant features of the Santa Ana are:

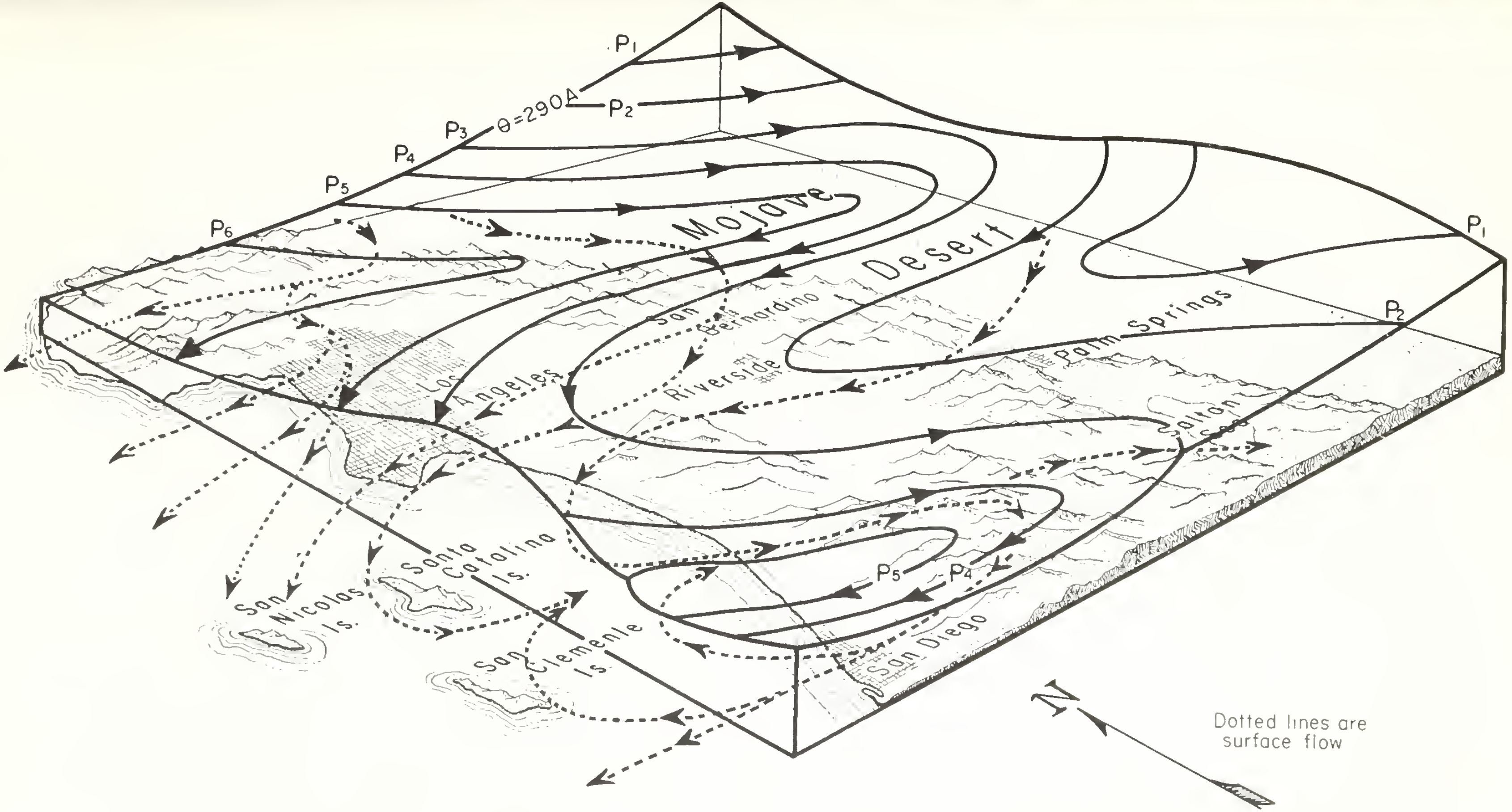
- The flow is nearly isentropic.
- Lee waves are responsible for nearly all of the observable features.
- The strength of the outflow of the Santa Ana appears to be determined by the thermal structure. Strong surface outflow occurs when there are strong quasi-horizontal reinforcing temperature gradients at the meso and synoptic scales.

A consistent and physically meangingful method of presenting the schematic structure is through isentropic analysis.

On an isentropic surface an increase in pressure corresponds to an increase in the Montgomery stream function. Therefore, flow on the surface is "baric" by definition because the pressure force and coriolis force are opposed.

Airflow is baric cyclonic about the cold dome of air in the Great Basin at all levels above the planetary boundary layer (fig. 31). As the flow reaches the San Gabriel Mountains, it is deflected predominantly to the east, but there is some non-isentropic flow to the west, particularly in the planetary boundary layer (fig. 32). The eastward deflection is reflected by a trough in the Lagrangian coordinate system as shown on the 290A and 286A surfaces (figs. 31, 32). Above and immediately downwind of the mountains, a lee ridge is formed by the conservation of absolute vorticity and vertical stretching. The flow in this ridge is isentropic and closely parallels the surface outflow of Santa Ana air. In this lee ridge the air flow is baric cyclonic on the north side as it flows offshore, but becomes baric anticyclonic as the Montgomery stream function turns onshore and forms an eddy between Los Angeles and San Diego. At a higher level—away from the frictional influences—the flow is baric cyclonic in the ridge at all levels. This lee flow is represented in a vertical cross section as a smooth field of potential temperature sloping down toward the coast in the low levels and upward in the higher levels (fig. 33). The major foehn islands are related to this lower mesoscale lee trough. As the outflow air impinges on small topographic obstacles, a foehn island is created. This type of foehn island is observed only in the outflow area over the plain.

Surfacing of the foehn both over the plain and in the mountain areas is determined by the static stability and the magnitude of the potential vorticity. With large amplitude waves, the Santa Ana surfaces and scours out the lee slope canyons. If the waves have a small amplitude, they separate from the lee slope near the ridge top, and normal up- and downslope winds are observed below the separation point. There are both periodic and antiperiodic components in the surfacing. The periodic component is a secondary factor. A 24-hour periodic component is introduced by the interaction of the large and small waves with the mountain and valley winds, and—in the wind shadow—with the sea breeze. The dominant component is antiperiodic and is determined primarily by the static stability and wind structure upwind of the mountain barrier. The intensity of the Santa Ana is determined by the gradient of the Montgomery stream function on the isentropic chart. The influence of latent heat, absent in the Santa Ana, but common in the European foehn, is relatively simple. It does not alter the dynamics of flow, but acts simply to increase the temperature of the foehn.



Dotted lines are surface flow

Figure 31.—*Descriptive model of Santa Ana illustrates a mature, intense Santa Ana with a well developed lee ridge. Isobars on isentropic surface indicate pattern of Montgomery stream function. The 290A surface is in the mid troposphere upstream of the mountains at the transition level over the mountains and in the outflow on the lee side.*

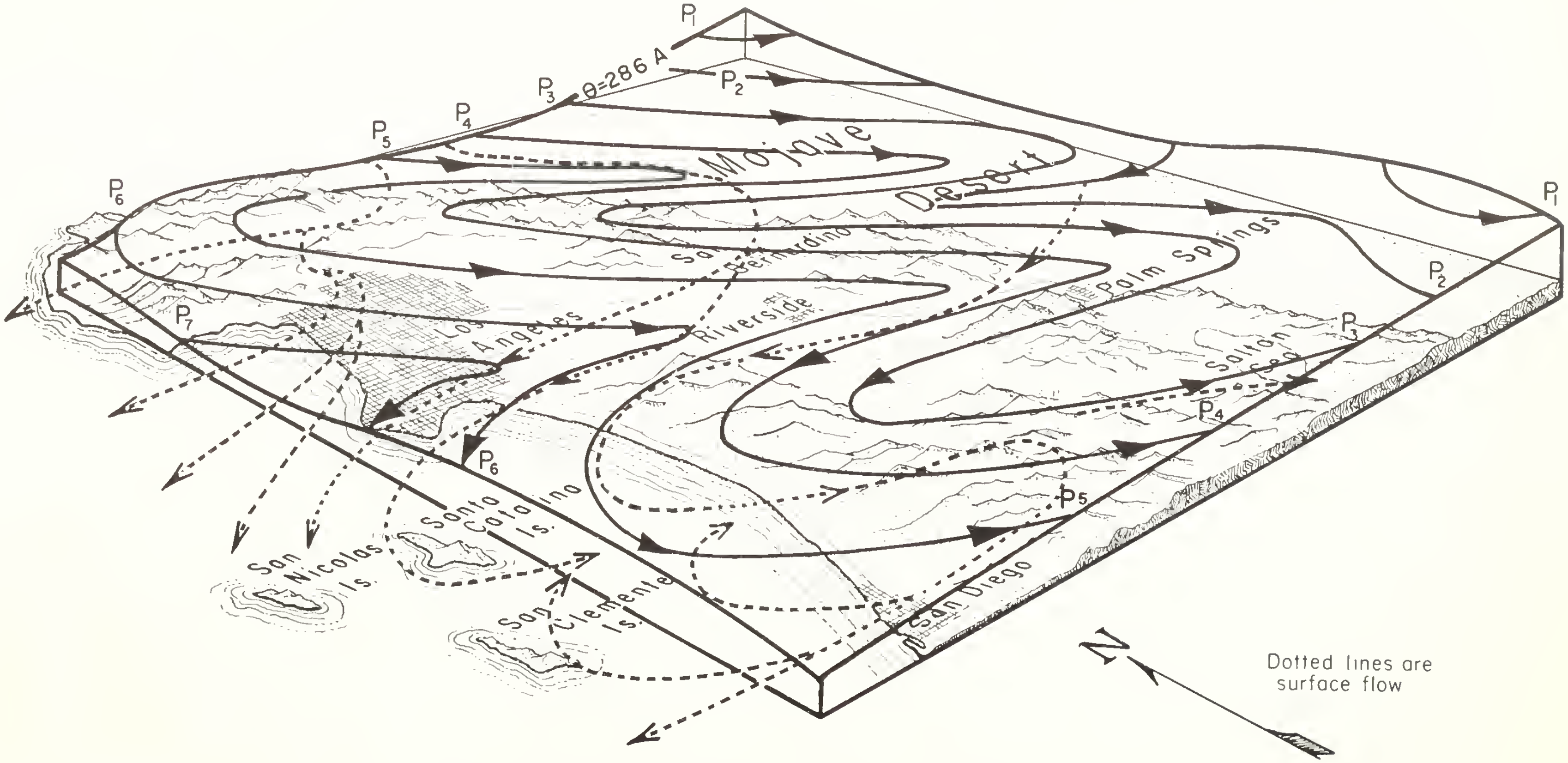


Figure 32.—*Descriptive model of Santa Ana within planetary boundary layer. Ideal case illustrated—a mature, intense Santa Ana, with a well developed ridge over the mountains and a trough to the lee of the mountains—is the same model as in figure 31. But in figure 31 the upper surface was the 290A surface, whereas in this figure it is the 286A surface. The 286A surface is in the transition layer over the mountains and in the outflow on the lee side.*

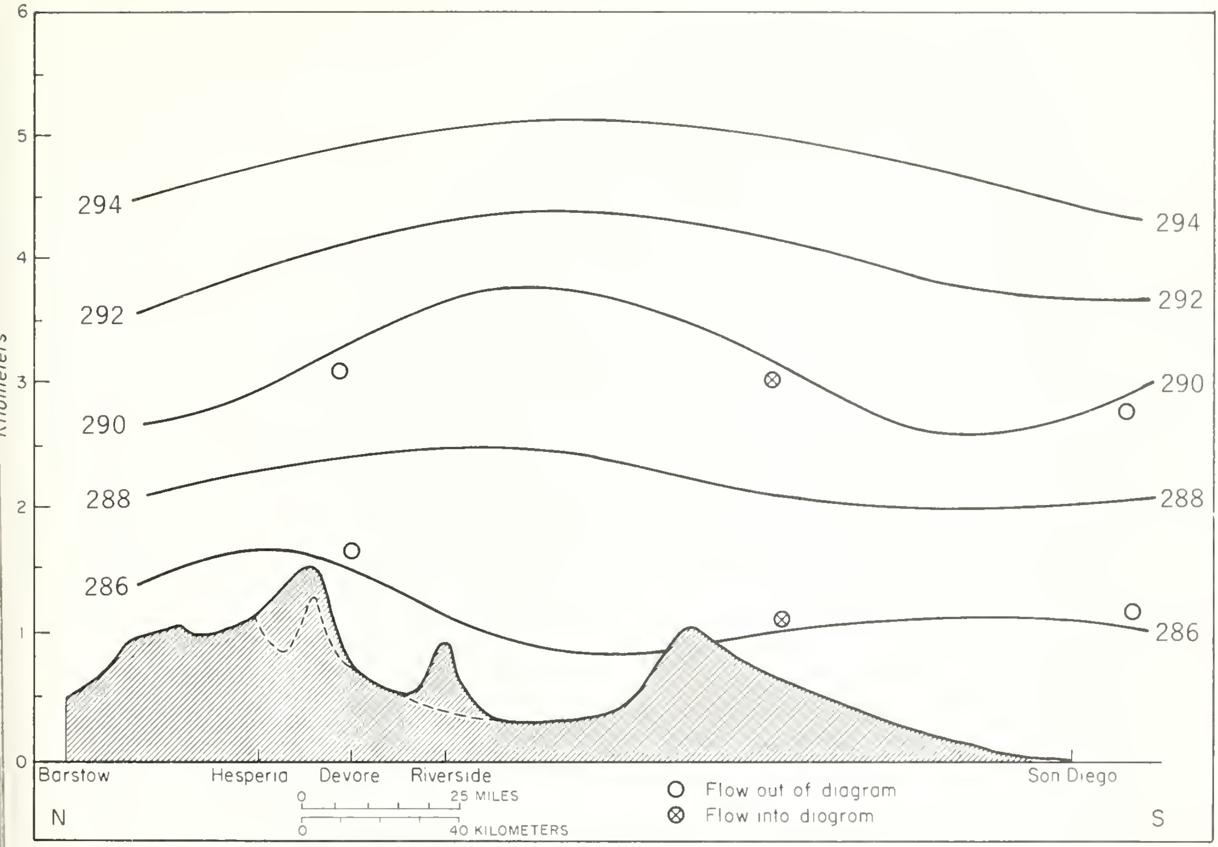


Figure 33.—*Ideal model of Santa Ana vertical cross section illustrates the long-wave characteristics of the higher and the lower level flow, and the vertical stretching to the lee side of the mountains.*

Recommendations

Most features of the schematic model are based on observations of the two case studies, features pointed out in the literature, and an application of meteorological theory. There are, however, two important features obtained by internal consistency of the model which need to be evaluated through additional studies. The interaction of the Santa Ana with the mountain-valley wind system and he land-sea breeze system should be examined in more detail. The second interaction of the synopic, meso, and local scales needs further study. The ntensity of the foehn, energy transfer processes from the synoptic scale to the local scale, and the development of the outflow can be examined by numerical analysis of the mesoscale energy properties on isentropic surfaces.

The data for analysis at this 1 to 250,000 scale has been loaned to the Department of Meteorology at the University of California at Los Angeles for further analysis of detailed outflow. We have retained the mesoscale data, at 1 to 3,000,000 scale, for numerical analysis of the energy properties, interaction, and intensity.

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Silvical Characteristics of Monterey Pine

(***Pinus radiata*** D.Don)

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Contents

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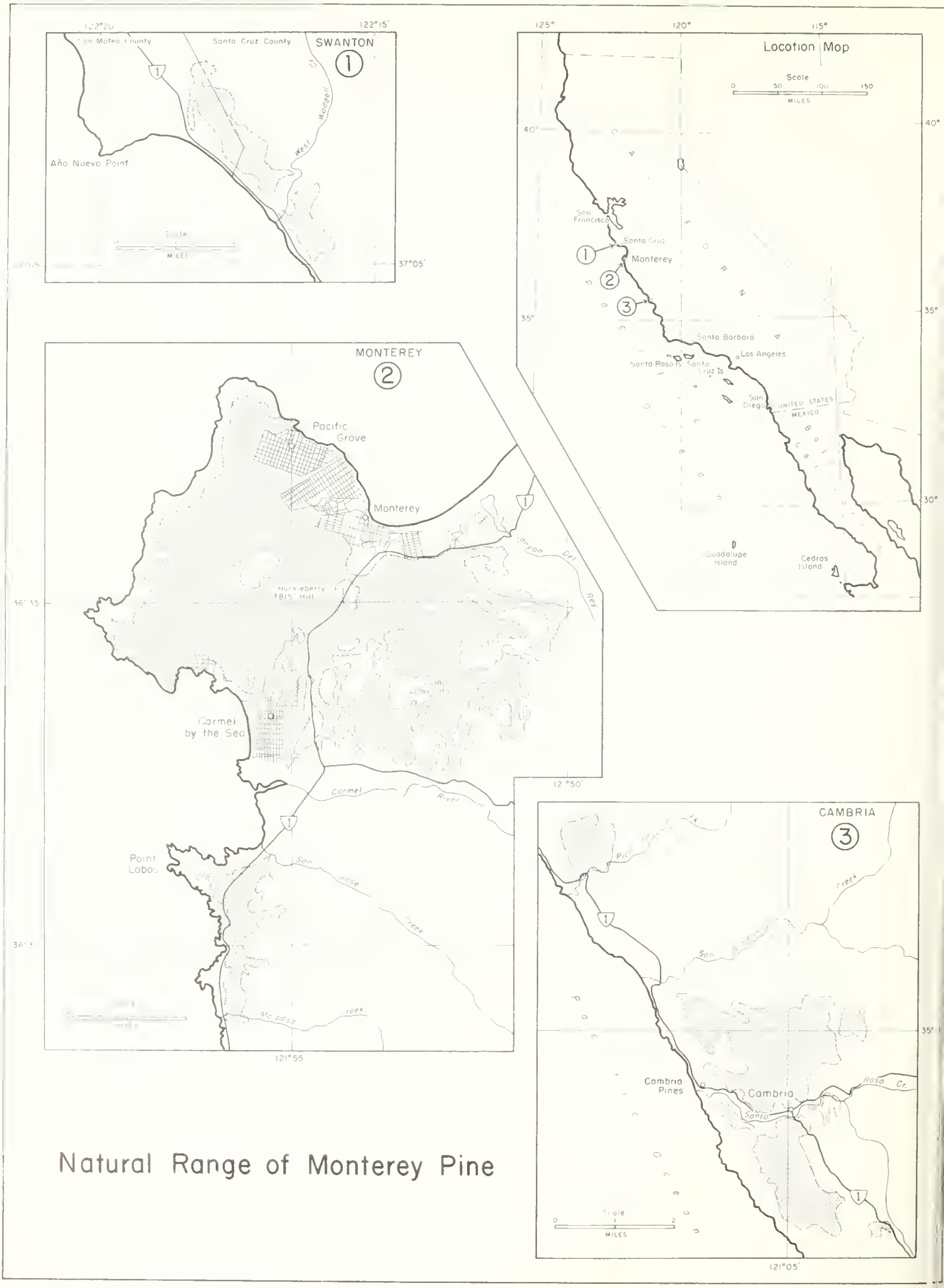

Figure 1.—*The natural range of Monterey pine.*

Monterey pine (*Pinus radiata* D. Don) is paradoxical. This tree, which now has little economic importance in its native stands, has been planted more abundantly throughout the world than any other American tree. Its introduction as a forest tree into the Southern Hemisphere has been particularly successful. Extensive stands of Monterey pine now grow in New Zealand, Australia, Chile, and South Africa. Plantings also have been successful in Spain, Argentina, and Uruguay.

The natural range of Monterey pine is extremely limited. On the United States mainland it is confined to three localities on the central California coast (fig. 1). The largest stand is 8,000 to 12,000 acres[1] on and adjacent to the Monterey Peninsula. The second largest is about 2,500 acres surrounding the town of Cambria, which lies about 85 miles southeast of Monterey. Another isolated stand of about 500 acres is at Pico Creek, about 6 miles north of the main Cambria forest. The northernmost grove probably is less than 1,000 acres,[2] and only a part of this area is clothed by pure stands of pine. It is in the Swanton area, 40 miles northwest of Monterey and about 14 miles from Santa Cruz.

Another natural stand is found on Guadalupe Island situated about 200 miles off the coast of Lower California (fig. 1).[3]

Habitat Conditions

Climatic

Monterey pine grows in a humid climate. The annual precipitation is seasonal, however, and varies from 15 to 35 inches. The minimum rainfall in one year has varied from 5.68 inches at Del Monte to 12.37 inches at Santa Cruz. And maximum annual rainfall has ranged from 28.98 inches at Monterey to 50.41 inches at Santa Cruz. About 70 to 75 percent of this moderate amount falls in the rainy season that extends from December through March. Three-fourths of the 50 to 55 rainy days in each year occur during these four months. Each of the other eight months have, on the average, less than 2 inches of rain. In fact, rainy days in July and August are rare (Lindsay [1932]; Martin and Kincer 1934).

Although Monterey pine grows in a humid climate throughout the year, humidity is higher in summer and winter than in spring and autumn. For example, the average minimum relative humidity at Monterey for July is between 60 and 70 percent (Lindsay [1932]). This high humidity is maintained by summer fogs. The characteristic patterns of fog movement inland seem to explain the distribution of the Monterey pine forest where other factors are not limiting.[4]

Forests on the Monterey Peninsula are shrouded by clouds or fogs at least one-third of the time. Consequently summer fogs contribute significant amounts of available moisture. As much as 0.57 inch of fog-drip per week was measured at higher elevations of the peninsula.[5]

Average mean daily temperatures range from 48° F. to 52° F. during January and 60° F. to 64° F. in July. Winters are relatively mild although frosts occur occasionally. The last killing frosts in the spring generally come between February 5 and February 28; the first killing frosts in the fall are expected between November 30 and December 10. The days free of killing frosts each year number 300 or more. The greatest seasonal range of temperature recorded near Monterey pine stands is 24° F. to 98° F. (Sprague 1941).

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[1] McDonald, John Bruce. *An ecological study of Monterey pine in Monterey County, California.* 1959. (M.S. thesis on file at Univ. Calif., Berkeley.)

[2] Forde, Margot Bernice. *Variation in the natural populations of Monterey pine (Pinus radiata [D.] Don) in California.* 1962. (Ph.D. thesis on file at Univ. Calif., Berkeley.)

[3] Howell 1941; Jepson 1910, 1923, 1925; Newcomb 1959; Sargent 1922.

[4] Forde, M. B. *Op. cit.* See footnote 2.

[5] McDonald, J. B. *Op. cit.* See footnote 1.

Edaphic

Monterey pine grows on a variety of soils developed from different parent materials. The soil series represented characteristically are coarse-textured sandy loams, strongly to very strongly acid in reaction, and extremely to moderately permeable. Sometimes they are leached in an A-2 horizon. The best sites have soils that are sandy loams to fine sandy loams in texture, well drained and moderately deep. McDonald[6] reported that he could not find trees growing on soils less than 9 inches deep. Near rock outcroppings, Monterey pine generally does not grow taller than 70 feet, and soils at least 3 to 4 feet deep appear necessary for trees to reach 100 to 120 feet (Lindsay [1932]).

Most of the Monterey Peninsula is formed by granitic rocks, but basalts, sandstones, shales, and schists also occur. The soils, however, are derived mainly from an overlying shallow marine deposit. The most extensive soil series is the shallow phase of Elkorn, which sustains a uniform forest with trees occasionally more than 100 feet tall and 36 inches in diameter. Most of this soil is 3 to 4 feet deep. It is a calcareous sandy loam that is well drained and often is high in organic matter.[7] The shallow phase of McClusky sandy loam also supports a large forested area, but is less productive. This soil is 20 inches to 5 feet deep, averaging 40 inches. Bedrock outcrops in a few places. The relatively heavy subsoil causes imperfect drainage. Other poorer soils in the Monterey area are Santa Lucia clay loam derived from slow weathering of silicious shales, and Chamise sandy loam. Monterey pine also grows on these soils and on coastal dune sand, which is fine, high in silica content, and poor at retaining moisture (Carpenter and Cosby 1929).

The rocks in the Cambria area are early Jurassic slates, cherts, sandstones, and limestones, but the Monterey pine forest grows almost entirely on Arnold sandy loam (Carpenter and Storie 1933). Derived from softly consolidated sandstone, this soil is low in organic matter and erodes easily. An edge of the Cambria forest extends onto Los Osos fine sandy loam.

At Swanton the rocks are shales and marine sandstones of the Miocene age. The pine forest grows mainly on the steep and shallow phases of Santa Lucia clay loam, which is high in organ matter, acid in reaction, permeable, well draine and easily eroded. Colma loam also is represente This soil, formed from weakly consolidated marir sediments, is slightly acid and well drained. Sma areas of Tierra loam, Lockwood loam, and Wa sonville loam also are within the forest.

Humus development generally is good on sit where mature pines reach heights of 80 feet c more. Here pole stands, 50 to 60 feet tall, an stands of larger trees have litter 3 to 6 inch deep with active disintegration on the bottom t form a definite humus layer. Beneath this laye considerable organic matter darkens the sc several inches deep. On poor sites humus do not develop (Lindsay [1932]).

Physiographic

In general, Monterey pine is found on gent to moderate slopes, from sea level to a maximu elevation near 1,000 feet, and from the sea t about 6 miles inland. At Swanton, where rainfa is more abundant, this species grows on all aspect But at both Monterey and Cambria, which a significantly drier, the hot and dry south aspec are not favorable sites. All areas where Montere pine is established naturally are well drained.

Swanton, at latitude 37° north, is the mo northerly area of natural Monterey pine stand Here patches of Monterey pine are scattered c the narrow coastal stretch of rolling terrain b tween the sea and the steep slopes of Ben Lomor Mountain. Most of the pines grow at elevatio between sea level and about 500 feet, but a fe are found on the steep slopes up to 800 feet. Tl best sites are on the hilly country a few hundre yards to a mile and a half from the coast (Linds [1932]).

The main pine stand in the Monterey area located on the Monterey Peninsula, latitude 36½ N. The highest elevation here is 815 feet. Tl forest continues southeasterly beyond the neck the peninsula, mainly on the northern side of tl ridge, to elevations of almost 900 feet, for abo 4 miles. Here it is broken by grassland and cha arral and disappears. Trees on the peninsula grc best on the gently sloping and flat land betwe the ridge and the sea. Inland, the best growth on the sheltered northern slopes. Growth is fa on some slopes and gully bottoms on the south si of the ridge, but tree sizes there do not compa with those attained on the northern slopes. Sou

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[6] McDonald, J. B. *Op. cit.* See footnote 1.

[7] Forde, M. B. *Op. cit.* See footnote 2.

of the Monterey Peninsula, patches of Monterey pine are found on Point Lobos and up to 1,000 eet elevation on the adjoining seaward slopes of he Santa Lucia Mountains.[8]

At Cambria the latitude is 35½° N. Here Monerey pine grows on gentle and moderate slopes, which are not more than 2 miles inland nor higher han 300 feet. Growth is poor on south slopes.

The latitude of Guadalupe Island is 29° N.

Biotic

Monterey pine occurs within the life zone classied as Austral Transition (Merriam 1898). Along he coast near Monterey it occasionally grows with Monterey cypress[9] and Gowen cypress. Further nland in this area the forest overstory is pure Monterey pine (Sudworth 1908), except near the op of Huckleberry Hill, where groups of bishop pine grow. The most common tree found with Monterey pine is California live oak, which generlly is an understory tree under 30 feet high Lindsay [1932]).

The plant associations of Monterey pine in the Monterey area vary considerably with different oils and aspects. Changes in these associations re both gradual and abrupt.

One typical association is the mesophytic pine orest found in canyons throughout the peninsula. Another, found on favorable sites on the gentle ower slopes, particularly on northern aspects, is omposed of well-developed pines that form a losed canopy. The understory is fairly open with cattered California live oaks and shrubs, and the round cover is grass, ferns, brambles, poison-oak, nd other soft-leaved species. On steeper parts of he peninsula where the soils are shallow, the ines are poorly formed and widely spaced, and ave a dense undergrowth of manzanitas, Caliornia huckleberry, blueblossom, and coyote brush. nland, California live oak becomes increasingly rominent until Monterey pine disappears and a rass-woodland type dominates.[10]

The Monterey pine forest at Cambria is surounded by grassland. Parts of the forest have been logged repeatedly for timber, and parts have been burned to improve grazing for cattle. These reas generally are open and lack undergrowth other than grasses. The stands which are relatively undisturbed resemble those growing on the better sites at Monterey where the understory is dominated by California live oak.

The drier forest sites at Cambria are covered by an open stand of pines with a dense understory of California live oak and shrubs. On shady areas California live oaks are infrequent and the ground under the forest is covered mainly by ferns, grasses, and soft-leaved shrubs.

The forest types at Swanton are not as clearly delineated as those at Monterey and Cambria. Where Monterey pine grows in pure stands the trees are widely spaced and heavily branched. This type is restricted, however. Generally, it is confined to drier, south-facing sites along the exposed seaward margin of the forest. More often, Monterey pine at Swanton is not the dominant conifer, but is associated with other trees—with redwood on lower slopes, with Douglas-fir on middle slopes, and with knobcone pine on the drier upper slopes where the soil is shallow and stony.

The redwood association is mesophytic with tall and dense tree and shrub layers, and with abundant ferns and herbaceous vegetation on the ground. Conspicuous codominant or understory species are California live oak, wax-myrtle, and California-laurel; and manzanita and ceanothus are prominent in the shrub layer.

The best individual Monterey pines grow with Douglas-fir on north-facing slopes with deep soil.

The vegetation growing with Monterey pine has been described in detail (Lindsay [1932]; Mason 1934).[11] [12] [13] Shrubs, forbs, and grasses are numerous, and the Monterey region is especially rich in endemic species. Floristic lists follow:

Trees—Conifers

Cupressus goveniana Gord. (Gowen cypress)
C. macrocarpa Hartw. (Monterey cypress)
Pinus attenuata Lemm. (Knobcone pine)
P. muricata D. Don (Bishop pine)
Pseudotsuga menziesii [Mirb.] Franco (Douglas-fir)
Sequoia sempervirens [D. Don] Endl. (Redwood)

Trees—Hardwoods

Aesculus californica [Spach] Nutt. (California buckeye)

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[8] Forde, M. B. *Op. cit.* See footnote 2.

[9] See floristic lists in this paper for scientific names.

[10] Forde, M. B. *Op. cit.* See footnote 2.

[11] Coleman, George A. *Report upon Monterey pine, made for the Pacific Improvement Company.* 1905. (Unpublished report on file at Pacific SW. Forest and Range Exp. Sta., U.S. Forest Serv., Berkeley, Calif.)

[12] Dunning, Duncan. *A working plan for the Del Monte Forest of the Pacific Improvement Company.* 1916. (M.S. thesis on file at Univ. Calif., Berkeley.)

[13] Forde, M. B. *Op. cit.* See footnote 2.

Alnus rhombifolia Nutt. (White alder)
A. rubra Bong. (Red alder)
Arbutus menziesii Pursh (Pacific madrone)
Lithocarpus densiflorus [H. & A.] Rehd. (Tanoak)
Quercus agrifolia Née (California live oak)
Q. chrysolepis Liebm. (Canyon live oak)
Umbellularia californica [H. & A.] Nutt. (California-laurel)

Shrubs

Adenostoma fasciculatum H. & A. (Chamise)
Arctostaphylos canescens Eastw. (Hoary manzanita)
A. glandulosa Eastw. (Eastwood manzanita)
A. hookeri G. Don (Monterey manzanita)
A. nummularia Gray var. *sensitiva* [Jeps.] McMinn (Littleberry manzanita)
A. pumila Nutt. (Dune manzanita)
A. tomentosa [Pursh] Lindl. (Shaggy-barked manzanita)
A. tomentosa [Pursh] Lindl. var. *tomentosiformis* [Adams] Munz (Woolly manzanita)
Artemisia californica Less. (California sagebrush)
A. douglasiana Bess. in Hook. (Douglas sagebrush)
A. pycnocephala DC. (Sandhill sagebrush)
Baccharis pilularis DC. var. *consanguinea* [DC.] C. B. Wolf (Coyote brush)
Castanopsis chrysophylla [Dougl.] A. DC. var. *minor* [Benth.] A. DC. (Golden chinkapin)
Ceanothus thyrsiflorus Eschs. (Blueblossom)
Cornus × californica C. A. Meyer (Western red dogwood)
Corylus cornuta Marsh. var. *californica* [A. DC.] Sharp (California hazel)
Cytisus monspessulanus L. (French broom)
Dendromecon rigida Benth. (Bush poppy)
Eriodictyon californicum [H. & A.] Torr. (Yerba Santa)
Eriogonum latifolium Sm. (Coast wild buckwheat)
E. parvifolium Sm. (Seacliff eriogonum)
Eriophyllum confertiflorum [DC.] Gray (Golden-yarrow eriophyllum)
E. staechadifolium Lag. (Lizard tail)
Garrya elliptica Dougl. (Silk-tassel bush)
Gaultheria shallon Pursh (Salal)
Haplopappus ericoides [Less.] H. & A. (Heather goldenweed)
H. squarrosus H. & A. (Sawtooth goldenweed)
Helianthemum scoparium Nutt. (Rush-rose)
Heteromeles arbutifolia M. Roem. (Toyon)
Holodiscus discolor [Pursh] Maxim. (Cream bush)
Lepechinia calycina [Benth.] Epl. in Munz (Pitcher sage)
Lonicera hispidula Dougl. var. *vacillans* Gray (California honeysuckle)
L. involucrata [Richards.] Banks (Twinberry)
Lupinus albifrons Benth. (Whiteface lupine)
L. arboreus Sims (Tree lupine)
Mimulus aurantiacus Curt. (Bush monkey-flower)
Myrica californica Cham. & Schlecht. (Wax-myrtle)
Osmaronia cerasiformis [T. & G.] Greene (Oso berry)
Pickeringia montana Nutt. (Pea chaparral)
Polygala californica Nutt. (California polygala)
Prunus virginiana L. var. *demissa* [Nutt.] Sarg (Western choke cherry)
Rhamnus californica Eschs. (Coffeeberry)
R. crocea Nutt. in T. & G. ssp. *ilicifolia* [Kell.] C. B. Wolf (Buckthorn)
Rhododendron macrophyllum D. Don (Pacific rhododendron)
Rhus diversiloba T. & G. (Poison-oak)
Ribes divaricatum Dougl. (Straggly gooseberry)
R. malvaceum Sm. (Chaparral currant)
R. menziesii Pursh (Canyon gooseberry)
R. sanguineum Pursh var. *glutinosum* [Benth.] Loud. (Red flowering currant)
R. speciosum Pursh (Fuchsia-flowered gooseberry
Rosa californica Cham. & Schlecht. (Californi wild rose)
R. gymnocarpa Nutt. ex T. & G. (Wood rose)
R. nutkana Presl (Nootka rose)
Rubus parviflorus Nutt. (Thimble-berry)
R. spectabilis Pursh (Salmon-berry)
R. ursinus Cham. & Schlecht. (California black berry)
Salix lasiolepis Benth. (Arroyo willow)
S. scouleriana Barratt (Scouler willow)
Salvia mellifera Greene (Black sage)
Sambucus callicarpa Greene (Pacific red elder)
Solanum umbelliferum Eschs. (Blue witch)
Symphoricarpos mollis Nutt. in T. & G. (Spreading snowberry)
S. rivularis Suksd. (Snowberry)
Vaccinium ovatum Pursh (California huckleberry

Ferns

Adiantum jordani C. Muell. (California maiden hair)
Dryopteris arguta [Kaulf.] Watt (Coast woodfern
Pityrogramma triangularis [Kaulf.] Maxon (Goldenback fern)
Polypodium californicum Kaulf. (California polypody)
Polystichum munitum [Kaulf.] Presl (Sword fern
Pteridium aquilinum [L.] Kuhn var. *lanuginosu* [Bong.] Fern. (Bracken fern)

Forbs

Achillea borealis Bong. ssp. *arenicola* [Heller] Kec (Yarrow)
A. borealis Bong. ssp. *californica* [Pollard] Kec (Yarrow)
Arnica discoidea Benth. (Coast arnica)
Astragalus nuttallii [T. & G.] J. T. Howell (Mil vetch)
Brodiaea Sm. sp. (Brodiaea)
B. crocea [Wood] Wats. (Golden brodiaea)
B. pulchella [Salisb.] Greene (Blue dicks)
Calochortus albus Dougl. ex Benth. (Fairy lanter
Castilleja affinis H. & A. (Scarlet cup)
Chenopodium californicum [Wats.] Wats. (Cal fornia goosefoot)
Chlorogalum pomeridianum [DC.] Kunth (Amo soapplant)
Chrysanthemum segetum L. (Corn chrysanthemu
Cirsium occidentale [Nutt.] Jeps. (Western thistl
Convolvulus cyclostegius House (Morning-glory)
Corethrogyne DC. sp. (Cottonaster)

Cynoglossum grande Dougl. ex Lehm. (Western hound's tongue)
Daucus pusillus Michx. (Rattlesnake weed)
Dentaria californica Nutt. (Toothwort)
Dudleya farinosa [Lindl.] Britt. & Rose (Bluff lettuce)
Erechtites arguta [A. Rich.] (New Zealand fireweed)
E. prenanthoides [A. Rich.] DC. (Australian fireweed)
Erigeron glaucus Ker. (Seaside daisy)
Eschscholtzia californica Cham. (California poppy)
Fragaria californica Cham. & Schlecht. (Wood strawberry)
Franseria chamissonis Less. spp. *bipinnatisecta* [Less.] Wiggins & Stockw. (Bursage)
Galium aparine L. (Goose grass)
G. californicum H. & A. (California bedstraw)
G. nuttallii Gray (Nuttall bedstraw)
Gnaphalium chilense Spreng. (Cotton-batting plant)
G. purpureum L. (Purple cudweed)
G. ramosissimum Nutt. (Pink everlasting)
Grindelia robusta Nutt. (Gum-plant)
Heracleum lanatum Michx. (Cow-parsnip)
Hesperocnide tenella Torr. (Hesperocnide)
Hieracium albiflorum Hook. (White hawkweed)
Horkelia Cham. & Schlecht. sp. (Horkelia)
Iris douglasiana Herb. (Mountain iris)
Lathyrus torreyi Gray (Torrey peavine)
L. vestitus Nutt. ex T. & G. ssp. *bolanderi* [Wats.] C. L. Hitchc. (Bolander peavine)
Lomatium parvifolium [H. & A.] Jeps. (Hog-fennel)
Lotus heermanii [Dur. & Hilg.] Greene (Bird's-foot trefoil)
L. scoparius [Nutt. in T. & G.] Ottley (Deer-weed)
Madia capitata Nutt. (Tarweed)
M. elegans D. Don (Common madia)
Marah fabaceus [Naud.] Greene (California bigroot)
Mesembryanthemum L. sp. (Ice plant)
Montia perfoliata [Donn] Howell (Miner's-lettuce)
Pedicularis semibarbata Gray (Lousewort)
Phacelia malvifolia Cham. (Stinging phacelia)
Ranunculus californicus Benth. (California buttercup)
Sanicula crassicaulis Poepp. ex DC. (Gamble weed)
S. laciniata H. & A. (Coast sanicle)
Satureja douglasii (Benth.) Briq. (Yerba Santa)
Scrophularia californica Cham. & Schlecht. (Figwort)
Sidalcea malvaeflora [DC.] Gray ex Benth. (Checker bloom)
Silene laciniata Cav. ssp. *major* Hitchc. & Maguire (Mexican silene)
Sisyrinchium bellum Wats. (Blue-eyed grass)
Smilacina stellata [L.] Desf. var. *sessilifolia* [Baker] Henders. (Star-flower)
Solidago californica Nutt. (California goldenrod)
S. spathulata DC. (Coast goldenrod)
Stachys bullata Benth. (Puffnettle betony)
Trientalis latifolia Hook. (Star-flower)
Trillium sessile L. var. *chloropetalum* Torr. (Rock lily)
Vicia americana Muhl. (American vetch)
V. benghalensis L. (Vetch)
Viola quercetorum Baker & Clausen (Violet)
Xerophyllum tenax [Pursh] Nutt. (Bear-grass)
Zigadenus fremontii Torr. (Star-lily)

Sedges

Carex L. sp. (Sedge)
C. globosa Boott (Sedge)

Grasses

Agrostis diegoensis Vasey (Thingrass)
A. semiverticillata [Forsk.] C. Chr. (Water bent)
Aira caryophyllea L. (Silver hairgrass)
Avena fatua L. (Wild oat)
Briza maxima L. (Big quaking grass)
B. media L. (Perennial quaking grass)
B. minor L. (Little quaking grass)
Bromus carinatus H. &. A. (California brome)
B. laevipes Shear. (Chinook brome)
B. orcuttianus Vasey (Orcutt brome)
B. rigidus Roth (Ripgut grass)
B. rubens L. (Foxtail chess)
Calamagrostis nutkaensis [Presl] Steud. (Pacific reedgrass)
C. rubescens Buckl. (Pinegrass)
Danthonia californica Bol. (California oatgrass)
Deschampsia caespitosa [L.] Beauv. (Tufted hairgrass)
D. danthonioides [Trin.] Munro ex Benth. (Annual hairgrass)
D. elongata [Hook.] Munro ex Benth. (Slender hairgrass)
Distichlis spicata [L.] Greene *stricta* [Torr.] Beetle (Desert saltgrass)
Elymus condensatus Presl (Giant wild-rye)
E. glaucus Buckl. (Blue wild-rye)
Festuca californica Vasey (California fescue)
F. dertonensis [All.] Asch. & Graebn. (Brome fescue)
F. microstachys Nutt. (Small fescue)
F. myuros L. (Rattail fescue)
Hierochloe occidentalis Buckl. (California sweetgrass)
Holcus lanatus L. (Velvet grass)
Hordeum californicum Covas & Steb. (California barley)
H. jubatum L. (Foxtail barley)
H. murinum L. (Mouse barley)
Koeleria cristata [L.] Pers. (Junegrass)
Lolium perenne L. (Perennial ryegrass)
L. temulentum L. Darnel (Darnel ryegrass)
Melica imperfecta Trin. (California melic)
Monerma cylindrica [Willd.] Coss. & Dur. (Thintail)
Phalaris californica H. & A. (California canarygrass)
Poa annua L. (Annual bluegrass)
P. douglasii Nees (Douglas bluegrass)
P. stenantha Trin. (Trinius bluegrass)
Polypogon interruptus HBK. (Ditch polypogon)
P. monspeliensis [L.] Desf. (Rabbitfoot grass)
Stipa lepida Hitchc. (Foothill needlegrass)
S. pulchra Hitchc. (Purple needlegrass)

Animals, birds, insects, and fungi also are parts of the biotic habitat conditions under which Monterey pine reproduces, grows, and dies. Each plays some role in the life history of the tree.

Life History

Seeding Habits

Flowering and Fruiting

Monterey pine flowers in late winter or early spring. Female flowers are borne in whorls, or nodal clusters, of three to seven on both the main stem and branches where they may be either subterminal or lateral (Lindsay [1932]). This pine is multinodal, usually producing one to three nodes each year. Consequently one to three clusters of cones also are produced.[14]

Male flowers usually are produced on side branches. Pollination seems to be most effective during the first week after the female flowers are fully open, and continues to be reasonably effective through the second week. Viable seed has been produced by both intraspecific crossings and in selfings (Pawsey 1961).

Cones seem to develop only after receiving viable pollen, even though that pollen may be incapable of producing seed (Pawsey 1961). Nonpollinated conelets wither and die in 3 months or less. Some normal-appearing mature cones have been found to contain only empty seeds or wings.

Cones mature in the autumn of the second season. They often open during the first warm days in the following spring.

Seed Production

Monterey pine is a prolific, and sometimes precocious, annual seeder. Female conelets occasionally are produced by 4-year-old seedlings, but trees raised vegetatively commonly begin to produce cones when 3 years old (Pawsey 1950). Generally, however, trees of good vigor do not produce abundant cones until they are 15 to 20 years old, or considerably older if the timber stand is dense (Goudie 1925; MacDonald *et al.* 1957).

The number of cones accumulated over several years on one tree about 55 feet tall was estimated as not less than 6,100 (Jepson 1910). Each cone produces from 120 (Adams 1950) to 200 (Fielding 1964; Scott 1960) seeds.

The size of cones and seeds varies considerably Young trees bear cones substantially larger than those on older trees (Fielding 1953). Cone size also is related to heredity, position in the crown, and tree vigor (Fielding 1964). Larger cones produce larger and heavier seeds (Healy 1940).[15] The number of seeds per pound ranges from 12,000 to 23,000, averaging 16,000 (Goudie 1925; U.S. Forest Service 1948). Commercial seed should be 98 percent pure and 95 percent sound (U.S. Forest Service 1948).

Seed viability is high and persistent (Sudworth 1908), and is about the same regardless of seed size (Healy 1940), averaging between 70 and 80 percent. Viability as high as 94 percent has been reported (Mirov 1946). Badran[16] reported germination of seeds from current year's cones to be 78 percent, dropping in a straight-line relationship with increasing age to 53 percent for seeds from cones remaining on trees for 11 years.

Extracted seeds can be stored under a wide range of conditions for 10 or 11 years with little loss in viability (Allsop 1953). Seed in cold storage for 14 years was 81 percent viable (Mirov 1946), and seed lots stored 16 and 21 years retained viabilities of 66 and 86 percent, respectively (Schubert 1952).

Not all Monterey pine cones survive to maturity Adults of the Monterey pine cone beetle (*Conophthorus radiatae* Hopk.) attack the green second-year cones in spring by girdling the axis of the cone near its base, and then extending a gallery distally along the cone axis. This injury prevents further cone development. Insect damage to cones in natural stands has been limited so far to the Monterey area, where it has varied by location from light to 100 percent (Ruckes 1958; Schaefer 1962).

Unusual climatic conditions, especially where Monterey pine grows as an exotic, can also affect seed production. In Australia, for example, a loss in the number of cones bearing viable seed has

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[14] Badran, Osman Adly. *Maintenance of seed viability in closed cone pines.* 1949. (M.S. thesis on file at Univ. Calif., Berkeley.)

[15] Forde, M. B. *Op. cit.* See footnote 2.

[16] Badran, O. A. *Op. cit.* See footnote 14.

been attributed to summer drought (Pawsey 1960a).

Seed Dissemination

Monterey pine cones may be opened by fire (Sudworth 1908), but lacking this agent, generally remain attached to trees for many years, and usually do not release all their seeds during the first year after maturing. Cones open when their moisture content is reduced to less than 20 percent (Fielding 1947). Cone opening without fire generally requires blocking of the water supply. This blockage occurs naturally by secretion of resin in the vascular tracheids of the peduncle (Allen and Wardrop 1964).

Cones sometimes remain closed several years. In exposed, sunny positions, however, they may open a year or two after ripening (Dallimore and Jackson 1923). Cones also open sooner when they are unsheltered from the hot, dry winds which occasionally blow from the interior valleys. Few cones remain closed longer than 6 years.[17]

After their initial opening, cones close and open repeatedly, depending upon air temperatures and relative humidities. Weather conditions which dry the cones occur most often in September and October or in the spring. Some seeds usually are shed each time the cones open. Consequently the oldest cones contain few seeds.

Seeds are dispersed by wind and gravity (U.S. Forest Service 1948) for distances of 130 to 200 feet (Jolliffe 1940–41). Other factors, such as rodents and birds, do not help significantly in seed distribution.

Several birds and mammals have been reported as ravenous consumers of Monterey pine seed. In fall, large flocks of common crows *(Corvus brachynchos)*[18] and numerous Steller's jays *(Cyanocitta stelleri)* and California jays *(Aphelocoma coerulescens)* as well as smaller seed-eating birds, feast on the fallen seeds. The California mouse (*Peromyscus californicus californicus* [Gambel]), deer mouse (*P. maniculatus gambelii* [Baird]), dusky-footed wood rat (*Neotoma fucipes luciana* Hooper), California ground squirrel (*Spermophilus beecheyi beecheyi* [Richardson]), western gray squirrel (*Sciurus griseus nigripes* Bryant), western spotted skunk (*Spilogale gracilis phenax* Merriam), striped skunk (*Mephitis mephitis holzneri* Mearns), racoon (*Procyon lotor psora* Gray), and gray fox (*Urocyon cinereoargenteus townsendi* Merriam) are listed as Monterey pine seed eaters,[19] although some of these animals seem unlikely.

Vegetative Reproduction

Monterey pine generally does not reproduce naturally by sprouts, but some instances of this happening in New Zealand have been reported (Lindsay [1932]). Sprouting in natural stands has not been recorded.

Cuttings of Monterey pine root easily if selected with care. Those rooting best are cut from first order branchlets (Sherry 1942) and from young trees. Cuttings from trees under 12 years old have rooted well (Thulin 1957), but slips from trees 2 to 7 years old seem preferred.[20] However, 60 percent of the cuttings from 20-year-old trees rooted when the basal cuts were in wood not more than 1 year old (Allsop 1953). In one study, branches with terminal buds bearing male cone primordia failed to root (Jacobs 1939).

The best time for collecting cuttings from 5- to 7-year-old trees is after the overwintering terminal buds are formed. And cuttings from the sunny side of the trees, where growth is most vigorous, are desirable. The best slips from 2- to 4-year-old trees are cut in spring from the first laterals after they have developed woody tissue (Allsop 1950).

Rooting success of Monterey pine cuttings has been as high as 95 percent. In this case slips were taken by pulling the branchlets from the top whorl of 2-year-old seedlings. When the stock was planted out after 14 months the root systems produced were as good as those of seedlings. Field survival (88 percent) and rate of growth (20 feet in five seasons) also compared favorably to the performance of seedlings (Field 1934).

Other experience indicates that planting stock raised from cuttings is not as hardy as seedling stock and requires more care in handling. Nevertheless, survival in plantations of bare-rooted plants propagated from cuttings was more than 90 percent (Pawsey 1950).

Single leaf-fascicles also can be set and raised successfully for planting stock (Pawsey 1950).

Limited observations suggest that trees vary in their ability to produce cuttings which root and that this variation is inherent (Duffield and Liddicoet 1949).

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[17] Badran, O. A. *Op. cit.* See footnote 14.

[18] Scientific names of birds from Peterson (1961).

[19] Coleman, George A. *Op. cit.* See footnote 11.

[20] Allsop 1950; Cutten 1946; Jacobs 1939; Mirov 1944; Sherry 1942.

Grafting Monterey pine by the single cleft method has been successful. Healthy unions are produced regularly by 80 to 90 percent of the grafts attempted (Thulin 1957).

Seedling Development

Establishment

Monterey pine seed germination is epigeous and relatively fast and complete without stratification (Bibby 1953). Germinative capacity averages about 60 percent, but may be higher than 89 percent (U.S. Forest Service 1948).

Although not necessary for good performance of seed, stratification increases the amount and rate of germination (Bibby 1953). In one case the germination for seeds stratified at 40° F. for 2 months was 89 percent after 15 days compared to 41 percent for unstratified seed (Grose 1958). The same treatment for half the time also hastened germination (Allsop 1952). In another instance stratification at 38° F. for varying periods of 3 to 28 days, or soaking at room temperature for 3 days, significantly increased the germination rate. Soaking for 7 to 14 days increased the speed of seed germination even more (Rodger 1957).

Temperature is another agent that influences germination of Monterey pine seed. The day-night temperature combinations cited as best for germination are, respectively: 80° F. and 60° F. (U.S. Forest Service 1948), 77° F. and 68° F. (Allsop 1952), and 72° F. and 64° F. (Allsop 1953). Germination capacity at a constant 68° F. was 25 percent greater than at 77° F. (Jacobs [1961]).

Natural reproduction generally is obtained easily after clear-cutting (Ure 1949), but several factors can play significant roles. For example, the density of reproduction can be reduced greatly by dense slash (Fielding 1947). The distribution of natural reproduction can be improved sometimes by scattering the slash (Chapman 1949a), and light slash has improved seedling survival and early growth. Another important factor in obtaining natural reproduction in Australia is the season of felling. Regeneration cuttings are most successful when timber is felled immediately after seed fall, and least successful when cuttings are completed just before seed fall (Fielding 1947). Microtopography also has influenced the number and growth of young trees (Thomson and Prior 1958). The requisites for abundant reproduction under exotic stands include mineral soil, negligible competition from other plants, and no serious drought (Chapman 1949b), although Monterey pine seedlings have been called drought-hardy (Adams 1951). Where conditions are favorable 1,000 to 10,000 seedlings per acre are not uncommon 2 years after logging (Hinds 1951; Kennedy 1957; Lindsay [1932]). On one area 10 feet square, more than 600 4-year-old seedlings were counted (Jepson 1910).

Clearcutting in exotic Monterey pine stands in areas of high rainfall may result in reproduction that is too dense. When this condition is likely, regeneration can be regulated by partial cutting that controls the amount of sunlight reaching the ground. When logging leaves 70 or more stems per acre, regeneration is sparse. If only 50 trees are reserved, regeneration is prolific (Anon. 1956a).

Some natural reproduction grows under the canopy of mature Monterey pines. In most stands this consists of spindly, isolated seedlings or saplings, but a dense understory of young pines can be found occasionally (Lindsay [1932]). Seedlings can get a start because the desirable seedbed and light conditions are not necessary for germination and early growth. For example, the best seedbed is a moist mineral soil, but many seedlings begin growth where pine litter is several inches deep (Lindsay [1932]). Maximum development of seedlings seems to require full sunlight, but the amount of light under the canopy of a fully stocked mature stand is not reduced enough to inhibit early growth. The critical factor in survival of reproduction under existing stands is soil moisture (Moulds 1955).

Monterey pine often becomes established under the canopy of California live oak. Successful penetration of the oak canopy by pine poles is evidence that the oaks act as nurse trees (Lindsay [1932]). Pine seedlings also invade grasslands. They can compete with annuals, but have difficulty becoming established in perennial grasses (Pryor 1941).

Dense reproduction almost always becomes established after Monterey pine stands are burned (King 1925; Lindsay [1932]; Sudworth 1908). Fires open the cones so that all available seed are shed on ideal, weed-free seedbeds, and standing dead trees provide a changing shade pattern like a lath house. Seedlings under exotic fire-killed stands number 500,000 (Entrican 1960; Hinds 1951; Kennedy 1957) to more than 1,000,000 per acre (Fenton 1951; MacArthur 1952).

New seedlings bear 5 to 10 cotyledons with 7 prevalent. First growth produces a shoot with primary needles, but secondary needles in fascicles of three appear when the plant is a few months old. Both primary and secondary needles are produced until the plant is about 3 years old (Lindsay [1932]).

No information on mycorrhizal symbionts in natural stands of Monterey pine has been published (Offord 1964). Several mycorrhizal fungi are native to California, however. Fungi proved or suspected of forming mycorrhizae in exotic Monterey pine stands have been listed by several authors.[21] The mycorrhizal fungi associated with Monterey pine have been compiled (Trappe 1962). They are:

Amanita muscarcia (Fr.) Hooker
Cenococcum graniforme (Sow.) Ferd. & Winge
Gomphidius rutilus (Fr.) Lund. & Nanf.
G. vinicolor Peck
Inocybe lacera (Fr.) Kumm.
Laccaria laccata (Fr.) Berk. & Br.
Lactarius deliciosus (Fr.) S. F. Gray
Rhizopogon luteolus Fr. & Nordh.
R. roseolus (Corda) Hollos
R. rubescens Tul.
Scleroderma aurantium (Vaill.) Pers.
S. bovista Fr.
Suillus granulatus (Fr.) O. Kuntze
S. luteus (Fr.) S. F. Gray
S. piperatus (Fr.) O. Kuntze
S. subaureus (Peck) Snell

Cantharellus cibarkus Fr. and *Marasmius oreades* Fr. are two additional mycorrhizal symbionts of Monterey pine which have been reported from Spain.[22]

The Monterey pine seedling grows a tap root. On poor sites this is almost the only root produced. In coarse-textured, rich soils, however, the tap root may produce as many as a dozen side roots per inch. Mycorrhizal associations with the roots in the top 4 inches of soil appear necessary for rapid growth (Adams 1951; Kessell 1943).

Early Growth

Monterey pine seedlings are fairly large when they emerge from the ground and growth is rapid. Both tops and roots develop best when seedlings get full light (Baker 1945). Root systems of new seedlings are small compared to tops. Although seedlings are supported at first by tap roots, this form of root system usually disappears as extensive lateral roots expand.

Nutrient requirements of seedlings are not high. A solution containing 100 p.p.m. of nitrogen, 1 p.p.m. of phosphorous, 10 p.p.m. of potassium, and 10 p.p.m. of magnesium provided enough minerals to maintain good growth. Adequate supplies of nutrients are available when foliar analyses show contents of 1.6 percent nitrogen, 0.1 percent phosphorous, 1.1 percent potassium, and 0.11 percent magnesium (Will 1961).

Trees one year old may be over 12 inches tall. Three-year-old trees generally measure 3 to 6 feet in height (Goudie 1925; Fenton 1951). Some individuals this age are 9 to 10 feet, however, and 10 inches in diameter 6 years after planting (Anon. 1957a).

Many examples of fast growth have been reported. One 6-year-old tree grew 8 feet in height; another grew 13 feet (Jepson 1910). A tree in an Australian plantation grew 20 feet in its fifth year to reach 30 feet (Stoate 1920–22).

Although plants established from cuttings are smaller in diameter than seedlings of the same height during the first 3 or 4 years (Pawsey 1950), their growth catches up. For example, mean annual growth for 7-year-old cuttings planted in light, well-drained sand in New Zealand were 0.97 inches in diameter and 4.4 feet in height (Field 1934).

Young stands can modify sites in short periods. In Chile a plantation of Monterey pines spaced 2 x 2 meters had produced a litter cover sufficiently deep to prevent erosion and to create favorable infiltration characteristics within 5 to 6 years (Roberts 1957).

Seasonal Growth

Monterey pine in its natural range generally begins height growth in February or March when the mean temperature reaches 51 to 53° F. Other conifers in the same area begin growth later. The pines grow fastest between February and June when mean temperatures vary from 51 to 61° F., and the mean maximums range from 62 to 75° F. Growth stops in September or October when available soil moisture is depleted (Lindsay [1932]). This level of soil moisture seems to be near 5.7 to 6.1 percent (Anon. 1929; Lindsay [1932]). When winter rains begin the temperatures are too low for trees to resume rapid growth. Although

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[21] Birch 1937; Clements 1938; Cromer 1935; Dos Santos de Azevedo 1959; Morrison 1957; Rawlings 1951, 1960; Walker 1931.

[22] Martinez, José Benito. *Third annual report of progress of research sponsored by P. L. 480*. 1963. (Unpublished report to Inst. Forest. Invest. Expt., Madrid.)

double growth rings are common in Australia, they are rare in California (Lindsay [1932]).

The annual height growth pattern of Monterey pine as an exotic varies from place to place and depends upon seasonal variations of climate and inherited characteristics (Fielding 1955). Seasonal growth begins in Australia when solar radiation reaches 400 gram-calories per square centimeter per month. Thereafter, growth is intimately related to the amount of rainfall (Anon. 1929). Growth is least in winter and summer, greatest in spring, and relatively uniform in the fall. The growing season lasts, on the average, 10 months. The dormant periods do not correspond to either the coldest or warmest periods (Jacobs [1961]).

In New Zealand little or no snow falls in the plantation areas and Monterey pine does not decrease growth appreciably during the winter (Baigent 1956). The growth of summer wood continues for at least 10 months in the North Island, but not quite as long in the South Island (Chapman 1949a).

The most detailed growth observations of Monterey pine originate from Canberra, Australia. Here shoot elongation begins in late winter and increases in rate until grading into a burst of spring growth. Spring growth of most shoots stops more abruptly than it begins, but growth slows in a short transition period. Shoots can be called dormant only for a few weeks immediately following spring growth. Although most shoots are relatively dormant during late summer, fall, and winter, they elongate appreciably and some grow actively during this period (Fielding 1955).

Sapling Stage to Maturity

Growth and Yield

In native stands Monterey pine is a moderately large tree; it varies in height from 32 to 124 feet, but generally is 70 to 110 feet tall, and from 2 to 3 feet in diameter at maturity. Occasionally it may exceed 5 feet in diameter (Dallimore and Jackson 1923; Lindsay [1932]; U.S. Forest Service 1908). Heights of 100 to 120 feet are regarded as good in Australia. Exceptional growth of 145 to 155 feet at 40 to 50 years has been measured in New Zealand and South Africa (Lindsay [1932]), and of 185 feet for mature trees in New Zealand (Chapman 1949a).

Trees vary widely in many characteristics. Some of these are growth rate, wood density, trunk form, branching habit, and abundance of cones (Bannister 1962; Fielding 1953, 1960). In dense stands, however, boles tend to be reasonably straight with little taper; and crowns are narrow and remain pointed for 35 to 45 years before rounding off and becoming flat. For example, trees 90 to 110 feet high may have crowns only 15 to 30 feet wide and clear boles of 25 to 50 feet. Open grown trees develop wide, irregularly and excessively branched crowns (Lindsay [1932]).

Stand density also determines the length of green crowns. Trees 36 to 40 years old and 70 to 100 feet high may have green crowns on one-sixth to one-fifth of the total tree heights when in dense stands, compared to one-third or one-half the total height when open grown (Lindsay [1932]).

Boles may have many irregularities, especially in understocked stands. They may be elliptical or irregular in cross-section, with sweep, crooked, or leaning. And trees may have double leaders or bayonet tops (Lindsay [1932]). Studies of Monterey pine stands developed from different initial spacings ranging from 6 to 11 feet found that bole crookedness and lean were not influenced by spacing (Rodger 1957).

Roots of mature trees are superficial (Wendelken 1955). They generally do not penetrate deeper than 2 feet, and are usually found in the top 12 inches of soil, but this lateral system is widespreading and strong (Lindsay [1932]). The large roots extend 30 to 40 feet from the tree[23] and interlock with roots of other trees in the stand (Wendelken 1955). Root grafting is common (Adams 1940; Rawlings and Wilson 1949; Pawsey 1962). Another feature of the Monterey pine root system is the reinforcing development of wood between horizontal roots and stems. These developments appear as swellings at ground level. They act as brackets and, with the rest of the root system, create windfirm trees. Growth of both brackets and lateral roots is stimulated by wind movement (Pryor 1937).

Young Monterey pine grow quickly; internodes 3 to 6 feet long are common on trees 5 to 15 years old (Lindsay [1932]). Height growth culminates on poorer sites as early as 15 years (Larsen 1915), but on better sites usually remains fast for the first 30 to 40 years. It slows considerably at 50 to 60 years.

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[23] Larsen, Louis T. *Monterey pine*. 14 pp. 1914. (Unpublished report on file at Pacific SW. Forest and Range Exp. Sta., U.S. Forest Serv., Berkeley, Calif.)

Native stands on average to good soil condi- ions will be 30 to 40 feet high at 10 years, 60 to 5 feet at 20 years, 70 to 90 feet at 30 years, and 0 to 110 feet at 40 years (Lindsay [1932]). Examples of faster height growth are common. n the redwood belt of California many Monterey ines were 30 to 50 feet tall, and 6 to 11 inches in iameter 12 years after planting. The largest tree was over 74 feet tall and 11.3 inches in diameter Sindel 1963). Annual height growth of 6 to 8 eet over a number of years has been reported for ndividual trees in an area where height growth veraged 4 feet a year for 22 years (Goudie 1925). n New Zealand the mean heights of trees at 20 ears are 98 to 116 feet for site I, 81 to 98 feet or site II, and 63 to 81 feet for site III (Ure 950).

Monterey pine is short-lived. Its average life s not more than 80 or 90 years, and a tree rarely ves beyond 150 years (Lindsay [1932]). Its ltimate height may be reached in 35 to 40 years Lindsay [1932]). Full size is attained in 80 to 00 years (Sudworth 1908), but the tree may e mature on poor sites at 40 years.

Generally understocked mature native stands verage less than 20,000 board feet per acre. etter stocking produces significantly higher yields. One 50-year-old stand considered better than aver- ge had 165 trees and 35,000 board feet per acre. These trees averaged 15.5 inches in diameter and 4 feet high (Larsen 1915). Another stand on a ood site had 43,000 board feet per acre at 25 ears. The trees were 77 feet tall, 14.1 inches in iameter, and numbered 270 per acre.[24] The eaviest stand measured near Monterey contained 95 trees and 120,000 board feet per acre. The verage tree was 20.3 inches in diameter and 94 eet tall (Larsen 1915).

Data from New Zealand show that Monterey ine can produce yields higher than those meas- red in native stands. For example, stands 35 to 0 years old yield 50,000 to 60,000 board feet er acre (Chapman 1949a). At 40 years a fully tocked stand on good soil had 10,000 to 12,000 ubic feet of timber per acre (Wilson 1923). Another New Zealand stand that had not been hinned produced 10,000 cubic feet per acre at 6 years. The trees averaged 120 feet high and 00 to 250 per acre (Ure 1949). Finally, a vol- me of 21,730 cubic feet per acre was produced by a 58-year-old stand that was originally planted at a 9 foot spacing, and unthinned. Each acre had 103 crop trees and 557 square feet of basal area. The average tree height was 135 feet (Blithe 1953).

Reaction to Competition

The tolerance of Monterey pine probably depends upon site factors and age. Although ratings have ranged from "very tolerant" to "intolerant," Monterey pine appears more tolerant than any other pine in western America. Foresters in California judged the tree "intermediate," the middle class in a scale of five broad divisions (Baker 1949, 1950). Reasons cited for judging Monterey pine tolerant are the occasional ability of reproduction to become established and to grow under a mature stand to form a two-storied forest (Lindsay [1932]), good growth in dense stands (Sudworth 1908), and the persistence of limbs and foilage in dense stands.[25]

Monterey pine has been recognized as less tolerant in Australia (Lindsay [1932]). And its intolerance to shade in New Zealand, resulting in absence of advance reproduction under either closed or partially closed canopies, has been described as a conspicuous feature (Baigent 1956).

Even where tolerant in youth, trees become less tolerant as they grow older. The crowns of mature Monterey pines require full light.[26]

Under some conditions Monterey pine seedlings can not compete against a dense ground cover (Kennedy 1957). Generally, however, they dominate and suppress weeds or scrubby growth (Crutwell [Cruttwell] 1953; Goudie 1925).

Monterey pine's ability to differentiate well-spaced dominant trees in dense stands is well known. Some trees emerge above the general canopy level early in life and quickly suppress competitors, eliminating any possibility of stagnation.[27] [28] Trees that remain dominant grow with little set-back (Crutwell [Cruttwell] 1953). Many plantations in New Zealand thin themselves so effectively that their final yield is almost equal to that from stands thinned repeatedly (Chapman 1949a; Ure 1949).

Monterey pine is not self-pruning. Its branches remain tough indefinitely, although stubs left on

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[24] Larsen, Louis T. *Op. cit.* See footnote 23.

[25] Larsen, Louis T. *Op. cit.* See footnote 23.

[26] Larsen, Louis T. *Op. cit.* See footnote 23.

[27] Harrison-Smith 1956; Hinds 1951; Kennedy 1957; Lewis 1957; MacArthur 1952.

[28] Coleman, George A. *Op cit.* See footnote 11.

trees after thinning may rot and sometimes brush off readily from trees 35 to 45 years old in thinned stands (Bednall 1957).

Some young stands of Monterey pine, especially those regenerated after fire, have excessive stocking of more than 500,000 trees per acre and require early thinning (Chapman 1951). The first thinning may be best when the trees are 3 or 4 years old and about 5 feet tall (Anon. 1957b; Fenton 1951; Ure 1949). Response to early thinning sometimes is slow (Adams 1940), but thinning generally produces quick and impressive results (Rankin 1936).

Older stands will respond to thinning either from above or from below (Lewis 1957). Opportune thinning can reduce cutting cycles, produce higher quality timber, and reduce danger from fires, insects, fungi, and windfall (New Zealand Forest Service 1955; Robertson 1951). Response in diameter growth appears the first year. Thinning at 17 years, for example, increased annual diameter growth almost immediately from ¼ to 1 inch (Harrison-Smith 1957). All trees respond more to severe thinning than to light thinning, and larger trees respond more than smaller trees (Jacobs 1962). Periodic thinning can maintain vigorous growth in some stands until the 60th or 70th year (Anon. 1956b).

Proposed thinning schedules for Monterey pine are as follows:

	Levels of stocking recommended for:	
	Kenya,[1] South Africa,[2] and New Zealand[3,4]	*Chile[5]*
Age (years):	*(number of trees)*	
2–3	1,000	
5–10	240–350	810
12–13	200	
14–15	150	610
18–20	80–125	
25	80–100	280–365

[1] Pudden 1957.
[2] King 1951.
[3] Anon. 1957b.
[4] Ure 1949.
[5] Robertson 1951.

The natural Monterey pine forests seem to be a stable vegetational type at Monterey and Cambria. The marked control of pines by soil types at both Monterey and Cambria also indicate Monterey pine is an edaphic climax, although the effects of fog and sea must not be overlooked (Lindsay [1932]).

Principal Enemies

Monterey pine has many enemies, both as a native tree and as an exotic. One survey at Monterey showed more than 10 percent of the trees and 20 percent of the seedlings and saplings were diseased (Lindsay [1932]). Some other native stands are worse.

Over 70 pathogens recently have been listed as occurring in native stands and plantations of Monterey pine in western North America. Of these, about 49 percent are saprophytes, 35 percent wound parasites, and 16 percent obligate parasites. Of the 86 other pathogens found on exotic Monterey pines, nearly 44 percent are classed as saprophytes, 31 percent as wound parasites, and 10 percent as obligate parasites; and pathogenicity was not classified for 15 percent (Offord 1964).

The most important pathogens in native stands and West Coast plantations are (Offord 1964):

Stem Diseases

Western dwarfmistletoe (*Arceuthobium campylopodum* f. *typicum* [Engelm.] Gill).—Trees of all sizes, including seedlings, are damaged, deformed, or killed. Not found at Swanton.

Coastal gall rust (*Peridermium cerebroides*[29] Meinecke).—Damaging at Cambria, Monterey, and Swanton, and in plantations throughout central coastal California.

Western gall rust (*P. harknessii* J. P. Moore).—Found in Oregon, Washington, and British Columbia, and in some plantations in California. Both gall rusts retard the growth of infected stems and kill some trees.

Root Diseases

Fomes root rot (*Fomes annosus* [Fr.] Cke.).—This most important root disease is especially damaging to trees of low vigor growing on thin, poorly drained, and heavy soils.

Shoestring fungus rot (*Armillaria mellea* [Vahl.] Quél.).—Widely distributed where oaks are present, but causes small losses only.

Velvet top fungus (*Polyporus schweinitzii* Fr.).—Occurrence is widespread. Often associated with vigorous young trees.

Foliage Diseases

Needle rust (*Coleosporium madiae* [Syd.] Arth.).—A heteroecious rust whose alternate hosts, the tarweeds (*Madia* spp.), are suppressed with increased age and density of pine regeneration.

Twig blight (*Diplodia pinea* [Desm.] Kickx).—Rarely found on native trees but a major twig blight on injured exotic Monterey pines, especially those wounded by hailstones.

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[29] A nomen nudum as described by Meinecke (1929); has not yet been described validly as a species.

Needle cast (*Hypoderma pedatum* Darker).

Needle cast (*Hypodermella limitata* Darker).

Needle cast (*Lophodermium pinastri* [Fr.] Chev.).—Usually a mild parasite but can become damaging when winters are mild and summers hot.

Needle cast (*Naemacylus niveus* [Fr.] Sacc.).—The most widespread and damaging needle cast in the areas of native Monterey pine.

A needle blight, *Dothistroma pini* Hulbary, has been destructive in Monterey pine plantations of East Africa (Offord 1964). Although this disease has not yet been reported on Monterey pine in California, it has been identified recently on several other conifers in the Western United States.

As an exotic, Monterey pine often is relatively free of diseases. Incidence of tree diseases is light, for example, in an extensive region in New Zealand, where more than 30 inches of rain fall each year (Crutwell [Cruttwell] 1953). When introduced, Monterey pine thrives best in climates similar to coastal central California. Pathological troubles become increasingly important as the climate diverges from the dry summers and wet winters of the native range (Rawlings 1957).

Pathogens reported most often for exotic Monterey pine are:

Shoestring fungus rot *(Armillaria mellea)*.—Reported from Chile, Great Britain, Kenya, New Zealand, and Spain.[30] [31]

Twig blight *(Diplodia pinea)*.—Attacks favored by overmature trees, overcrowded forests and poor tree vigor resulting from excessive competition for soil moisture, warm humid weather, and tree injury by leaf-sucking insects, frosts, or hail. Found in Argentina, Australia, Chile, New Zealand, Union of South Africa, Southern Rhodesia, and Spain.[32]

Needle cast *(Lophodermium pinastri)*.—Attacks are favored by cool wet summers and mild wet winters. Identified in New Zealand, Union of South Africa, and Spain.[33]

Needle cast *(Naemacyclus niveus)*.—Found in Kenya, New Zealand and Spain (Gibson 1962; New Zealand Forest Service 1960; Scott 1960).

Twig canker (*Phomopsis strobi* Syd.).—Important only where unseasonable frosts occur. Reported in Australia and New Zealand.[34]

Seedling blight (*Phytophthora cactorum* [Leb. & Cohn] Schroet.).—Found in New Zealand (Newhook 1957, 1959).

Root rot (*P. cinnamomi* Rands).—*Phytophthora* spp. epidemics require abnormally early rewetting of soil in the autumn, with wet conditions continuing until spring (Newhook 1959). Poor soil drainage also enhances attacks (Sutherland, Newhook and Levy 1959). The pathogens kill the fine rootlets. Observed in Argentina and New Zealand (Newhook 1957; Scott 1960; Spaulding 1956).

Almost 90 insects found on native Monterey pine have been recorded[35] (Burke 1937; Essig 1926; Keen 1952). These pests include a variety of defoliators, sap suckers, needle and twig miners, cambium miners, and wood borers. Although several insects are destructive and often weaken infested trees, only five can be classed as tree killers. They are:

Red turpentine beetle (*Dendroctonus valens* Lec.).—Sometimes confined to fire-injured trees or to trees more than 80 years old,[36] but often becomes primary in attacking and killing trees (U.S. Department of Agriculture 1927; Keen 1952), even healthy ones (Essig 1926). Infests stems from near the ground to 20 feet high (Essig 1926).

California five-spined ips (*Ips confusus* [Lec.]).—Is destructive to saplings, poles, young trees up to 30 inches in diameter, and to the tops of mature trees (Keen 1952; Struble 1961).

California four-spined ips (*I. plastographus* [Lec.]).—Often destructive to small and large trees (Essig 1926), and associated with attacks by the Monterey pine ips and the red turpentine beetle (Keen 1952; Struble 1961). Larvae mine the cambium layer.[37]

Monterey pine ips (*I. radiatae* Hopk.).—Usually attacks weakened trees and works downward from the crown (Essig 1926). Is generally a secondary enemy associated with other bark

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[30] Birch 1937; Gilmour 1954; Green 1957; Kennedy 1957; New Zeal. Forest Serv. 1955; Rawlings 1948; Scott 1960.

[31] Martinez, José Benito. *Op. cit.* See footnote 22.

[32] Anon. 1957b; Bancroft 1911; Birch 1936, 1937; Capretti 1956; Curtis 1926; Eldridge 1957; Ferreirinha 1953; Gibson 1958; Gryse 1955; Hutchinson and Henry 1957; Laughton 1937; Purnell 1956, 1957; Rawlings 1948, 1955; Waterman 1943; Young 1936.

[33] Anon. 1957b; Allsop 1954; Hutchinson and Henry 1957; Rawlings 1955; Scott 1960.

[34] Birch 1935, 1937; Rawlings 1955; Scott 1960; Stoate and Bednall 1953.

[35] Coleman, George A. *Op. cit.* See footnote 11.

[36] Coleman, George A. *Op. cit.* See footnote 11.

[37] Coleman, George A. *Op. cit.* See footnote 11.

beetles, but may become primary, especially in plantations (Keen 1952; Struble 1961).

Monterey pine weevil (*Pissodes radiatae* Hopk.). —Larvae mine the cambium layer of the tops, stems, or bases (above or below ground) of young trees[38] (Essig 1926; Keen 1952).

Other important insects in native stands are:

Spittlebug (*Aphrophora permutata* Uhl.).—The young stages of the spittlebug work on the windward sides of exposed trees in the sand dunes, denude branches, and sometimes injure cones[39] (Keen 1952).

Monterey pine cone beetle (*Conophthorus radiatae* Hopk.).—This major pest in central California attacks and aborts second-year cones. It has killed as much as 90 percent of the cones in some stands at Monterey, but has not been found at Cambria or Swanton (Schaefer 1962).

Silver-spotted halisidota (*Halisidota argentata* Pack. var. *sobrina* Str.).—These tent caterpillars feed on the foliage and sometimes denude many branches in protected areas[40] (Essig 1926; Keen 1952).

Twig beetles of the *Pityophthorus* group, possibly *P. carmeli* Sw. (Keen 1952), are sometimes abundant and destructive. This minute bark-boring insect saps the strength of trees by killing small branchlets.[41]

Monterey pine tip moth (*Rhyacionia montana* Busck).—Larvae infest the terminals of Monterey pine (Essig 1926).

Monterey pine midge (*Thecodiplosis piniradiatae* Snow & Mills).—A common and serious pest that can practically denude heavily infested trees (Essig 1926). It works at the bases of newly formed needles and causes them to become swollen and shortened. Heavily attacked twigs are sometimes killed (Keen 1952).

Sequoia pitch moth (*Vespamima sequoiae* Hy. Edw.).—The larvae bore into the cambium layer of branches and boles where they feed and cause the flow of pitch in which they live[42] (Essig 1926).

Many insects also have been identified in exotic stands of Monterey pine. They include 30 insects in Australia (Minko 1961), and 7 in South Africa (Tooke 1943) that are capable of causing economic losses. Present attacks are confined mainly to nursery stock and natural regeneration growing under maturing stands.

The two most commonly mentioned insects that attack Monterey pine abroad are:

Hylastes ater Payk., a common bark beetle.—Lives and breeds in recently felled slash and attacks young seedlings.[43]

Sirex noctilio Fabr., a horntail or wood wasp.—Found in Tasmania and New Zealand. Successful insect attack requires the rapid growth of a symbiotic fungus, which is inoculated into the tree during oviposition; and successful invasion by the fungus depends upon a weakened sap flow within the tree. An insect build-up, therefore, is favored by a series of dry years.[44] Attacks sometimes only kill trees which should have been removed by earlier thinning (Entrican 1960).

No animals have been reported as serious pests in native Monterey pine forests. Some young trees in plantations in California have been browsed. And some have been broken or girdled by rubbing by the Columbia black-tailed deer (*Odocoileus hemionus columbianus* (Richardson)); and others have had bark removed from limbs by the dusky-footed woodrat (*Neotoma fucipes monochroura* Rhoades) (Sindel 1963). In general, mice, rats, rabbits, hares, opossums and deer have caused minor damages overseas (Crutwell [Cruttwell] 1953; Davis 1942; Goudie 1925). But in South Australia, rabbits—unless controlled—can cause severe seedling losses (Fielding 1947).

Fire is one of the enemies of Monterey pine. Young trees, with their thin bark are especially susceptible to fire damage, and older trees are easily scorched (Lindsay [1932]; Pryor 1940). Fire risk is always grave in plantations (Anon. 1956a). Pruning in young stands to a height of 7 to 8 feet is a desirable measure for fire protection. Otherwise, the lower limbs persist and become festooned with needles, creating a situation ideal for crowning fires. Removal of the lower limbs helps to keep a fire on the ground and makes control comparatively easy (Chapman 1949a).

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[38] Coleman, George A. *Op. cit.* See footnote 11.

[39] Coleman, George A. *Op. cit.* See footnote 11.

[40] Coleman, George A. *Op. cit.* See footnote 11.

[41] Stevens, R. E. *(Pityophthorus twig beetles on Monterey pine.)* 1958. (Unpublished report on file at Pacific SW. Forest and Range Exp. Sta., U.S. Forest Serv., Berkeley, Calif.

[42] Coleman, George A. *Op. cit.* See footnote 11.

[43] Anon. 1957b; Boomsma and Adams 1943; Fenton 1951; Kennedy 1957; New Zealand Forest Service 1955.

[44] Anon. 1957b; Coutts 1965; Gilbert and Miller 1952; Hutchinson and Henry 1957; New Zealand Forest Service 1955; Rawlings 1953, 1955; Rawlings and Wilson 1949.

Climatic factors are sometimes hostile to exotic Monterey pine stands. The most adverse weather conditions are summer rainfall, unseasonable frosts, hail and wind (Rawlings 1957). Summer rainfall favors attack by leaf-cast fungi and *Diplodia pinea,* particularly when high temperatures and humidity are maintained for long periods (Rawlings 1957).

Temperatures below 12° F. and unseasonable frosts of much less severity are liable to damage Monterey pine. This tree sometimes will tolerate temperatures as low as 0° F., but frost rings may form which destroy the timber's usefulness for lumber (Rawlings 1957).

Monterey pine is particularly susceptible to injury by hail. Direct damage consists of defoliation and splitting of bark on twigs and branches (Rawlings 1957). These injuries attract attacks by *Diplodia pinea.*[45]

Wind is one of the most important factors in the growth of Monterey pine as an introduced species—both in direct and in indirect effects. In some instances wind may be a limiting factor in the use of this species for forestry. It sometimes determines the form of the tree and the structure of the wood (Rawlings 1957). Prevailing west winds in Australia have caused windthrow, lean, and eccentric growth, but soil moisture, aspect, and exposure were contributing factors (Pryor 1937). Southeast and northwest winds caused leans and defects, including elliptical stems, irregular growth, sweep, sloping grain, and compression wood (Fielding 1940; Millet 1944). Windthrow may be severe where trees are grown on non-forest land where rooting is notoriously shallow ([Hocking] 1945). The whipping of crowns while the cambium is active may bark the boles which leads to dead tops (Hocking 1947).

Special Features

Monterey pine is the most important conifer yet introduced to the Southern Hemisphere. Its rapid growth and adaptability to a wide range of conditions prove it valuable for providing softwoods to that region, particularly Australia, New Zealand, and South Africa (Lindsay [1932]).

The most remarkable quality of Monterey pine may be its extreme variation of tree types (Thomson 1950). These widely different types within small uniform areas suggest a wide genetical variation between individuals. Because this variation includes characteristics important to foresters, such as vigor, stem form, and limb size and angle,[46] the possibility of establishing elite strains seems good.

In California, young Monterey pines have become favored as Christmas trees (Metcalf 1955).

Races and Hybrids

The two-needled pine found on Guadalupe Island usually is considered to be *Pinus radiata* var. *binata* (Engelm.) Lemmon (Lindsay [1932]; Newcomb 1959). Another variety, the golden-eaved Monterey pine (var. *aurea),* is propagated from layers and cuttings as an ornamental tree in New Zealand and has no significance for foresters. Considerable morphological diversity within the species has been recognized in both natural and exotic stands,[47] [48] but no other varietal names are now used, except rarely. However, *P. radiata* var. *macrocarpa* Hartw. has been suggested to designate the form at Cambria (Fielding 1961).

Monterey pine has been hybridized artificially with knobcone pine and bishop pine (Righter and Duffield 1951; Rodger 1957; Stockwell and Righter 1946). In vigor, the knobcone cross (*Pinus* × *attenuradiata* Stockwell and Righter) is between the parental species. It resembles Monterey pine in appearance, but has heavier branches (Fielding 1950). An interesting feature is its resistance to frost injury. At 3 years seedlings were undamaged by a 15.4° F. temperature, which

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[45] Bryan 1954; Laughton 1937; Legat 1930; Rawlings 957.

[46] Bannister 1959; Chapman 1949b; Pawsey 1950; Poole 1947; Thulin 1957.

[47] Bannister 1954, 1958, 1959; Fielding 1953, 1961, 1962; Jacobs 1937, 1961; Lindsay 1932; Pawsey 1960b; Sherry 1947.

[48] Forde, M. B. *Op. cit.* See footnote 2.

either killed or permanently deformed Monterey pine seedlings, and at 8 years the hybrids withstood a minimum temperature of 11.8° F. (Stockwell and Righter 1946).

The bishop pine cross has good form, but has no advantages over Monterey pine. It has bishop pine's undesirable habit of producing many cones on the main stem (Fielding 1950).

Natural hybrids of Monterey and knobcone pines have been found near Point Año Nuevo[49] (Bannister 1958; Lindsay [1932]; Stebbins 1950) and the possibility of natural hybridization between Monterey and bishop pines at Monterey has been discussed[50] (Stebbins 1950). Putative hybrids between Monterey pine and knobcone pine were spontaneous in five widely separated areas in New Zealand (Bannister 1958; New Zealand Forest Service. 1960).

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[49] Forde, M. B. *Op. cit.* See footnote 2.

[50] Duffield, John Warren. *Interrelationships of the California closed-cone pines with special reference to Pinus muricata D. Don.* 1951. (Ph.D. thesis on file at Univ. Calif., Berkeley.)

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Artificial Ripening of Sugar Pine Seeds

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CONTENTS

Seeds of sugar pine (*Pinus lambertiana* Dougl.) are shed from the cone usually during September and October. They become mature some time before the cones open. But the precise time of seed maturation is highly variable, depending on a number of factors, including weather conditions, locality, tree age, and tree vigor. To aid the cone collector in harvesting only cones with predominantly mature seeds, such indices of cone and seed maturity as cone specific gravity have been developed.[1] [2] If collection of immature cones could be followed by artificial ripening of the enclosed seeds, cone collecting operations could become more flexible; the cone collecting period could be lengthened; and immature cones from logging operations in fall could be used.

Artificial ripening of seeds has proved to be feasible in most of the conifers in which it has been investigated. Silen[3] demonstrated that immature seeds of Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) could be artificially ripened in the cone by a damp storage method. He suggested the possibility of commercial ripening of seeds. Church and Sucoff[4] reported that the viability of immature seeds of Virginia pine (*Pinus virginiana* Mill.) increased if the seeds were left in the cones on felled trees. Later, Fenton and Sucoff[5] found that ripening and subsequent germination of Virginia pine seeds collected between August 30 and September 20 and removed from the cone could be improved by prolonged cold dry storage in closed containers. Similarly, Schubert[6] found that seeds of some western pines matured during cold storage after removal from the cone. Seeds of both ponderosa (*Pinus ponderosa* Laws.) and Jeffrey pine (*Pinus jeffreyi* Grev. & Balf.)—but not sugar pine—were capable of further maturation during prolonged storage. Schubert also reported that abnormal ponderosa and Jeffrey pine seedlings were obtained most often from immature fresh seeds and that the frequency of seedling abnormalities decreased during storage.

The studies cited suggest that immature seeds of some conifers reach a stage where they no longer depend on the tree or the cone for further development. In this study, immature sugar pine seeds at different developmental stages were permitted to develop either in the immature cone after removal from the tree, or after removal from the cone. The results suggest that ripening immature sugar pine cones artificially is possible.

Methods

Exploratory studies were begun during the sumners of 1957 and 1958, and a full scale investigaion was made in 1959. The conclusions from the data for all 3 years were essentially the same. Therefore only the data for 1959 are reported here because they were more complete.

Seed collection.—About 25 cones were collected biweekly from each of three mature sugar pine trees located at 4,000 feet elevation in the University of California's Blodgett Forest, in the central Sierra Nevada of California. Cone collection began during the first week of June and continued until second week of October, when seeds were shed from the trees. As a measure of ripeness, green cone specific gravity was determined by the water displacement method within 2 days of collection. Cones then were segregated into

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[1] Fowells, H. A. *An index of ripeness for sugar pine eed.* U.S. Forest Serv. Calif. Forest & Range Exp. Sta. Res. Note 64, 5 pp. 1949.

[2] Schubert, G. H. *Effect of ripeness on the viability of ugar, Jeffrey and ponderosa pine seed.* Proc. 55th Annu. Meeting, Soc. Amer. Foresters 1955: 67–69. 1955.

[3] Silen, R. R. *Artificial ripening of Douglas-fir cones.* . Forestry 56: 410–413. 1958.

[4] Church, T. W., Jr., and Sucoff, E. I. *Virginia pine seed iable two months before natural cone opening.* U.S. Forst Serv. NE. Forest Exp. Sta. Res. Note 102, 4 pp. 1960.

[5] Fenton, R. H., and Sucoff, E. I. *Effects of storage treatments on the ripening and viability of Virginia pine seed.* U.S. Forest Serv. NE. Forest Exp. Sta. Res. Note NE-31, 6 pp. 1965.

[6] *Op. cit.*

specific gravity classes. Two-thirds of the cones of a specific gravity class collected on a given day were opened by hand and their seeds pooled.

Maturity test.—Germination of fresh seeds measured their physiological maturity at the time of collection. Three 150-seed samples were randomly selected from each of the pooled seed lots immediately after removal from the cone, and planted in two parts vermiculite and three parts sand in a darkened room at a temperature of 25°C.

Germination was recorded every 2 days for 60 days. Germination is defined here as the resumption of growth of the embryo, recognized by a definite rupture of the seed coat and the appearance of the radicle or hypocotyl. The germination percentage was based only on filled seeds, and statistical significance determined after angular transformation of the data.[7] Germination and seedling development were classified as normal or abnormal on the basis of the embryo development, and on seedling behavior during a 6-week period after germination.

Artificial ripening of the seed in the cone was investigated by randomly selecting 10 cones of each specific gravity class from each biweekly collection. These cones were dusted with 50 percent Captan, sealed individually in plastic bags, and stored in the dark at 10°C. within 2 days of cone collections. Preliminary studies had shown that storage at 10°C. reduced to some extent external and internal fungal contaminations not inhibited by the fungicide, but did not inhibit embryo development. The seeds from the stored cones were hand extracted during the first week of October and three 150-seed samples from these seeds were tested for germination.

Artificial ripening of seeds removed from cones was studied by randomly selecting 800 seeds from cones of each specific gravity class collected on a given date. These seeds were first treated with 50 percent Captan and then stored in moist vermiculite at 10°C. within 3 days of cone collection. Three 150-seed samples from each of these seed lots were tested for germination, starting the first week of October.

Anatomical development of the seed extracted before, during, and after storage was investigated. During seed storage in the cone, one cone representing each of the specific gravity classes from each of the collection dates was selected randomly for analysis at the end of the first, the second, and the last week of storage. After seed was extracted from cones in each of the treatments, 50 seeds were randomly selected for anatomical studies. The dry weight of the female gametophyte plus embryo was determined for the remaining seeds.[8]

Finally, from each of the different specific gravity classes of cones collected on a given date, 100 seeds were selected at the end of the first, the second, and the last week of storage from the seed sample stored in moist vermiculite. Half of these seeds were used to determine the anatomical development during storage; the remainder was used to determine the dry weight of the female gametophyte plus embryo during and after storage in moist vermiculite.

Results

Changes in cone specific gravity.—In the first week of June the cones averaged 15 cm. in length and had specific gravities of 1.01 to 1.50 (fig. 1). By the fourth week of June—at the time of fertilization—specific gravity had decreased to 0.91 to 1.00. After fertilization the cones elongated rapidly, and the final mean cone length of 35.0 cm. was reached by the fourth week of July.

Concurrently, the specific gravity of the cones continued to decrease gradually until the end of August, when this drop became more rapid. Cones having specific gravities as high as 1.00 to 0.96 were found until the last week of August, but cones of specific gravity of 0.80 or less were found only after the last week of August. By the time the cones began to open in October their mean specific gravity had dropped to less than 0.75. Specific gravity of mature sugar pine cones has been reported to be 0.80 or less.[9] [10]

Germination behavior of fresh seeds.—None of the seeds collected through the end of July germinated (table 1). However, some of the seeds collected during the second week in August did

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[7] Snedecor, G. W. *Statistical methods.* 534 pp. Ames: Iowa State College Press. 1956.

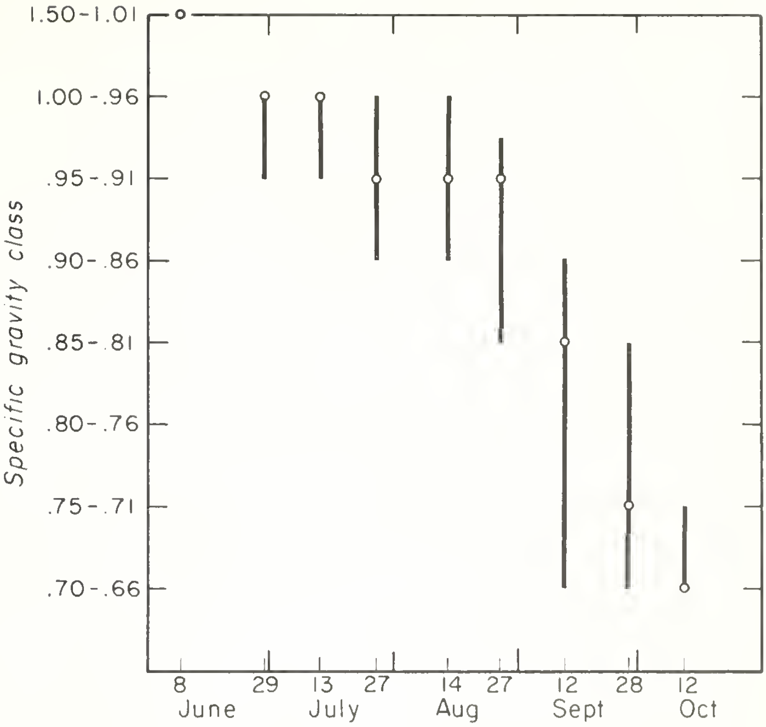
[8] Krugman, S. L. *Germination potential of sugar pine seed (Pinus lambertiana Dougl.) during maturation and associated biochemical changes.* 1961. (Ph.D. thesis on file at Univ. of Calif., Berkeley.)

[9] *Op. cit.*

[10] *Op. cit.*

Figure 1.—

Specific gravity of freshly collected sugar pine cones. The mode and range of specific gravity classes for each collection date are shown.



germinate. The inability to germinate, speed of germination, and incidence of abnormal germination were related to specific gravity of the cone. Only 3 percent of the seeds from cones having a high specific gravity germinated. And all of these seeds germinated abnormally. In contrast, 25 percent of the seeds from cones having low specific gravity (less than 0.91) germinated. And about half of these seeds germinated abnormally. Furthermore, 90 percent of the germination was completed only after 16 days.

The type of abnormal germination also varied with specific gravity of the cone. The most prevalent abnormality among seeds from the heavier cones was reverse germination. The cotyledons protruded first, rather than the radicle, and these seedlings died within 2 weeks. In some seeds, both the radicle and the cotyledons appeared, but radicle growth ceased in a few days. All of these seedlings were dead within 4 weeks of planting. In the most prevalent form of abnormal germination among seeds from less dense cones, the cotyledons grew through the female gametophyte, but remained tightly restricted within it. These seedlings died within 6 weeks of germination. Schubert[11] reported a similar type of abnormal germination in immature sugar pine seeds; Stone[12] encountered it in germinating mature sugar pine seeds that had been stored several years.

Germination of seeds collected August 27 was much better than germination of seeds collected August 14, and the seeds collected August 27 also germinated faster. Germination percentages of the seeds collected during the last week of August ranged from 67 to 82. Germination was 90 percent completed in 5 days, in contrast to those seeds collected on earlier dates. Abnormal germination was confined to seeds from cones having a specific gravity greater than 0.86. In the most prevalent form of abnormal germination, cotyledons were restricted within the female gametophyte. But only 40 percent of these abnormal seedlings eventually died, since the cotyledons would often grow out of the female gametophyte.

Germination of seeds collected during the second week of September increased slightly—ranging from 78 to 95 percent. All seeds collected in September that germinated did so normally.

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[11] *Op. cit.*

[12] Stone, E. C. *Auxin and respiration changes during stratification of sugar pine, Pinus lambertiana Dougl., seed and their relation to subsequent embryo growth.* 1948. (Ph.D. thesis on file at Univ. of Calif.)

Germination behavior of stored seeds.—Seed storage in the cone or in moist vermiculite increased germination significantly—compared to nonstored seeds of the August 14 collections. But storage had no significant effect on earlier or later seed collections (tables 1, 2). None of the seeds collected before August 14 germinated.

For the August 14 collections, seed storage in the cone proved a better ripening method than moist vermiculite. For all cone specific gravity classes, seeds stored in the cone germinated better than vermiculite-stored seeds. After August 14 there were no significant differences in total germination between treatments.

Rate of germination of stored seeds collected August 14 varied with specific gravity of the cone. All stored seeds from cones having specific gravities less than 0.96 had higher germination than fresh seeds collected at the same time (tables 1, 2).

Total germination (normal + abnormal germination) of seeds extracted from cones having specific gravities of 0.90 to 0.86 increased from 25 percent for fresh seeds to 56 percent for seeds stored in vermiculite and 74 percent for seeds left in the cone.

Normal germination increased from 10 percent for fresh seeds to 35 and 39 percent for seeds stored in vermiculite and in the cone. And storage in the cone resulted in some germination among seeds from all cone specific gravities. Only 3 percent of the fresh seeds extracted from cones having specific gravities 0.95 to 0.91 germinated, contrasted to 50 and 65 percent for these seeds when stored in moist vermiculite and in the cone.

Fresh seeds and seeds stored in vermiculite from cones of the highest specific gravity class (1.00 to 0.96) collected on August 14 failed to germinate. But after storage in the cone 25 percent of these seeds germinated.

In the most common form of abnormal germination among stored seeds, the cotyledons grew through the female gametophyte. However, unlike the abnormal germination of fresh seeds, a small percentage of these abnormal seedlings did sur-

Table 1.--*Type of germination of sugar pine seeds from cones with different specific gravities collected on various dates*

Collection date	Cone specific gravity	Type of germination	
		Normal	Abnormal
		Percent	
June 8	(1/)	0	0
June 29	(1/)	0	0
July 13	(1/)	0	0
July 27	(1/)	0	0
August 14	1.00 - 0.96	0	0
August 14	.95 - .91	0	3
August 14	.90 - .86	10	15
August 27	1.00 - .96	65	2
August 27	.95 - .91	80	5
August 27	.90 - .86	80	2
August 27	.85 - .81	79	0
September 12	.90 - .86	80	0
September 12	.85 - .81	78	0
September 12	.80 - .76	95	0
September 12	.75 - .71	84	0
September 12	.70 - .66	83	0
September 28	.85 - .81	80	0
September 28	.80 - .76	86	0
September 28	.75 - .71	93	0
September 28	.70 - .66	90	0

[1] No germination by seeds collected on these dates regardless of cone specific gravity.

Table 2.--*Type of germination of sugar pine seeds following ripening in the cone and in moist vermiculite at 10°C*

Collection date	Cone specific gravity	Percent germination after storage in...			
		Cone		Vermiculite	
		Normal	Abnormal	Normal	Abnormal
		Percent			
June 8	(1/)	0	0	0	0
June 29	(1/)	0	0	0	0
July 13	(1/)	0	0	0	0
July 27	(1/)	0	0	0	0
August 14	1.00 - 0.96	5	20	0	0
August 14	.95 - .91	40	25	20	30
August 14	.90 - .86	39	34	35	21
August 27	1.00 - .96	81	7	73	10
August 27	.95 - .91	82	0	84	9
August 27	.90 - .86	80	0	82	0
August 27	.85 - .81	86	0	76	0
September 12	.90 - .86	83	0	83	0
September 12	.85 - .81	86	0	80	0
September 12	.80 - .76	87	0	93	0
September 12	.75 - .71	85	0	86	0
September 12	.70 - .66	89	0	83	0
September 28[2]	-- --	--	--	--	--

[1] No germination by seeds collected on these dates regardless of method of ripening.

[2] Seeds of this date were mature and needed no further ripening.

vive. For seeds collected August 14, and stored in the cone, about 10 percent of the seedlings having abnormal germination survived. In contrast, less than 4 percent of abnormally germinated seedlings produced by seed collected August 14 and stored in vermiculite survived. There was no relationship between cone specific gravity and survival after an abnormal germination.

Anatomical development of fresh seeds.—During the first week of June the female gametophyte was almost completely cellular in structure, but the archegonia had not yet formed. By the last week of June, all stages from unfertilized archegonia to early proembryos were present within a cone regardless of its specific gravity. By the second week of July seeds from all cones included well developed proembryos and corrosion cavities (embryo cavities).

During the last week of July, seeds from all cones included some embryos composed of 100 o 200 cells. And the remaining portions of the archegonia had collapsed. The corrosion cavity occupied one-third to one-half of the female gametophyte.

Only in the August 14 collections were there differences between embryos extracted from cones of different specific gravities. The cones having the highest specific gravity (1.00 to 0.96) had significantly shorter embryos than cones of lower specific gravities (table 3). Their average length was 2.4 mm., compared to 3.8 mm. and 4.2 mm. for embryos from cones having specific gravities of 0.95 to 0.91 and 0.90 to 0.86. Of the seeds extracted from cones having the lowest specific gravity (0.90 to 0.86), 15 percent included embryos whose mean length (9.1 mm.) equaled that of embryos in mature seeds collected 2 weeks later. Thus, the 10 percent normal germination of fresh seeds from these cones could have been from this small portion of apparently anatomically mature seeds.

Anatomical development of stored seeds.—The female gametophyte of seeds collected before August 14 disintegrated within the first week after removal from the cone and storage in moist vermiculite, and within 2 weeks in the stored cone. In no instance did the embryos from the pre-August collections complete their development

Table 3.--*Embryo length of seeds collected August 14 before and after 50 days of storage*

Cone specific gravity	Mean embryo length[1]		
	At time of collection	After storage[2]...	
		Cone	Vermiculite
	Millimeters		
1.00 - 0.96	2.4	4.8	([3])
.95 - .91	3.8	6.3	5.3
.90 - .86	4.2	7.4	5.8

[1] A difference of 0.8 mm. is significant at the 0.95 level.

[2] Cones and seeds stored at 10°C.

[3] Female gametophyte and embryo disintegrated during storage.

after the seed had been removed from the tree.

In contrast, embryos from seed collected August 14 increased in length during both storage conditions (table 3). Seeds from cones with the lowest specific gravity (0.90 to 0.86) stored in the cone produced larger embryos than similar seeds stored in moist vermiculite. The smallest embryos found after storage were in seeds from cones having the highest specific gravity, 1.00 to 0.96. However, the final mean embryo length after both types of storage was less than the mean embryo length (8.1 mm.) from seeds collected during the last week of August.

Besides growing longer during storage, certain seeds of the August 14 collections became heavier (table 4). Seeds stored in their cones doubled their dry weight, but those stored in moist vermiculite failed to increase in dry weight. Differences in cone specific gravity did not influence changes in seed weight after seed storage.

Seeds stored in moist vermiculite increased significantly in embryo length and in their ability to germinate—despite their failure to increase in total dry weight. This difference suggests a shift in the available nutrients from the soluble or the storage form in the female gametophyte to the embryo.

By the end of August, the embryos had reached 95 percent of their final size. Any additional enlargement of the embryos during storage appears to be due to lengthening of their cotyledons; mean length of the embryo axis showed no increase. After this time no significant changes in the mean embryo length or dry weight of the female gametophyte and embryo could be related to cone specific gravity or storage condition.

Table 4.--*Dry weight of the female gametophyte and embryo from seeds collected August 14 before and after 50 days of storage.*

Cone specific gravity	Weight of gametophyte plus embryo[1]		
	At time of collection	After storage in[2]..	
		Cone	Vermiculite
	Milligrams		
1.00 - 0.96	77.2	155.3	([3])
.95 - .91	78.3	157.6	78.1
.90 - .86	76.5	156.3	74.3

[1] A difference of 21.2 mg. was significant at the 0.95 level.

[2] Cones and seeds stored at 10°C.

[3] Female gametophyte plus embryo disintigrated during storage.

Discussion

This study showed that a proportion of immaure sugar pine seeds harvested after a certain date ould be brought to maturity in storage. For these rtificial ripening treatments to succeed, the imature seeds must reach a stage of physiological nd anatomical maturity at which the seeds are o longer dependent directly on the tree for nutriion. In the 1959 study, sugar pine seeds had eached this stage of development by August 14. y then some seeds were no longer dependent for urther maturation on either the tree or the cone, nd were able to mature in vermiculite. Others ere independent of the tree, but still dependent n the cone; they failed to mature in vermiculite.

Whether storage of immature seeds collected uring mid-August is at all practical is questionble. Problems in artificial ripening were encounered with the August 14 collections. First, a high ercentage of artificially ripened seeds germinated bnormally. Perhaps a longer storage period would ave reduced this abnormal germination. Second, ones of all specific gravities collected on August 4 failed to open normally when dried after storge. Third, mold on the seeds was a serious probem in many of the cones, although mold formation as not excessive on the cone surface. This mold ormation greatly reduced the number of seeds vailable for testing and added to the variation in inal germination. The presence of mold definitely owered seed quality.

Cones collected during the last week of August or all 3 years of the study contained mostly ature seeds. Additional ripening of cones colected then eliminated the few immature seeds nitially present, and made the cones easier to pen by hand. Cones collected during the last eek of August and artificially ripened would open aturally if slowly air-dried at temperatures of 5°C.

The artificial ripening of seeds in immature ones harvested after the middle of August appears ossible in a commercial operation. But if this method is to be used successfully, the forest manager must first recognize that the rate of seed maturation can vary from tree to tree, locality to locality, and year to year.

Thus, past collection dates are of limited value as the sole measure of when harvesting and artificially ripening of immature sugar pine cones would be possible. However, the use of cone specific gravity can be helpful and can be used as a guide for seed maturity. In the 3 years of this study, cones with a specific gravity of 0.85 to 0.81 always held seeds advanced enough in their maturation to be artificially ripened in the cone. Fowells[13] and Schubert[14] both recommended that cones having a specific gravity of 0.80 or less be collected to obtain mature seeds; their recommendations were confirmed is this study.

Cones of specific gravities greater than 0.80 also can produce mostly mature seeds. But they can not be depended upon to yield only mature seeds consistently if they are opened shortly after harvesting. Additional moist storage of cones from the specific gravity class 0.85 to 0.81 or lower would make earlier collection to obtain mature seeds possible. This procedure would add several additional weeks to the cone collecting season. In addition, should immature cones be collected, it would be possible to ripen further the enclosed seeds.

The method of storage used in this study—cones in individual bags—would not be suitable for a commercial operation. Silen[15] used a method of storage for immature Douglas-fir cones that could also be used with pines. He obtained full germination from Douglas-fir seeds collected in the first week of August by storing the cones at 63°F. in damp peat moss. Such a method may be applicable to bulk sugar pine cone samples, and should be studied further.

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[13] *Op. cit.*

[14] *Op. cit.*

[15] *Op. cit.*

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Transport of Intercepted Snow from Trees During Snow Storms

David H. Miller

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Foreword

The West looks to winter snowfall for much of its water, and there is a good deal of evidence from Forest Service and other research that management of mountain lands for wood, forage and recreational amenities can affect the accumulation of snow into a long-lasting pack. Studies of the physical processes that influence this accumulation, however, have lagged behind empirical studies.

To help research workers interested in planning future basic studies, Dr. Miller has reviewed past research related to the basic processes by which intercepted snow is transported from tree branches during periods of snowfall—the second step in a complex chain of events that affect the accumulation and melting of snow.

This paper is the second of several reporting results of his investigation. The study was part of the cooperative snow research program of the Forest Service and the State of California Department of Water Resources. Valued aid has also come from the University of California at Berkeley, and from the U. S. Army Cold Regions Research and Engineering Laboratory.

—JOHN R. McGUIRE, *Director*

Contents

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The Author

DAVID H. MILLER has been studying problems in snow hydrology and meteorology for more than 20 years—in operations work of the U.S. Army Corps of Engineers (1941–43) and in research with its snow studies (1946–53), and with the U.S. Forest Service (1953–64). He earned bachelor's (1939) and master's (1944) degrees in geography and meteorology at the University of California at Los Angeles, and a doctorate (1953) at the University of California. Dr. Miller is now on the faculty of the Department of Geography, University of Wisconsin, Milwaukee.

Forest covers much of that portion of the earth that receives some of its precipitation in the form of snowfall. Yet iany questions about the amount of snowfall that enetrates forests to reach the soil surface remain nanswered. In some places, as Seppänen (1961) oints out, more snow accumulates in forest than n open locations, and in other places less; the elation differs in different years. The diversity of orms taken by tree groups, the diversity of forms f snowfall and of conditions in which it is devered to forest, and the inadequacy of sampling nd measuring techniques make it impracticable o settle the questions by direct measurement. Iowever, it has proved difficult to find simple but niversally applicable relations between snowfall i forested and unforested places that might serve urposes of prediction. This failure leads us to ispect that the action by which forest receives, itercepts, holds, and disposes of snowfall is not simple, unitary phenomenon but rather a series f events or processes, which require individual udy.

In this belief, I have in an earlier report (Miller 964) examined processes involved in the delivery f snowfall to forest, and continue in this paper by xamining five basic processes by which this intercepted snow is transported from the branches durg periods of snowfall. My aim has been to dermine the general magnitude and hydrologic gnificance of each process, and its response to onditions of weather, vegetation, and site.

Snowflakes deposited in the crowns of trees rm aggregations of all shapes and sizes, dependg on the streamlining action of the wind and the aracteristics of the supporting surfaces. Changes o not end with deposition; snow on the ground periences many changes in physical properties, id it is likely that accelerated changes are exrienced by small bodies of snow suspended in a oving air stream, freely exposed to a continuing change of mass and energy with it and with rrounding surfaces. The bodies of snow lose ass by attrition of the various media of transport, hich act through such mechanical forces as wind pressure and gravity and such thermodynamic forces as radiative and convective heat exchange. Wind pressure tears a cohesive snow body apart and distributes its fragments far downwind. Thermodynamic forces facilitate the transport of intercepted snow by changing it to a more mobile physical state—to melt water or to vapor.

Partial melting of snow that releases its hold on the branches and lets it slide off works faster than does melting that goes to completion, with concurrent removal of the melt water by stem flow or dripping from branch tips. Removal by evaporation requires still more heat than melting, but confers added mobility; vapor diffuses downward or upward from the zone of the tree crowns, depending on the gradient of vapor pressure and the intensity of turbulent mixing in the air stream. And vapor is carried farther from the original body of intercepted snow than is melt water or partly-melted masses of snow that slide to the ground.

Investigation of the processes of mass transport of water applies the principles of continuity (the water budget) and of conservation of energy in a system (the heat budget). These principles constitute two frameworks in which we can examine the complicated events involved in the transport of intercepted snow from tree crowns when snow is still falling.

This paper also discusses other kinds of data that fall outside the principles of continuity and conservation of energy, for the sake of the indirect information they can provide about the sizes of the mass-transport processes and the factors that influence them. There is, as Goodell (1959) states, a deficiency in "basic data to test hypotheses" and of suitable instruments. The data discussed here include measured or estimated weights of intercepted snow at the end of storms, reports of snow breakage and probable amounts of critical snow loads, and calculations of the difference in accretion to the snow mantle at sites in and near forest, involving certain errors inherent in such calculated differences. However, emphasis has been put on events occurring during single snow storms, rather than upon seasonal or yearly summing of end-products or other resultant effects. A wide range of research in peripheral fields of inquiry has been drawn upon in order to evaluat the mass-transport processes.

Wind Erosion

Air movement during snowstorms exerts mechanical forces upon intercepted snow by shaking its supports, eroding the masses of snow, blowing them off their supports, and transporting the fragments downwind. Snow masses are usually built up relatively slowly, but torn apart and blown away abruptly. Hirata (1929) notes that one reason for interception processes to differ between snow and rain is that snow readily falls off the branches. Assessment of the falling and blowing processes has, however, seldom been carried out in the field. Nor has it ever been done in wind tunnels, although the processes lend themselves to experimentation in controlled environments and might be understood by an extension of existing theory on snow transport by drifting.

Wind forces that act directly on snow masses in tree crowns are set in operation by large-scale and meso-scale motion systems in the atmosphere. This momentum is transmitted downward to the canopy and through it as a succession of micrometeorological flows and forces within the space occupied by tree crowns. However, it is not yet clear how existing knowledge of the spectrum of turbulent eddies in the air stream can be used to reconstruct the field of forces within the forest, nor how information about the drag of forest on air stream can be converted, with the aid of data on aerodynamic and mechanical properties of trees, into information about vibration as a factor in the removing of intercepted snow from the branches. Wellington (1950) shows that snow bodies in deciduous trees are often less affected by direct action of the wind than by its indirect action in shaking the tree crowns, which occurs with gust periods of the appropriate length. Eddies of somewhat greater length cause wind speed to alternate between quiet periods when snow accumulates and gusts that blow it away.

Salamin (1959, 1960) describes, with excellent photographs, intercepted snow in various shapes. He points out that if snow is held by conifers in form of cushions or balls, it falls less easily than does snow held by deciduous trees. If loose snow occurs in firs, it falls gently when it blows off the trees, and is more likely to be carried into an opening. He feels that most intercepted snow falls or blows off tree branches.

Heikinhcimo (1920) refers to the fact that tree below the cloud base receive snow unmixed wit rime, and are easily blown clear. Sakharov (1949 describes snow blowing from a spruce upper stor but not from spruce reproduction. Goodell (1959 found that only a third of the fresh, cold, dry sno intercepted by a spruce tree could be shaken ou of it, or about the same fraction of rain that Gra and Wilson (1944) could shake off a small pin Pruitt (1958) reports that a windstorm had onl minor effect on cohesive intercepted snow. A though we have no quantitative information eithe on cohesion of snow bodies or the erosion powe of wind on them, it should not be difficult to ge experimental data to extend existing theory o erosion of a snow cover.

Cionco's (1965) model for air flow in vegeta tion has an attenuation coefficient of the win speed profile down into the canopy that is relate to drag of the top surface. His model could pro vide a means of formulating the eroding power the wind on snow masses at different levels the canopy. This coefficient, however, depends leaf type, density, and rigidity—properties not y quantified for many kinds of forest.

A counterpart of wind action in plastering stic snow onto tree foliage is found in its transport intercepted snow, a phenomenon often remark and seldom measured. Snow masses cohere winds below a threshold speed, then may blow as clumps that do not completely disintegrate du ing the time they are airborne. Snow that develo strong cohesion can accumulate in masses lar enough to catch the wind; Morey (1942) c served that heavy accumulations are more likely blow off than light. Cramer (1960) made simi observations in a study of helicopter effects. Stro adhesion of snow to foliage resists blowing, a is affected by snow temperature.

From the only available data on wind effe (Govt. Forest Exp. Sta., Japan 1952), a criti speed for snow on an isolated tree in a relativ warm storm is reported as about 3 m./sec. T force removes the more vulnerable snow, ab half the total load. When wind rises to this sp during a storm, it blows intercepted snow off, is illustrated in the storm of February 19–22 (

in Govt. Forest Exp. Sta., Japan 1952), in which ind speed increased to 3 m./sec. between mid-ight and 0400 on February 20, and snow load ecreased from 10 kg. to 5 kg. When lighter winds ollowed, snow load increased to 21 kg. by 1000. igher wind speed near the end of the storm re-ulted in another decrease in load. Blowing of inercepted snow out of the experimental tree in 11 torms is shown (fig. 10 in Govt. Forest Exp. Sta., apan 1952) by a trend line from zero loss at a ind of 1 m./sec., to loss of half the intercepted now at 3 m./sec.

Takahashi (1953) notes that intercepted snow n the sloping branches of Cryptomeria does not ccumulate at wind speeds higher than 3.5 m./sec. f snow falls into a layer of quiet air near the surace, interception may be larger than in a mounain region that projects up into the moving stream f air. A peak that projects into the cloud level, owever, is in a region of riming and exposed rees become heavily loaded—though not with now alone.

From the Fort Valley studies, Pearson (1913) escribes the large deposits of snow in crowns of onderosa pine, especially in still air and when nowfall was moist. He found that the bulk of it lows off into the openings, less of it melting and vaporating; he ascribes deeper snow in the openngs to this effect. Amplifying this, Jaenicke and oerster (1915) mention occasional heavy deosits in the crowns that mostly blow off into penings, but report that there was no accurate easure of them.

In stands with high crowns, such as the virgin nes at Fort Valley, the wind profile often disays a secondary maximum in the trunk space, here large quantities of snow could be carried. forest types with many openings, a large downard transport of momentum would support rapid w-level wind speed and snow transport. In stands here a dense, continuous canopy separates the unk space from the free air, light air movement d slow transport of snow can be expected. kharov (1949) estimates that 25 to 30 per cent ore snow reaches the ground under a single-oried spruce stand subject to wind action than der a two-storied stand in which the under-story not shaken or exposed to wind action.

Snow blown out of tree branches differs from t original snowflakes because it has undergone canges caused by close contact. But the length of sy of snow in the branches and the changes occring during this time are not known.

Effects of Wind on Snow Loads

Some reports on snow-broken trees after heavy storms indicate the total effects of wind on snow loads as a composite of wind delivery to trees and transport of intercepted snow from them in particular topographic sites. Suominen (1963) made a study of a forest in southern Finland devastated in the winter of 1958–59 by snow loads that must have exceeded 30 mm over wide areas. Damage was determined by surveys made a few days afterward (Seppänen 1959). Suominen notes that trees at the edges of fields or lakes suffered less damage than those on lee edges or within forest bodies. In the belt from the edge to 25 m. within the forest, 41 percent of the stands escaped damage, but only 15 to 17 percent escaped in stands farther than 50 m. within the forest. Suominen's conclusion that silvicultural management had only a minor effect on the distribution of damage confirms the importance of exposure to wind. In stands exposed to a free sweep of wind, much of the intercepted snow was blown out of the crowns before it broke the trees. Exposure of windward-edge trees to additional impaction of snow was less important than exposure to the power of the wind to move snow from the crowns. This finding indicates perhaps, that in this storm a relatively minor role was played by adhesion of snow to branch surfaces.

Damage by snow breakage in a storm on the east shore of the Sea of Japan in December 1960 (Sugiyama and Saeki 1963) was heaviest to stands on lee slopes, especially if they were sides of valleys; less damage occurred to forest on plains, and still less to those on windward slopes. Trees on exposed edges of stands, mostly plantations, similarly incurred less damage than did trees on the lee sides and around openings. Although snow in this storm was of moderate density—0.10 to 0.12—and fell in "mild" winds at temperatures slightly below the freezing point, adhesion of snow on branches apparently was a minor factor in comparison with the effect of wind in removing excess snow load. Similar heavy damage on steep lee slopes was reported by Hirata and Hotta (1951) from a storm on the opposite side of Honshu, Japan.

Falling speeds and surface/volume ratios of the clumps of blowing snow determine how far the clumps will be carried in the air stream. Field research on wind during storms should provide a pattern for wind-tunnel simulations. Mesometeorological phenomena include long-period pulsations, which permit snow to accumulate and become cohesive in the quiet periods, and be carried away in the gusts, if cohesion does not become too strong. Pulsations of a period of several minutes are determined by the movement of storm cells in which kinetic energy is transmitted downward.

Wind in the trunk space, however it may be related to wind above the tree crowns, is the vehicle for transporting snow detached from the bodies of snow in the branches. Its turbulence affects how much snow it can carry as suspended load. The volume of solid particles in the air during blizzards on the plains is measured by drift meters near the ground, and this method is applicable to forest sites. Measures also can be made of such relevant properties as density, aggregation, and cohesion of the blowing clumps of snow. The transport of single snowflakes in the air stream above the forest canopy might be compared with the slower flow of larger particles in the stream below the canopy, for wind-tunnel modeling.

The height from which intercepted snow is blown affects its movement. High crowns give it a longer period of travel while falling and allow higher wind speeds, as is suggested by the notes on snow blowing made by foresters in the Fort Valley observations among virgin ponderosa pine (Jaenicke and Foerster 1915, Pearson 1913). Gay[1] notes a similar effect of canopy height in Australia, in studies of tall mature mountain ash *(Eucalyptus delegatensis)*, immature ash, and low snowgum *(E. niphophylla)*.

The duration of airborne transport of a snow fragment has a bearing on its evaporation while in this vulnerable situation. Diunin's (1961) experiments on evaporation of drifting snow particles may serve as models for work with blowing fragments. The larger particles have the advantage of greater effective size and a shorter period in suspension to reduce their potential evaporation.

Field observation of suspended snow particles suggests to me that a considerable amount of gravity flow takes place on slopes during snowstorms, and redistributes snowflakes as well as fragments of intercepted snow blown from branches. West's (1961) measurements of snow cover that was deeper (by 80 to 300 mm. more water equivalent) in downslope than in upslope sectors c small openings in forest, which he interprets on thermodynamic basis, seem to me also to be explainable as gravity flow of the density-curren type.

Mass transport in mosaic landscapes of tre groups and openings present a difficult problem i measurement. To the practical questions of performance and locating of precipitation gages a well as to a physical understanding of sno transport by wind, such measurements are basi The air stream receives snow fed into it intermittently from above, but deposits snow more o less continuously beneath it, where—as Diuni (1961) shows—it evaporates only very slowl The process is similar to that of a liquid curren traversing a region of alternating sources and sink of heat. This process might be useful in laboratory modeling of the situation.

Role of Forest Canopy

The role of forest canopy when snow is delivered to or blows out of it may resemble that c shelterbelts or screens of crop-plant stalks used t manage the winter-time distribution of sno drifted by the wind. If screens 60 to 80 cm. hig and 3 to 4 meters apart increase snow depth t 50 to 60 cm. and provide the most uniform cove would tree belts 3 to 4 meters high, 20 to 3 meters apart, be most appropriate for accumula ing snow in depths of 300 cm.—representative depths in many western ranges? Diunin's (1961 discussion of spacing of shelter belts and oth results of experiments with drifting snow on th steppes also has implications for management mountain lands. It may be possible to influen by changes during wind transport, not only th gross pattern of deposition of snow but also suc properties as its grain size, density, thermal co ductivity, and albedo.

The influence of forest on land outside th direct shade of its canopy is exerted through th snow-transporting process as well as by mov ment of heat and vapor; both forest and ope areas have to be included in a research site. A land managers tend to move away from gre acreages in pure stands of one species to me such other objectives as developing wildlife hab tat, forage, and recreational amenity, or to a commodate harvesting methods that create sma openings for regeneration, the question of th transport of blowing snow in mosaic patterns

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[1] Gay, L. W. *The influence of vegetation upon the accumulation and persistence of snow in the Australian Alps.* 1958. (Unpublished thesis on file at Australian Forestry School, Canberra.)

ree groups and openings becomes increasingly ital.

Snow that blows into openings in the forest or nto bordering fields (Baldwin 1957 and Morey 942, among many authors), increases the advan-ige of these places in collecting snow. Since phe-omena measured in openings have come under ne influence of forest, they do not form a true asis for comparison of forested and open areas. n forest stands with openings, blowing of inter-epted snow means that less snow falls to the forest oor. Hoover (1960) has asked, "How much of ne snow in the openings was blown off the foli-ge of surrounding trees?" and from this he ques-ons the "conventional emphasis" on snowfall in-erception in Rocky Mountain hydrology.

The finding that eddies smaller than 100 m. re the prevailing size in a snowstorm (Rogers nd Tripp 1964) suggests a critical dimension for penings receiving excess snowfall. This is in eneral agreement with the findings of Costin, *et* *l.* (1961). Exploratory work with a dense net-ork of wind sensors, including bi-vanes, in and bove trees of reproducible dimensions and pat-rns, would provide the fundamental background gainst which can be studied the processes of now transport themselves.

In studying the distribution of snow, it is neces-ry to study the whole forest. Tree groups and penings are interdependent members of the hole; interception in tree groups is affected by r circulation in nearby openings, just as inter-ption in openings is a function of the border-g trees. Snow that fell on tree branches may in e passing of the next eddy be blown away; snow at fell in openings is sheltered from the wind, d is less subject to being shifted around. In this change, the openings are not the losers.

Snow board measurements of snowfall were ade after each of five storms in the Beaver Creek sin, Arizona by Ffolliott, Hansen, and Zander (1965). In openings to the lee of a stand of uneven-aged ponderosa pine of 40-ft. height, the excess deposit of snow within 100 ft. of the edge was about 15 cu. ft. of water equivalent in a foot-wide cross-section extending outward from the edge of the forest. This mass represents more than an inch of water equivalent transported from the nearest 150 ft. of pine stand, and is a sizable fraction of the snowfall intercepted by the pines.

Research on snow drifting as a function of wind speed, turbulence, and surface roughness is applicable to the blowing of intercepted snow from the tree crowns. Wind-tunnel and water-flume (cf. Theakston 1963) studies that have been successful in determining the effects of shelter belts, fences, and structures on snow transport near the ground required correct simulation in the laboratory of particle size and density, turbulence-element sizes, and roughness factors. These studies also have determined the correct reproduction of the distribution of drifting snow with height, shelter belt or fence height, and permeability.

The study by Shiotani and Arai (1954) appears especially relevant to the problem of blowing of intercepted snow because they considered crown height, depth, width and other dimensions of the trees. Drifting snow differs from wind transport of intercepted snow in vertical concentration of the solid component, in particle size and density, in the manner of introduction of the solid flow into the air, and in the role of turbulent eddies in keeping particles in suspension rather than detaching and lifting them from the ground. However, with valid scaling, laboratory experiments will make it possible to develop an adequate theory of wind transport of intercepted snow from which could be determined not only the redistribution it produces in the water budget, but also the lengths of paths of blown fragments and the probability of their evaporating and undergoing other changes while airborne.

Intercepted Snow Sliding from Tree Branches

Intercepted snow may slide off tree branches thout wind intervention if the branches provide a unstable or slanting support. Bodies of snow anced on the ends of branches bend them into eply sloping surfaces or produce elastic de-mation. Because both situations are unstable, the branches tend to release potential energy and return to normal when disturbed. The triggering action may be the impact of snow falling from a higher branch, or the rebound of a lower branch that was suddenly unloaded, or rapid melting of the bonds holding snow on the sloping surface.

These events release an instability that becomes greater the more heavily the branch is loaded with snow, and the farther the snow is balanced away from the trunk of the tree. The resulting readjustment of the intercepted snow in a forest crown is continuous throughout a storm; bodies of snow are continually being built up and producing local instabilities that, almost at random, are released. At times, the snow on many elastically stressed branches all through the forest may be set off all at once by a gust of wind. But the most widespread releases of snow masses are caused by the simultaneous melting of the frictional bonds holding them on the branches. This transport process is important in heavy snow storms, but measurements of it are scanty.

Where snow falls from warm maritime air masses—as in Japan, Western Europe, and Western North America—it often falls through a layer of air that has a temperature above the freezing point. Experiments on intercepted snow in Japan (Govt. Forest Exp. Sta., Japan 1952; Watanabe and Ôzeki 1964) took place at air temperature up to +2 or +3 C; Ratzel (1889) and Aniol (1951), report that about 40 percent of snow in Germany falls at air temperatures above freezing; in the crest region of the Sierra Nevada in California, snow is reported at air temperatures to about 35° F., and a third of it falls at temperatures above freezing (Miller 1955, p. 25).

A snowflake survives its fall through the warm layer of air if it reaches the relative safety of the cold snow mantle soon enough. Its chances of survival are poorer when it remains in the warm layer of air, as it does when intercepted by tree foliage. For a time, heavy snowfalls accumulate faster than they melt, but a slight rise in temperature starts the melting of the accumulated masses, particularly at places where they are most vulnerable—the points of attachment to their supports.

Melting in the warm air at the level of the tree crowns may be increased by solar radiation, which is not always low during snowstorms. In the Sierra Nevada, daily amounts during storms often exceed 50 langleys (Miller 1955, p. 25), about one-sixth of the clear-day amount in winter, and enough to compensate for net loss of heat from the snow by long-wave radiation. Heat supplied by warm air and solar radiation during a storm is usually less obvious in complete melting of snow masses than in partial melting that lets them slide off the branches. The large decreases in snow load (Govt. Forest Exp. Sta., Japan 1952) that occur after the supply of relatively small amounts of heat indicate the sliding of partly-melted snow masses of the branches. In one storm, the snow loads decreased by 10 mm.in a few hours, in response t increased air temperature or solar radiation. Average decreases usually are smaller.

Though rapid, removal of intercepted snow b sliding is not instantaneous because it takes time t melt the bonds of adhesion holding the snow mas to the pendant branches, or to produce enoug free water to lubricate the zone of frictional contact. The cumulative effect is shown by the fac in some experiments that, although the total loa subject to sliding decreased for several hours, th hourly weight of snow released remained nearl uniform. This transport process did not displa an exponential decrease.

Heat Requirements

Sliding of partly melted masses requires relatively little heat, considering how much snow i transported. If it is assumed that melting of 2 percent of the intercepted snow releases the hol of the rest on the branches, hourly rates of decrease of snow load of 1 to 2 mm. represent a hea requirement, strategically applied, of 2 to 3 ly/hr By using potential energy stored when snow lie on sloping branches or imposes elastic loading o them, this mode of mass transport requires onl a small amount of thermal energy.

In one storm (shown in fig. 11 in Govt. Forest Sta., Japan 1952), during a day on whic snow fell with light wind through the dayligh hours and air temperature rose from —2 C to + C, the snow load on the Cryptomeria tree bein weighed, expressed in mm. of water equivalent decreased from about 25 mm. at 1000 hours t 2 mm. at 1500 hours. The rate of decrease wa linear, not exponential with time. In an averag of several storms that continued from night int the daylight hours, an average load of 8 mm. th had persisted from 0400 to 0800 decreased afte sunrise at an hourly rate of about 20 percent o the load still on the tree. Running between 1 and mm./hr., this high rate of transport probably reflects the influences of both insolation and war air.

Decrease in intercepted snow on the tree du ing daytime is related to insolation, which supplies some heat even while more snow is fallin Percentage loss of load in 13 storms plotted again insolation gives a graph (fig. 9 in Govt. Fore

Exp. Sta., Japan 1952) in which no storm falls elow an envelope line extending from the origin pward at a slope of 0.9 percent loss of snow for ach langley of insolation. This relation can be pplied to estimate the ratio of heat supply to mass ransported. With low radiation, the rate of loss f intercepted snow may be slow or fast, presum- bly depending on air temperature; with high radi- tion, it is always fast. (Air temperature was lose below freezing in all experiments.) If the ree had, on the average, an initial burden of 8 mm. of intercepted snow and continued to receive ew snow at a rate of 1 mm./hr., an hourly rate f net loss of 9 percent load corresponds, by the elation cited, to diffuse insolation incident at the ate of 10 ly./hr. Assuming absorption of 0.25 of he short-wave radiation and equilibrium in long-wave radiation, the cost of mass transport in adiative energy is calculated as 1.5 ly. for the re- ease of 1 mm. water equivalent. This ratio be- ween transport and insolation, with convective eat fluxes assumed to have no differential effect mong storms, confirms the statement postulated arlier that release of intercepted snow occurs fter about 20 percent of it has melted. Bodies of now in unstable positions on branches may be eleased after less melting has occurred; those on table supports may remain and melt in place for longer time.

When air temperature is slightly above freez- g, the joint effect of air temperature and insola- on can be approximated by examining the hourly ss rate of 20 percent of an 8-mm. load of inter- epted snow, cited earlier in this section, and esti- ating new snowfall at 1 mm./hr. The total loss f snow is then equal to 2.6 mm./hr. and its re- ase by 20 percent melting requires 4.2 ly/hr. If 5 ly./hr. represents the contribution of insola- on absorbed by the snow-covered tree, 1.7 ly./hr. presents the amount by which sensible-heat flux om air to snow exceeds latent-heat flux away om the snow.

In the storm of February 19–22 (fig. 3, in Govt. orest Exp. Sta., Japan 1952), the load of inter- pted snow on the tree remained constant at 2 mm. from 0800 February 20 through the rest the day, while snow continued to fall and tem- rature rose nearly to the melting point. After idnight, the air became cooler, and the load of ow slowly increased until daylight, when air mperature rose to the melting point. In the en- ing 6 hours, while light snow continued to fall, mm. of intercepted snow came off the tree—a rate of transport of nearly 3 mm./hr. Final disappearance of snow was associated with further warming to +4 C.

The effect of sensible-heat flux from warm air on disposition of intercepted snow is exerted jointly with that of latent-heat flux and condensation of vapor on the snow. High air temperature produces a steep temperature gradient from air to snow and a rapid flow of sensible heat. This heat is divided between melting and evaporating snow in dependence on vapor pressure, in accordance with the psychrometric relation. Since melting usually predominates over evaporation in this division of energy, and since it is more likely than evaporation to break the adhesion between snow mass and foliage, high air temperature usually favors the loosening and sliding of snow bodies. The study in Japan (Govt. Forest Exp. Sta., Japan 1952, p. 143) shows the role of temperature in rapid decreases of snow load during storms. In one storm, when air temperature suddenly rose 1 C.° above freezing, the loss of weight was 3 mm./hr. The decrease of weight, at first slow, then fast, suggests that a couple of hours of melting are needed before the snow masses begin to lose their attachments to the pendant branches of the tree. Takahashi (1953) reports that all intercepted snow drops off a tree with steeply sloping branches at air temperatures higher than +0.4 C., though not instantaneously.

Tree crowns are good media of heat exchange. Gates, Tibbals, and Kreith (1965) have derived coefficients of convective heat transfer from irradiated needles to air from wind-tunnel experiments, which show the effectiveness of this heat exchange. Similar experiments with broad leaves by Knoerr and Gay (1965) show that wind speed has a small effect on heat transfer, since the leaf-air temperature gradient changes in compensation. This compensation does not occur between air and snow.

As among the several processes of mass transport, the falling or sliding of intercepted snow is more likely to happen than removal by wind if air temperature is high. Blowing of snow is favored by low air temperatures, until the snow becomes cohesive or cemented to branches by refreezing after a brief warm period. Sliding of intercepted snow seems more closely associated with melting than with evaporation, which is slow to remove ice bonding the snow mass to the tree. Because melting is halted by low air temperature, the removal of snow by sliding is also reduced by low air temperature.

Heavy amounts of intercepted snow are likely to slide off conifers, according to Horton (1919), who compared conditions in winter and summer. Baldwin (1957) says that if accumulations are so heavy that they force spruce and hemlock branches to droop, the snow slides off. From his measurements in white pine, however, "the greater the fall of snow in any one storm, the higher the percentage intercepted." Branch stiffness of pine seemed to account for this difference.

The importance of transport of intercepted snow by partial melting and sliding from the branches is attested to by many studies. The species or varieties of trees that silviculturists believe to be well adapted to sites receiving heavy falls of wet snow and their meteorological corollary (rises of air temperature above freezing) are those with branch form that favors sliding. The Kammfichte—a variety of spruce—has a pendant habit, whereas the Plattenfichte—with stubby branches that support ice in glaze storms—is vulnerable to snow breaking (Anon., 1954). Watanabe and Ôzeki (1964) report smaller snow loads on *kumasugi*, a variety of Cryptomeria with branches that under load are depressed 20° or 30° below the horizontal, than on a variety with stiffer branches. Baldwin (1957) differentiates species that have stiff branches from those that droop enough to let snow slide off; pendant branches of a fir in the Rockies are termed an accommodation to heavy snow loads (Butters 1932). It is notable that these ascriptions refer not to a strengthening of the tree against snow but to a device by which potential energy can be easily released; the heavier the load has grown, the more easily it is released.

Sources of Heat

Heat supplied to intercepted snow during periods of snowfall comes primarily by convection, secondarily by radiation, and to a small degree by conduction. Convective heat flow is assured whenever air temperature lies above freezing, a frequent situation in many snow storms. At a temperature differential of 1 C., I calculate from wind-tunnel experiments on needles that provide data on the Reynolds and Nusselt numbers (Gates, Tibbals, and Kreith 1965) that a snow mass 1 cm. in diameter will receive a convective heat flow of about 5 ly./hr. If air filled with melting snowflakes can maintain a temperature of +1°C., this rat of heat supply will melt 0.8 mm. water equivalen per hour. The flux to larger bodies of snow i slower; otherwise, snow would melt faster than i accumulates on the ground in warm storms o mean snowfall intensity of 1 to 2 mm. water equivalent per hour. To the snow-shrouded tree of th experiments in Japan, the rate of heat supply b convection and condensation that I calculate earlier from the data on weight loss, 1.7 ly./hr., o which +3 might be sensible heat and —1 latent is consistent with the few data we have on convective heat fluxes to and from an isolated tree.

Heat flux to intercepted snow by long-wav radiation during periods of snowfall is probabl about the same as that emitted by the snow. I the short-wave lengths, winter measurements i the Sierra Nevada at latitude 39°N show that insolation on stormy days is about 50 ly. and midday intensities are 6 to 8 ly./hr. With an albed of 0.67, newly intercepted snow in the tree crown would have a net surplus of whole-spectrum radiation of 2 to 3 ly./hr., corresponding to a meltin rate of 0.25 to 0.35 mm. water equivalent pe hour.

Heat flow by conduction from the tree to intercepted snow occurs only if air temperature fall suddenly. If a cold snow storm following warm weather brings a temperature drop of 5°C., cooling of the biomass yields about 2 langleys, whic would melt the first quarter millimeter of sno to be deposited. As cold snow continues to fall the film of melt-water freezes and bonds the intercepted snow to the branches (cf. Heikinheim 1920).

Advective components of the heat supply t snow have, like the radiative components, been ir cluded in research on melting of the snow cove but mostly as residuals or in formulas with suc empirical coefficients as those for film heat transfer. These coefficients cannot easily be transferre to snow masses, with their small, irregular surfac areas. Advective heat transfer can be measure only by experimental instruments that are mo appropriate to large meadows than small sno masses. Instruments in engineering wind-tunnel research on heat transfer may be useful in questio of heat exchange between the solid surfaces of permeable medium and the moving air strea Heat transfer by condensation of vapor on th snow presents more complicated instrumentatio problems.

Stem Flow and Dripping of Melt Water

Melting of intercepted snow and subsequent removal of melt water during periods of snowfall by dripping off branch tips and flowing down the stems is minor in some forests and climates, large in others. If drainage through the branch system is adequate, the flow of melt water down the stems bypasses the snow mantle and enters the soil and perhaps directly into ground water; it enters a different hydrologic storage than the snow mantle represents—a storage from which there is less delay and more winter-time outflow into the streams than from melting at the surface of the snow cover.

The hydrologic implications of stem flow were recognized as early as the 1890's by Ney (1894, p. 18), who noted that drip of water from spruce branches corresponds areally to the shallow root plate, and that stem flow down a pine trunk can follow the tap root down to the absorbing roots. Melt water dripping from the ends of branches also has as much mobility as stem flow and may penetrate the snow mantle to reach the soil. Whether dripping or flowing occurs depends on branch form and attitude. Both forms at times represent important media of transport of water.

Measuring Stem Flow

Stem flow of intercepted rain is most commonly measured in summer, when heat is available to evaporate it as it moves along the drainage network of the tree. Consequently, the observed rates of flow near the ground may not indicate the amounts of flow generated in the crowns and may not correctly reflect winter conditions. Leyton and Carlisle (1959) stress the need for valid measurements of stem flow "during fog and winters with now." Stem flow and dripping of melt water from ntercepted snow are favored by humid, cloudy weather just above the freezing point. These same onditions favor melting over evaporation and lso represent weather in which much snowfall is ntercepted. In some climates, such weather is fre-uent in winter; Delfs (1954) speaks of long eriods in the uplands of northwestern Germany hen crowns of spruce remain wet and melt water asily becomes stem flow in measurable quantities, nd his later report (1958) over several years' ork confirms this. Eidmann (1959) reports stem ow in spruce as something less than 1 percent of recipitation. In relatively mild temperatures, Rowe and Hendrix (1951) found stem flow in pine to be about 3 percent of snowfall. In snow storms of six winters, stem flow averaged 1.5 mm. per storm. The heat required to produce this much melt water is 12 ly. per storm.

In deciduous trees, intercepted snow already lies *in* the drainage net, like rain that has fallen into stream channels; in conifers, it lies *on* foliage that slopes at many angles and may not connect with the central drainage network. Other hydraulic characteristics are the smooth bark of some hardwoods, such as beech. This indicates that only small amounts of channel storage are to be filled, and that channel roughness is small. However, Leonard (1961) reports that stem flow from northern hardwoods was negligible during snowfall periods.

In winter, stem flow is less likely to be measured than visually estimated at random, and often is assessed as negligible. But when air temperature lies near freezing and humidity may be so high that the melt water that corresponds to channel storage—the wetting value (Benetzungswerte) of branches and bark—is not evaporated quickly, then appreciable amounts of water may reach the ground by stem flow and dripping. The careful observations of stem flow by Hamilton and Rowe (1949) in chaparral during rain storms in which snowfall was occasionally intermingled led them to conclude that "snowfall appeared to decrease stemflow" during the storm. Because the periods of snowfall were usually "followed by intervals of rain in the same storm," they could not separate stem flow caused by melting of intercepted snow. However, since stem flow from rain was large, averaging 6 mm. per storm, the "decrease" mentioned might still indicate several mm. of stem flow in a snow storm and the succeeding rain.

Stem flow appears to be greater in marine climates, with large values of snowfall, heat supply, and humidity favoring the melting of intercepted snow. When heat is supplied to snow in the presence of high vapor pressure, evaporation is suppressed in favor of melting. Stem flow varies from winter to winter because of its dependence on storm temperatures and humidities, that is, the variable marine component in the climate. Rowe and Hendrix (1951) report that stem flow in pine varied from less than 1 percent of snowfall in one winter to almost 6 percent in another. No data are reported for individual storms, but the standard deviation of stem flow in the six winters was 1.8

percent. Stem flow varies over so large a range, from year to year, and from visual reports of "negligible" in some investigations, to measured values of several percent of moderately heavy amounts of precipitation in others, that estimates should be made with caution. There is need for more winter-time measurement of this transporting and distributing process.

Observing Drip

Dripping of melt water, like stem flow, is more often mentioned from casual observation than it is measured; subjective reports seem to be in conflict with the measurements that have been made. Is this a transport that by reason of its nuisance to field men is reported beyond its hydrologic magnitude? Or is it truly a means by which appreciable amounts of water move? The methods of measuring drip have been subjective and the sampling density required by the highly variable nature of the process is not known.

Drip observations should be accompanied by data on air temperature, humidity, and radiation; such information determines the relative roles of dripping, evaporation, and blowing in the disposition of intercepted snow. Methods of measuring stem flow are well known, although low temperature creates a problem. However, visual observation may not be adequate for deciding whether or not to set up stem-flow measurements, because stem flow is intermittent and may go unobserved.

Films of melt water on foliage are affected by its roughness, wetting coefficient, and geometrical pattern. These are parameters that have been considered qualitatively by students of rainfall interception. The subject of water films on foliage and bark might well be reopened where Horton (1919) left it, and in particular by use of such measurements as those Grah and Wilson (1944) made by weighing sprinkled plants. For example, their calculated depth of 0.08 mm. of water averaged over the total surface area of the foliage of young plants of *Pinus radiata,* when compared with similar measurements for other conifers, could be related to hydrophobic or hydrophilic properties of the surfaces; their laboratory determinations of removal by dripping and shaking are relevant to such questions of the disposition of melt water as: How thick is the film of melt water? How extensive is it, and how much water is stored in it? How does depth affect its movement, and how well does its movement correspond to overland flow, as related to detention storage on a drainage basin? How important are the surges in flow that some observers have noted, and how do they depend on bed friction? O'Loughlin's (1966) conclusion that evaporation from an entire draining film is independent of the rate of evaporation per unit area makes it important to record the recession of water flow in films following each surge.

Study of mass transport by dripping of melt water requires observations of water collecting into drops on needles, clusters of needles, and branches. Therefore, the relevant parameters of foliage and branches in this collecting process need to be identified and quantitatively expressed because the atmospheric factors that favor melting probably do not have much to do with the way melt water is partitioned between stem flow and dripping. The geometry of foliage—pattern, roughness, and occurrence of such blind alleys as drip points—is more important. Although laboratory experiments with foliage cannot be made as rigorously analytic as those dealing with well-measured atmospheric conditions, studies of individual trees or species will be inadequate unless each factor is quantified as well as possible. Bark roughness, for instance, should be amenable to methods for measuring roughness of machined surfaces or skin friction of pipes. The suggestion that Horton's indexes of stream-network dimensions might apply to tree crowns may provide a key to describing the characteristics of branch patterns that determine water collection and stem flow.

Perhaps it would be instructive to establish the conditions for maximum stem flow, that is, when most of the intercepted snow melts and when most of the melt water flows down the trunk. The effect of wind in shaking water loose before it can run to the trunk should be examined in terms of thickness of the melt-water film, with reference to such studies on rain interception as that by Grah and Wilson (1944). In the absence of wind, stem flow might be analyzed by unit-hydrograph methods, simulating values for water input, surface and channel storage in the drainage network, and outflow.

Examination of melting snow in place and the movement of melt water from it might be supplemented by surveys on the ground beneath, recording drip marks on the snow mantle, and collecting drops by the flour method to determine sizes and volume. In sampling with pans, drops would be separated from clumps of unmelted snow and snowflakes; in addition, the erratic areal distribution of dripping melt water requires a high sampling density.

Questions of mass transport in liquid state include determining the rate at which the film of melt water in tree crowns is generated, how thick and extensive it is, how it is directed into dripping or stemflow, and how these phenomena are related to heat supply, wind speed, and the properties of a tree crown as a collecting and concentrating network. Laboratory experiments do not appear complicated, and much information from research on the disposition of intercepted rain water may be transferable to this problem.

Vapor Transport from Melt Water

Observations of evaporation during storms of the film of melt water derived from intercepted snow are generally lacking. This fact derives from the lack of observations in tree crowns and also from the infrequent development of the phenomenon itself.

The conditions for evaporation of melt water during snow storms are unusual: generation of water from the snow, and heating it enough to produce a vapor pressure higher than that of the air, which, in the circumstances that favor melting, is likely to be high. Evaporation requires much heat, which is not easily obtained while snow is falling. The whole-spectrum radiation-flux resultant is close to equilibrium. And convective heat flux is limited by an air temperature unlikely to exceed +3 C. during snowfall and a wet-bulb temperature that cannot exceed 0 C. in air coexisting with snowflakes. Vapor pressure of the air is then 5.7 mb., only slightly less than that of a film of water at 0 C. (6.1 mb.); accordingly, while evaporation would occur, supported by sensible-heat flux from air to water, neither the sensible-heat nor the latent-heat flux between air and melt-water would be larger than those between the air and adjacent bodies of unmelted snow. Unless appreciable amounts of radiative heat, more greatly absorbed by the water than by the snow are received, melt water and its generating snow bodies evaporate equally slowly, both being restrained by the limit set to convective fluxes by the psychrometric relation.

However, an advantage of the melt-water film over the snow as to evaporation may lie in its greater surface area; many observers, including Delfs (1954), have stressed the extensive areas of wetted surface. But large areas may result not only from the mobility of water flowing from many well distributed bodies of snow, but also from slowness of the rate of evaporation from it. It seems clear that laboratory comparisons of evaporation of melt water with its movement as a liquid need to be made in a few typical conditions of air temperature and vapor pressure, under typical values of insolation up to 10 ly./hr. Increasing amounts of radiant energy widen the gap between snow bodies and melt water as to evaporation, but presence of the storm clouds sets upper limits to the role that radiation can play.

Area of the melt-water film and shape factors representing its complex form and distribution may be determined by study of data on evaporation of intercepted rain that are being developed in the revival of research on interception in England (Rutter 1963). The possibility that evaporation of melt water, which is usually a small mass-transport factor, might become important in special conditions of weather and tree form, warrants the separate discussion it has received here. The briefness of the discussion indicates the present lack of information from field or laboratory.

Vapor Transport from Intercepted Snow

Evaporation directly from intercepted snow into he atmosphere while snow is falling[2] has not to my knowledge been measured or observed. Evaporation is hard to measure in any situation; in tree crowns the problems are multiplied. Methods of estimating evaporation are adequate in only few situations, least of all in forest, where there is "need for a more direct method of measuring the

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[2] The occurrence of evaporation after a storm or in reaks between periods of snowfall represents a different ieteorological situation from that considered here, and ill be considered in a later publication.

losses in vapor form from intercepted snow," because snow can leave the canopy in different ways, among which "it is extremely difficult to isolate the loss caused by vaporization" (Goodell 1963). Wind-tunnel experiments on this process apparently never have been undertaken, nor has the vapor flux upward from a snow-bearing, as distinguished from a rain-wet or transpiring forest canopy been measured. However, a review of some facts about evaporation from other surfaces and in other environments may be helpful in discussing factors that influence evaporation from intercepted snow.

The low vapor pressure of snow does not promote a large vapor flux from it, particularly when the vapor pressure in the air is nearly as large as that of the snow surface, as is true during storms. Insolation penetrating the storm clouds is likely to be absorbed by the falling snowflakes and provide energy for their evaporation, that will humidify the air below the cloud close to saturation. The intercepted snow has neither a special radiative or convective heat source strong enough to raise its surface temperature and vapor pressure much higher than air temperature and vapor pressure.

Cold, humid air does not provide a large supply of sensible heat for the evaporation of intercepted snow, and air full of falling snowflakes cannot be other than cold and humid; both conductive and radiative heat sources are small.Diunin (1961), in the most complete study to date on the evaporation of snow, reports experimental findings that can be related to intercepted snow, although his primary concern was with evaporation of blowing snow during blizzards. The reason that less snow accumulates in forest than is removed from open areas of west Siberia is that some evaporates during transport by wind. Diunin formulated this condition in terms of the psychrometric relation, including measurements of the diffusion layer and form coefficients, and made extensive experiments in controlled-environment chambers on snow surfaces, blocks, hemispheres, and particles of many shapes, as well as in wind tunnels on snow surfaces. In quiet air, evaporation in a month was measured as 1 to 2 mm. per mb. deficit in vapor pressure of the air. (A saturation deficit of about one-half mb. is typical of most snow storms.) From Diunin's wind-tunnel experiments on snow surfaces, I estimate that at a wind speed of 4 m./sec., measured 5 cm. above a snow mass, the quiet-air value of evaporation is increased about 20 times; daily evaporation during a snow storm, if the saturation deficit remained 0.5 mb., would be 0.7 mm.

Particles blown from the trees and carried in the wind stream experience only slight motion relative to the air, but their small size favors evaporation, until they come to rest on a surface again. Diunin concludes that evaporation of suspended snow particles is common enough that some lands should be reforested in order to shorten the paths of drifting, reduce evaporation of drifting snow, and restore regional water budgets.

Diunin's experiments on evaporation were conducted in blizzard conditions in which dry air from higher levels of the atmosphere can replace air that has become saturated from evaporation of the drifting snow. The experiments do not take the place of measurements in snow storms, when a deep layer of air is near saturation and the snow-bearing forest canopy is not the sole source of vapor. They do, however, form the basis for a tentative conclusion that vaporization of intercepted snow during periods of snowfall is not large.

Further work on this problem may also follow the lines of Nordon's (1963) study of convective transfer of water in a permeable medium, and of forest research by Denmead (1964) and Anderson (1964) on the penetration of convective and radiative energy into forest as a porous medium. For example, Denmead measured downward sensible-heat flux into a plantation of 5.5-meter *Pinus radiata* near Canberra, Australia, under conditions of a slight inversion on an afternoon in May when the net surplus of whole-spectrum radiation at the canopy top was 5 ly./hr., and found it to be about 2 ly./hr. His calculations of the vertical distribution of the latent-heat source in the stand of trees, which corresponded in his study to transpiration but in a snow-bearing stand would correspond to evaporation and melting, show that its maximum rate, located about 1 meter below the forest top, was 4×10^{-2} cal/cm.^{3} hr. If the branches hold bodies of snow of density 0.2 that occupied 0.1 of the stand volume, one body weighing 1 gram would be found in each 50 cm.^{3} of the crown volume, and would yield 1.8 cal./hr. of latent heat, equivalent to evaporation of $1.8/600 = 0.003$ g. of mass in an hour. If the whole-spectrum radiation surplus were taken as 2 ly./hr. for storm conditions and the sensible-heat flux the same as in the situation where Denmead measured it, the latent-heat source through the stand would average 0.8 × 10^{-2} cal./cm.^{3} hr. through the 5-meter depth of the pine crowns, and the rate of evaporation from a body of one gram of snow would be 0.0006 g./hr. In a column of 1 cm.^{2} cross-sectional area through the stand, 4 ly./hr. would be available to melt or evaporate snow. Assuming that the air is dry enough to permit evaporation, 0.007 g. of water equivalent would evaporate in an hour, that is, 0.07 mm. from the entire snow-laden forest canopy. The 24-hour average would be less than these figures, because the radiation surplus would be zero or negative at night; total evaporation in a day would approximate 1 mm., considerably less than the estimates I made some years ago (Miller 1961) on the basis of less complete information about the fluxes of sensible heat and radiation into forest. These estimates of evaporation of intercepted snow on the basis of heat supply would also apply to evaporation of melt water. They do not deal, however, with the problem of partition of heat between evaporation and melting. As in the deductions from Diunin's results, there remains a question whether or not the air would continue dry enough to permit evaporation to continue throughout the storm.

Vapor flux upward from a snow-laden canopy is similar to that from a transpiring forest or crop. The forest in a snowstorm, however, has a far smaller surplus of radiation, and the upward flux of latent heat depends more than it does in most crops upon the downward flux of sensible heat. The recently perfected "evapotron" (Dyer and Maher 1965) should prove valuable in field observations of vapor flux from forest stands of uniform roughness that are extensive enough to provide suitably long fetches of the air stream.

Vapor flowing from intercepted snow is both mixed upward into the free air and condensed on the snow surface on the ground of forest and adjacent open areas. The exact division is not known but could be determined by analysis of the fields of temperature, vapor pressure, radiation, sensible-heat and latent-heat flux above, in, and below the forest canopy. Vapor pressure is critical in determining the equilibrium between melting and evaporation of a body of snow acting as a wet bulb, and should be precisely measured at various levels in the crowns while the storm is in progress.

Diunin (1961) emphasized the vital need for "experimental, laboratory, and field" investigations into snow evaporation in general, and his recommendations apply to this particular problem. Micro-meteorological measurements in laboratory models and in large areas of uniform forest crowns during snow storms are essential to this perplexing problem.

Mass Transport Processes and Their Residues

The snow load on trees results from continuous delivery of snow to the branches and continuous removal by the media of transport (table 1). Data on size or weight of the residual snow load conveys no unique information about the separate processes of delivery or removal. But determining snow load under conditions that minimize some of the transport processes may give useful indirect knowledge of the others. As an illustration, the measurements of weight of a snow-loaded tree during storms (Govt. Forest Exp. Sta., Japan 1952) show abrupt decreases that can hardly be due to evaporation, or to stem flow or drip of melt water, and at the recorded wind speeds probably not to blowing of snow; they were no doubt caused by sliding of snow from the pendant branches, and their association with rises in air temperature shows the bearing of temperature on adhesion.

The difference between buildup of intercepted snow and its removal from the tree crowns is altered during nights when temperature is around freezing and air is calmer than in the daytime. These circumstances, according to Shidei (1954), favor "remarkable" growth of the snow load, especially after the snow has bridged gaps between the small branches and coalesced into a single sheet that envelopes the tree. Delays in this bridging action account for irregularities in the trace when weight of load, as recorded by spring tension on a deflected branch (Kataoka 1954), is plotted against accumulated snowfall. From lapsed-time photographs of white pine, Lull and Rushmore (1961) found that "snow accumulated on the needles, beginning at the bases of several needle fascicles, and later bending them over to form a platform."

Some indications regarding the amounts of snow in trees at the end of a storm are given by

Table 1.--*Processes of transport from intercepted snow during storms*[1]

Weather element	Transport by--				
	Falling or blowing of dry snow	Sliding or falling of partly-melted bodies of snow	Dripping or flowing of melt water	Vapor flux from melt-water film	Vapor flux from snow
Wind speed	++ a	+ b	+ b, c	+ d	+ d
Air temperature		++ c	+ c	+ d	+ d
Vapor pressure		+	++	-	--
Insolation		++	+	+	+ d

[1] + indicates an element of storm weather that favors a mode of transport from the crowns; ++ indicates strongly favors; - indicates an element of storm weather that discourages a mode of transport from the crowns; -- indicates strongly discourages.

a = Effect of wind is conditioned by the rate at which masses of intercepted snow are streamlined and wind packed, or develop internal cohesion.
b = Conditional on air temperature being above 0°C.
c = Conditional on air being near saturation.
d = Conditional on low vapor pressure in air.

Table 2.--*Snow deposits on wood dowels at end of several snow storms, near Fairbanks, Alaska*[1]

Date	Snowfall	Width of dowel	Length covered	Depth
	Cm.	*Inches*		*Cm.*
Nov. 21	16	11/16 and larger	full	4
Dec. 5	6	3/16 and larger	full	3
		2/16 and 1/16	quarter	1
Dec. 19	10	9/16 and larger	full	3
		8/16 to 3/16	full	2
		2/16 and 1/16	quarter	1
Dec. 26	0.2	14/16 and larger	full	1
		13/16 to 9/16	quarter	1

[1] Data scaled from graph in Pruitt (1958).

Pruitt's (1958) measurements of depth and lengths of deposited snow on dowels of different sizes (table 2). Depths of 3 to 4 cm. far exceed the widths of the deposits; appreciable depths of snow were found on supports as narrow as 0.3 cm.

Maximum depths of snow on branches of several species of conifer (Lull and Rushmore 1961), presumably occurring at the ends of storms, were 10 to 11 cm. on balsam fir, spruce, and hemlock, and 16 cm. on white pine. Goodell (1959) weighed a 4-meter spruce tree after a snow storm of 10- to 11-mm. water equivalent and found a load of 16 kg., which corresponds to 5 mm. water equivalent if the crown projectional area of the tree is taken as 3 $m.^2$ Higher loads are reported in wet snow storms, such as 25 mm. (Costin, *et al.* 1961) in *Eucalyptus dalrympleana.* Some silvicultural studies of snow breakage report the weights of snow that caused the damage, but the method of measurement is seldom stated and the rounding of values suggests that they are estimates; however, even estimates are valuable if they refer to critical values (Bühler 1886, Rosenfeld 1944).

Information on snow loads at any given time in a storm usually can be obtained by shaking snow off small trees or blowing it off by a helicopter onto plastic sheets and perhaps melting it by a heater to permit measuring it in tanks. More basic data, however, would be gained if the bodies of snow in tree crowns were to be observed as entities to be enumerated in order to determine distribution by size, and dispersion through the crown space. Particular attention would be given to exterior or interior location, in analogy to the sun and shade leaves in studies of transpiration and its distribution through the crowns.

Snow Breakage of Trees and Their Responses

If intercepted snow is removed slowly, the accumulation in the branches during a storm may put excessive stress on a tree, especially as multiplied by the lever effect of a crown on a tall stem and the increase in sail area of the crown. Some factors in interception, unfortunately, are ambivalent; high winds, for example, may remove snow as fast as they deliver it, or, in other circumstances may produce heavy loading of the crown if the snowflakes adhere to sloping surfaces. For this reason, information on snow damage to trees does not have direct value in studying interception processes; such indirect value as it may have, however, should be used.

The weight of snow critical for a tree of a particular species, age, and growth form is not easily determined because silvicultural reports of snow breakage do not usually include information that can be interpreted in terms of amounts of intercepted snow. For example, Naegler's (1940) report of heavy breakage in a storm with 50-mm. precipitation gives only a general upper limit of interception; it does not tell how much of the snowfall remained in the tree crowns, or whether, in fact, the trees may have incurred additional loading from horizontally-driven snow not recorded by the precipitation gage.

In a critical analysis of many reports of snow breakage in forests of western Honshu, Saeki and Sugiyama (1965) developed three conditions for heavy snow damage: (a) snowfall at a rate of more than 20 cm. depth per day; (b) air temperature varying between −3° C. and +3° C. between night and day, which ensures high density and strong adhesion of the snowflakes; and (c) a relatively small value of mean maximum depth of snow on the ground in the region, expressing the premise that tree strength where deep snow is unusual is likely to be small. Frequency of critical loading per decade was mapped, showing extensive areas of three occurrences per decade, and small areas of lee slopes presenting still higher hazards. These conditions of heavy interception embody a high rate of delivery and absence of blowing or sliding to remove intercepted snow. At high rates of delivery, evaporation can have only a minor effect; if air temperature drops below freezing at night, melt water will not accumulate in amounts large enough that transport by stem flow, dripping, or evaporation would remove much of the snow load. In the weighing experiments carried out by other investigators in Japan on single trees, some snow-removal process usually intervened before a damaging load was reached; but in a closed forest these transport processes do not operate so effectively—especially on lee slopes.

Delfs (1958) reported that snow breakage—although apparently not to a catastrophic degree—occurred in the spruce stands he studied when a loading of 20 to 30 mm. water equivalent was reached with wet snow. More commonly, he reports depth of snow on the branches as 8 to 10 cm., suggesting that the snow load did not usually exceed 10 to 12 mm. water equivalent. More damage occurred on exposed edges than inside the stands, as reported for thinned jack pine by Godman and Olmstead (1962). This finding suggests an augmentation of the measured 30-mm. water equivalent of the snowfall by horizontal precipitation of the type described by Slatyer (1965) at edges of groves of trees.

Attempts to deduce information about intercepted snow from reports of its effects on trees cannot be pushed very far because silviculturists cannot draw reasonable conclusions even about tree factors from snow-breakage reports unless they know the history and management of the stand and the concurrent weather (Hoffmann 1964). These data usually are not available to the hydrologist either. If complete data were at hand on all conditions surrounding a significant snow breakage event, they could be analyzed from an engineering standpoint to obtain information about intercepted snow, by using such concepts as those of Doerner (1965), who described deflection of a conical tree in terms of vertical loading on the trunk and lateral force on the crown. Both factors would be increased by intercepted snow; conversely, data on the moment of inertia and modulus of elasticity of a trunk that had broken under a snow load, and on crown area and weather, would permit calculating the loading critical for a given tree and, hence, the upper limit of interception. The probability of such an extreme event could be evaluated from weather data by methods like those of Saeki and Sugiyama (1965).

The effect of the weight of intercepted snow on trees is indicated in Hoover's (1962) comment about factors that tend to increase the size of the snow load: the leaf area, rigidity, and arrangement of the receiving surfaces. Said he: "Trees with dense stiff foliage, horizontal or upturned stiff branchlets, considerable vertical spacing between branches, and closely crowded together, hold a maximum of snow in their crowns. The fact that trees of that type suffer greatly from snow breakage indicates their efficiency in holding snow."

Trees that are often heavily loaded are thought to develop evasive forms, such as pendant branches that let snow slide off if it is heavy enough to bend them down (Delfs 1955; Iashina 1960). Trees in a region with deep snowfalls propagate from these pendant lower branches (Takahashi 1962). Rusanov (1938) states that winds accompanying the rare snowfalls in the deserts of central Asia prevent snow breakage of saxaul (*Haloxylon ammodendron*) shrubs and permit profuse branching; Watts[3] believes that snowfall is a limiting factor in the unusual areal distribution in California of digger pine (*Pinus sabiniana*), a tree with open foliage but a broad crown and forked branching. Similar comments are often found in the literature, but are not detailed enough to outline the critical frequency-loading relation that produces a particular response in a tree. Although a tree may tend to adjust to a certain frequency of snow loading, many do incur snow breakage. Is it the occurrence of several heavy snow storms per winter, or the extreme fall once in several decades, that affects genetic selection of tree form? Without such information, form alone cannot serve as a very precise index to either frequency or amount of interception. Because evidence from tree form is inconclusive, the question of evaluating the processes of transport of snow must be resolved by measurement in the laboratory and in the field.

Differences in Accretion to the Snow Mantle

An indirect means of estimating intercepted snow in a forest canopy at the end of a snow storm has been the comparison of accretion to the snow mantle produced by the storm in and near the forest. This method encounters the difficult problem of securing accurate measurements of any atmospheric or atmospherically-carried property above or in forest that are not influenced by the proximity of openings, or near forest stands that are not influenced by their proximity. Until these problems are solved, the interpretation of data on accretion to the snow mantle is biased

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[3] Watts, D. *Human occupance as a factor in the distribution of the California digger pine.* 1959. (Master's thesis on file at Dep. Geog., Univ. Calif., Berkeley.)

to an unknown extent by the wind field and other conditions during snowfall. However, it is desirable to examine some of the available data to see what indirect information can be deduced about qualitative characteristics of the interception processes.

Rauner (1963) concluded that a forest stand narrower than 2 or 3 km. does not have a climate independent of its surroundings. Observations of snow transport by wind suggest to us that separating the dichotomy, forest vs. open, is as difficult in the case of snow as with heat or vapor in the air. Rainfall is more easily measured than snowfall, yet Bleasdale (1959) questions the validity of measurements of it made in forest openings, where additional turbulence in the air stream is evidenced by prevalence of damage at forest edges. Leyton and Carlisle (1959), recommend against ground-level measurements in forest openings, saying that

> . . . true interception can only be defined in terms of precipitation incident on the canopy. It is well known that this may be very different from precipitation in the open at ground level, especially if one includes snow and ice.

With specific reference to snowfall in a mosaic of forest bodies and openings, Hoover (1962, p. 36) points out that

> The great difficulty of obtaining exact values for incoming snow hampers comparison of snow accumulation between kinds and arrangement of tree cover as well as comparisons of open with tree-covered areas. There are no snow gauges unaffected by wind and, to date, no way of accurately measuring incoming snow when wind velocities exceed a few miles per hour. Comparisons based on the amount of snow on the ground almost invariably show more snow in openings than under the crowns but leave unanswered the following questions:
>
> 1. Is the excess in the opening a result of evaporation of snow from tree crowns?
> 2. Was intercepted snow merely blown, or shaken off, into the opening?
> 3. Did the wind eddies due to the surrounding tree crowns cause excess snow deposition in the opening?

Processes Producing Differences

Measurements of differential accretion to the snow mantle in and near forest beg the question of evaluating the physical processes of mass transport that produces the difference, and remain inconclusive, in particular as long as the input of snowfall to the forest remains unknown. Furthermore, if snow gages are considered inaccurate instruments, or, in Wilson's words (1954) "the deficiency in catch due to interception by the forest canopy is small compared with that due to wind," then elevating a snowfall gage to the upper surface of the tree crowns may not provide a better measure of actual delivery of snow. For this reason the validity of comparisons between accretion to the snow cover in forest and that to the snow cover in adjacent open areas, here called △A for brevity, fluctuates with exposure of the forest body and the floor of the opening to winds changing during the progress of a storm. It also fluctuates with other factors influencing the trajectories of snowflakes nearing the ground; a smaller fault, mentioned by Costin, *et al.* (1961) is that the melt-water going into the ground is not detected.

After it became clear to early investigators that a single sample cannot give an accurate estimate of accretion of snow to the forest floor, more samples were used to improve the estimate, and in some studies also to indicate variation from place to place. Some measurements of accretion at each sampling site have been found related to crown coverage immediately above; vertical transport processes such as drip off the branch ends are then dominant over horizontal transport. In other investigations, such as by Rowe and Hendrix (1951), the small sector of canopy directly above each catchment site had little specific relation to accretion, although the yearly sum varied from 700 mm. to 1440 mm. Kittredge (1953) found crown coverage above each sampling site closely related to accretion in only one type of forest—the cut-over mixed conifer stand, although cover provided a useful means of stratifying the measurements in all stands he studied.

A heavily replicated sampling program in the Soviet Union (Luchshev 1940), which used gages, illustrates variations of snowfall in pure spruce 18 m. tall (50 gages) and in aspen with a 10-m. spruce understory (30 gages). The variations were expressed as the average difference from the mean in each stand (table 3). The average error among gages under the canopy is several percent of storm precipitation, and is larger when snow is wet than dry.

From Leonard's (1961) means and coefficients of variation of catches in five gages in each of three plots of northern hardwoods, in nine snow storms exceeding 8 mm. and averaging about

Table 3.--*Average difference, in mm., of individual snow sampling gages from the mean, by type of forest stand and size of storm, in mm.*

Stand	Precipitation as dry snow			Precipitation as wet snow		
	2-5	10-15	15-20	2-5	15-20	> 20
Spruce	0.1	0.2	0.4	0.1	0.4	0.5
Aspen/spruce	0.2	0.6	0.6	0.1	1.0	0.9

Source: Luchshev, 1940.

15 mm., the standard deviations can be calculated as about 2 mm. Leonard ascribes some of the variation to the circumstance that large accumulations of snow in the branches might or might not fall on a sampling site in a given storm.

Several kinds of water substance reach the ground in and near forest. Snowflakes fall directly from the atmosphere, small agglomerations of loosely-cohering snow drop from nearby branches, fragments of snow bodies of more coherent structure are blown from distant branches, chunks of snow melted at planes of adhesion to a branch slide off, melt water drops to the ground, and crystals condense from vapor. Snow that has descended directly from the clouds is, unless driven by wind, the same wherever it lights, but snow that has rested on tree branches has experienced more or less radical changes during its arboreal phase. It may have been consolidated by wind action, or partly melted, or otherwise metamorphosed. To understand the hydrologic significance of accretion to the snow mantle, the different qualities of snow transported in each fashion need to be separately measured and related to storm weather. Comparisons of kinds of accretion in different winters and regions might indicate the relative importance of the major processes of snow transport during storms, and elucidate the roles of wind and temperature.

Forest Types Producing Differences

A few paired measurements of snowfall accretion in and near forest stands in individual storms may be cited to indicate the general level of △A, in mm. of water equivalent. These data do not group themselves well by species, age, or other putative biological factor in interception. And they are accompanied by too little information about physical dimensions of the measurement sites to make a logical grouping possible.

Bühler (1918) cites differences in snow depth after a major storm in 1884. Assuming a snow density of 0.1, his findings show △A values of 25, 23, 29, 20, and 15 mm. in stands of spruce of ages 15, 25, 40, 50, and 90 years, respectively. This storm broke many trees, as the large values suggest. Bühler did not consider the values precise, since he states that snow may be carried long distances by the wind into a gage.

Measurements in virgin ponderosa pine of northern Arizona, made by silviculturists at the Fort Valley experimental forest, Arizona, more than 50 years ago, record values of △A in several years. Mattoon (1909) reports greater deposits of new snowfall in forest than in the open "parks" or treeless tracts, △A being —2 mm. in one storm. Pearson (1913) sums up the storms of four winters, reporting △A larger in midwinter than in spring. Jaenicke and Foerster (1915) report individual storms of two winters. In 1910–11, △A in 13 storms averaged 0.7 mm., nearly half of the storms having zero or negative values. In 1912–13, △A in 30 storms averaged 0.03 mm., 26 storms having zero or negative values. The authors grouped their forest stations according to shelter afforded by the groups of pines. Mean values of comparison between accretions to snow cover in forest and to adjacent open areas were as follows:

	1910–11 13 storms	1912–13 30 storms
	- - - -(mm.)- - - -	
Forest site:		
"No crown protection"	—0.8	—0.4
Slight protection	0	—0.4
Protected	+0.4	+0.3
Well-protected	+0.9	+0.5
Surrounded by tree crowns	+2.3	+1.4

In well-protected and surrounded locations △A averaged 1 to 2 mm. in each storm; less protected sites received more snow than the open park.

Burger (1934) reports measurements after a storm in the selection forest of the experimental Sperbel- and Rappengraben studied by Swiss hydrologists. In beech, △A was 2 mm.; in 40-year-old heavily thinned spruce and fir, it was 4 mm.; in dense 50-year-old fir, 10 mm.; in a natural fir group in the selection forest, 15; and in old fir with undergrowth it was 17 mm.

During a study of rainfall interception (Ovington 1954) in quarter-acre plots of 20-year-old introduced and native species in Kent, one small snow storm occurred. Assuming a snow density of 0.1, △A in *Quercus* was 1 mm.; in *Larix* and *Nothofagus* 2 mm.; in *Pseudotsuga, Thuja,* and *Pinus negra,* it was 2.7 mm., and equaled the amount of precipitation.

Maule (1934) measured snow deposited on the ground by six storms in New Haven, Connecticut, and reported mean values after each storm in stands of hemlock and northern hardwoods of uneven ages and in 6- by 6-ft. plantations of red and white pine and Norway spruce. The means and standard deviations of △A, in mm. in each stand are as follows:

	In individual storms	Mean △A	Std. dev.
	- - - - - - -(mm.)- - - - -		
Forest stand:			
Northern hardwoods, unevenaged	0 0 0 0 2 1	0.5	0.8
Hemlock 50–70 ft. tall	1 2 6 0 3 5	2.8	2.3
Red pine 24 ft. tall, 16 years	1 2 7 0 2 5	2.8	2.7
White pine 26 ft. tall, 10 years	1 2 7 0 3 3	2.7	2.4
Norway spruce 30 ft. tall, 19 years	2 2 9 2 4 8	4.5	3.2

Mean values of △A in the hemlock and pines were about 3 mm., and standard deviations among storms are nearly as large. In the spruce, △A was large, with only moderate variation, and in hardwoods only 0.5 mm.

From figures 1–14 in Kittredge's (1953) report on his study of several aspects of snow cover in the Sierra Nevada of California, observations of accretion of snow can be selected that probably correspond to single continuous storms without long breaks but storms that deposited enough snow to load the trees well. Only those storms for which precipitation in the open site was between 1 and 2 inches are selected. In nine sites where accretion was measured by snow-boards or gages (the larger of the two readings being accepted), from 2 to 45 storms were available. Values of △A can be seen in different topographic sites and forest stands, accepting a variable sample of storms. Table 4 presents information about each stand, with means and standard deviations of △A in the number of storms indicated, at measurement stations beneath tree crowns and beneath gaps in the canopy.

Considering sampling points located beneath tree branches, △A varies from 3 to 17 mm., with large values of standard deviation reflecting large differences among storms.

Sampling points under gaps in the canopies of mature white fir and cut-over mixed conifers had low values of △A and large standard deviations. Those in the immature white fir had the largest value of △A. Furthermore Delfs (1958) found large values of △A in openings in a pole stand of spruce, about the same size as at points under the canopy. Stålfelt (1963) found that winter precipitation "screened off from the gages by the crowns" of spruce in Sweden totaled as much as 0.8 of the value of △A under well-developed spruce crowns that reached nearly to the ground. In the fir openings in the Sierra Nevada, more snowfall seems to reach the ground than in spruce openings in Europe. Plotting values of △A at points under gaps in the canopy against crown coverage within 20 ft. of the point or averaged for the whole stand revealed no relation. If both species and crown coverage of the whole stand are considered, △A is largest in the pines and the pine-dominated mixed conifers; it was smallest in the fir and the cut-over mixed conifer stand, in which many fir trees remained.

In the mature stands of pine and white fir, sampling points under the canopy and under its gaps have about the same values of △A. The two classes of sampling points differ the most in the cutover stand of mixed conifers. This striking difference in behavior between tree groups and openings may possibly be related to earlier selective logging of the sugar pines, the tallest trees of the mixed-conifer stand. While the large openings in the mature pine stand presumably developed naturally, with foliage covering most of the vertical extent of their borders, those in the logged stand might have porous open borders that afford little opportunity for snow to be caught, and would favor transport of snow into the openings. Artificial openings may thus affect mass transport processes much differently than openings bordered by snow-catching foliage reported by Delfs (1958) and Stålfelt (1963).

At sites near 1600 m., △A averaged 6 mm., and at the higher sites 9 mm. Sites with northwest aspects averaged higher than the two of southeast aspect, but the distinction is not clear cut. The large differences in △A among sites are a matter of interest even if not explicable on the basis of available information.

Table 4.--*Site characteristics and* ΔA *in the Sierra Nevada, California*[1]

Forest type		Site characteristics				Crown coverage			Record	Number of storms		ΔA, mm.[2]	
Species	Age	Height	Elevation	Aspect	Slope steepness	C^3	O^3	Whole stand		C^3	O^3	C^3	O^3
		Feet	*Feet*		*Percent*				*Years*				
Ponderosa pine, mature	all ages	120	5,200	SE	15	35	9	21	7	37	42	3±9	5±6
Ponderosa pine reproduction	28	15	5,220	SE	10	40	-	79	5	13	-	7±13	-
Mixed conifers, virgin	all ages	140	5,580	NW	3	62	29	35	5	18	10	12±10	7±7
(Sugar pine, ponderosa pine, white fir, incense cedar)													
Mixed conifers, cut-over	all ages	110	5,550	NW	35	55	27	37	7	32	40	17±11	1±7
White fir, mature	140	100	5,200	N	31	51	41	41	7	45	14	3±14	2±8
White fir, immature (pole size)	70	80	5,280	NW	16	70	58	68	5	27	7	15±11	8±2
Red fir	200	120	6,260	N	21	75	2	52	7	3	2	10±8	7
Open logged area[4] (15 acres)			5,200	NW	13	0	0	0	7	(5/)		(4/)	
Open screened area[6]			5,250	NW	1	0	0	0	5	-	21	-	1±17

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[1] Source: Various tables and graphs in Kittredge (1953).

[2] Presented as Mean ± Standard Deviation.

[3] C = Stations under canopy; O = Stations under gaps in canopy. Crown coverage taken within 20 ft. of the station; of the entire stand also in percentage.

[4] Taken as the base station for comparison.

[5] All storms.

[6] Near edge of fir forest.

Also in the Sierra Nevada, but at a lower elevation (1000 m.) and in second-growth ponderosa pine, Rowe and Hendrix (1951) carried out measurements over 6 years, during which 11 snow storms of 1 to 2 inches water equivalent occurred. Sealing △A in these storms from their figure 2 yields values from 5 to 7 mm. Stem flow of melt water from intercepted snow was 0 to 2 mm. in these storms. From the brief published report on this long thorough study, it is hard to estimate such other transport processes as blowing of snow, although with records of wind pulsations it should be possible to evaluate the buildup of snow on the branches and its subsequent blowing off into the near-by openings, which were considerably larger than the 40- by 55-ft. study plot in the forest. Storms with low total wind movement would provide the most reliable measurements of accretion, as West and Knoerr (1959) comment in discussing their measurements in and near a tree group at a site at 2,100 m. elevation in the Sierra Nevada. However, even without meteorological observations, the findings of Rowe and Hendrix require a re-examination of exaggerated ideas of △A, and their measuring of stem flow calls attention to other transport processes.

Some investigations using paired sampling sites in and near forest publish only monthly or seasonal sums of accretion. Such limited information does not permit separation of the transport processes during storms from those after storm, which may act quite differently. Empirical relations between accretion at paired stations might have local use, in places with the same regimes of snow storms, wind, advection of heat, and radiation as those at the site studied. The comparisons have been determined to have little generality—a warning issued, in fact, by the first scientist to make such readings; Krutzsch (1864) stated that his observations were good only for the site (near Tharandt) where he made them. He felt that elsewhere they indicated only that intercepted precipitation might make a valuable contribution to the moisture content of the atmosphere.

When data on △A are presented only in terms of a ratio to precipitation, they should not be interpreted as indicating either (a) the amount of intercepted snow, or (b) the rate of vapor flux from it. Interpretation (a) implies that snowfall continuing without limit can increase the weight of snow that can be held by trees. Interpretation (b) implies that continued snowfall confers energy upon the intercepted snow to expedite its evaporation at rates equivalent to 15 to 25 langleys per hour. These are very large rates of heat flux in a situation more commonly considered one of radiative equilibrium and an isothermal field of temperature. Any validity in the empirical relation $\triangle A = a + bP$ (in which P is snowfall, and a and b are calculated coefficients) might rather be sought in the hypothesis that heavier snowfall produces larger bodies of snow in the branches that are more susceptible to wind transport into the opening, thereby increasing △A by biasing the "open" catch upward. The coefficients a and b give no information about the processes by which snow, water, and vapor are transported from intercepted snow in the branches. As Delfs (1955) states, they have limited predictive value in forests that vary in species, habit, foliage density, or stand structure. Calculation of △A does not provide a measure of intercepted snow or its removal from trees. Although calculating it from snow-board measurements avoids the problems of gage defects, there remain unknown differences in aerodynamic characteristics and snow deposition between the tops of tree groups and the bottoms of openings in forest.

Calculation of △A by comparing gage readings cannot be recommended as a practical approach to questions of interception of snowfall and its transport during snow storms until accurate measurements of snow movement—resolved into vertical and horizontal components—can be made above, within, and beneath the zone of tree crowns. Furthermore, measurements of the wind field in terms of its ability to suspend and transport snowflakes must be included. Sampling profiles through the foliage zone have proved effective in determining the flux of radiative energy into and through the active layers of trees and crop plants, and are currently being used in research on the turbulent flux of heat and vapor. Until similarly aerodynamically adequate meters to measure the flux of snow in the atmosphere are developed, the practice of comparing amounts of snow caught in and near forest in the kind of sites customarily employed can provide little knowledge of the processes of interception of falling snow by foliage or of transport of intercepted snow from foliage during snow storms.

Research Approaches

This discussion of the ways in which intercepted snow is transported from tree crowns during snow storms indicates a great need for quantitative determination of each transport in its relation to the varying conditions of storms and forest stands. The means of acquiring these data and improving our capabilities for measuring the fluxes vary in difficulty, precision required, and urgency; fortunately, the modes of transport that are probably most important during snow storms do not seem to be the most difficult to measure, and should receive priority in further research.

Studies of Transport Processes

The transport processes are not equally understood. Stem flow has, perhaps, been the most successfully measured, where measurement has been attempted, although in other situations it has often been overlooked. The solid-state flux of snow in the air stream has been least successfully measured, in spite of the existence of methods that could be modified for the purpose. Failure to measure this horizontal transport has resulted not only in a lack of information about the influence of forest on adjacent land, but also in an inability to evaluate and possibly to correct the errors inherent in the technique of paired sampling points in and near forest.

Of all the transport processes, the evaporation of intercepted snow and the flux of vapor from forest into the free air is, although much alluded to, perhaps the hardest to measure. The practice of estimating vapor flux as a function of rate of snowfall is without physical justification. Considering it a residual does not suffice if other modes of mass transport are unmeasured. The snow that remains in the branches when a storm ends has seldom been measured; it has only been estimated from reports of snow breakage of trees, and from observations made at ground level without the meteorological data that would permit us to separate the usable measurements of snow accretion in and near forest from those biased by differential action of the mass transport agencies. These indirect methods give inadequate information about the intercepted snow and the transport processes that affect it. It is almost impossible to generalize this information or use it as a predictor; it is necessary to study the individual mass transports as independent natural phenomena.

One of the most important of these processes, especially in view of its capability for lateral transport, is the solid flux of snow dropping and blowing from the tree branches and carried with the wind. This transport presents problems of sampling more than of sensing, because it is visible and the particles can be caught and weighed. Methods of measuring the solid flux in an air stream also might be applied to determine the delivery of snow to the forest top. They could be developed from practices for measuring drifting snow, and consider differences in particle size and aggregation, density, sinking speed, and source relative to the transporting air stream. Installations of drift meters and bi-vane and vertical-direction anemometers, in profiles from the ground to several meters above the forest canopy would, in a relatively few storms, secure a good sampling of the downward transmission of momentum in eddies of the sizes that determine the building and destruction of bodies of intercepted snow and on the horizontal component of suspended particles moving into the air stream. Moreover, these methods would easily be extended to the special cases of trees at the edge of a forest body, trees bordering openings in forest, forested slopes that might produce density currents, and trees being weighed, as in the study in Japan (Govt. Forest Exp. Sta., Japan 1952), to determine how much snow is delivered and removed.

Profiles of wind speed would provide a basis for wind-tunnel modeling, and thus permit the generalized application of information on blowing snow to many kinds of forest. There is sound reason for combining the recommendation for use of drift meters with that for determining the vertical and horizontal components of the field of motion of the air, with its eddies and pulsations in and below the forest canopy. Each set of measurements will aid interpretation of the other. Erosion by gusts of bodies of intercepted snow supplies suspended material for horizontal transport; the efficiency of horizontal transport depends on the prevalence of upward motion in the turbulent air stream. Furthermore, the flows of snow and air are themselves intricately interrelated, since snow particles have little inertia. The likelihood that large amounts of snow are redistributed by this mode of transport gives priority to this research.

The release of partly-melted snow bodies to fall or slide from the branches involves both atmospheric conditions and properties of the branches themselves—slope, friction, strength, deformation under load, and ease of being triggered to release potential energy stored as they are bent. Watanabe and Ôzeki (1964), in particular, have demonstrated that many relevant characteristics of trees are measurable in the field; other characteristics are measurable in the laboratory. Wind-tunnel studies would seem ideal for evaluating the variables of support and adhesion of snow to branches, because the variables of heat supply could also be introduced into the experiments. It then could be determined what fraction of the intercepted snow in trees of different growth forms and species melts before the rest is released from its support.

Whether atmospheric heat causes a body of snow to melt partially and slide off the branches or to melt completely in place depends on support and adhesion characteristics. In laboratory experiments these characteristics can be varied with different values of foliage friction and branch inclination. And, laboratory methods can determine the conditions that favor heat supply at the lower, supporting surface of a snow mass rather than its sides and top. They can also measure initial cohesive and frictional forces to determine how much melting takes place before mechanical bonds give way and sliding starts. Such laboratory studies would form a transition to field work on small trees of known foliage friction and other properties, under atmospheric conditions observed in detail, with surveys of the snow mantle beneath trees to identify fallen chunks of intercepted snow and to measure their size, density, and wetness. Drip pans might be used if there were a means of separating blown from fallen snow, perhaps on a basis of density or aggregation.

It would be worthwhile, for example, to see whether the estimate reached on page .... that the melting of 20 percent of the intercepted snow on an isolated tree coincides with gravity movement of the remainder will hold true for trees of different branch form than the cryptomeria described in this paper. Lastly, extending the tentative calculations of heat flux reported in this paper, trees with intercepted snow could be weighed under different conditions of radiative and turbulent heat flux to determine the fraction of the total mass transport that takes place by sliding and falling of partially-melted bodies of snow.

Movement of melt water from intercepted snow is visible and easily collected if it moves as stem flow, but with more difficulty if it moves as drip. It is important to determine the frequency of each of these movements and their typical rates of flow during storms of different types. There are two basic questions: (a) determination of the rate of melting as a function of supply of energy, which is a function of atmospheric variables that involves the division of heat between melting and evaporation; and (b) partition of melt water between stem flow, dripping, and possibly evaporation, which is a function of foliage attitude and branch structure, and of the hydraulics of a branching film of water clinging to the leaves and bark. Basic research on the disposition of intercepted rain may throw light on these two questions of snowfall interception.

Thorough melting of snow in place in tree crowns involves heat transfer to securely held bodies of snow over long periods, without localization of heat at such critical points as the zone of adhesion. Convection and condensation of vapor are important during storms, and some heat is added by short-wave radiation; the net flux of long-wave radiation is not likely to produce a deficit as large as in clear weather. Laboratory experiments can reproduce all avenues of heat flow in various combinations. Combined at the same time with measurements of melting of suspended bodies of snow and of snow on the wind-tunnel floor, they would make it possible to establish at least empirical relations between mass and energy transfer at a cold boundary overlain by stable air in contrast with that at surfaces distributed throughout the medium. As a result, turbulence theory could be used to transfer the extensive knowledge about melting snow on the ground and on glaciers to the special situation of tree crowns. The flow of melt water through suspended bodies of snow might also differ from that in a snow cover.

Controlled-environment chambers seem useful for studies of heat supply, melting, and flow or drip of melt water on small trees of different forms and species, offering the possibility of comparison with melt rates of a plane snow surface in the same environment. Successful transfer of such studies into the field would require quantitative description of the tree variables as well as the atmospheric ones, although the pattern of occurrence of melt water seems to display a predominance in marine climates.

Vaporization of melt water and intercepted snow produces an invisible flux of great mobility, which can be measured only with difficulty, even in geometrically simple situations. The film of melt water on foliage and branchwood of a tree is not geometrically simple, and so it seems likely that empirical laboratory studies of branches or small trees of different degrees of wetting should take priority, but without neglecting efforts to conceptualize and describe numerically the shape and area of the film.

Evaporation of bodies of intercepted snow can also begin in the laboratory, along the lines shown by Diunin's (1961) work in the framework of the psychrometric relation. However, due regard should be given to the size of the snow agglomerations moving in the air stream and the greater size of the bodies of snow held in mid-air by the branches. These larger bodies need to be enumerated and located by some kind of census of a typical snow-laden tree before wind-tunnel experiments are designed. Attempts made in other disciplines to estimate evaporation as a residual of changes in mass of water require extreme precision in measurement that is probably not feasible for the dispersed bodies of snow *in situ,* but perhaps may be feasible for individual bodies held in a moving air stream. Quite a different approach is to measure the vapor flux emanating from a forest canopy of sufficient uniformity and area to warrant measurement by the evapotron or other device from agricultural meteorology.

The fraction of the total vapor flux from intercepted snow that diffuses downward to condense on the snow mantle presents difficult sampling problems, and is probably smaller than the upward flux from the snow-bearing canopy as a whole, at least during snow storms. Neither flux of vapor may be large under these conditions, because it is difficult to conceive of a steep vapor-pressure gradient from the forest canopy either up into the clouds or down to the snow mantle. However, the return of intercepted water to the major flux of the atmospheric circulation that supports further precipitation downwind has interesting hydrometeorological implications, noted by such forest scientists as Krutzsch (1864) and Eitingen (1953).

Much effort in forest climatology has been limited to the human level, that is, within the trunk space, although it has long been known that the level of greatest activity, physical and biological, is the upper canopy. The classical picture of the dark cool forest climate reflects this limitation in scale; the concentration of effort on measuring accretion to the snow mantle on the ground has drawn research attention away from the place where interception phenomena occur with full intensity—in the tree crowns. For this reason, it has been possible only to sketch the processes by which snow particles, melt water, and vapor are transported from the tree crowns; few measurements have been made. It is highly desirable that future research shift its focus from the quiet inactive zone of the trunk space to the active zone of the tree crowns, and study their interaction with radiation and the atmosphere, with its solid suspensions, i.e., snowflakes.

In estimating interception by comparing accretion to the snow mantle in and near forest, the investigator faces aerodynamic questions of delivery of snowfall to the top of a forest body and the depths of a forest opening, and of mass transports that confound the sought-for distinction between accretion in forest and near it. An unfortunate parallel was drawn in the past with the processes that operate during rain storms. These processes can be measured with ordinary instruments because vertical transports predominate over horizontal ones. But the processes in snow storms are quite different; horizontal transports are so great as to make uncertain the measurement of snowfall in any situation whatever. Detailed rainfall studies such as those by Kittredge, *et al.* (1941), Hamilton and Rowe (1949), Luchshev (1940), and many others, were made not simply to plug a gap in a local water budget but to examine fundamental hydrologic processes. Their studies had a degree of detail in sampling and meteorological data not matched in studies of snowfall.

Even long programs of observations of accretion to the snow mantle are hard to interpret in terms of mass transport from snow intercepted in the tree branches, especially in the absence of meteorological data. Satterlund and Eschner (1965) feel that studies of snow on the ground "have probably passed the point of diminishing returns under most forest conditions. Snow losses should be studied where they occur—in the trees themselves." While these authors are referring primarily to post-storm conditions, their recommendation applies with equal force to conditions during storms.

Applying the differential-accretion, or △A method, to observations from precipitation gages in and near forest introduces the familiar defects of such gages as scientific instruments. The use of troughs on the forest floor, instead of gages, as has been reported by Delfs (1958a), Grunow (1965), and others, is helpful there. But this use does not eliminate, as Grunow notes, the problem of gages in openings, nor of mass exchange between openings and surrounding forest. Proper use of the △A method awaits development of measuring instruments that are aerodynamically correct, arrayed in replicated patterns above, in, and beneath the canopy, and accompanied by measures of horizontal and vertical wind speed. Such a study need not depend on the openings in forest as places to make measurements, but can concentrate upon the canopy itself.

Micrometeorological methods of measuring heat transfer to bodies of intercepted snow in tree crowns and vapor flux away from them should start with profiles measured near individual bodies of snow under controlled heat supply, as, for example, in a wind tunnel. Results of these experiments can be extended, at increasing scales, first to several bodies of snow on a tree branch or in a small tree standing in a climatic chamber, using branches and small trees that provide a sample of different growth forms and different species; then to a snow-laden tree in a well-measured field site; and finally to the crown space of a tree group considered as a porous volume of finite depth and semi-infinite extent, generating vapor that diffuses out of its lower and upper boundary surfaces.

The forest crown as an environment for bodies of intercepted snow is a medium not easily described in quantitative terms; yet, without numerical expression of its attributes, the laboratory experimenter cannot know how to build a model that will adequately simulate natural phenomena nor how to simplify the problem with minimal distortion. Neither can the analyst of the atmospheric processes that act upon intercepted snow set up hypotheses for testing with assurance that he is approximating the true situation in a drainage basin. Because such categories as age, closure, and even species do not index those geometrical and mechanical properties of forest that are relevant to the phenomena of snow interception, new forest parameters need to be recorded.

Among the data required on vegetation are totalizing measurements, like biomass, in cm^3 volume or grams per cm^2 of stand area. Surface area of foliage, crown depth and volume, lengths of branchwood of various diameters, are other measures that have proved their utility in scattered studies, and should have general use in preference to such indexes as closure, stocking, basal area, or stem density, which have uncertain relations with physical phenomena in the crown space.[4] For the measurement of other attributes of forest stands, however (for example, branching pattern and crown structure), no methods exist at present.

Laboratory data on the changes in individual bodies of snow has to be related to the universe of snow bodies in tree crowns in the field. The first step might be to take a census of snow masses, by size, shape, location, and type of support. Next, instrumental measurements of density, cohesion, wetness, and other physical properties should be made on representative snow bodies, in order to determine internal structure, crusts, adhesion zones, liquid-water content, permeability to air and water, and manner of draining of these bodies. Changes in these qualities indicate the action of radiative and atmospheric forces and define the individual transport processes.

Weighing experiments following the thorough Japanese example might be undertaken in representative sites within a forest stand and at windward and leeward edges. The measurements would be accompanied by a census of snow bodies and a sampling of their properties. In this site should be made measurements of wind speed and gustiness, air temperature, humidity, fluxes of short-wave and long-wave radiation, and fluxes of snow particles and vapor as extensions of earlier laboratory and controlled-environment experiments. As a result of these observations of mass and distribution of intercepted snow and of atmospheric conditions, simultaneous visual observations of blowing, dripping, melting, sliding, and stem flow could be associated with specific quantities of snow carried in each transport process. Such field measurements of the bodies of snow, their arboreal environment, the wind forces and heat fluxes acting on them, and the fluxes of snow, water, and vapor to which they give rise would provide—if carried out in a few snow storms of different synoptic types—ample data for developing and testing a comprehensive theory of the mass transport of intercepted snow from the crown of a forest.

Mechanical strength of foliage, fine branches, large branches, and trunks—all measurable by

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[4] The measurement of branch angle and lengths by Watanabe and Ôzeki (1964) demonstrate the value of this kind of numerical data in interception work.

standard engineering techniques—have not yet been used in interception studies but are needed in studying the vibration of tree crowns, deformation under wind stress, and bending under snow load. Some of these attributes are commonly associated with species, and these relations need to be given quantitative support by determining the general level and dispersion of each attribute of a species by measurement in a wind tunnel and a mechanical-engineering laboratory. The recommendation in the *Allgemeine Forstzeitschrift* (Anonymous 1954) for research on growth form and breaking strength, in order to develop means of reducing damage by snow breakage, is equally relevant to the general problems of snow interception.

The crown space of a tree group is a porous medium through which air, vapor, momentum and radiation flow, and throughout which are distributed many small bodies of snow that are sinks of heat and momentum and sources of water in all three physical states. Recent models and experiments with flow in porous media may be helpful in formulating concepts of this system that will be aerodynamically and thermodynamically valid. The forest mosaic, as a complex of tree groups and of interstices, whether "natural" or made by strip, patch, or group-selection cutting, influences the distribution of radiation and particularly the movement and advected properties of the air stream, hence the processes by which snow is transported. To extend findings about transport processes in single trees and in tree groups to drainage basins covered by mosaic systems of forest and openings will require some means of characterizing the mosaic. The means might come from current work in image recognition of remotely-sensed data or from quantitative geography and ecology.

Obtaining the required measurements of mass transfers in the complex forest mosaic environment will require intensive and well-planned sampling on a micrometeorological scale within this porous medium, and on a larger scale at its boundaries, particularly the upper surface. However, if the processes that transport energy and water have been individually analyzed and relevant factors identified, relatively short records in the laboratory and during selected field periods should suffice to establish the limits and variation in each process. Elements requiring observation over long periods are those for which standard instruments are generally available and in which great detail is not important.

This is the trend in many lines of geophysical research: brief studies of high observational intensity with continuous records of many fluxes in a dense sampling network, in order to determine how the transport processes can be predicted as functions of more commonly observed factors. The more that can be done in controlled environments, the more simple can be the field experiments, and the more generally applicable will be the results. If all relevant conditions are recorded, accurate relations between them and the mass transports can be established; once these are known, short cuts can be taken with confidence, and a few key factors in any forest site can become the basis for successful application of the universal relations between the mass transports of water from intercepted snow and the sources of energy and momentum that cause them.

Summary of Recommendations

Suggestions for promising research may be summed up as follows:

- Each mass-transport process should be regarded as separately influenced by conditions of storm weather, tree geometry, and characteristics of the bodies of intercepted snow.
- Measure one or two mass-transport processes selected as significant in a particular region with respect to their action in carrying snow, water, or vapor; measure the wind fields and energy flows associated with them in the tree crowns; and measure the relevant characteristics of the tree crowns and bodies of intercepted snow.
- So little research has been done with snow in controlled environments that almost any laboratory experiment would be useful, as long as its modeling simulates field conditions properly and will permit transfer to field sites; intensive experiments, adequately instrumented in controlled wind fields and heat fluxes, with typical tree crowns bearing bodies of snow will shorten subsequent field work. Use laboratory work to save field time.
- The mass-transport processes that move intercepted snow from tree branches to other resting places in or near forests can be understood and their magnitude determined if their physical nature is kept in mind. Snow is eroded and transported by mechanical forces, such as wind, and its physical state is changed by thermodynamic phenomena that release it from supporting branches, melt it, or evaporate it. Investigation of these processes, therefore, requires measurement of the wind field

and the fluxes of energy, as they occur in the special environment of tree crowns, as well as of the transported snow, water, and vapor. Simulation of simplified aspects of this environment in climatic chambers offers the opportunity to witness the effects of varying wind speed, snow adhesion, branch attitude, radiant energy fluxes and convection. Finally, these experiments would provide basic relations for productive measurements in the field that will evaluate the transports and verify techniques for predicting them in forest sites and weather of every kind.

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Rainfall and Streamflow from Small Tree-Covered and Fern-Covered and Burned Watersheds in Hawaii

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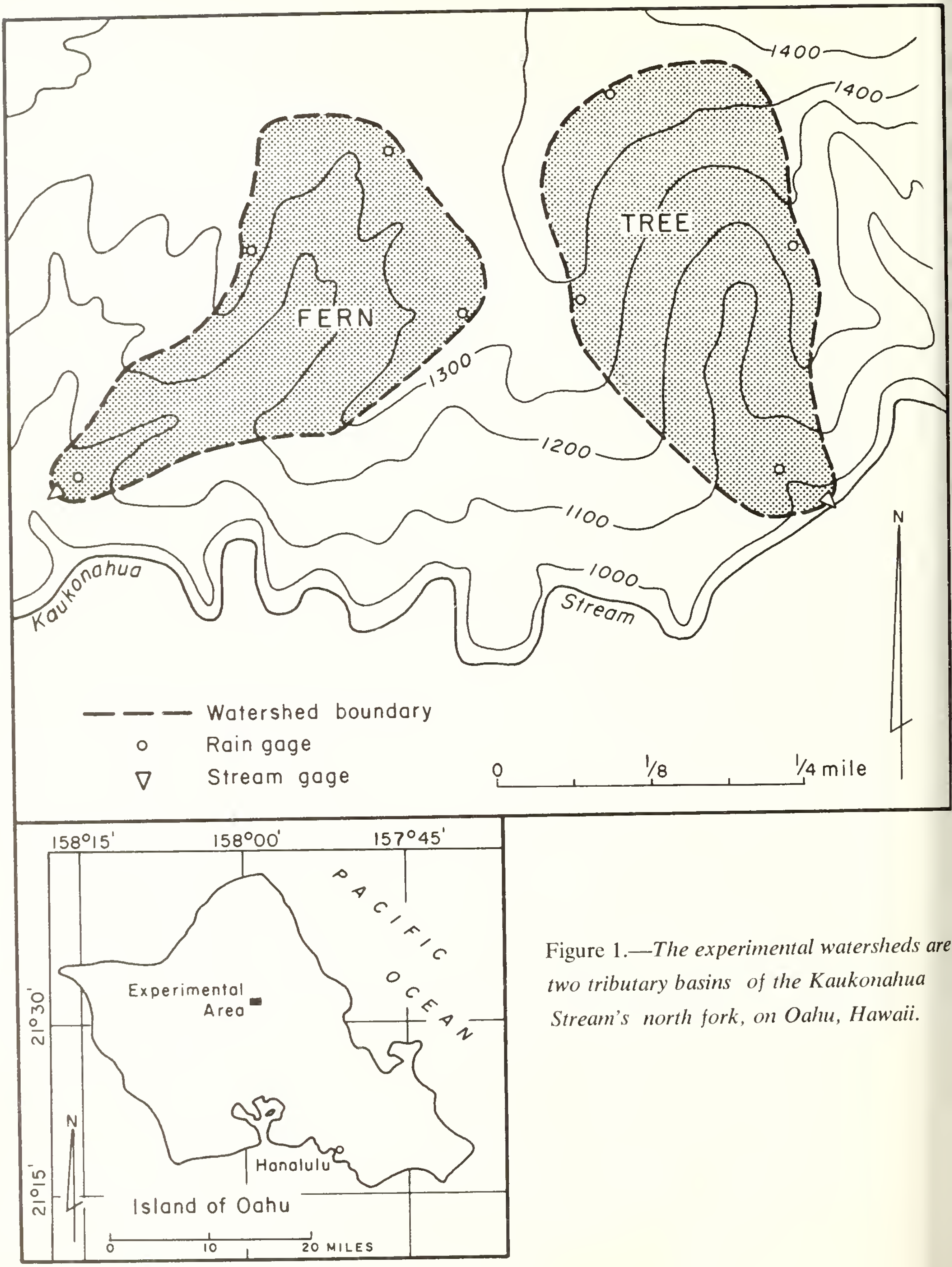

Figure 1.—*The experimental watersheds are two tributary basins of the Kaukonahua Stream's north fork, on Oahu, Hawaii.*

In Hawaii a supply of water may depend on anything from rain on the roof at Kona to elaborate tunneling for water at Honolulu. Historically the people of Hawaii have looked *mauka*—to the mountain watersheds—for much of their water. What they now see are watershed slopes clothed with vegetation that protects the soil and helps deep percolation of water. But 80 years ago, these same slopes were denuded—only rigid protection and widespread planting since then has brought vegetation back to its present state. Now the question is being asked: "Can these mountain watersheds be safely managed to produce even more water and other products to meet the expanding needs of this island State?" (Anderson, Hopkins, and Nelson 1962).

In 1951, the Hawaii Division of Forestry began a study to learn more about the role of mountain watersheds and their vegetation and water supply. Two small watersheds on Oahu were selected and measurements of streamflow and rainfall were made.[1] The sites represent rather critical mid-elevation, moderate rainfall zone, under two rather distinct vegetation covers: planted trees and native false staghorn fern (*Dicranopteris linearis*).

Some foresters believe that a fern cover on a watershed will produce more streamflow than will a cover of native or planted trees. If this were true, fern could be removed in those areas where it is important to increase the water percolation to groundwater storage, such as on the island of Oahu. In other places, such as the above-surface catchment ditches on east Maui, a fern cover might put more water in the ditches. Conversion of native watershed cover, including fern, to introduced hardwoods for timber production, is one of the significant changes now under way on Hawaii's watersheds. Will such conversions be beneficial or detrimental to water supplies? And does a fern cover help or hinder streamflow from a watershed?

This paper provides some answers to these questions by reporting on an analysis of rainfall and streamflow data from two small watersheds in Hawaii. It describes the statistical techniques used, and suggests the principal hydrologic processes in effect under three different watershed conditions.

Watershed Physiography

The watersheds studied are two tributary basins f the north fork of the Kaukonahua Stream, on ahu (fig. 1). The fern-covered watershed is 9.7 acres, and the tree-covered watershed is 38 cres. They lie on an elevation of 1,000 to 1,400 eet, generally face south, and have slopes of 66 nd 56 percent, respectively. They are rather typi-al of Oahu's streams at that elevation, on the eeward side of the Koolau Range.

The watersheds are situated in the rock-type apped by Stearns and Vaksvik (1935) as the "Koolau Volcanic Series," a typical olivine basalt of the "aa" or the "pahoehoe" texture. Each lava flow is 10 to 30 feet thick and dips from 5 to 15 degrees to the northwest.

Soils in the experimental watersheds lie within the area mapped as the "Helemano Series." This series is typical of soils found on steep slopes at elevations ranging from 500 to 1,200 feet. Permeability is classed as intermediate, 2 to 6 inches per hour, with medium internal drainage. The watersheds were examined by Chester Wentworth, geologist with the Board of Water Supply, City and County of Honolulu; and by Z. C. Foster, soil conservationist with the Agricultural Extension Center, University of Hawaii. Both scientists reported no fundamental differences in rock or soil between the two watersheds.

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[1] This work was under the direction of staff foresters ollin Lennox, Karl Korte, and Albert MacDonald. In e analysis reported in this paper, we checked their com-ilations and extracted additional rainfall and stream-ow data from their charts.

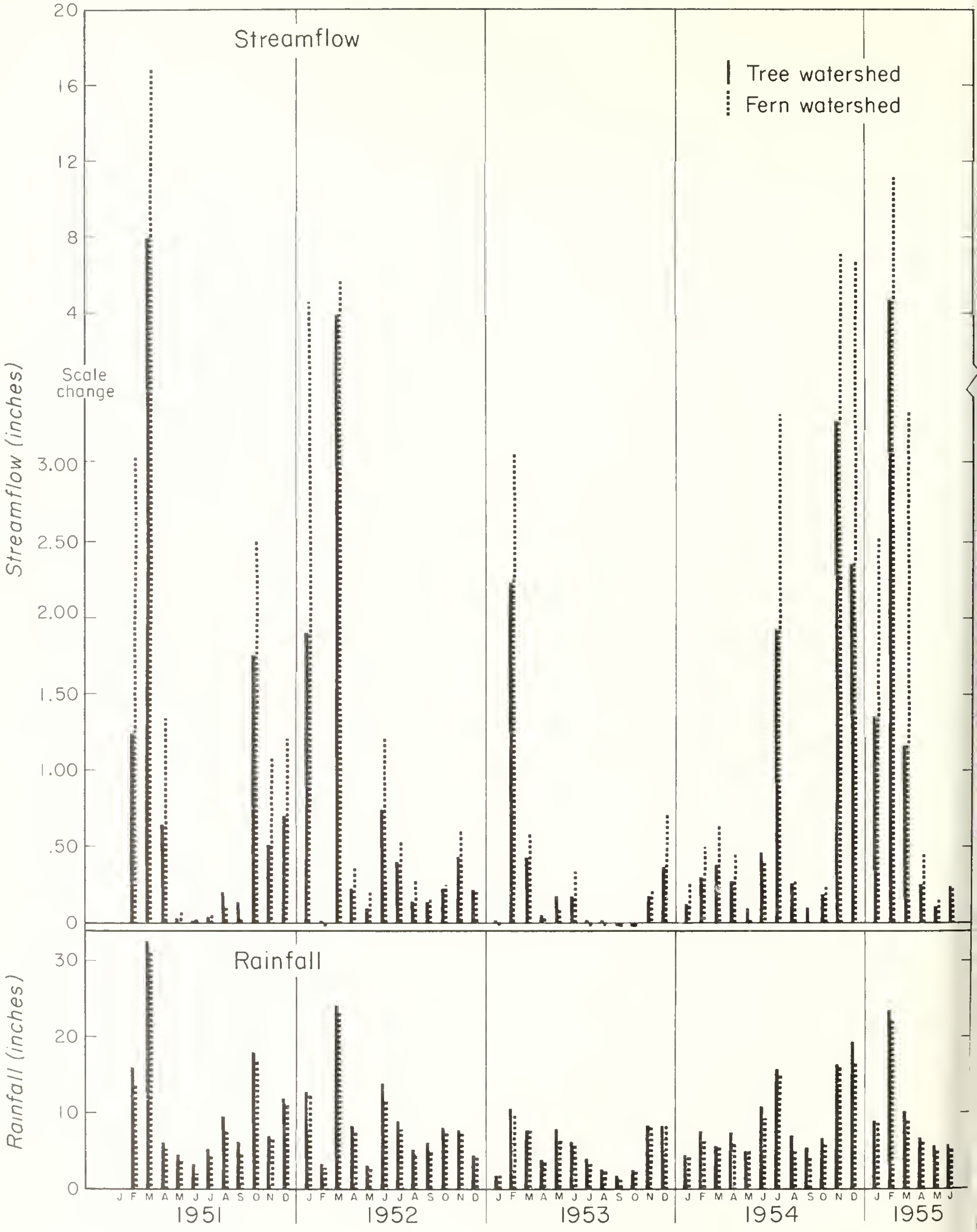

Figure 2.—*Comparison of monthly runoff and precipitation on the tree-covered and fern-covered watersheds.*

Vegetation Cover

The watersheds are usually referred to by their "original" vegetation: predominantly planted trees in the "tree watershed," and mixtures of native trees with large areas of false staghorn fern in the "fern watershed."

Tree-Covered Watershed

When the study was started in 1951, the tree watershed was dominated by turpentine trees, various eucalypts, and rubber trees, originating from plantings in the early 1930's. Tree diameters in 1951 ranged from 12 to 20 inches. About 80 percent of the basin was forested, with vegetation canopy being heaviest on slopes that were most exposed to the northeasterly trade winds.

Fern-Covered Watershed

The vegetation on the fern watershed underwent changes during the period of this study. Originally, the area was dominated by false staghorn fern, with some scattered koa and ohia trees, and patches of kukui trees in the drainage ways. In 1951, about 65 percent of the basin was open forest and 35 percent dense fern. In August 1953, this vegetation was burned, and reburned a month later. From then until March 1954 the entire basin was planted to small trees, mostly brushbox, and blackbutt eucalyptus; some 13,000 trees in all were planted.

Vegetation Changes

Vegetation in both watersheds would be expected to have changed—both with age and with the burn-planting treatment of 1953. Changes would be expected to be small in the tree watershed, for the trees were already 19 years old at the start of the study. Therefore growth in the ensuing 4½ years of the study probably had little effect. In contrast, the burn-planting treatment of the fern watershed would be expected to result in a more drastic change.

Two burnings on the fern watershed affected both the vegetation and the current water regime. The hydrologic effects of vegetation removal might be expected to include (a) reduction in the interception storage, (b) inducing of quicker paths for runoff, and (c) reduction in transpiration. The first effect would be expected to cause runoff to start with less rain and to produce a constant increase in the runoff per storm. The second effect would be expected to increase peak flows. The third effect could increase both percolated water and total streamflow.

Instrumentation and Data Collection

Measurements of streamflow and rainfall on both watersheds were begun in January 1951, and continued through June 1955. Streamflow was continuously measured by an "H" type of flume of 1-foot depth and width made of redwood and set in a concrete cut-off wall. The flume and concrete section were calibrated by the U.S. Geological Survey. Streamflow stage was recorded on a Stevens "L" type recorder, with an 8-day record on each chart.

Precipitation in each watershed was measured by both standard gages and intensity recording gages (fig. 2). Standard gages were set at three sites in each watershed, representing different slope facets. All gages were set below the ridge to avoid excess wind influence on catch. A recording gage was operated on each watershed, with the gage located near but not at the stream-gaging station. Both rainfall and streamflow were recorded on the same chart.

Streamflow-Rainfall Analysis

In analyzing the data gathered, we had the following aims:

- To determine monthly and annual streamflow from the two watersheds.
- To relate by multivariate analysis total streamflow for storms and peak discharges of individual storms to storm-rainfall characteristics and prestorm rainfall.

- To determine the differences between streamflow-rainfall relations in the two watersheds and explore possible causes.
- To determine the effects on streamfall-rainfall relations of burning vegetation on the fern watersheds and of protecting trees on the other watershed.

We assumed that the streamflow was accurately measured throughout the study period, but we tested the rainfall measurements for consistency.

Rainfall Data Testing

Rainfall data from the eight individual rain gages on the watersheds used in the study were tested for consistency with each other and with nearby rain gages. We used the double-mass technique, that is, simple comparisons of accumulations of an individual gage against the means of many nearby gages (Anderson 1955; Kohler 1949). This technique can detect and correct for inconsistencies in precipitation measurements, such as those due to changes in exposure of the gage. Rainfall catches in the six standard gages were found to be consistent throughout the period of record; catches for the two intensity gages were found to have changed throughout the period of record, and were adjusted to give a consistent record throughout the study period.

Seasonal differences in rainfall were found during the testing. Average monthly rainfalls for the wet season (November–April) and the dry season (May–October) together with standard deviation were as follows:

	Wet season	Dry season	Difference
Watershed:	(inches)		
Tree gulch	10.65±7.20	6.91±3.94	3.74
Fern gulch	9.69±6.54	5.84±3.69	3.85
Differences	0.96	1.07	

The tree watershed, which is slightly nearer the Koolau summit received about 1 inch more rain per month in both the wet season and the dry. Annual rainfall was 105 inches for the tree watershed and 93 for the fern watershed. Average rainfall for the study period was about equal to the long-term average as judged by comparison with long-term records from nearby gages.

Monthly and Total Streamflow

Streamflow measurements for the individual watersheds were used when available to obtain monthly and total streamflow (fig. 2). For short periods, streamflow data were not available. Missing records were estimated by simple correlation of streamflow between the study watersheds and nearby streams. In filling in missing records for the tree and fern watersheds, daily discharges from the Poamoho and north fork of the Kaukonahua Streams were used, together with daily rainfall records. The method was similar to that used by the U.S. Geological Survey and probably gives comparable accuracy.

The means and standard deviation of monthly streamflow, by wet season and dry season, were as follows:

	Wet season	Dry season	Difference
Watershed:	(inches)		
Tree gulch	1.307±1.798	0.304±0.472	1.003
Fern gulch	2.704±3.866	0.400±0.777	2.304
Difference	−1.397	−0.096	

Annual streamflow was about 10 and 19 inches for the tree and fern watersheds, respectively. Almost all the difference in runoff between the two watersheds occurred in the wet season. Dry season flow was greater in the fern watershed, but was also more variable. For the 4½ year period of record (fig. 2) the fern watershed had 7 months with no flow, and the tree watershed 2 months. The difference in number of months of no flow is primarily associated with greater rainfall in tree watershed. The driest year was 1953, when July-to-October flow was nearly zero. The wettest months were January and February of 1955, with the largest runoff from a general "Kona storm" in February. Similar streamflow results were reported by Rice (1917) and Mink (1962) for nearby large streams.

Monthly Rainfall-Streamflow Relations

The response of each stream to a given amount of rainfall was different in the dry months (April–October) from the wet months. (November–March). Those differences were reflected in the regression coefficients relating monthly streamflow to rainfall in the month and to rainfall in the month before (equations 1–4, table 1). Explained variance ranged from 85 to 95 percent; errors of estimates ranged from 0.18 inch to 0.94 inch.

The equations imply that, for average watershed wetness, 3½ to 4½ inches of monthly precipitation were necessary to produce significant amounts of streamflow. The equations also show increased proportion of rainfall becoming streamflow for large amounts of monthly precipitation. For example, streamflow doubled when rainfall rose from 10 inches to 15 inches per month.

Further tests were made of the equations 1–4

Table 1.--*Monthly streamflow relations, fern and tree watersheds, Oahu, Hawaii 1951-1955*[1]

Equation No.	Watershed and period	Equation	n	R^2	Syx
(1)	Fern, May-Oct.	$QM=-0.55+0.096P+0.0054PSQ+0.025AP$	26	0.85	0.32
(2)	Tree, May-Oct.	$QM=-0.34+0.056P+0.0028PSQ+0.012AP$	26	.88	.18
(3)	Fern, Nov.-Apr.	$QM=-1.89+0.289P+0.0094PSQ+0.050AP$	27	.95	.95
(4)	Tree, Nov.-Apr.	$QM=-0.62+0.121P+0.0036PSQ+0.004AP$	27	.93	.51
(5)	Fern, prefire	$QHAT=-0.14+1.952Q(Tree)$	31	.94	.55
(6)	Fern, post fire	$QM=0.034+1.065QHAT-0.02SEA-0.31Q(Tree)\cdot SEA$	22	.98	.39
(7)	Fern, prefire	$QM=0.017+0.890QHAT-0.05SEA-0.27Q(Tree)\cdot SEA$	31	.98	.53

[1] Equations 1-5 are from regression on principal components (Wallis 1965); equations 6 and 7 are from ordinary full model multiple regression. In the above equations May to Oct., SEA=1; Nov. to Apr., SEA=-1; all other variables are in inches: QM is monthly streamflow, P is monthly rainfall and PSQ is its square, AP is monthly rainfall in the antecedent month, QHAT is QM for tree watershed calculated from equation 5, and Q(Tree) is measured streamflow in tree watershed for a month. n is number of months, R2 is explained variance in percent, and Syx is standard error of estimate in inches.

of table 1 to see if the variance was correlated with the amount of rain and to test for any serial correlation in the flow. We found no correlation between the variance and the size of the flow; nor, in using Durbin-Watson statistics (Durbin and Watson 1951), did we note any trend in flows for the tree watershed. But a possible increase was indicated in the flow of the fern watershed, perhaps associated with the burn of August 1953.

Effects of Burning on Monthly Streamflow

To find out if monthly flows changed after the fern watershed was burned, we first ran a simple regression of monthly runoff against time in months after January 1951. We obtained a highly significant deviation of runoff after August 1953 for the fern watershed, but only a slight deviation, which was not significant, for the tree watershed. Both these tests and the usual double mass comparison of fern and tree monthly flows showed an ncrease in runoff of about 20 percent after the burn.

A closer estimate of the effect of the burning of he fern watershed on its flows probably can be made by comparing the streamflow of the two watersheds before and after the burning. This echnique is the familiar "calibrated watershed pproach" (Wilm 1949). We wanted to know ot only if the burning had an effect, but also if he effect was different in the wet and dry seasons. irst, the pre-fire monthly flows of the fern watershed were regressed against those of the tree atershed (see equation 5, table 1). Next, the values of the fern watershed flow for the post-fire months were regressed against the predicted values (from equation 5) and with seasonal variables included (see equation 6, table 1). As a control, the analysis was run against the pre-fire flows (see equation 7, table 1).

Not surprisingly, quite accurate prediction resulted from direct comparison of streamflow of adjoining watersheds. The explained variances were 98 percent. The equations of monthly flows (equation 6 and 7, table 1) may be simplified by substituting -1 for the wet season and $+1$ for the dry season:

Wet season:
  Pre-fire $Q\ (\text{fern}) = -0.06 + 2.01\ Q\ (\text{tree})$
  Post-fire $Q\ (\text{fern}) = -0.10 + 2.39\ Q\ (\text{tree})$
Dry season:
  Pre-fire $Q\ (\text{fern}) = -0.16 + 1.46\ Q\ (\text{tree})$
  Post-fire $Q\ (\text{fern}) = -0.14 + 1.77\ Q\ (\text{tree})$

The implied effect of the burn was to increase the regression coefficient of the equations by 20 percent in both periods (from 2.01 to 2.39 in the wet season and from 1.46 to 1.77 in the dry season). This increase agrees quite closely with the results of the double mass analysis, reported earlier in this paper.

Storm Streamflow and Flood Peaks

Responses of the two watersheds to rainfall are reflected in the amount of streamflow and the maximum discharge resulting from individual storms. We studied the relation of these two streamflow characteristics to amounts and intensities of rainfall during a storm and to the amount of rainfall in the week immediately antecedent to the storm. Separate analyses were made for each watershed and for the pre-fire and post-fire periods.

In this study the precipitation record was divided into storm events, a storm being defined as "a succession of days with daily recorded rainfall, in which no day had less than 0.10 inch of rain." Storm rainfall for a watershed was a simple average of the four gages in each watershed. And maximum intensities of rain for the storm were taken from the recording gage in each watershed and adjusted to "watershed intensity" by using the ratio of watershed rainfall to catch in the intensity gage.

For each period, pre- and post-burn, a sample of storms was selected to represent as wide a difference in total storm rainfall and intensities as possible—together with a maximum of diversity in the amount of rain occurring antecedent to the storm. A total of 36 storms was used for the tree watershed and 39 storms for the fern watershed for the pre-fire period. For the post-fire period, 43 storms were selected for each watershed.

Variables and Functions Tested

Storm characteristics or variables used in the analyses are defined as follows: [2]

Dependent variables:

QS = total storm discharge, unit, inches depth.
QPI = maximum discharge, unit, inches depth per hour.

Independent variables:

AP7 = total rainfall in 7 days before storm (to index pre-storm soil moisture conditions), units inches depth.
AP30 = total rainfall in 30 days before storm, units inches depth.
P5 = maximum 5 minute rainfall intensity during storm, units, units inches per hour.
P15 = maximum 15 minute rainfall intensity during storm, units inches per hour.
PS = total storm rainfall, units inches depth.
S = seasonal class, dry season S = 1, wet season S = 0.

Means and standard deviations of the streamflow and rainfall variables are given in table 2.

Linear and non-linear expression and logarithmic transformations of the variables were tested. Selection of variables used was based on tests of significance and contributions of the variables to explain variation in streamflow.

Analytical Methods

To determine streamflow response to rainfall, we used multivariate analysis techniques.[3] Important steps in the analysis were as follows: (a) a factor analysis, known as principal components with varimax rotation, to diagnose the adequacy of the rainfall data of selected storms (Cooley and Lohnes 1962; Horst 1965); (b) a regression on principal components to determine quantitative relations between the precipitation variables and streamflow; (c) a determination of factor contribution to explain variation and the variables associated with each factor[4]; and (d) a test for autocorrelation.

To simplify the comparison of rainfall-streamflow relations, we omitted variables that were not significant or added nothing to explain streamflow variation. Eliminated variables were (a) the 5-minute intensity of rainfall (P5), which added nothing to the information not included in P15 (and P15 could also be more accurately determined from the charts); (b) antecedent 30-day precipitation (AP30) and the 7- to 30-day antecedent rainfall (AP30–AP7), which did not improve prediction over use of simple AP7; and (c) logarithmic transformation from the variables, which gave no improvement in relationships that could not be better explained by testing quadratic and joint variables of the non-transformed variables, and therefore arithmetic variables were used as being simpler to interpret and use. Tests for autocorrelation of the data, arranged by storm size, gave non-significant Durbin-Watson coefficients (Durbin and Watson 1951).

Storm Streamflow-Rainfall Relations

The relationship between storm characteristics and storm runoff between the two watersheds in the two periods, together with the seasonal effect

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[2] Units of inches refer to inches equivalent depth of water over the watershed area.

[3] Although most of the techniques used here have been known for many years, only recently have computer programs and certain extensions of the programs made them applicable to hydrology. Initially in our factor analysis we used the University of California BC TRY computer package of Prof. R. C. Tryon. Later we used a program written by J. R. Wallis for principal components analysis (Wallis 1965), which includes mathematical formulation of factor contribution from rotated factor weights contributed by Prof. W. M. Meredith, University of California, Berkeley.

[4] Factors (or dimensions) represent such physical characteristics of the storms as amount of rain, intensity of rain, or wetness of watershed. A factor may consist of one or more variables.

Table 2.--*Means and standard deviations of variables used in storm analyses*[1]

Watershed and period	Statistic	Variable symbol[2]				
		QS	QPI	PS	AP7	P15
Fern, prefire	Mean	0.83	0.11	2.99	1.44	0.86
	S.d.	1.68	.22	3.09	1.25	.93
Tree, prefire	Mean	.26	.07	2.60	1.48	.92
	S.d.	.49	.25	2.71	.99	.88
Fern, post fire	Mean	.49	.11	1.95	1.70	.87
	S.d.	1.19	.41	2.35	1.42	.87
Tree, post fire	Mean	.27	.05	2.04	2.72	.98
	S.d.	.55	.21	2.23	2.68	.76

[1] Listing of all variables for the selected storms are available upon request to Director, Pacific SW. Forest and Range Expt. Sta., P.O. Box 245, Berkeley, Calif. 94701. Original records may be seen in Honolulu, Hawaii.

[2] QS is total storm runoff in inches, QPI is maximum discharge during storm in inches per hour, PS is total precipitation for storm in inches, AP7 is total precipitation in the 7 days antecedent to storm in inches and P15 is maximum 15-minute precipitation intensity during storm in inches per hour.

of the relationships, were evaluated by the following model:

> Storm runoff = F (storm precipitation (PS), storm precipitation squared (PSSQ), storm precipitation times 7-day antecedent precipitation (PSAP7), season (S).

The adequacy of the selected storms for evaluation of storm-runoff relations was tested by principal components analyses of the correlation matrices of the precipitation variables. The resulting factor weight matrix after varimax rotation is illustrated for the tree watershed in the post-fire period:

Variable:	Dimension number (1)	(2)	(3)
PS	.98	−.02	.29
PSSQ	.98	−.05	.08
PSAP7	.21	0	.98
Season	−.04	.99	0

Dimension No. 1 consists of the storm precipitation and its square, with heavy loadings occurring only on these two variables. Dimension No. 2 is the season variable; and dimension No. 3 represents the interaction variable, that is, storm precipitation x antecedent 7-day precipitation. Similar factor weight matrices were obtained for other watersheds and other periods. The loadings on the variables and dimensions are such as to indicate that we may well use this set of data to test the effect of these variables on the dependent variable of storm runoff.

When the above variables were related to storm runoff by regression on principal components, explained variance ranged from 78 to 93 percent (for equations 8–11, table 4). The proportion of explained variance associated with each of the dimensions for the two watersheds and the two periods is shown in table 3. In general, the largest part of the explained variance—67 to 87 percent—was associated with the storm precipitation; another 9 to 22 percent was explained by the interaction of antecedent and storm precipitation. Seasonal effects added 1 to 3 percent.

The regressions of storm precipitation, antecedent precipitation, and season on storm runoff from the two watersheds provide some clues to the hydrologic processes in effect in these watersheds and the effects of the burn on these processes (table 4). We see that the seasonal effect on runoff was remarkably uniform, amounting to about one-tenth inch less runoff per storm in the dry season (May to October) than in the wet season (November through April). The interaction of storm and antecedent 7-day precipitation seemed to be quite important in the fern watershed in both the pre- and the post-fire periods, but not important in the tree watershed in either period. Hence, these two watersheds behaved quite differently in their reaction to antecedent wetness conditions. If the different responses to antecedent precipitation were due to soil conditions developed under the fern vegetation, then the effect persisted after the burning of the fern watershed into the post-fire period. The

Table 3.--*Explained variance, storm analyses, by watershed and period*

STORM DISCHARGE

Watershed and period	Variables and explained variance for dimension number...[1]			
	(1)	(2)	(3)	R^2
Fern, prefire	PS, PSSQ 67	Season 3	PSAP7, PS 22	92
Fern, post fire	PSSQ, PS, PSAP7 89	Season 1	PS 3	93
Tree, prefire	PS, PSSQ 67	Season 2	PSAP7 9	78
Tree, post fire	PS, PSSQ 87	Season 2	PSAP7 5	93

PEAK DISCHARGE

Watershed and period	(1)	(2)	(3)	R^2
Fern, prefire	P15SQ, PSSQ 54	Season 2	PSAP7, PSSQ 32	88
Fern, post fire	P15SQ, PSSQ 89	Season 1	PSAP7 4	94
Tree, prefire	P15SQ 78	Season 1	PSAP7, PSSQ 3	82
Tree, post fire	P15SQ, PSSQ 90	Season 1	PSAP7 1	91

[1] Definition of variables PS, etc. are given in text. SQ after a variable indicated variable is the square; PSAP7 is PS times AP7.

Table 4.--*Storm streamflow and peak flow relations to storm and pre-storm characteristics, fern and tree watersheds, Oahu, Hawaii, 1951-1955*[1]

STORM STREAMFLOW

Equation No.	Watershed and period	Equations	n	R^2	Syx
(8)	Fern, prefire	$QS=-0.26+0.209PS+0.017PSSQ+0.033PSAP7-0.10S$	39	0.92	0.50
(9)	Tree, prefire	$QS=0.00+0.085PS+0.007PSSQ+0.000PSAP7-0.12S$	36	.78	.24
(10)	Fern, post fire	$QS=-0.12+0.200PS+0.012PSSQ+0.036PSAP7-0.11S$	43	.93	.33
(11)	Tree, post fire	$QS=-0.04+0.113PS+0.010PSSQ+0.003PSAP7-0.11S$	43	.93	.16

PEAK DISCHARGE

Equation No.	Watershed and period	Equations	n	R^2	Syx
(12)	Fern, prefire	$QP=-0.004+0.032P15SQ+0.003PSSQ+0.004PSAP7+0.00S$	39	.88	.08
(13)	Tree, prefire	$QP=0.034+0.059P15SQ+0.002PSSQ-0.007PSAP7+0.02S$	36	.82	.11
(14)	Fern, post fire	$QP=-0.039+0.070P15SQ+0.006PSSQ-0.001PSAP7-0.01S$	38	.94	.11
(15)	Tree, post fire	$QP=-0.023+0.039P15SQ+0.004PSSQ-0.001PSAP7-0.03S$	43	.91	.07

[1] Equations are from regressions on principal components, with dimensions set at 3. Variables are defined in text. n is number of storms. R^2 is explained variance in percent, and Syx is standard error of estimate.

effect of storm precipitation was different between the watersheds, but not between the periods within a watershed. About twice as much runoff per storm is indicated for the fern as for the tree watershed. For the fern watershed, no difference in the reaction of storm precipitation occurred between the pre-fire and post-fire periods (equations 8 and 10, table 4).

What then was the source of the increase in monthly flows previously found in the post-fire period in the fern watershed? The answer is suggested by the difference in the regression constant, which may be interpreted as a difference largely in interception storage. The difference of 0.14 inch per storm (—0.12 —(—0.26)) is the equivalent of 17 percent increase in the average storm runoff; that is, of the mean QS of 0.83 from table 2. This increase is consistent with the 20 percent increase found in the monthly flow analysis.

The lack of change in the coefficients relating precipitation to runoff in the pre- and post-fire periods may be interpreted as indicating that the burning of the watershed had little effect on the infiltration or percolating capacity—at least not in the range such as to affect rainfall excess or storm interflow or both. If infiltration or percolation capacity were affected, enough detention characteristics in the watersheds remained to mask the effect of such changes. On the other hand, the increase in the regression constant indicates that the burning of the watershed had its expected effect in reducing any storage that was readily available for evaporation, such as the interception storage. As for the consistent seasonal effect of one-tenth inch less runoff per storm in the dry season, that implies a higher evaporation and transpiration in that season. Local climatological studies indicate greater evaporation potential during the dry period (Chang 1961). The similar coefficient for the seasonal effect between watersheds indicates about equal change in evaporation on the two watersheds with season.

The coefficients and constants for the tree watershed, pre-fire and post-fire, differed only slightly, indicating—as expected—little change in hydrologic conditions. This finding further suggests that the changes in the fern watershed were real and caused by the removal of the fern vegetation.

Peak Discharge-Rainfall Relations

The same storms used in the storm runoff studies were used in the peak discharge evaluations; however, the 15-minute intensity of storm precipitation was substituted as one of the variables. To test the adequacy of the sample of storm and antecedent rainfall, the varimax rotated factor weight matrix resulting from a principal component analysis was studied. For the tree watershed in the post-fire period, the analysis showed the following:

	Dimension number		
Variable:	(1)	(2)	(3)
P15SQ	.96	.01	.06
PSSQ	.95	—.07	.17
PSAP7	.14	0	.99
Season	—.03	.99	.06

We see from this analysis that the 15-minute intensity and storm precipitation load together on dimension No. 1, hence, they both represent storm rainfall characteristics. Again the seasonal effect loaded on the single dimension, dimension No. 2: the variable expressing the interaction of storm size and 7-day precipitation loaded on dimension No. 3. Therefore, we concluded that the sample of storms was adequate for testing these variables for their effect on peak discharges.

The factors contributing to peak discharges were evaluated from the regression on principal components. Explained variance ranged from 82 to 94 percent (table 3), with 54 to 90 percent being associated with the storm characteristic variables. The seasonal contribution was not large—only 1 to 2 percent. The interaction of storm size and 7-day antecedent precipitation was apparently unimportant.

The coefficients relating storm intensity to peak discharges give some clues to the processes of peak discharge development in these watersheds. One clue is the curvilinearity indicated by both storm variables being best expressed as squares of precipitation. This is apparently true curvilinearity and not merely a missing threshold (subtracting a threshold value of 0.25 inch per hour from P15 actually decreased prediction). From the curvilinearity, we may infer that increasing rainfall intensities produce runoff from larger and larger new areas.

The effect of the fire in the fern watershed may be seen in the effect on the rainfall coefficients and on the variability of flow. The variability of the flow was doubled as a result of the burning, as is shown by the standard deviations in table 2. The coefficients of the rainfall-runoff were greater in the post-fire periods (table 4). Both effects suggest changes in the processes affecting peak flows, involving changes in the surface roughness, changes in the time of concentration of runoff from the parts of the watersheds, and local changes in the flow paths, such as changes from interflow through the soil to surface flow. Further clues might come from analysis of the hydrograph shapes; such an analysis was not part of this study.

Conclusions

From this short-term study of rainfall-runoff relations on two small watersheds in Hawaii, we concluded that:

- Streamflow was a relatively small proportion of the average annual rainfall of 93 to 105 inches, being as little as 6 percent and at most 25 percent of the rainfall in individual years and watersheds.
- Rather large differences in runoff characteristics can be expected from adjoining watersheds; streamflow differed by a factor of at least 2.
- There will be less runoff per unit rainfall in the dry season than in the wet season, with runoff per storm of 0.1 inch (12 to 38 percent) less in the dry season.
- If false staghorn fern is removed from watersheds, such as by fire, short-term increases in storm runoff and peak flows can be expected. An increase of 20 percent in storm runoff was found for the first 2 years after the burn. Peak discharges were greater only for larger than average storms.
- Changes in hydrologic processes that result from treatment of these watersheds may be inferred from principal components analyses of rainfall-runoff relations.

The technique of using "paired watersheds" for analysis has one possible weakness: each pair is unique and its response to rainfall—or as in this study, to burning—may in some degree be unique. Therefore, we cannot be certain that the greater streamflow from the fern watershed was due entirely to difference in vegetation. If measurements were made now of streamflow and rainfall—some 13 years after tree establishment on the fern watershed—we might have further evidence of the effect of fern vegetation as opposed to that of trees on a watershed. We recommend such a study be made.

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Detection and Classification of Ash Dieback on Large-Scale Color Aerial Photographs

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Contents

Acknowledgments

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The Author

RALPH J. CROXTON is studying problems in aerial detection of forest diseases, with headquarters in Berkeley, Calif. In 1964, he joined the Forest Service's Forest Insect Laboratory staff, at Beltsville, Md., where he did the work reported in this paper. In 1965 he transferred to the Pacific Southwest Station. Native of Anderson, Indiana, he earned a B.S. degree in silviculture (1952) at Purdue University and a M.F. degree (1964) at Yale University.

Surveys of ash trees killed by ash dieback in the Northeastern United States indicate that the disease is slowly preading and becoming more intense. In a ground urvey, Tegethoff and Brandt (1964) found that 7.2 percent of sampled ash trees in the six-state rea surrounding New York State were either dead r dying.

Both white ash[1] and green ash are susceptible o this disease, but green ash comprises only a mall part of the ash component of hardwood tands in that region. Consequently, white ash—a aluable species in great demand—bears the brunt f the losses. Since trees of all ages are known to e susceptible, ash dieback will cause a future hortage of white ash logs because of current morlity in the sapling and pole sizes—even if it subdes quickly.

The first symptoms of the disease are dwarfing f the leaflets and the appearance of a sickly yelw-green color of the foliage. The disease begins the smallest twigs and spreads to larger ranches. As the dead twigs are shed and stageadedness develops, the tree may produce epirmic branches below the active infection (Brandt 963; Silverborg *et al.* 1963). Killing of the igs, branches, and limbs continues rapidly; ithin 2 to 7 years the tree is dead.

A primary causal agent has not been found, t forest pathologists agree that ash trees never ecover from ash dieback (Brandt 1961; Zabel *et al.* 1963; Tegethoff and Brandt 1964). Ross (1963) reported that two fungi, *Cytophoma pruinosa* (Fries) Hohn. and *Fusicoccum* sp., are secondarily associated with the disease. Similar declines of other hardwood species have been observed.

Forest pathologists suspect that both ash dieback and other hardwood declines may be induced by drought (Yops *et al.* 1964). New York State has had three major periods of drought since the early 1950's. The reduction in vigor caused by droughts or other adverse climatic conditions (Hepting 1960, 1963; Ross 1964) may lead to an intensification of damage from these secondary fungal invaders that are thought to be ordinarily saprophytic or only weakly parasitic.

Despite the lack of knowledge about the causes of ash dieback, its effects and widespread distribution on valuable host species warrant periodic surveys so that trends of spread and intensity can be followed. The large geographic area already involved suggests that aerial methods of surveying are desirable, if feasible.

This paper reports on a study to determine if ash trees could be identified on large-scale aerial photographs and then be placed into broad classes according to dieback symptoms. If ash could be distinguished from other hardwoods and classified on film, an aerial survey technique could readily be designed and made operational.

Methods

Preparation of Training Aids

The first need was to determine the appearance ash, associated species, and ash dieback, on rial film so that interpreter training aids could be prepared. Color photography was selected because the symptoms of ash dieback include a distinct yellowing of the foliage and because the foliage of many hardwood species shows differing hues and chromas which may make separation easier. An area known to have ash dieback was photographed on August 18, 1964, near Red

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[1] Scientific names of trees and shrubs are listed in the pendix.

Hook, New York, using photographic scales of 1:1,584 and 1:7,920.[2] A Hulcher[3] 70-mm. camera with a 150-mm. focal length lens was used to expose Anscochrome D-200 color film with a skylight (1A) haze filter. This film has an ASA rating of about 160 when used in aerial photography.

After the film was developed, the color transparencies in strip form were taken to the field and used in a portable, battery-powered light table to enable ground identification of selected healthy ash, diseased ash, and trees of associated species. Each ash tree chosen was given a dieback rating of 1 through 5, based on the following dieback-symptom classes:[4]

Class 1: Trees healthy; leaves dark green; no dead bare twigs in living crown.

Class 2: Top thin; leaves tending to clump at end of twigs; foliage paler green than normal; leaves may be dwarfed; some dead twigs; possibly some cankers at base of twigs.

Class 3: Twigs dying back; less than 50 percent of crown dead; leaves clumped at ends of twigs and branches, and leaflets dwarfed; foliage pale green; cankers possibly visible on branches and stems.

Class 4: Branches dying back; more than 50 percent of crown dead; epicormic branches may be present, leaves clumped and leaflets dwarfed; foliage pale green; cankers sometimes visible on branches and stems.

Class 5: Tree dead.

After a tree was identified and classified on the ground, it was located, circled, and numbered directly on the color transparency.

In the laboratory, these circled trees on the film were carefully studied stereoscopically and detailed descriptions were prepared for each of the five classes of ash plus each of 13 associated species at both scales. From these descriptions it became a fairly simple matter to produce a dichotomous key containing all 13 species and all classes of ash dieback. Part of the film was used togethe with the descriptions and key to train four interpreters; the remainder was reserved to test thei abilities after they were considered proficient.

Preliminary Test

With all training aids available to them, the interpreters were asked to identify a number o circled trees on the film as to species. If a tre was thought to be ash, they were to indicate it dieback class.

The results of this test were encouraging. Th four interpreters identified ash with better than 9 percent accuracy at the larger scale and 78 percen accuracy at 1:7,920 scale. The five dieback classe were correctly interpreted (within one class) 8 percent of the time at 1:1,584 and 71 percent a 1:7,920. We then decided to determine if the interpreters could scan an area on the film and selec the ash satisfactorily, when trees were not circled

Final Scan Test

Ash stands infected by dieback were selecte and marked on the ground within the boundarie of forests owned by the New York State Conservation Department. Stable ownership of the tes area was desired because of the long-range natur of the study. The study area was located i Dutchess County near the Taconic Parkway eas of Poughkeepsie, New York. Markers of whit butcher paper were placed in clearings adjacent t the areas to be photographed to aid in spottin these test areas from the air. The photograph were taken on June 11, 1965, with the sam scales, film,and equipment used in the first photographs. This date was selected because by then th new growth on ash was fully expanded. Dwarfin of the leaflets is an important characteristic c trees infected with dieback (fig. 1), and this symptom could have been confused with normal bu immature leaves if an earlier date had been chose

Many of the seriously diseased ash on the 196 Red Hook film strip (photographed in late sum mer during a drought year) had all brown leave Others showed yellow and red colors on certai portions of their crowns and the remainders wer yellow-green. We suspected that these were n the true characteristic colors of ash dieback, b expressions of premature fall coloration induc by the interaction of dieback and drought. Ther fore the Red Hook area was rephotographed, t the larger scale only, on June 11, 1965. Of t many individual ash trees compared on the t

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[2] A photographic scale of 1:7,920 means that 1 inch, measured on the photo, represents 7,920 inches on the ground. These unusual scales were chosen because they become whole numbers when converted to chains per inch: 1:1,584 equals 2 chains per 1 inch, and 1:7,920 equals 10 chains per inch.

[3] Trade names and commercial products or enterprises are mentioned solely for necessary information. No endorsement by the U.S. Department of Agriculture is implied.

[4] Tegethoff and Brandt (1964) used the same classification system in their ground survey of ash dieback.

Figure 1.—*Three classes represented by healthy, diseased, and dead ash trees. Leaflets have become dwarfed and foliage thin in the center tree.*

films, most had refoliated in the spring of 1965. Although the foliage was slightly sparser, the trees had produced new leaves of a pale green color rather than the browns, reds, and yellows present during the previous autumn. These atypical dieback colors were therefore removed from the training key.

After the film for the Poughkeepsie study area was developed, additional sample trees of ash, associated species, and ash dieback just outside he new study area were identified on the ground and located on film. This procedure was necessary because the trees in the new Poughkeepsie area to be interpreted were some 17 miles from he trees at Red Hook upon which the training aids were based. No differences in ash appearance were found at the new location, so no further updating of the training material was needed.

Fourteen plots were selected on the transparencies, each placed near the center of a photo frame to minimize tree image displacement. Each plot represented roughly ½ acre, making a total study area of about 6¼ acres. The plots were outlined in ink on the transparencies, with the boundaries meandering between tree crowns to assure that all interpreters would be examining the same borderline trees.

The film (figs. 2, 3) was interpreted by three photo interpreters, none of whom had seen the study area on the ground. Use of training aids was encouraged during the test. The smaller scale film was interpreted first to eliminate bias caused by memory. Interpreters were asked to circle on transparent plastic overlay material every ash within the plot boundaries and to assign each one a dieback class number. For this test the number of dieback classes was reduced from five to three, but class numbers 1, 3, and 5 were retained so that the results could be more easily compared with those of the preliminary study. Comparison

Figure 2.—*Stereogram of a part of the Poughkeepsie, New York, study area at a scale of 1:7,920. See fig. 3 for larger-scale view of area outlined.*

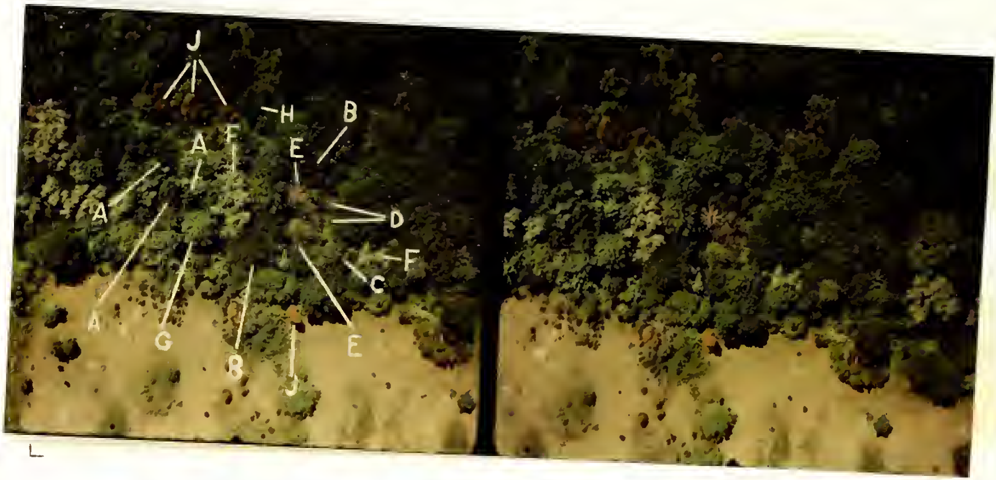


Figure 3.—*Stereogram of a portion of the same area as fig. 2 at a scale of 1:1,584. Species indicated are:* A, *healthy ash;* B, *healthy American elm;* C, *class 3 ash;* D, *dead American elm (twigs fine, many crooks);* E, *dead ash (twigs coarse, rather straight);* F, *healthy black willow;* G, *healthy sugar maple;* H, *healthy red maple;* J, *paper birch badly damaged by a leaf skeletonizing insect.*

of dieback class ratings for the two tests showed the following:

Dieback classes used in preliminary test	Dieback classes used in area-scan test
1	1
2 3 4 (lower ½)	3
4 (upper ½) 5	5

A master template prepared for each plot contained all tree images identified as ash by each interpreter. Each circled tree on these templates was carefully examined on the ground. Information was gathered not only about species and dieback classification but also diameter at breast height (d.b.h.), total height, crown class, crown diameter, and soil moisture. At the same time, any ash trees not identified by the interpreters were located in the field and accurately plotted to provide information on errors in which interpreters failed to see existing ash trees. We found that the study area actually contained 155 ash trees—four were black ash and the remainder white ash. Because these ash species looked alike on the film they were combined in the analysis.

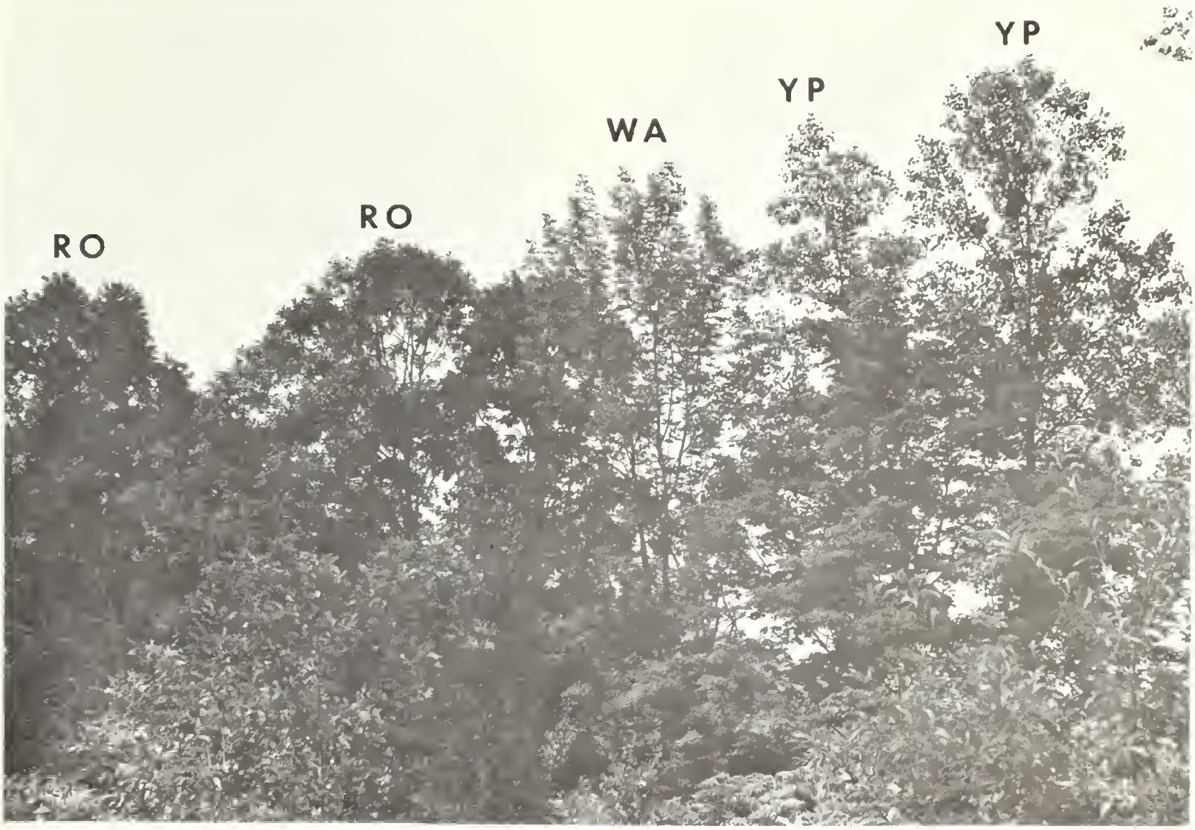


Figure 4.—*Skyline view of red oak, white ash, and yellow-poplar crowns clearly shows the upswept finger-like branching habit of white ash.*

Ash Characteristics

Fortunately, ash has several distinctive characeristics that enabled it to be distinguished from he associated species on color film. Certain of hese attributes came to light during the final scan est; the principal ones are listed below in order of heir importance:

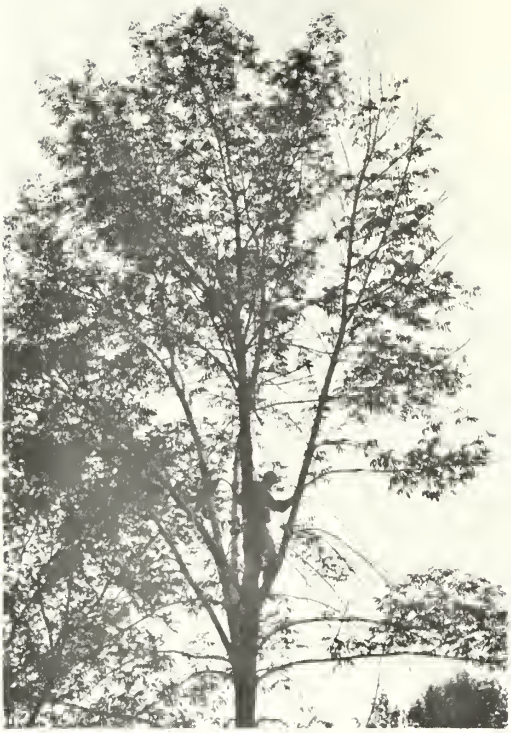
1. The limbs, branches, and twigs of ash are pswept and erect (figs. 2, 3). On healthy ash the eaves are distributed well down the twigs, giving columnar effect. Therefore, from above an oberver sees the ends of many vertically-oriented olumnar twigs. In side views of ash crowns, it is asy to visualize why the vertical view gives this pswept finger-like appearance (figs. 4, 5). Meran elm (figs. 3, 6) lacks this characteristic.

2. The ends of most of the adjacent terminal shoots are at varying heights above the ground, resulting in a ragged and irregular crown when viewed from above.

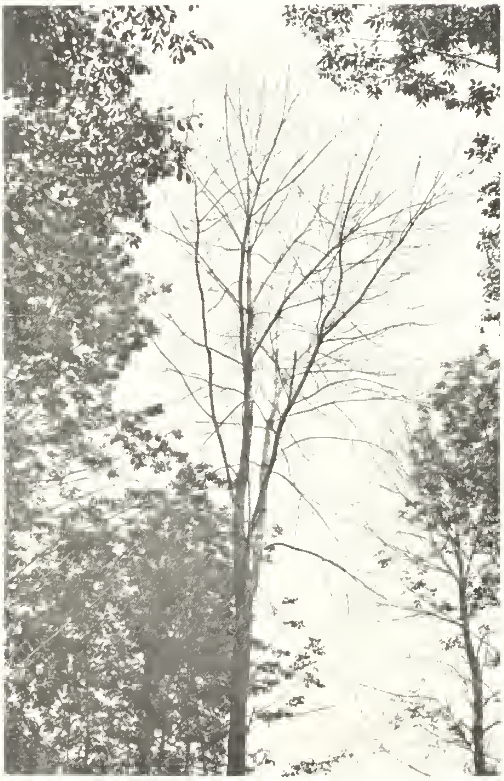
3. Twigs are well separated in the tops of the crowns, allowing the observer from above to look down deeply into the crown interior. These intertwig openings appear as dark shadows regularly spaced over the crown surface.

4. Healthy ash has a dark green color. Although American elm has the same color, it would have been eliminated by any of the first three characteristics listed. Conversely, red maple has the first three characteristics, but healthy red maple is notably yellow-green. Furthermore, the columns

Class 1



Class 3



Class 5

Figure 5.—*The three dieback classes of ash show differences in crown density, leaflet size, and dead twig distribution. Trees are 11 inches d.b.h.*

Figure 6.—*Differences in branching habits between an American elm,* left, *with branches and twigs extending radially in all directions, and a white ash,* right, *with branches and twigs upswept and vertically oriented. These characteristics are apparent on the vertical photography. The white ash has ash dieback.*

of foliage on red maple are much smaller (and more numerous) than ash since red maple has small simple leaves and ash has large compound leaves.

5. Ash has an opposite arrangement of the leaves and therefore, when viewed from above, the terminal leaf pair is superimposed upon the third and fifth pairs below it, and the second pair is directly above the fourth and sixth pairs. This arrangement quite often results in a distinct four-pointed star shape at the twig tip. Occasionally this star shape can be found on other species through the chance superposition of tree parts but never as often as on ash crowns.

6. The immature leaves at the tips of ash twigs reflect, absorb, and reemit incident light differently than the older leaves farther down the twigs. Therefore on healthy ash a light green spot is visible at the twig ends, and the rest of the foliage is dark green.

7. In the Poughkeepsie area, healthy black ash cannot be distinguished from white ash. However, local color variations of healthy black ash are to be found. Healthy black and white ash on the Poughkeepsie film were compared with many images of healthy black ash recorded on film in previous years near Ely, Minnesota. Healthy Minnesota black ash has a decided yellow-green color. Ash dieback has not appeared as yet in that part of the Lake States, but if it should reach Minnesota, accurate classification of dieback would be hindered by this color variation. Minnesota black ash also did not display the wide spacing of twigs over the crown as described in 3 above.

8. As the symptoms of dieback become progressively more severe, certain of the above traits become more prominent. Dwarfing of the leaves and leaflets reduces the interpreter's ability to resolve the outline of the tree, but this condition is more than offset by the clarity which results from the accompanying clustering of leaves at the twig tips. Without the distraction of a background of lower leaves, the cross shapes at the tips become much easier to see. The clumping of leaves at the twig tips is a helpful dieback clue in itself. On color film the change from dark green to pale yellow-green is an enormous advantage in identification and classification.

Results and Discussion

Ash Identification

The three interpreters—identified in this paper as A, B, and C—were able to identify correctly 59.4 percent, 65.2 percent, and 70.3 percent of the ash, respectively, at 1:1,584 scale. At the 1:7,920 scale, the results were about half as good: 28.4 percent, 36.8 percent, and 41.3 percent (fig. 7). The 1:7,920 scale is clearly unfit for use in identifying ash. Therefore all further discussion will pertain only to the 1:1,584 scale, unless otherwise indicated.

Errors in identifying ash can be of two types:

- **Omission errors:** existing ash trees are not seen by the interpreter.
- **Commission errors:** non-ash trees are erroneously interpreted as ash.

Commission errors were much more of a problem than omission errors (fig. 8). Of the 155 ash trees present, 29 were in the intermediate crown class and 4 were suppressed. Suppressed trees will never be visible, and probably not more than half the intermediate crown class trees will be seen from the air. Therefore 88 percent represents the probable maximum accuracy. Since ash decreases in shade tolerance as it becomes older (Fowells 1965) these invisible trees in the lower crown classes perhaps would not survive anyway.

Although the percentage of ash accurately identified could be accepted with only moderate improvement (75 percent would be considered good), far too many commission errors were made. A total of 27 species were mistaken as ash. American elm contributed most to this type of error, but black cherry, black birch, and sugar maple also were often incorrectly identified (table 1).

The study area purposely included a considerable extent of site I cove-type, hemlock-hardwood stands that were densely stocked and had tall small-crowned trees. Both the density and the small crowns made species separation difficult. Furthermore, on such sites a maximum number of species can endure. By coincidence the study area was located in a transition zone where, according to Oosting (1956), the hemlock-hardwoods association is changing to deciduous forests. This change also contributed to the variety of the flora, and the greater the number of species present, the greater the odds that some of them will show images similar to ash. Thus the study area chosen approached the ultimate in difficulty of species identification by photo interpretation. The modest percentages of success quoted above should be viewed in that light.

Except for American elm, at least one of the interpreters was able to avoid making many commission errors for each of the troublesome species (table 1). That is, at least one interpreter was able to grasp the essential differences between species

Table 1.--*Distribution of commission errors,*[1] *by species, among three interpreters (photographic scale: 1:1,584)*

Species	Total commission errors by interpreter		
	A	B	C
	Percent		
American elm	35.9	40.1	26.5
Black cherry	11.7	9.0	3.9
Red maple	8.3	3.4	2.0
Sugar maple	1.4	6.7	13.7
American hazelnut	5.5	0	16.7
Bigtooth aspen	8.3	1.1	1.0
American basswood	5.5	6.0	2.0
Black birch	2.8	9.4	7.8
American beech	.7	6.0	0
Northern red oak	4.8	3.4	4.9
Other[2]	15.1	14.9	21.5
Totals	100.0	100.0	100.0

[1] Commission error is one in which a non-ash tree is identified as ash.

[2] Includes: red elm, black locust, staghorn sumac, butternut, white pine, common apple, black oak, chestnut oak, ironwood, blue beech, quaking aspen, paper birch, eastern hemlock, shagbark hickory, pignut hickory, false pignut hickory, and black willow.

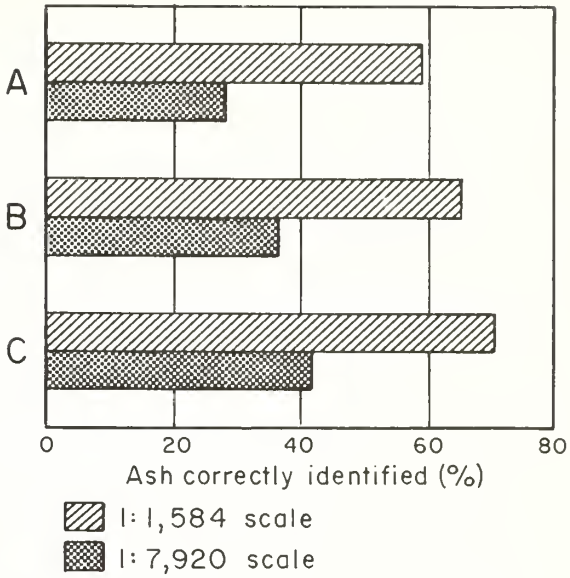


Figure 7.—*The percentage of ash trees correctly identified by three interpreters was much greater at the larger photographic scale. (Basis: 155 trees.)*

even with the weak training aids available to him. All three interpreters were hampered by using training aids prepared from small samples. The information gained in the present study should make it possible to strengthen training aid material and upgrade identification accuracy above the level of 75 percent.

Even the most troublesome species—American elm—did not thwart all interpreters to the same degree (table 1). Furthermore, when commission errors, in which elm was identified as ash, are examined in terms of the elm's dieback class (table 2), it is apparent that interpreter A could separate either healthy or slightly diseased elm from ash, and interpreter C was not inclined to call elm as ash regardless of its disease class. This situation indicates that better training of interpreters should produce better results in distinguishing between these two species.

As expected, the greatest difficulty in ash identification occurred on small trees less than 8 inches d.b.h., 50 feet tall, and 10 feet in crown diameters. Little improvement can be expected here for the lack of resolution results largely from screening and shading by the foliage of adjacent overtopping crowns.

Interpreters became progressively more accurate at identification as the symptoms of dieback worsened (table 3). With data from all three interpreters combined, we found that only 26.8 percent of the healthy (class 1) ash trees were correctly called ash. But moderately diseased (class 3) trees were correctly identified 33.5 percent of the time, and dead or dying (class 5) ash 39.7 percent of the time.

For wet, moist, and intermediate sites the percentage of correct ash calls remained fairly constant, but the omission and commission errors decreased steadily as dryness of site increased (table 4). This results partly from a decrease in numbers of species which occupy dry sites and partly from

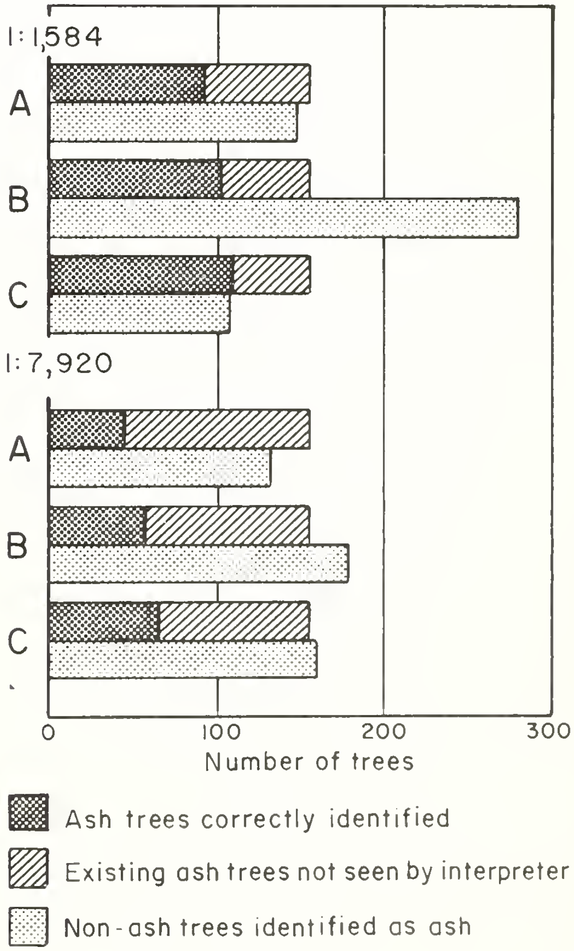


Figure 8.—*At the 1:1,584 scale, interpreters made fewer errors in identifying existing ash trees than they made at the 1:7,920 scale. At both scales, many non-ash trees were interpreted as ash.*

Table 2.--*Number of American elm trees mistakenly identified as ash by interpreters, by equivalent ash dieback class*[1] *(photographic scale: 1:1,584)*

Equivalent ash dieback class[1]	Interpreter		
	A	B	C
	— Number of trees —		
1	9	39	5
3	11	32	10
5	32	36	12
Totals	52	107	27

[1] Although elm has a different disease (*Ceratocystis ulmi* (Buism.) C. Moreau), the same symptom classes were used as for ash dieback.

Table 3.--*Combined attempts*[1] *at classifying ash trees at two scales, by ash dieback class*

Ash die-back class	No. of ash correctly classified		No of ash incorrectly classified		No. of ash not seen, thus not classified[2]		Total attempts	
	1:1,584	1:7,920	1:1,584	1:7,920	1:1,584	1:7,920	1:1,584	1:7,920
1	67	30	14	2	105	154	186	186
3	63	10	38	28	49	112	150	150
5	110	77	10	18	9	34	129	129
Totals	240	117	62	48	163	300	465	465

[1] Multiplying 155 ash trees by three interpreters gives 465 attempts at classification.
[2] Classification shown was made on the basis of ground survey.

Table 4.--*Omission and commission errors*[1] *made in identifying ash trees, by soil moisture class (photographic scale: 1:1,584)*

Soil moisture class	Interpreter A			Interpreter B			Interpreter C		
	Ash correctly identified	Omission errors	Commission errors	Ash correctly identified	Omission errors	Commission errors	Ash correctly identified	Omission errors	Com-missi error
	Number								
Wet or moist	39	31	122	38	32	163	46	24	61
Intermediate	39	27	18	47	19	85	45	21	29
Dry	14	5	5	16	3	19	18	1	12
Totals	92	63	145	101	54	267	109	46	102

[1] Commission error: non-ash tree is mistaken as ash. Omission error: existing ash tree is not seen by interpreter.

he tendency toward larger crowns to be present vhere a poorer soil moisture regime causes lower stocking levels. On a dry site, root competition is nore severe, and each tree occupies more space, ermitting a better crown development.

Ash Dieback Classification

We found no evidence either to corroborate or o contradict Pomerleau's[5] contention that ash lieback is correlated with wet site conditions. In he present study 56.9 percent of the ash on the four wet-site plots had ash dieback, whereas 61.5 ercent of the ash on the combined moist, intermediate, and dry plots had the disease. These small lisparities in percentages may be of a random ature. None of the four black ash was diseased. The four ranged from 3 to 13 inches d.b.h. and all vere in the intermediate crown class.

Sixty percent of the 155 ash trees growing in he study area had ash dieback and will eventually lie. Of these diseased trees, 32.2 percent were in he intermediate stage and 27.8 percent were dead r dying (table 5).

In the d.b.h. classes 2 through 6, there were nore healthy trees than diseased but in classes 7 hrough 19, more were diseased. The Chi-square est shows a significant difference at the .001 level f probability. One might infer that trees greater han 6 inches d.b.h. are more susceptible to dieack than the smaller trees. Furthermore, the fact hat every ash less than 2 inches d.b.h. was healthy nd every ash greater than 14 inches was diseased, einforces this supposition that larger size is posiively correlated with the frequency of attack by sh dieback.

The underlying cause for this relationship is bscure but we may speculate. Oppenheimer 1960) observed that desert plants often have xtensive and deeply penetrating root systems. onversely, he described one situation where Poplars dried up in desiccated river beds where neir roots ran near the surface as an adaptation o [shallow] soil aeration in normal times, but urvived at higher elevations where the roots had lready penetrated to nine feet in five years." The atter is analogous to the ash study area, which ormally has a high water table.

It is a well-established fact, according to Oppenheimer, that under dry conditions plants develop relatively more roots than shoots and that this is a hereditary character. If we can assume that the reverse would hold on wet sites, we have a logical explanation for the prevalence of dieback on larger ash trees. It can be postulated that ash grows chiefly on soils with high water tables, that soil aeration is poor, and that the ash will tend to have small shallow root systems with relatively large crowns. This imbalance would be efficient under normal periods of high rainfall well distributed in time, but such trees would suffer quickly and severely when extended drought desiccates the upper soil levels containing the bulk of the ash root systems.

Regardless of its cause, the fact that large-sized ash trees are attacked more often by ash dieback than are small trees, has not been previously reported. This finding may help future investigators of the disease. Zabel and his co-workers (1963) thought that ash dieback appeared most commonly in sapling and pole-size trees, but provided no supporting evidence. Ross (1966) found that the disease occurred nearly uniformly in all d.b.h. classes, but possibly his poor representation in the upper size classes (fewer than 35 trees over

Table 5.--*Distribution of healthy and diseased ash trees, by diameter breast height*

D.b.h. (inches)	Healthy trees (class 1)	Diseased trees (class 3+5)	Total ash	
	Number			
1	0	0	0	1
2	2	0	2	
3	4	3	7	
4	5	6	11	
5	8	6	14	
6	13	8	21	
7	11	13	24	2
8	4	10	14	
9	3	6	9	
10	3	4	7	
11	5	15	20	
12	2	4	6	
13	0	6	6	
14	2	4	6	
15	0	2	2	
16	0	4	4	
17	0	0	0	
18	0	1	1	
19	0	1	1	
20+	0	0	0	
Totals	62	93	155	

[1] More healthy than diseased.

[2] More diseased than healthy.

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[5] Pomerleau, R. *The relation between environmental nditions and the dying of birches and other hardwood es.* 1953. (Unpublished report of the Symposium on rch dieback, on file at Forest Biology Div., Dep. Agr., tawa, Canada.)

8.0 inches d.b.h.) obscured the trend. Below 8.0 inches d.b.h., his data did show a tendency for larger sizes to have a greater incidence of disease.

From our standpoint in remote-sensing technique research, it is a definite advantage to know that the trees most susceptible to dieback (the larger ones) are also the ones which are most easily seen by the photo interpreter and which the ground crews see indistinctly through the screen of understory vegetation.

While working on 1:1,584-scale photographs, all three interpreters were consistent and were able to place 77.2 percent, 77.2 percent, and 80.7 percent of their attempts exactly into the proper dieback class (table 3). At the 1:7,920 scale, so few ash trees were identified that their subsequent classification was not meaningful. As expected, the interpreters could classify dead and nearly-dead trees at this scale much easier than either class 1 or class 3 trees.

We had some difficulty in deciding whether parts of multiple-stemmed trees had been correctly classified by the interpreters. In the ground data collection, trees forked below 4.5 feet were tallied as separate trees and each was given a dieback class rating. Even when the interpreter could see crown separation, he obviously could not tell whether the tree forked above or below breast height. He had to make this decision at least once on every crown. And his decision influenced the agreement between numbers of ground classification attempts and photo classification attempts. Also a given tree that forked at 5 or 6 feet above ground could show different stages of dieback within each fork. The interpreter in this case would be inclined to classify each fork separately and identify it incorrectly. There were many variations of this problem. In future studies multiple-stemmed trees should be described in detail while investigators are on the ground.

Summary and Conclusions

1. Of the 155 ash trees on the 6¼-acre study area, 60 percent had ash dieback and are doomed to die. The disease had attacked trees ranging from 2 to 19 inches d.b.h.

2. Frequency of attack by ash dieback was strongly and positively correlated to increased d.b.h.

3. Black and white ash could not be differentiated on the film. Black ash being more tolerant of wet soils, is almost always found along streams and on the edges of swamps, however, and these terrain features are evident on the photographs. None of the four black ash was diseased.

4. Ash had several distinctive identification characteristics: upswept and erect branching habits, irregular crown peripherys caused by variable heights of adjacent twigs, well-spaced openings in the crowns that appeared as dark shadows, a dark green color of healthy foliage, and frequent star shapes and light green spots at the twig tips.

5. Ash can be identified with fair accuracy at 1:1,584 scale, but not at 1:7,920.

6. Once they had identified ash, interpreters could classify ash dieback disease well and consistently at the 1:1,584 scale, but not at 1:7,920 scale.

7. The ability of interpreters to identify and classify ash and ash dieback at the 1:1,584 scale is acceptable at present, but the number of errors in which other species were mistaken as ash must be reduced. Improvement can be expected. Since the most efficient photographic scale is near 1:1,584, further study should be directed towards scales of 1:1,584, 1:2,376, 1:3,168, and 1:3,960.

8. Demanding of fertile amply-watered sites, ash has a large number of associates. Interpreters will have to be well-trained to distinguish ash from these associates.

9. The fact that at least one of the interpreters could differentiate ash from each of the difficult associated species indicates that improvement in training aids is the key to the identification problem.

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Appendix

Common and scientific names of trees and shrubs mentioned in this paper.

pple, common	*Malus pumila* Mill.
sh, black	*Fraxinus nigra* Marsh.
sh, green	*Fraxinus pennsylvanica* var. *lanceolata* (Borkh.) Sarg.
sh, white	*Fraxinus americana* L.
spen, bigtooth	*Populus grandidentata* Michx.
spen, quaking	*Populus tremuloides* Michx.
asswood, American	*Tilia americana* L.
eech, American	*Fagus grandifolia* Ehrh.
eech, blue	*Carpinus caroliniana* Walt.
irch, black	*Betula lenta* L.
irch, paper	*Betula papyrifera* Marsh.
utternut	*Juglans cinerea* L.
herry, black	*Prunus serotina* Ehrh.
lm, American	*Ulmus americana* L.
lm, red	*Ulmus rubra* Muhl.
Hazelnut, American	*Corylus americana* Walt.
Hemlock, eastern	*Tsuga canadensis* (L.) Carr.
Hickory, false pignut	*Carya ovalis* (Wang.) Sarg.
Hickory, pignut	*Carya glabra* (Mill.) Sweet.
Hickory, shagbark	*Carya ovata* (Mill.) K. Koch.
Ironwood	*Ostrya virginiana* (Mill.) K. Koch.
Locust, black	*Robinia pseudoacacia* L.
Maple, red	*Acer rubrum* L.
Maple, sugar	*Acer saccharum* Marsh.
Oak, black	*Quercus velutina* Lam.
Oak, chestnut	*Quercus montana* Willd.
Oak, northern red	*Quercus rubra* L.
Pine, eastern white	*Pinus strobus* L.
Sumac, staghorn	*Rhus typhina* L.
Willow, black	*Salix nigra* Marsh.
Yellow-poplar	*Liriodendron tulipifera* L.

GPO 973-550

Sequential Sampling of Ribes Populations in the Control of White Pine Blister Rust (*Cronartium ribicola* Fischer) in California

Harold R. Offord

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Forest and Range Experiment Station
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Forest Service - U. S. Department of Agriculture

Contents

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HAROLD R. OFFORD is a consultant to the Station, where he served as chief of the division of forest disease research from 1956 until his retirement in 1964. Native of Toronto, Canada, he earned bachelor's and master's degrees in biochemistry at the University of British Columbia. Much of his career has been devoted to work on methods of controlling white pine blister rust and other forest diseases, with various agencies of the U.S. Department of Agriculture, including the Bureau of Plant Industry, Bureau of Entomology and Plant Quarantine, and California Region and Berkeley Experiment Station of the Forest Service.

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The control of white pine blister rust (*Cronartium ribicola* Fischer) is a widespread and well known problem in forested areas throughout the United States. In California, as in other white pine regions, control is based on the suppression of the alternate host plants—native currants and gooseberries (*Ribes* spp.)—to prescribed population levels. The success of this control effort is usually determined by a formal survey which provides maps and data to show the size and distribution of the residual ribes population. Local climate and plant associations determine whether the rust hazard is high, average, or low. And this rust hazard in turn sets the tolerable limits for the incumbent population of ribes.[1] Administrative inspections, or combinations of such inspections and formal surveys, also are used in appraising the need for control work or its effectiveness.

In forest disease control work in which a distribution map of host or pathogen is available, or not needed, sequential sampling can minimize survey effort. And in an orderly and statistically useful way, it can allow for increased sampling in accord with control needs.

This paper reports on a study in which a sequential sampling plan was developed for surveying ribes populations in California. The cost and usefulness of this plan are compared with those of the standard survey method now in use. The term "cost" as used here means the time needed to do the survey and does not imply an economic analysis of all factors involved. Advantages of sequential sampling for ribes surveys and some of its limitations also are described.

The sequential plan herein described is based on ribes survey records and control standards in California and may need to be modified for use elsewhere. There are still several unresolved theoretical questions that relate to the efficient field use of sequential sampling. These are now being studied by statisticians at this Station. Nevertheless, studies to date indicate that sequential sampling is probably at least as good as the sampling method now in general use. Therefore, computer programs have been designed and tested to produce sequential plans suitable for further tests under a variety of field conditions.

Ribes Surveys

Cost and efficiency of ribes surveys has been he subject of intense interest and considerable tudy since the control work was formalized in he early 1930's. Harris (1941) described field methods used for sampling ribes populations, giving special attention to work in sugar pine forests of California. Much of the background and detail on studies subsequent to his publication is in unpublished reports not readily available for reference. In 1964 the California Region of the U.S. Forest Service completed a revised training aid for surveymen entitled "Ribes Surveys in California." This publication effectively brings up-to-date procedures for the planning and conduct of this work.

Ribes survey, or "checking" as it has been traditionally called in blister rust control work, is an integral and continuing part of the total control job. In California three types of checking are recognized. In control parlance they are known as *advance*, *regular*, and *post checks*. *Advance check* shows the distribution, number, and size of host plants as an aid in the planning of eradication work. *Regular* or *inspection check* (fig. 1) determines if a specific blister rust control unit has been worked to prescribed control standards. *Post check* appraises the status of the ribes population and ribes regeneration, and from this the

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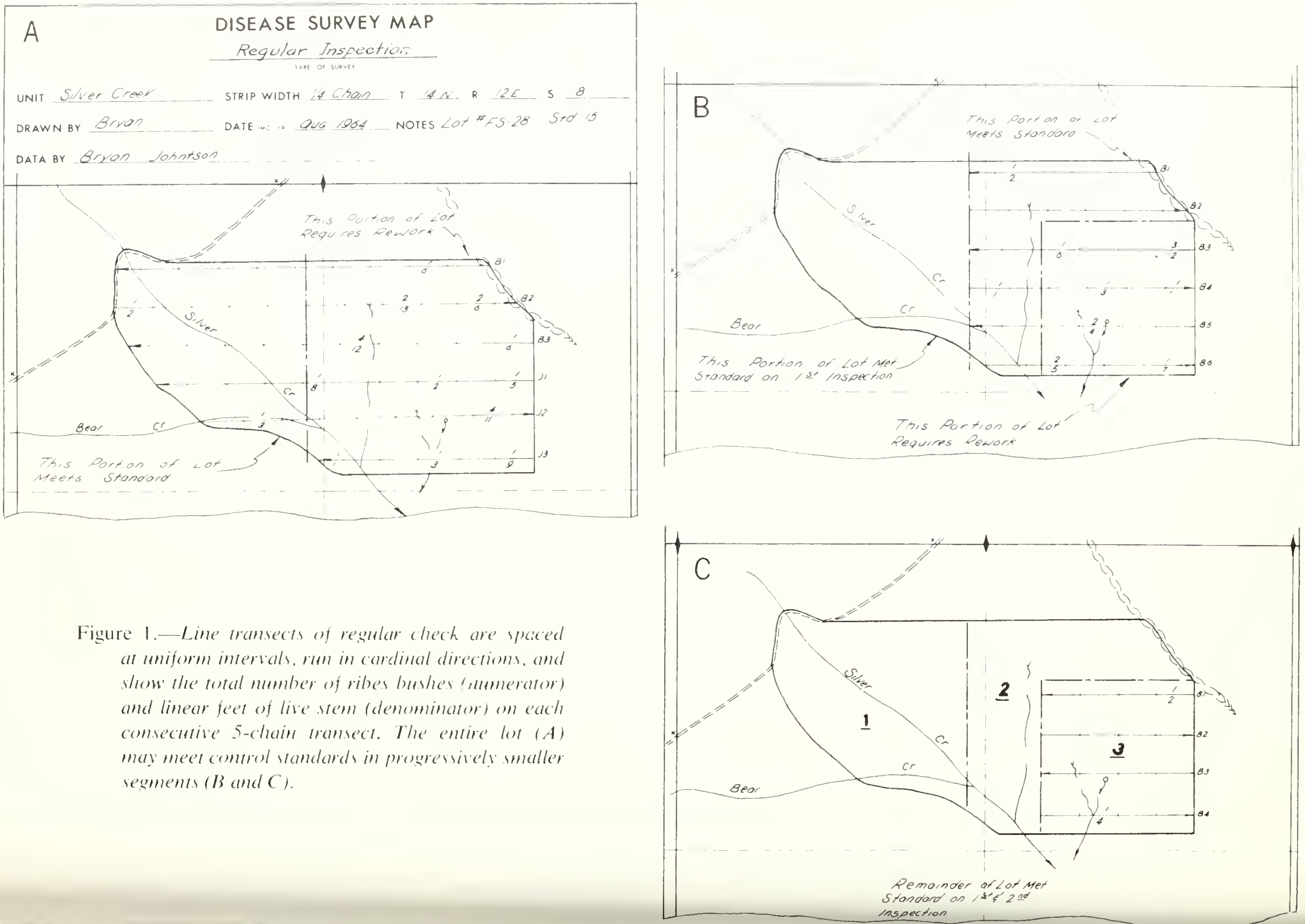
[1] Refers collectively to native currants and gooseberries, *Ribes* spp.



DISEASE SURVEY MAP

Regular Inspection

TYPE OF SURVEY

UNIT Silver Creek STRIP WIDTH 1/4 Chain T 14 N. R 12 E S 8

DRAWN BY Bryan DATE Aug 1964 NOTES Lot #FS-28 Std 15

DATA BY Bryan Johntson

Figure 1.—*Line transects of regular check are spaced at uniform intervals, run in cardinal directions, and show the total number of ribes bushes (numerator) and linear feet of live stem (denominator) on each consecutive 5-chain transect. The entire lot (A) may meet control standards in progressively smaller segments (B and C).*

ed for and the timing of another eradication job. ll of these checks employ the systematic continu- is strip transect plot.

Essentially the current approved regular check California samples about 5 percent of the area ider examination. For each block of land (or ntract lot) continuous strips ¼-chain wide 6½ feet), and spaced at 5-chain intervals, are n across contours in cardinal directions. Ribes ishes and the linear feet of live stem (FLS) e counted and measured as found, allocated to ccessive 5-chain transect, and later summarized a checker's map to show the location of the mpling strips and the ribes population (fig. 1).

The present strip-transect survey (fig. 1) has rved control needs effectively for more than 30 ars. This checking method was designed to max- iize information on the distribution of ribes thin the control area. For acceptance in the control program any alternative method must be more economical than the regular method at a fixed level of reliability or must provide higher levels of reliability for common levels of cost. This paper reports evidence suggesting that where a ribes distribution map is already available or not needed, and where systematically acquired ecologic data are not essential to the control decision, checking objectives can be achieved economically by random plots sequentially evaluated.

With some modification for regional conditions and control objectives, similar types of ribes surveys are made in all white pine areas of the United States where blister rust control work is being undertaken. Recent estimates from California show that the costs of checking are about 20 percent of the total costs of blister rust control. Thus, any improvement in the cost or efficiency of checking would find wide application.

Sequential Sampling

Theory and Use

Sequential analysis provides a method of sta- ical inference that does not depend on a sample fixed size. Randomly chosen sampling units are amined until the accumulated measurements fall ove or below prescribed class levels. Theory pporting sequential analysis was devised by ld (1943, 1945, 1947) from research with the lumbia University Statistical Research Group 945). Independently Barnard (1944, 1946) ognized the merits of sequential sampling and possibility of reducing costs by minimizing nple size. Their publications—along with Wald's 947) text on sequential analysis—triggered in- se interest in the practical uses of sequential npling in industry and in biological surveys ich can be categorized as quality control blems.

In forest surveys the regularly-spaced plot or nsect often has been strongly favored over ran- nly chosen plots. Among the cogent reasons this are: (a) the simplicity and ease of locat- and mapping the plots or transect lines, and) the desire to obtain representative coverage what may be a variable pattern of trees, shrubs, l other vegetation over the land area. Statisti- ins concede the validity of the first but not second thesis; they point out that sampling errors either are not known in the case of regularly spaced plots, or are computed incorrectly by theories and formulae based on random selection. The testing and use of sequential sampling in forest surveys has without doubt been restricted by the natural bias of foresters against randomly selected plots—especially in rough or brushy terrain, which is difficult to walk over. Also, depending upon the survey objective, the ecologic variations within a block of land may strongly dispose against chance location of plots. Freese (1962) and Smith and Ker (1957) have summarized essential aspects of sampling in relation to forest problems.

The impact of plot size and shape and the number of plots per unit of land area on the usefulness of any random or systematic sampling plan has long been recognized, but not satisfactorily worked out.[2] In the concluding section of this report, field comparisons between standard and

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[2] Mathematical statisticians F. N. David, of the University of California, and W. G. O'Regan, of the Pacific Southwest Forest and Range Experiment Station, are now studying theoretical aspects of this problem. One of the more thorough field studies of this problem was reported April 16, 1942, by J. N. Mitchell, G. J. Taylor, C. W. Fowler, and S. D. Adams, in an unpublished blister rust report (California) titled "The forty-acre checking experiment."

sequential surveys are based on the use of plots of similar size and shape (5 chains long by ¼-chain wide).

The great advantage of sequential sampling over systematic sampling is the smaller sample needed by sequential procedures to make decisions on quality of lots that are either extremely good or extremely bad. In forest surveys, for example, systematic sampling by fixed-sample size requires a large amount of time to count or measure the plant or the pest where populations are high, and in addition permits inadequate attention where populations are low. Table 1 summarizes other factors pertinent to the merits of well-known and widely used sampling schemes.

Because of uncertainty about variation in the distribution of plant and animal populations, biologists lagged behind manufacturers in testing and applying sequential sampling to their operations. Evans (1953) analyzed some factors that affect contagious distributions in plant and insect po lations. He concluded that Neyman Type A a negative binomial expressions were generally most applicable to sampling of plant and ins populations. Oakland (1950), Stark (195 Morris (1954), and Waters (1955) were amo the first of the biologists to devise sequential pl for inspection and survey. Their experience c firmed conclusions of the Columbia Univers Statistical Research Group (1948) about the u fulness of sequential sampling.

More recent applications of sequential sampl to forestry problems are those by Smith and (1958) in reproduction surveys, Dick (1963) forest stocking, and Kozak (1964) in damage cone and seed insects in Douglas-fir. All of th workers showed that sequential procedures p vided meaningful answers to questions of qua of work at about half the cost of other sampl methods.

Table 1.--*Factors influencing choice of type of sampling*[1]

Factor	Single sampling	Double sampling	Sequential sampling
Protection against rejection of good inspection lots and acceptance of bad inspection lots	Practically equal		
Average number of items inspected per inspection lot	Most	Intermediate	Least
Variability in number of inspected items from inspection lot to inspection lot	None	Some	Some
Sampling costs when samples can be drawn as needed	Most expensive	Intermediate	Least expensive
Sampling costs when all samples must be drawn at once	Least expensive	Most expensive	Intermediate
Estimation of average inspection-lot quality (if estimate is based on large number of inspection lots, differences from one type of sampling to another may not matter)	Most precise	Intermediate	Least precise
Training inspectors to use plans	Easiest	Intermediate	Hardest
Psychological: 'give inspection lot more than one chance'	Worst	Intermediate	Best

[1] Source: Columbia University Statistical Research Group. 1948, p. 96.

Sequential Plans for Ribes Surveys

My interest in sequential sampling of ribes populations in the Western States dates from the early 1950's, when relaxation of wartime security gave access to the classified research of Wald (1943) and others. The first sequential plan for ribes survey was field-tested in 1956 on the Sequoia National Park, California, and in 1957 on the Rogue River National Forest, Oregon. This plan, based on a negative binomial distribution, was developed from highly reliable data on the number of ribes and their size in linear feet of live stem from a 10-acre study plot at Cow Creek, Stanislaus National Forest in central California. To compare theoretical and actual ribes count for Poisson, Neyman contagious, and negative binomial distributions, Wadley (1950) used these same ribes data from the 10-acre study plot at Cow Creek, as well as similar ribes data from five other study areas in California and Idaho. Using the chi-square test, he showed that the negative binomial gave much the best fit in all six examples. Fracker and Brischle (1944) had previously used these same sets of field data to compare actual total ribes with those of fitted Poisson and Neyman contagious type distributions. They concluded that the best fit was a mixed distribution of about one-third Poisson and two-thirds Neyman contagious. They did not report on the negative binomial distribution in their study.

As the following comparisons from these first ield trials show, the "sequential" sampling method provided answers of similar significance (in the blister rust control sense) to the "regular" method and at a much lower cost. The sequential plan of he 1956 and 1957 field tests was based on bush counts and made use of per acre acceptance limits of two bushes or less and rejection at levels above wo bushes.

In October 1956, Sequoia National Park T. 5 S., R. 29 E., sec. 26, N ½, ribes data from post-check unit of 320 acres, a comparison howed:

- Sequential mean of 0.50 ribes per acre 8 man-hours of checking time).
- Regular mean of 0.67 ribes per acre (26 man-hours of checking time).

Also in October 1956, Sequoia National Park T. 15 S., R. 30 E., sec. 31, NE ¼, a comparison of 160 acres of supposed blockout showed:

- Sequential—blockout OK (5 man-hours of checking time).
- Regular—blockout OK (21 man-hours of checking time).

In July 1957, a comparison test run on a 160-acre post-check unit on the Rogue River National Forest showed:

- Sequential mean 1.2 ribes per acre (6⅓ man-hours of checking time).
- Regular mean 1.5 ribes per acre (35 man-hours of checking time).

These encouraging results clearly justified further study of the distribution characteristics of ribes populations on a broader sample basis than was done in 1956 and 1957. All subsequent field tests used sequential plans derived from feet of live stem (FLS) measurements rather than bush counts to conform with accepted biological needs of the control program and with criteria used in the regular checking method.

A Fortran program devised by Kozak and Munro (1963), and modified in 1964 by A. M. Weil and D. A. Sharpnack of the Forest Service for the IBM 7094 computer, was used to compare the goodness of fit for normal, Poisson, binomial, and negative binomial distributions of ribes for some 61 blister rust control lots in the Sierra Nevada of California. Statistics derived in 1956 and 1957 from the Cow Creek plot, from Sequoia National Park and Rogue National Forest tests, and those from 61 different lots coded for computer calculation, all suggest that the negative binomial distribution provides the best fit both by chi-square test and by inspection of the tabulated field data.

There is some question about the suitability of the chi-square test where as much variance and overdispersion exists as in the classes of ribes making up the populations in the different control units. Nevertheless, statistics for the mean, the class frequency, and variance of the 61 lots indicate that most individual lots generally follow accepted theory of the negative binomial $(q\text{-}p)^{k}$ as described by Fisher (1941) and others.[1] The distribution curve for class numbers of ribes bushes or linear feet of live stem per sampling unit is strongly skewed towards the zero side of the mean and would be described in general terms as unimodal. In nearly all cases the variance was more than five times the mean.

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[1] Anscombe (1949, 1950), Bliss (1953), Bliss and Owen (1958), Fisher (1953), Kozak (1964), Oakland (1950), Wadley (1950), Waters (1955).

In white pine forests the distribution of ribes, as shown by actual survey maps and by field inspection, takes on the following characteristics: After the incumbent population has been disturbed by one or more eradications, the residual population of the whole block as measured on 1/16-, 1/8-, or 1/10-acre sampling units (plot size commonly employed in surveys or in field studies) shows a disproportionate and increasing number of zero-count plots and a steadily decreasing number of plots having counts of one, two, three, and more of the items being recorded. This observation is consistent with the known distribution of ribes in wildland areas, and also with the fact that eradication workers tend to find and remove a much higher portion of the large than of the small bushes. The negative binomial is a discrete distribution and feet of live stem (FLS) is a continuous variable. But sequential plans used in all field trials comparing sequential and regular sampling of ribes (including preliminary trials of 1956 and 1957 in California and Oregon and those of 1964 on the Lassen and Shasta National Forests) were based on the assumption that the negative binomial provided a useful and reliable expression of the true distribution of ribes populations on areas that have had at least one working.

From these preliminary field trials and from theoretical considerations just reviewed, the negative binomial has been used in this study as the most useful approximation of the manner in which residual ribes populations on worked areas are apt to be distributed.

Sequential Graphs for Prescribed Control Purposes

Sequential sampling is applicable to surveys that can be based on prior knowledge of the distribution of the item to be measured and on agreement on meaningful class distinctions for the accept (pass) and reject (fail) decisions. Such information is available for evaluating ribes surveys. Blister rust control maps and checking records of the past 30 years provide a vast reservoir of quantitative data on the size and distribution of ribes populations in sugar pine forests of California. These records show the distribution of ribes bushes and their live stem equivalents after one or more eradication jobs have been completed. And much specialized knowledge on the ecology of ribes in California is available from the studies of Quick (1954). Other white pine regions of the country have similar knowledge about ribes populations. Thus, a sequential plan for ribes survey can be devised that is specifically adapted to populations of known parameters and to prescribed standards of rust control. To facilitate development of a usable sequential plan, the field data reported in this paper are related to the so-called regular check and to blister rust control standard 15 and standard 60.

In standard 60 control work, the contract lot is accepted if the regular 5 percent check shows 60 or less feet of ribes live stem (FLS) per acre; it is rejected if the check shows 61 or more FLS per acre. Standard 15 has a similar meaning as to acceptance or rejection. For blister rust control purposes, standard 15 means that the local rust hazard is more serious than that in the standard 60 situation, and that the ribes population in the case of the standard 15 must be reduced to a lower and biologically safer level.

Data from regular survey maps (fig. 1) for 24 standard 60 lots and 28 standard 15 lots were tabulated to show by 5-chain transects the FLS classes and the frequency of each of the recorded classes in the entire lot. These data were punched on cards for the subsequent computer analysis. The calculations furnished all the statistics[1] essential to build sequential graphs for control standards 15 and 60 at 90 and 80 percent confidence levels, and for typical average sample number (A.S.N.) curves and operating characteristic (O.C.) curves (figure 2 for standard 15 at 90 percent confidence level and figure 3 for standard 60 at the 90 percent level). The several graphs (figs. 2–6), and table 2 are related to acceptance-rejection limits of FLS populations (m_1 and m_2) that are representative of the pass and fail criteria for control standards 15 and 60. In all cases (figs. 2–6) equal values were assigned to the probabilities of errors for the pass and fail decisions (i.e., alpha and beta both had the same values of 20 and 10) in preparing the plans at the 80 and 90 percent confidence level.

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[1] Equations and mathematical steps needed to devise and check out the computer program for construction of sequential plans are on file at the Pacific Southwest Fores and Range Experiment Station. Also on file are the desk calculator checks of selected problems as well as the computer print-out sheets which show all essential statistics for 52 contract field lots and 9 study plots. For thes 61 problems all pertinent statistics for negative binomia (and other distributions) are provided at 90 and 80 percent confidence levels and for at least four different pair of prescribed acceptance-rejection limits for ribes FL classes.

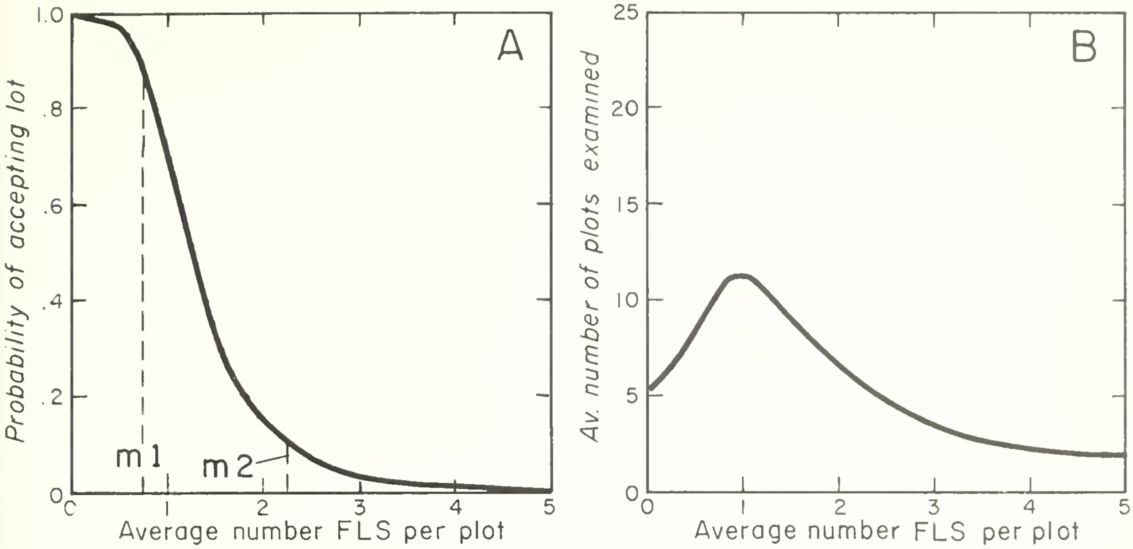

Figure 2.—A, *operating characteristic curve (OC) and* B, *average sample number curve (ASN) for ribes sequential plan. Confidence level of 90 percent and standard 15 level of rust control, acceptance-rejection levels (*m_1 *and* m_2*) of 0.75 and 2.25 feet of live stem (FLS).*

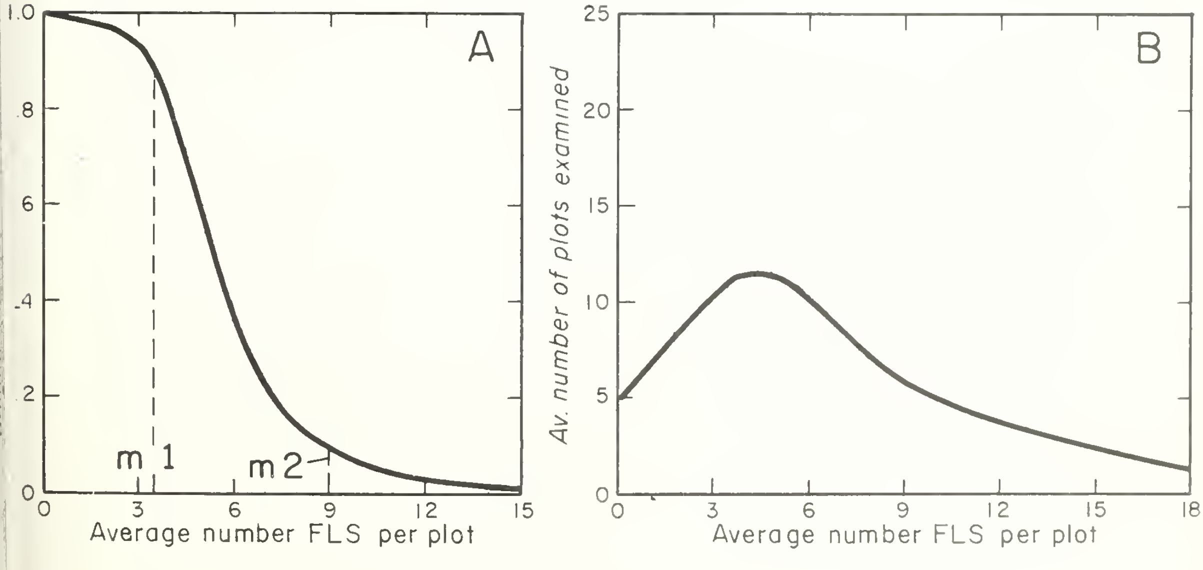

Figure 3.—A, *operating characteristic curve (OC) and* B, *average sample number curve (ASN) for ribes sequential plan. Confidence level of 90 percent and standard 60 level of rust control, acceptance-rejection levels of (*m_1 *and* m_2*) of 3.5 and 9.0 feet of live stem (FLS).*

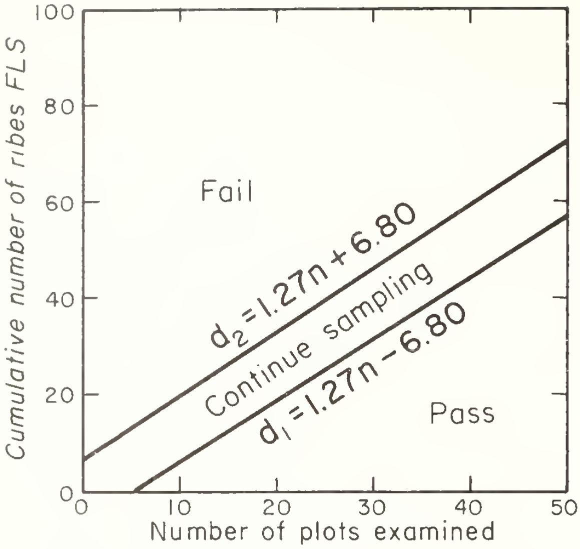

Figure 4.—*Sequential decision lines fo standard 15 level of rust control i California. Confidence level of 90 percent, based on Cow Creek No. 2, Stanislaus National Forest data; with rang of 0–26 feet of live stem (FLS), mea 2.93 FLS, variance of 19.45 FLS, an acceptance-rejection levels of 0.75 FL (lower line) and 2.25 FLS (upper line*

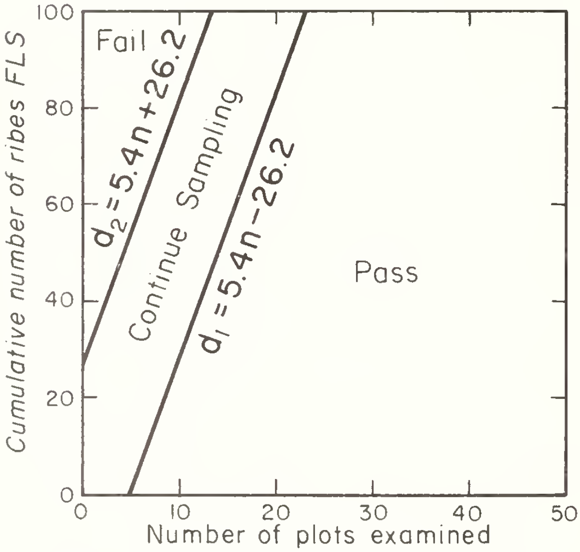

Figure 5.—*Sequential decision lines fo standard 60 level of rust control in Cal fornia. Confidence level of 90 percen based on Cow Creek No. 2, Stanislau National Forest data; with range o 0–26 FLS, mean 2.93 FLS, varianc 19.45 FLS, and acceptance-rejectio levels of 3.5 FLS (lower line) and 9. FLS (upper line).*

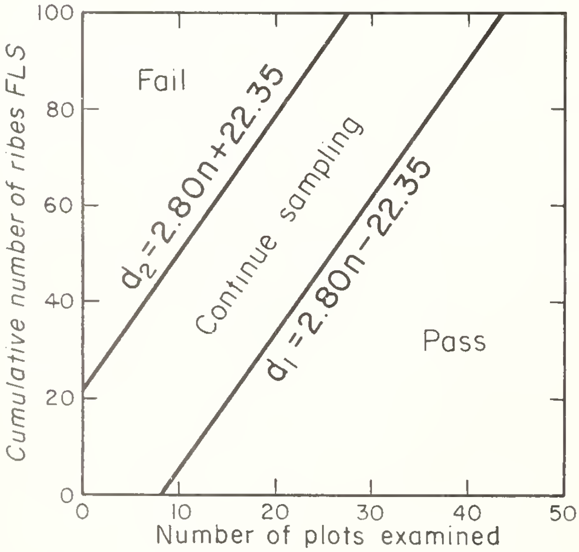

Figure 6.—*Sequential decision lines f standard 60 level of rust control i California. Confidence level of 80 percent, based on Lassen National Fore No. 8 data, with range 0–23 FLS, me 3.87 FLS, variance 58.11 FLS, a acceptance-rejection levels of 2.0 Fl (lower line) and 4 FLS (upper line).*

Table 2.--*Sequential table (equivalent to figure 6) for sampling ribes populations for standard 60 level of rust control in California, 80-percent confidence level*

Number of $\frac{1}{16}$ - acre plots examined	Cumulative feet live stem (FLS)[1]	
	Fail[2]	Pass[3]
1	25	--
2	28	--
3	30	--
4	33	--
5	36	--
6	39	--
7	42	--
8	45	1
9	48	3
10	50	6
11	53	9
12	56	12

[1] Rounded to nearest even foot of live stem from decision lines: $\begin{cases} \text{Fail } (d_2) = 2.80n + 22.35 \\ \text{Pass } (d_1) = 2.80n - 22.35. \end{cases}$

[2] If cumulative FLS equals or exceeds figure shown in this column, decision is made and no further sampling needed; otherwise, continue sampling.

[3] If cumulative FLS equals or is less than figure shown in this column, decision is made and no further sampling needed; otherwise, continue sampling.

The decision lines for each sequential plan (figs. 4–6) are derived from sample counts of ribes populations on typical tracts of sugar pine forest land and from the equation appropriate to the distribution of the ribes population under study. Sequential plans of this study are based on the negative binomial as given by:

$$d_1 = bn + h_1 \text{ (lower line)}$$
$$d_2 = bn + h_2 \text{ (upper line)}.$$

In these equations b provides the slope of the line, n is the appropriate sample number, and h_1 (always a minus value in the negative binomial) and h_2 are the intercepts for the decision lines at slope b.

The computer program for this study has been devised from theories of sequential analysis (Wald 1947) and the negative binomial distribution (Fisher 1941). Applications of these theories to biological problems have been described by Bliss (1953) and others.[5]

In the ribes sampling study the essential statistic k used in constructing the graphs (figs. 2–6, and table 2) was derived from iterative calculations based on the ratio of the total number of class units in the sample to the number in the zero class using field records of checking for contract lots that had been worked to standard 15 or 60. This iterative method of calculating k was judged to be the most useful for ribes sampling work after a large number of single-lot and a few pooled-lot examples were tested by other recognized methods for estimating or calculating k (Anscombe 1949; Bliss 1953; Fisher 1953). There is, of course, a danger in the use of a k derived from representative field lots and applying a sequential plan based on this representative k to another field lot. It is believed, however, that the use of such a representative k does not affect the field usefulness of the sequential plan when similar control standards and acceptance-rejection limits are involved. Further field studies should give a measure of the reliability of this assumption.

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[5] See footnote 3.

Reliability and Costs of Sampling

The reliability of and potential savings for sequential sampling of large tracts of forest land were indicated by the three preliminary field trials of sequential and regular sampling checks of ribes populations (by bush count) made in 1956 and 1957. In table 3 results of 13 additional trials made in 1964 on the Shasta and Lassen National Forests compare sequential and regular checks of ribes populations (by live stem count) for relatively small contract lots. In 9 out of these 13 field trials, we reached the same blister rust decision of pass or fail. In all 13 trials, the sequential method took less time than the regular method.

For both sampling methods there is much more variation in data for the mean live stem per acre (1964 tests) than for the mean bushes per acre (1956–1957 tests). Ecologic variance and sample size are largely involved. Within reasonable limits variation in per acre ribes live stem or ribes bush count between sampling methods does not, i itself have practical significance in the control program because quality control decisions usuall involve rather large differences in class means For example, in California we accept lots havin 0 to 15 FLS per acre for standard 15 and thos having 0 to 60 FLS for standard 60. From control standpoint an incorrect "pass" decision i a more serious error than an incorrect "fail" cal The latter mistake adds to the control cost bu not to the loss of the pine. On this score (table 3 the sequential and regular methods were of comparable accuracy except for two conflicting decisions ("pass" calls that might preferably have bee "fail") charged to each method.

In the two lots (PR-250 and IN.B) wher sequential check did not give the same contro decision as the regular check, there were som factors involved that merit comment. For lot PR 250 there was a congregation of the random plot

Table 3.--*Regular and sequential check of ribes populations, for several blister rust conti lots on the Lassen and Shasta National Forests--a comparison of time taken to sample (cost and consistency of the two methods)*

Lot number	Acres in lot	Regular check			Sequential check		
		Time taken to sample	Ribes population	Pass or fail	Time taken to sample	Ribes population	Pass o fail
		Hours	*FLS/acre*		*Hours*	*FLS/acre*	
Lassen N.F.							
PR-270	40	2.15	10.0	Pass	2.10	4.8	Pass
PR-274	42	4.50	63.5	Fail	.40	85.3	Fail
PR-286	80	9.00	11.0	Pass	3.05	6.6	Pass
PR-250	53	2.50	54.0	Fail[1]	2.40	0	Pass
PR-322	80	10.25	14.2	Pass	3.50	85.0	Fail
PR-284	80	9.10	12.0	Pass	3.15	6.7	Pass
PR-326	80	8.55	21.7	Pass	2.25	0	Pass
FSR-263-S	40	4.05	28.0	Pass	2.15	9.6	Pass
FSR-263-N	40	5.10	51.0	Pass	2.25	68.0	Fail
FSR-239	78	7.30	46.2	Pass	4.10	43.0	Pass
FSR-237	36	4.10	36.6	Pass	2.30	10.4	Pass
In. B.	23	3.10	32.8	Fail[1]	3.00	4.0	Pass
Shasta N.F.							
P7	40	4.00	44.0	Fail[1]	2.50	22.5	Fai

[1] Blister rust control standard 15. Other lots were standard 60. All lots worked to appro priate standard.

on a dry brushy slope where few if any ribes occurred. Where there is such a clearly defined difference in ribes habitat the control lot could be stratified and checked on ecologic lines—in this case two sub-blocks of about 30 and 23 acres. With random rather than systematically placed plots, however, some of the advantages of ecologic stratification may be lost when small control blocks are being sampled. Because of the minimum sample-size requirement for a pass decision sequential sampling may not offer much savings in checking small control lots. This factor was of some importance in the case of the 23-acre lot (table 3) marked IN.B. and should be considered before size of block is reduced too much to permit the sampling of more ecologically uniform areas.

Field Use of Sequential Sampling

For the blister rust supervisor and surveyman the essentials of a sequential plan for sampling ribes populations are as follows:

- The appropriate graph (as given by figs. 4–6) or the equivalent numerical guides (table 2 for fig. 6). On the basis of these guides the surveyman accepts or rejects the lot under examination. Either the graph or its corresponding table can be used in the field depending on the preference of the supervisor.
- The operating characteristics curve (OC curve as in figures 2A and 3A) and the average sample number curve (ASN curve as in figures 2B and 3B). Figures 2 and 3 are idealized curves based on actual calculations for a representative field lot of standards 15 and 60. Reservations about the reliability of a representative k as previously made apply also to these OC and ASN curves. The OC curve tells the supervisor in advance of the actual field sampling what to expect on the probability of correctly labeling the lot. The ASN curve shows about how many samples might be needed for a decision of specified accuracy at various prescribed levels of FLS per acre.
- Designation of the desired confidence level, and the acceptance-rejection limits of the ribes populations that are to be appraised.
- An objective and convenient scheme for making random selections of sample plots and an established procedure for determining size, dimensions, and estimated number of sampling units or groups of sampling units that will be needed to provide a reliable checking job.

There are several legitimate ways of randomly selecting small sample plots from the entire area. The following method has been used in some of the field trials. A map of the entire area (control lot) was covered by a transparent grid to divide the entire lot into numbered plots of prescribed sample size and shape. Then from a table of random numbers, or by drawing numbered disks to represent coordinates of measurements, center points of the sample plots were marked on the field map. In ribes survey the sequential sampling has used the same shape and size of plot or transect that has been used for many years for regular checking work. Thus, as mapped in figure 7, the random sequential plots numbered from 1 to 12 (the order drawn) are each 5-chains long by ¼-chain wide and are the same shape and size as the 32 line transect plots of the "regular check" (also shown in figure 7). In figure 7 the edge or margin of the lot was not eliminated from the random sampling scheme. Any one of these 5-chain-long plots might have had its origin ⅛ chain from the edge of the lot.

After the randomly drawn points for the sequential check were spotted on the map the actual plot area to be checked was obtained by joining the starting point of plot 1 to the starting point of plot 2. This line provided the azimuth of plot 1 which extended for 5 chains. Then plot 2 was identified by connecting the beginning of plot 2 with the starting point of plot 3, and so on. Each plot was ¼-chain wide. In this way we randomized both plot location and azimuth or plot direction.

When the surveyman goes into the field he should have his map showing the location and compass bearing for the group of plots that will probably be needed to conclude the check. Single plots should be checked in the random order as drawn. Other random methods of locating continuous strips across contours (more closely simulating the regular checking use of continuous strip transects) may be used instead of the scheme illustrated in figure 7. If the area under examination is difficult to walk over (i.e., steep or brushy) and it is considered uneconomic to check single plots in the order

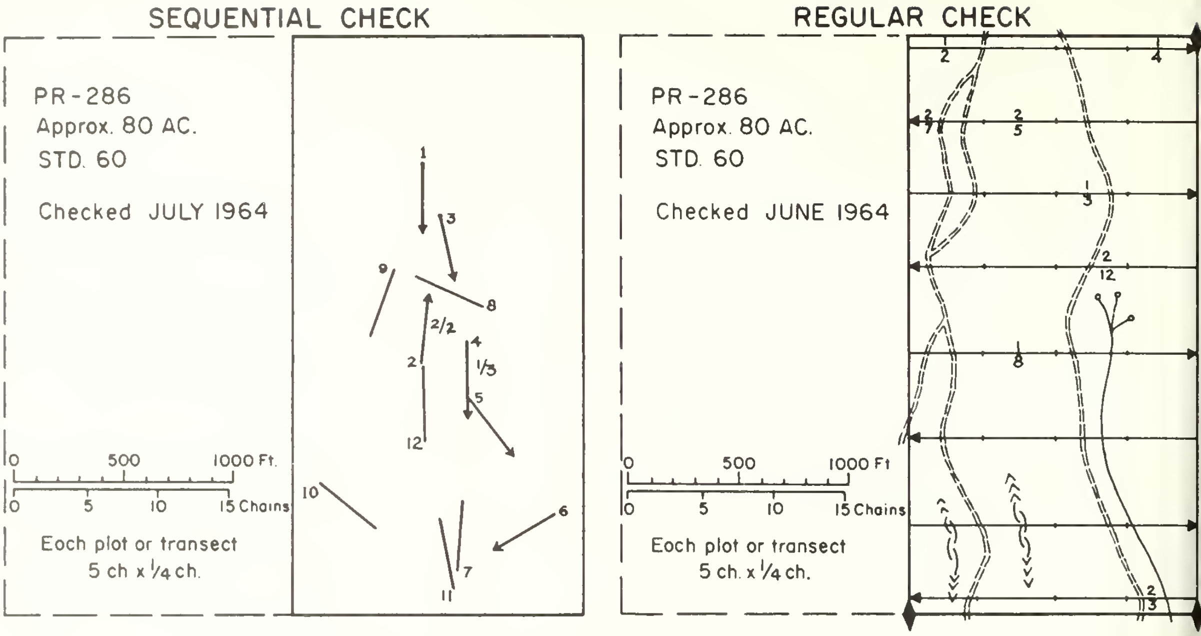

Figure 7.—*Ribes bush and live stem data for sequential and regular checks on the same 80-acre lot, SW ¼ of section 13, T.26N, R.6E. Note location of 12 randomly drawn plots of the sequential check; this check was terminated at plot 6 because a decision had been reached; plot 2 showed two ribes with 2 feet of live stem and plot 4 showed one ribes with 3 feet of live stem.*

drawn, the use of a "group convenience" plan may be justified. On a 40-acre lot, for example, field experience shows that a sequential decision may be reached when about eight plots have been checked. In the group convenience scheme, therefore, eight plots would be chosen at random and located on a map of the control lot. Then the starting point, or first plot to be checked, would be determined by chance and the remaining plots joined in a closed traverse to minimize walking. Decision to accept or reject is then made in the usual manner.

From the control objectives as noted in table 4 the most appropriate sequential plan is selected from prior knowledge of the ribes population and rust hazard in the block to be sampled. If prior information about ribes population is not available, an estimate of the variance may be made from a small group of plots to be checked by the group convenience scheme. Such a procedure would be helpful in maintaining control over the size of sample.

To date sequential ribes surveys have not been tested extensively enough in the field to prescrib with confidence the most efficient sample number shape, and size of sampling plot for work block of various sizes. Until more experience is gaine table 4 may serve as a guide for choosing a suitabl sequential plan for additional field trials of contro lots for several combinations of rust standards a 90 and 80 percent confidence levels. For man checking objectives, and at the estimated reliabilit of present regular survey methods, sequential pro cedures probably should be used at the 80 percen confidence level (fig. 6 or table 2). When th blister rust hazard is high (standard 15) and whe a high level of confidence is desired, the sequenti plan provided by figure 4 is suggested; for stanc ard 60, at less exacting acceptance-rejection leve figure 5 may be most useful. The plan of figure or table 2 may be the most widely applicable on for control units of about 40 acres for a mediu or low hazard situation at standard 60 level. Th combination of lot size and control standard is on commonly encountered in field operations.

In the sequential checking procedure there

Table 4.--*Guide to selection of sequential plan most appropriate to the desired blister rust control objective in sugar pine forest areas of California*

Blister rust hazard	Blister rust control standard[1]	Acceptance-rejection levels prescribed[1]	Confidence level	Graph in this report
	Feet live stem	*Feet live stem*	*Percent*	
High	15	0.75-2.25	90	Fig. 4
Low	60	3.50-9.00	90	Fig. 5
Medium	60	2.00-4.00	80	Fig. 6[2]

[1] Standards and acceptance-rejection levels as recommended for field use in California refer to average allowable linear feet of ribes live stem per acre or per cumulative sampling unit. Survey records show a consistent trend of ratio between live stem and bush counts on sample plots. Thus live stem class means of 0.75-2.25, 2.00-4.00 or 3.50-9.00 might be used as bush counts for certain survey objectives.

[2] See table 2 for a numerical equivalent.

the opportunity, as in the regular checking, of observing off-plot ribes in following the compass traverse between random sampling units. In some cases sequential check may involve more walking than the regular check, though usually it does not. Information on "off-strip" ribes is valuable in deciding when to truncate sequential measurements if no clear-cut decision has been reached. Much work has been done and more is being done by Forest Service statisticians on reliability of truncating sampling measurements. We know that sequential sampling can, in theory, continue without a definite decision until most or all of the lot has been sampled. But in practice, guide lines should be set whereby administrative judgment and unbiased sampling are used at optimum levels to achieve control objectives. In control units where rust hazard is high the best checking procedure might consist of a rapid sequential check of the unit as a whole with supplemental checking directed to stream type or a moist meadow, where rust-spreading ribes are apt to occur.

In conclusion the attention of field supervisors is directed to the idea of using an appropriate sequential plan to aid decision making on the need for control work. This is a substitute for an informal administrative examination where a formal quality control check is not specified. In using a sequential guide for this administrative check there is no need to tie into control lot boundaries or to run accurate transect lines provided all random sample plots are comparable in size and shape and are known to be within the area under examination.

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Freezing Spring Temperatures Damage Knobcone Pine

Stanley L. Krugman

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Contents

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STANLEY L. KRUGMAN is conducting studies of forest tree physiology as part of the Station's research on the genetics of western conifers at Berkeley and Placerville, California. A native of St. Louis, Mo., he completed his undergraduate work (1955) in forestry at the University of Missouri. He earned a master's degree (1956) in forestry and a doctorate (1961) in plant physiology at the University of California, Berkeley, where he did research on seed physiology in conifers before joining the Forest Service in 1962.

Freezing temperatures during spring have been reported to be a principal cause of mortality of first-year pine conelets. Schubert (1955) observed that a minimum temperature of −7 C. in June killed 93 percent of he conelets on an individual sugar pine tree (*Pinus ambertiana* Dougl.) growing on the Stanislaus-Tuolumne Experimental Forest in central California. Similarly, Barras and Norris (1964) attributed conelet mortality in red pine (*Pinus resinosa* Ait.) hroughout Wisconsin to freezing spring temperaures. Hard (1963) noted that in a red pine plantation, spring frost-killing of conelets was associated with topography and elevation.

Unusually low spring temperatures rarely kill the entire crop of first year conelets. Certain conelet developmental stages are, however, more susceptible than others to low temperatures. Foresters generally believe that conelets at the stage of maximum pollen receptivity are most vulnerable (Campbell 1955; Hutchingson and Bramlett 1964). The variability in temperatures within a tree crown or within a stand also accounts for partial conelet kill (Hard 1963; Peace 1962; Schubert 1955).

Besides killing first-year conelets, freezing spring temperatures may also reduce the number of sound seed in the cones that survive. Either certain ovules are killed without the cone being destroyed, or the pollen is made sterile, which causes ovule abortion at a later stage of development (Andersson 1965).

The opportunity to investigate the effects of freezing temperatures on conelet and seed development arose in late April 1964, when an unseasonal cold front caused extensive damage to conelets of knobcone pine (*Pinus attenuata* Lemm.) in the central Sierra Nevada of California. At the time of the frost, investigations of conelet development following controlled and wind pollination had just been started. These circumstances made it possible to determine those conelet developmental stages most susceptible to low temperature damage. The effects of the frost on final seed set were also investigated. This paper reports the results of that study.

Methods

Study area.—The Badger Hill plantation lies 12 miles east of Placerville, Calif., at an elevation of 3,300 ft. It includes 27 different geographic sources of knobcone pines. The plantation was established as a breeding orchard for the mass production of knobcone × Monterey hybrids.

Sampling procedure.—Two weeks before the rost, about 200 developing conelets had been enclosed in plastic pollination bags for the purpose of making controlled pollinations. As the bagged conelets reached maximum pollination tage, they were hand pollinated with either a mixture of 1-year old Monterey pollen or a mixture of 1-year old knobcone pollen. Bagged unpollinated conelets served as controls.

Two days before the frost, the developmental tages of 200 bagged and unbagged conelets were recorded. Care was taken to include a range of tages—from conelets still covered by bud scales (conelet-bud large [stage 1]) to conelets whose scales had closed completely after pollination (conelet scales closed [stage 5]) (table 1). To obtain the complete range of developmental stages, four geographic seed sources of knobcone pine were included. On April 22, the morning of the frost, four unbagged and four bagged conelets of each developmental class were chemically fixed for an anatomical study. On April 24, about 41 hours after the frost, four conelets of each class were collected, two conelets of each class were examined immediately, and two were placed in a chemical fixative. Subsequent sampling was done 3 days later (April 27) and thereafter at about 2-week intervals for a period of 4 months. Damage to all classified cones that remained on the trees was visually estimated at about 2-week intervals for the first year. Additional cones were collected in 1965 and their contents were examined.

Table 1.--*Percent mortality in bagged and unbagged conelets of different developmental stages, after a spring frost*

Developmental stage number	Developmental stage at time of frost	Unbagged	Bagged
		Percent	*Percent*
1	Conelet-bud large: conelet not visible	0	0
2	Conelet bud opening: conelet visible	20	45
3	Conelet scales partly opened	18	30
4	Conelet scales open to maximum	2	8
5	Conelet scales closed	0	0

Temperature conditions.—Temperature data for this study were provided by two recording thermographs—one in a standard weather shelter at the north end of the plantation, and the second in the middle of the crown on an experimental tree at the south end of the orchard. Five maximum-minimum thermometers near the unbagged conelets provided additional information on temperature extremes in the tree crowns. Temperature extremes inside two pollination bags were recorded by individual maximum-minimum thermometers.

The mean air temperatures during the week before the frost was 18 C. during the day and 7 C. during the night. On the evening of April 22—the first night of the frost—the temperature dropped to a low of −3 C. at the weather shelter and a low of −2 C. in the tree crowns; it remained below the freezing point for 4 hours (table 2). During the next 3 days, freezing temperatures prevailed for periods up to 16 hours in the tree crowns. A temperature low of −6 C. was reached in the early morning hours of April 24. The cold period was immediately followed by 4 days of warming temperatures. A high of 20 C. was recorded in the afternoon of April 28. Temperatures remained well above freezing during the week that followed the frost.

The maximum and minimum temperatures in pollination bags differed from the temperatures outside the pollination bags. The maximum temperature in the pollination bag recorded the afternoon of April 24 was 10° C., with a minimum of −4 C. On April 27, a maximum temperature of 16 C. was recorded in the pollination bag, with a minimum of 4 C. But the duration of these extreme temperatures was not recorded.

Temperatures were within 3 C. at both the south and north ends of the breeding orchard. This condition was somewhat surprising because the orchard slopes from south to north, varying from 9 to 16 percent in steepness. From the limited temperature instrumentation there was no suggestion of frost pockets.

Table 2.--*Thermograph temperatures as recorded in the tree crown during freeze period*

Date	Maximum temperature	Minimum temperature	Duration of freezing temperatures
	C.°	*C.°*	*Hours*
April 22	13	-2	4
April 23	3	-4	16
April 24	6	-6	13
April 25	12	-2	6

Results

Conelet mortality.—Both the presence of pollination bags and the conelet developmental stage at the time of the frost were factors in conelet damage by low temperatures. Conelets in pollination bags were most susceptible to cold damage—sustaining on a percentage basis twice as much mortality as unbagged conelets (table 1). Forty-five percent of bagged conelets emerging from the bud scales (stage 2) were killed, compared to 20 percent mortality for unbagged conelets at the same stage of development. Conelets whose scales were partly open (stage 3) were almost as vulnerable to low temperatures. Thirty percent of the bagged stage 3 conelets were killed, compared to 18 percent for unbagged conelets. Similarly, bagged conelets whose scales were opened to their maximum, suffered higher mortality (8 percent) than unbagged conelets (2 percent).

Unexpectedly, conelets in two of the stages—(a) still completely covered by bud scales (stage 1), and (b) those whose scales were completely closed (stage 5)—had no mortality whether they were bagged or unbagged.

The higher mortality among bagged conelets probably resulted from the more rapid thawing rather than exposure to lower temperatures because both bagged and unbagged cones were exposed to essentially the same minimum temperatures. But the maximum temperatures in the two pollination bags were consistently higher than the free air temperatures, suggesting a more rapid warming cycle. Usually, greater frost injury can be expected if thawing is rapid (Levitt 1956). But since the cycles of the temperatures were not recorded for the bagged conelets, I can only speculate on this point.

The length of time from exposure to low temperature to visual appearance of conelet damage depended on the developmental stage at the time of the frost. Cold damage to elongating conelets (stage 2) could be seen within 2 weeks of the cold period; damage to conelets in developmental stages 3 and 4 was apparent only after 3 or more weeks. The injured conelets first lost their luster and then began browning and shriveling.

In contrast, a conelet's ability to continue elongation after frost damage did not depend solely on its developmental stage at the time of the frost. Of 50 conelets that were measured and eventually died, 40 continued to elongate during the 2 weeks after the frost. Of the conelets that were killed, those just emerging from the budscales (stage 2) had the least elongation. Only 18 percent of the stage 2 conelets that eventually died elongated after the frost, compared with 40 percent for stage 3 and 43 percent for stage 4 conelets.

No obvious signs of cold damage were observed in sectioned material collected 2 days after the first cold exposure. But 5 days after the first frost, definite indication of damage was observed in both fresh and fixed sectioned conelets. Longitudinal sections revealed collapsed cells in the vascular region of the middle and lower cone axis, in which the cytoplasm had coagulated into a dense mass. In contrast, the vascular system of the conelet scales appeared undamaged. Other cells in the cone axis had lost their turgidity. This type of cold damage is apparently the result of the dehydrating effect of extracellular ice formation (Siminovitch and Scarth 1938; Levitt 1956). Severe cold damage was characterized by brownish-black necrotic areas scattered throughout the middle and lower regions of the conelet axis in fresh hand-sectioned conelets. This condition was the result of a complete breakdown of the injured cells.

In most of the sectioned ovular material the ovular region appeared undamaged and the megaspore mother cell had not been formed. Even in those ovules (conelet stages 4 and 5) where an occasional megaspore mother cell had developed, however, the megaspore mother cell appeared not to have been damaged by the frost.

Two weeks after the frost—concurrent with the rapid visual deterioration of the conelet—the whole cone axis was necrotic. The vascular system of the developing conelet was badly destroyed, and obvious degeneration of the ovule was now apparent.

Typically for this species, the dead conelets did not immediately absciss. Some remained on the trees as long as 15 months after the frost. But most of the dead conelets fell during the winter months after the spring kill.

Contrary to my expectation, the amount of sound seed produced in the surviving cones was comparable to seed production for frost free seasons. The amount of seed produced per cone under both bagged and unbagged conditions showed no apparent reduction (table 3). The results might be explained if the cold period reduced seed number equally in all conelet classes. This possibility,

Table 3.--*Number of knobcone seeds per cone the second year after a spring frost*

Conelet stage at time of frost	Unbagged				Bagged[1]			
	Sound	Hollow	Total	Number of cones	Sound	Hollow	Total	Number of cones
	Number of seeds per cone[2]							
Conelet-bud large	36	75	111	4	42	76	118	5
Conelet-bud opening	40	81	121	4	41	58	99	6
Conelet scales partly opened	35	72	107	6	38	71	109	6
Conelet scales open to maximum	37	79	116	8	39	70	109	8
Conelet scales closed	39	69	108	10	42	74	116	7

[1] Knobcone pollen mixture was used in the control pollination.

[2] Seeds were extracted by removing the cone scales from the cone.

however, is unlikely for two reasons: (a) conelet mortality was so closely related to developmental stage of the conelet at the time of the freeze, and (b) seed set was comparable to that of the 2 previous years which did not have unseasonal spring freezes.

Discussion

This study showed that newly developing conelets of knobcone pine are not equally susceptible to freezing damage. Conelets are most susceptible to frost damage before pollination, when they are rapidly elongating and not protected by bud scales. In contrast, the post-pollination stages are resistant to cold temperatures.

In addition, only certain parts of the conelet are initially damaged by the frost. The ovules showed damage only after the deterioration of the vascular system of the cone axis. Although the freezing temperatures were severe enough to kill some conelets, the seed set of the surviving cones was not affected. Both of these observations showed that the ovules are more resistant to cold damage than is the cone axis.

The high mortality of conelets at certain developmental stages is an example of the impact a late spring freeze can have on a cone crop. In some years, low spring temperatures can be an important factor in reducing the annual cone crop. And an unseasonal spring freeze could be an important contributing factor to periodicity in mature cone production. The higher mortality of conelets in the pollination bags strongly suggests that to avoid conelet mortality due to freezing temperatures, care must be taken in the location of breeding orchards.

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GPO 973-549

MIADS2

An Alphanumeric Map Information Assembly and Display System for a Large Computer

Elliot L. Amidon

U. S. FOREST SERVICE RESEARCH PAPER PSW-38

Pacific Southwest
Forest and Range Experiment Station
Berkeley, California
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Forest Service - U. S. Department of Agriculture

Glossary

Block: a map or portion thereof; a unit for which tables will be produced; block contains one or more strips.

Card: an 80-column punch card.

Cell: the map area assigned a code (analogous to one dot in a dot grid); cell is a rectangle one-fifth inch (measured horizontally) by one-sixth inch, or one-thirtieth square inch.

Code: (1) integer system—unsigned, nonzero, two-digit integer (i.e., a number between 01 and 99 inclusive); (2) alphanumeric system—two characters.

Code System: a list of up to 98 code numbers (integer system) or 2,205 codes (alphanumeric system) and their definitions. Code 99, used for boundaries and other special purposes discussed elsewhere in this report, is ignored in all computations.

Line: a horizontal series of cells containing codes or blanks which are punched into one card.

MIADS: Map Information Assembly and Display System (integer).

MIADS2: Map Information Assembly and Display System (alphanumeric).

Source Map: a map, photo mosaic, or similar data source.

Strip: rows of lines made by listing ("printing") cards. Strip width is fixed at 7.2 inches (owing to use of 36 x 2 = 72 card columns). Strips are fastened together on their vertical edges to make an overlay.

CONTENTS

The Author

ELLIOT L. AMIDON is studying problems in production economics, with particular emphasis on multiple-use problems in forest lands. Native of Washington, D. C., he earned a bachelor's degree (1954) in forest management at Colorado Agricultural and Mechanical College. Awarded a Fulbright Grant in 1955, he spent a year at the University of Helsinki, where he studied forestry in Finland. He received a master's degree (1960) in agricultural economics from the University of California. Assigned to the Pacific Southwest Station's Berkeley staff since 1959, he has also served at the Lake States and Northeastern Forest Experiment Stations.

In 1964, the development of the Map Information Assembly and Display System (MIADS) was first announced (Amidon 1964). Since then, resource planners have found it useful in attacking a wide variety of land-oriented problems. But in the ensuing two years, it became apparent that what was needed was a more encompassing system—one that took advantage of the latest advancements in computer science. The result is a greatly expanded and improved system we call MIADS2. Basically unchanged is the original aim of a computer-oriented system—to record, update, assemble, and display map information quickly and efficiently. The principles and definitions, first published in 1964, still apply. The integer-computer programs used in MIADS, although still useful, are unsophisticated when compared to the programs used in MIADS2. Two major reasons underlie the need for an improved system.

First, MIADS was restricted to a 2-integer code system. Some tasks appeared too large at first glance; but could be reduced if very careful planning preceded hand coding. For many problems a 99-code system was simply too small. There was not much "slack" for adding codes, particularly if the need for them arose half-way through a massive coding job. The conversion to the character system in MIADS2 makes about 2,200 codes available. This not only permits formidable problems to be tackled, but perhaps as important, adds mnemonic value to the code system. For example, whereas "grass" was "03" before, it became "GR." Actually, not all of the alphanumeric codes are equally useful; equal signs (== ===) may be fine for roads, but what good is -) or /)?

The other major reason is more subtle but nearly as important. The programs were designed to run on either a small decimal computer or a large binary machine. The end result reflected restrictions which were primarily imposed by the smaller processor.

A host of lesser reasons motivated us to extend the original system. One of them is always present—technological change in both computers and their languages. Much of the data preparation work performed by tabulating equipment could be shifted to the computer. Similarly, some of the user's job setup time could be saved by using control cards with English words. The cards could be pre-punched and their functions easily remembered. Experience indicated that some options should be dropped—particularly cumulative tables—while others—like tape handling capability—should be added. Finally, we realized that hand coding, the most costly part of any job, could be reduced by letting the computer fill in "patches" of repetitive codes.

This paper describes MIADS2, compares differences between it and MIADS, and explains its new features. Table I summarizes the differences between the two systems.

Characteristics of the System

Codes

According to combinatorial theory, the maximum size of a code system is reached by raising the total number of characters to a power. The power, or exponent, is simply the number of characters per code. For example, if only three characters were available—A, B, and C— a two-character code system would contain three squared, or nine, unique codes—AA, AB, . . . , etc. For the same character set, a three-character code would contain more information—three cubed, or 27, items. We decided that a two-character code would be enough for attacking most problems and allow, given a common print spacing, a nearly-square grid cell.

The integer system used in MIADS consisted of

Table 1.--*Comparison of features of MIADS and MIADS2*

Item	MIADS	MIADS2
Theoretical code system size	100	2304
Processor	Small or large, e.g. IBM 1620, 7090, 7094	Large (32K), e.g. IBM 7040, 7090, 7094
Language	Fortran II or IV	Fortran IV and MAP
Speed (large processor)		
1. Mapping program (thousand map cards)	3 4 min.	3 4 min.
2. Combinations program (thousand card pairs)	1-2 min.	1.5-5 min.
Input media	Cards	Cards, magnetic tape
Tab room equipment	Several machines	Keypunch and verifier
Code systems combined	2-4	2
Map card data preparation	Hand coding (all cells)	Hand coding, computer fills cells
Data editing	Reproducer (e.g. IBM 514)	Computer
Types of tables	13	9
Control card		
1. Parameters	Numeric	Alphanumeric
2. Sequence	Fixed	Variable
Number of blocks	Limited	Unlimited

ten characters— 0 to 9. It allowed a maximum of 100 codes in the system. Actually, 98 were available for manipulation because zero-zero (00) was equated to blank (nothing) and 99 was reserved for a boundary code. The alphanumeric system used in MIADS2 consists of 48 characters available in the printer set, or a theoretical maximum of 2,304 codes. But for a variety of reasons (discussed in the operating manual) about 100 codes were excluded from use on map data cards. Some printers have 64 characters (allowing 4,096 codes), and the current programs will accept up to 64, with minor modifications.

The same combinatorial principles apply to combinations from two or more code systems. Assume that mapped information is coded into two 98-integer code systems. The combinations program has to search for 1 to 98 pairs of two-character codes out of the 98-squared, or 9,604 possibilities. With the alphanumeric system, the number of possible combinations rises to about 5 million.

Computer Programs

MIADS2, like MIADS, contains two mainline programs: (a) the mapping program (MAP2), and (b) the combinations program (COMBN2). Both contain Fortran IV and MAP subprograms developed and tested on the DCS monitor system at the University of California Computer Center, Berkeley, California.[1] With version 13 of Fortran IV and a 32K IBM 7094 computer, the mapping and combinations programs will reside in memory wit respectively, 652 and 9,000 words left over. Th particular storage allocation should not be co sidered as "best." It is merely the end result of long series of compromises among speed, storag and program options. The programs are segmente into many smaller routines or "building block on the assumption that users may have differe criteria and will want to modify their progra accordingly.

Data Preparation

The basic data collection procedure has n changed. MIADS (integer) map data input can al be processed by MIADS2. The user sets up implicit coordinate system by putting strips of gr paper over a map and hand coding the desir information into cells. There is, however, one d ference—he need not put a code in every ce Often there will occur a "patch" of several gr cells, all of which are to be assigned the same co Previously the coder or the keypunch operat wrote the code in every cell. The computer w now do this copy work if the coder outlines t border of the "patch" with the code (fig. 1)— need only outline the left-most edge. Verificati of hand coding work is easier if the entire bor is filled. But this time-saving advantage has

---

[1] The MAP subprograms were provided by Robert Russell, programer at the Pacific Southwest Forest a Range Experiment Station, Berkeley, Calif.

A

```
        0606                          0606                 1

      06    06                      06060606               2
    06      06                    0606060606               3
    06      06                    0606060606               4
      060606                        060606                 5

   OUTLINED PATCH               HAND OR KEYPUNCH FILLING
```

B

```
  --INPUT--                         --OUTPUT--          --LINE NO.--


       0606ABABABAB99                 0606ABABABAB99              1
     06      06AB     AB99          06060606ABABABAB99            2
   06        06         AB99      060606060606060606AB99          3
   06        06AB       AB99      0606060606ABABABABAB99          4
     060606AB           AB99        060606ABABABABABAB99          5
             AB       AB99                ABABABABAB99            6
               ABABAB                       ABABABABABABABABAB    7

    OUTLINED PATCH                          COMPUTER FILLING

NOTE ERRORS IN LINES 3 AND 7 DUE TO BOTH A MISSING LEFT-HAND 'AB' AND
     A TERMINATING BOUNDARY CODE '99'.
```

Figure 1. — *The job of hand-coding — translating map characteristics into numbers — is considerably reduced under MIADS2.* A, *cells were hand-filled under MIADS;* B, *the computer does the filling in under MIADS2, and only the left-most edge of each "patch" must be hand-filled.*

price since an omitted code can cause errors (fig. 1). The coder may fill a patch by hand since excess codes do not affect the filling process. The reduction in hand-coding cost attributable to the filling option is directly related to the size of the "patches." This option also makes very large patches feasible, changing the capability of the system to extract and manipulate map data.

Options and Output

Options

A major structural change for both the mapping and combinations program is the procedure for setting up a job. Previously all map records were counted before processing and control cards were inserted before blocks, in a precise fashion. The current control procedure allows control cards to be placed with the blocks of map records to which they apply.

A deck setup for a mapping program run can be illustrated only in a general way (fig. 2). Except for segmenting a deck into jobs and blocks, no regular pattern is needed. Control cards are inserted as needed. Obtaining useful results for even a single block of map records may require as few as two or a maximum of 461 control cards. Consequently, by using English or pidgin English words on control cards, deck setup is easier. Information on control card suboptions and other

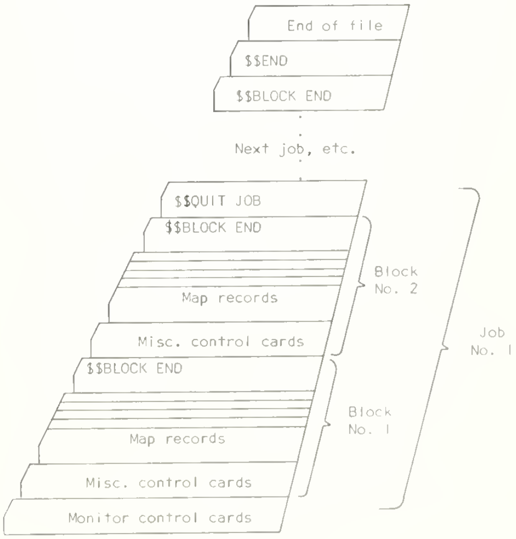

Figure 2.—*MAP2—general deck setup for a run, showing block and job segmentation.*

details related to deck setup will be found in the operating manual. The deck setup for MIADS2 control card operators is as follows:

MIADS2 Control Cards (apply to both programs):

1. $$HEADER
2. $$TITLE
3. $$QUIT JOB
4. $$END
5. $$TAPE
6. $$LINES

Additional Control Cards for MAP2:

1. $$BLOCK END
2. $$SCALE
3. $$CODES REMOVED
4. $$RATES
5. $$FILL
6. $$TABLES
7. $$OVERLAY

Additional Control Cards for COMBN2:

1. $$CHANGE
2. $$EXCLUDED
3. $$COMBINE
4. $$CARDS
5. $$PRINT
6. $$PUNCH

Output

The types of tables printed out by MAP2 have been reduced from 13 to 9. Previously, acreages, products, and their corresponding proportions could be cumulated over codes within a block as well as accumulated over blocks. It was necessary either to anticipate cumulation when designing the code system or to change the codes around into the desired ascending order later. Such forethought was practical with the small integer code system, but not with the large one. Therefore, the cumulative option was dropped. Tables and other items that can be produced by MAP2 under MIADS2 are as follows:

Block Tables

Block Code:

1. Frequencies
2. Proportions
3. Acreages
4. Products
5. Product proportions

Block Items

1. Block frequency total
2. Block acreage total
3. Acreage represented by one grid cell
4. Scale in inches per mile
5. Block product total

Accumulated Block Tables

Accumulated Block Code:

1. Proportions
2. Acreages
3. Products
4. Product proportions

Accumulated Block Items

1. Total block acreage
2. Total block product.

Block acreage could be computed in four wa in MIADS. Because map scale—or more precisel representative fraction—is always sufficient calculate block area, the other three ways we dropped.

In MIADS, combinations could be found fro two to four code systems simultaneously. Th combinations program (COMBN2) still change codes within one system, but will combine onl two code systems. The explanation for this is th same as that given for reducing table output fro MAP2. Combining several large systems at onc requires too much advance planning. Beside given a capability of combining two systems, an additional number may be combined by successiv runs.

Various mixtures of printing and punching, both, are permitted with MIADS2. Tape input output is comparatively restricted in that only o tape job is permitted per run—one file in lengt that is, tape writing or reading always starts the beginning of a tape. This limitation implie that each large job (e.g., a coded National Fore map) will be assigned to one tape. If this pr cedure is inconvenient, simple programs can written to store and manipulate the map ta records.

Time Estimates

Time to load the object deck is about a hal minute for either computer program.

Processing time for the mapping program independent of the size of the code system. B it does vary with the number of map records a table output. Running time is essentially the sa as previously stated for the integer code syste on an IBM 7090 computer—¾ minute per 1,0 map records. This same estimate applies to co changing with the combinations program.

Combining codes is somewhat more expensi than map program processing. A fixed amount time is required to sort the combinations soug before processing the pairs of map records. Most jobs will involve less than a thousand combinations and a rule-of-thumb of 1½ minutes per thousand pairs of records is accurate enough. For larger problems, a time estimation procedure is provided in the operating manual.

Total cost, the sum of all hand and computer work, appears to be unchanged from the original system. For large jobs, that is, 3,000 map records or more, the cost per acre should still be about 15/100 of a cent, based on map scale of 2 inches per mile.

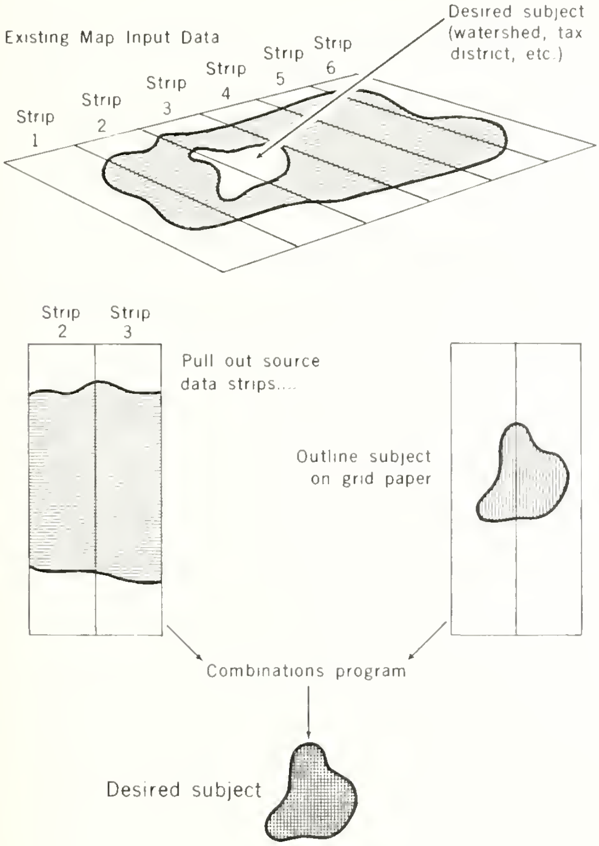

Figure 3.—*Filling and combining to "pull out" a portion of map data.*

Applications of the System

The major use of the system will continue to be for inventory type work. Of the less obvious uses, perhaps the most interesting is the ability to assemble, display, and update input data for analytical models. For example, a prototype model which integrates MIADS and linear programing into a larger computer-oriented system has been described recently (McConnen, Navon, and Amidon 1966;[2]).

The large code system now available will allow much larger and more complex applications than ever before. The addition of the filling option also adds a capability that, while possible before, would have required too much hand coding. Very large "patches" can be filled as readily as small ones. Consequently filling, followed by application of the combinations program, can be used to extract irregular blocks of map data cards from an existing code set (fig. 3). Low-cost filling also enables the user to extract alternative configurations of mapped data. He can "cut and try" alternative boundaries for compartments within a forest, or determine the effect of alternative rules on, say, recreation area boundaries (fig. 4).[3]

Finally, a problem whose scope grows beyond

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[2] Navon, Daniel I. *Computer-oriented systems for vildland management.* (MS. accepted by J. Forestry.)

[3] The fill option as a tool for making "policy maps" was first recognized by Dr. R. J. McConnen, formerly project leader of production economics, Pacific Southwest Forest and Range Experiment Station, Berkeley, Calif.

the capability of an integer code system, or becomes too costly on a small computer, can be transferred to MIADS2 without any difficulty.

The examples in the appendix, along with the imagination of the user, will suggest potential applications of MIADS2.

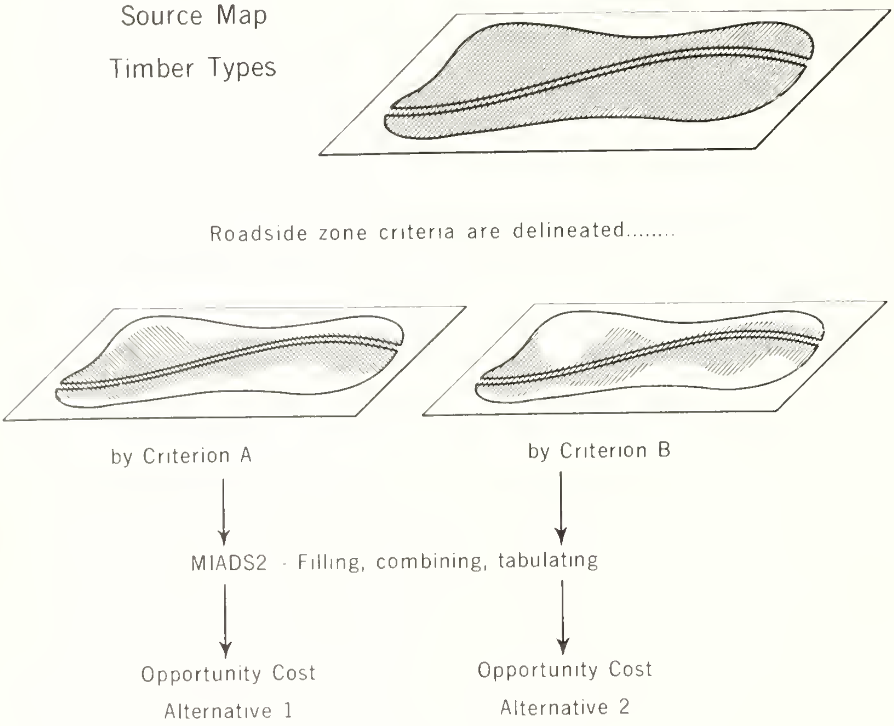

Figure 4.—*The fill option helps produce "policy maps." In this example two compartment boundaries are defined.*

Future Development

The point at which to end development work is seldom clearcut. The MIADS system is no exception. At this point, we wish to describe some revisions and extensions of MIADS2 that show promise. Generally, the proposed modifications were not judged worth incorporating into the system because they lack general application. For some users, however, their development may be quite worthwhile under their particular circumstances. The suggested changes fall into temporal order—improving the old integer system, modifying the present alphanumeric programs, and pointing out some promising extensions.

Integer System

Mapping Program

No particular problem has been encountered to date with the mapping program in MIADS, but the IBM 1620 computer programs do require a 60K memory. And since 40K is much more common, the program should have been segmented so it could be run in two passes. In MIADS one minor change has been made, not in the program, but to the reproducer wiring diagram. Listing will suppress all zeros, as before, except the nine integers with trailing zeros, i.e., codes 10, 20, . . . , 90.

Combinations Program

The IBM 1620 computer program fits 40K but is so slow as to be impractical except for small numbers of combinations or a couple hundred map records. Processing is faster if the most frequently occurring combinations are at the beginning of the list. The absolute expected frequency will seldom be known, but even a relative ranking will help.

Two alternative algorithms were developed. The first, for a 60K memory, was about 10 times faster than the published program. The second method, which would fit a 40K memory, was 4½ times faster than the published routine. This gain, although substantial, was not enough to justify program revision. For large jobs the user should switch to the large computer version.

The control procedure specified prevented more than one input combination from having the same output code. This restriction was unnecessary from the standpoint of the combining algorithm.[4] Its effect is not obvious and is best illustrated by an example.

Suppose several forest land classes are uniquely coded for multiplication by such rates as growth per acre. Later, for some other alternative use, such as recreation or grazing, these categories can be lumped. They cannot be all assigned the same output code by this combination program. A clumsy way around this problem would be to change codes in each system before combining. This change, however, should not be necessary, and is not—with MIADS2.

Alphanumeric System

In MIADS2, both MAP2 and COMBN2 are basically character-handling routines. Generally speaking, Fortran is more suitable for computational work than character manipulation. For as Golden (1965, p. 153) has reported: "It can be claimed with some justification that Fortran is far from ideal as a character manipulation language." Assuming a trend toward languages, as well as hardware, of a more general nature, then character-handling in the future should become easier. This trend would reduce the effort, say, of writing MIADS-type subroutines, allowing code system size to be specified for the particular problem at hand.

The computer time required by MIADS2 appears to be reasonably low. However, it can be reduced further, perhaps a fourth or more, by modifying the input-output subprograms. The MAP2 and COMBN2 programs process data independently, in the sense that they have their own data conversion routines. Because the output of one program is often input for another, time is spent converting external codes to internal ones used by the processor, and back. A programer can reduce conversion time, for example, by storing the internal codes on tape, ready for input to the next run. He then must keep close track of the data flow, but it might be worthwhile for large jobs.

The combinations program is based on the binary search method. It requires that the combinations sought be sorted. The set-up time for sorting is only three seconds for 500 combinations, but rises to about 211 seconds for 2,299 combinations. Sorting is done by a modified version of the exchange method. Programers generally agree that no one method of sorting is always best. If very large numbers of combinations are to be sorted often, however, another method should be considered. There are many alternative sorting algorithms (Gotlieb 1963).

Adaptations and Extensions

One of the advantages of the original integer system was its adaptability. A given set of data could be processed on a small, variable-word-length computer (IBM 1620) or a large, fixed-word-length computer (e.g., IBM 7090, 7094). MIADS recently has been adapted to both an IBM 7040 and an IBM 360 computer, model 30.[5] Although computer time cost was always less on the larger machine, total cost of a job might not be, because of accessibility or other circumstances. Ideally, the same alternatives should still be available. They are not, however, largely because of reasons mentioned earlier. These reasons may be grossly summarized by stating that the smaller processor places too many restrictions on the flexibility of the larger system; in addition, the disparity in processing cost becomes even larger. Therefore, we put almost all our resources into a large processor system.

MIADS2, however, can be extended to processors of various sizes and capabilities because of its structure. Each program is a collection of many smaller subprograms. A programer can modify, add, or delete them to suit his circumstances. For example, by using the same techniques incorporated in MIADS2, we were able to write an alphanumeric mapping program in Fortran II for an IBM 1620 computer. It was deliberately restricted to 40,000 locations, although the computer available had 60K. The program had few options, but the control and map data cards would be accepted without change by MIADS2. The routine will fill and process one block of map cards, producing a single overlay and acreage table. The maximum number of codes permitted in the system is 729. After trying a number of input-output configurations, throughput was raised to eight full

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[4] This limitation was uncovered by R. E. England in the course of applying MIADS as part of his thesis work under the direction of Professor Louis Hamill, Department of Geography, University of Alberta, Calgary, Alberta, Canada.

[5] Personal correspondence with C. L. Kirby, Forestry Branch, Department of Forestry, Calgary, Alberta, Canada, Sept. 9, 1966.

data cards per minute. This speed is only half that of the original integer program, and it had many more options. Since this was an exploratory effort, machine language coding was not justified. Installations with disks and the capability of mixing Fortran and machine language subroutines may be able to triple processing speed. Although the program is relatively crude, it does demonstrate that the MIADS2 techniques can be adapted and extended to smaller processors.

Appendix

A. Examples of Computer Input/Output

I. A comparison of MIADS and MIADS2 mapping program input based on a simplified example.

The arithmetic behind the mapping program tables is described in U.S. Forest Service Research Paper PSW-17 (Amidon 1964, pp. 24–28). The MIADS integer input for the simplified example on page 27 of that publication is repeated below. Following it is the corresponding MAP2 input.

MIADS DECK SETUP

```
    1
 DERIVATION OF MAPPING PROGRAM TABLES. NUMERICAL EXAMPLES.  11/22/63
    1    2    3    1    2    3 2
 3
 1       100
 1      1000
      4E-1      5E-1      6E-1
01010102020202020303                                                     2 1    1
01010101020202030303                                                     1 2    2
```

MIADS2 DECK SETUP

```
$$HEADER               1
$$TITLE DERIVATION OF MAPPING PROGRAM TABLES. NUMERICAL FXAMPLES. 11/22/63
$$SCALE            43380
$$CODES REMOVED
03
$$TABLES               2
$$OVERLAY              1
$$RATES
01      4E-102      5E-103      6E-1
01010102020202020303                                                            1
$$BLOCK END
$$SCALE           137178
$$TABLES               1
01010101020202030303                                                            2
$$BLOCK END
$$END
```

2. A MIADS2 job consisting entirely of control cards.

By presenting an extreme example, the variation possible with a MAP2 job setup is shown. The input listed below consists entirely of control cards. The program output is also shown.

```
$$TITLE    NOTE- THIS JOB CONSISTS ENTIRELY OF CONTROL CARDS.
$$TITLE GRID CELL AREA IN ACRES AND SCALE IN INCHES PER MILE FOR VARIOUS
$$TITLE      MAP REPRESENTATIVE FRACTIONS
$$SCALE              5280  OR 12 INCHES PER MILE
$$SCALE             12000
$$SCALE             13718
$$SCALE             15840  OR  4 INCHES PER MILE
$$SCALE             23760
$$SCALE             31680  OR  2 INCHES PER MILE
$$SCALE             43380
$$SCALE             63360  OR  1 INCH   PER MILE
$$SCALE            137178
$$SCALE            999999,THE LIMIT FOR THIS PROGRAM--NEARLY 1 MILLION.
$$QUIT JOB
```

```
                      FORTRAN 4 MAPPING PROGRAM, MIADS2 SYSTEM, 1966

               QUESTIONS CONCERNING PROGRAM MODIFICATION SHOULD BE DIRECTED TO

                    ELLIOT L. AMIDON
                    P.S.W. FOREST AND RANGE EXPT. STA.
                    P.O. BOX 245
                    BERKELEY, CALIF

         NOTE- THIS JOB CONSISTS ENTIRELY OF CONTROL CARDS.

     GRID CELL AREA IN ACRES AND SCALE IN INCHES PER MILE FOR VARIOUS

          MAP REPRESENTATIVE FRACTIONS

$$SCALE              5280  OR 12 INCHES PER MILE

                              INCHES PER MILE =  0.12000000E 02

                              ONE CELL(1/30TH SQ.IN.) =  0.14814815E 00 ACRES

$$SCALE             12000

                              INCHES PER MILE =  0.52800000E 01

                              ONE CELL(1/30TH SQ.IN.) =  0.76522803E 00 ACRES

$$SCALE             13718

                              INCHES PER MILE =  0.46187491E 01

                              ONE CELL(1/30TH SQ.IN.) =  0.10000230E 01 ACRES

$$SCALE             15840  OR  4 INCHES PER MILE

                              INCHES PER MILE =  0.40000000E 01

                              ONE CELL(1/30TH SQ.IN.) =  0.13333333E 01 ACRES
```

```
$$SCALE             23760

                                 INCHES PER MILE =  0.26666667E 01

                                 ONE CELL(1/30TH SQ.IN.) =  0.30000000E 01 ACRES

$$SCALE             31680  OR  2 INCHES PER MILE

                                 INCHES PER MILE =  0.20000000E 01

                                 ONE CELL(1/30TH SQ.IN.) =  0.53333333E 01 ACRES

$$SCALE             43380

                                 INCHES PER MILE =  0.14605809E 01

                                 ONE CELL(1/30TH SQ.IN.) =  0.10000172E 02 ACRES

$$SCALE             63360  OR  1 INCH   PER MILE

                                 INCHES PER MILE =  0.10000000E 01

                                 ONE CELL(1/30TH SQ.IN.) =  0.21333333E 02 ACRES

$$SCALE            137178

                                 INCHES PER MILE =  0.46188164E 00

                                 ONE CELL(1/30TH SQ.IN.) =  0.99999380E 02 ACRES

$$SCALE            999999.THE LIMIT FOR THIS PROGRAM--NEARLY 1 MILLION.

                                 INCHES PER MILE =  0.63360063E-01

                                 ONE CELL(1/30TH SQ.IN.) =  0.53140729E 04 ACRES

$$QUIT JOB
```

3. A demonstration of code filling and removal. The input listed below can be processed by either MAP2 or the exploratory IBM 1620 program. The 1620 output also is shown.

```
$$TITLE  1620 TEST DATA
$$TITLE            A DFMONSTRATIUN UF CUDE FILLING ANU REMUVAL
$$TITLE EXAMPLE IS A 'CHECKER8UARO' OF PUBLIC ANU PRIVATE LAND, WITH
$$TITLE   OWNERSHIP ALTERNATING IN EACH SQUARE MILE(640 ACRES).
$$SCALE            63360 NUTE- UNF SQUARE INCH EQUALS 640 ACRES
$$TITLE THE FIRST STEP IS TO FILL UP THE EMPTY CELLS WITH CUDES
$$TITLE THE SECOND STEP IS TO MAKE FEDERAL LAND UVERLAY BY REMUVING P'S
$$FILL
$$CODES REMOVED         READING STOPS WHEN A PAIR OF BLANKS IS ENCOUNTERED.
P2P3P4P5P6P7P8
99999999999999      99999999999999999999999999999999999999999999               1
99F1        99      99F2        P2        F3        P3        99               2
99F1        99      99F2        P2        F3        P3        99               3
99F1        99      99F2        P2        F3        P3        99               4
99F1        99      99F2        P2        F3        P3        99               5
99F1        99      99F2        P2        F3        P3        99               6
99F1        9999999999F2        P2        F3        P3        99               7
999999999999F4        P4        F5        P5        F6        99               8
          99F4        P4        F5        P5        F6        99               9
          99F4        P4        F5        P5        F6        99              10
          99F4        P4        F5        P5        F6        99              11
          99F4        P4        F5        P5        F6        99              12
999999999999F4        P4        F5        P5        F6        99              13
99F7        P6        F8        P7        F9        P8        99              14
99F7        P6        F8        P7        F9        P8        99              15
99F7        P6        F8        P7        F9        P8        99              16
99F7        P6        F8        P7        F9        P8        99              17
99F7        P6        F8        P7        F9        P8        99              18
99F7        P6        F8        P7        F9        P8        99              19
9999999999999999999999999999999999999999999999999999999999999999              20
$$END
```

```
    1620 TEST DATA
              A DEMONSTRATION OF CODE FILLING ANO REMOVAL
   EXAMPLE IS A 'CHECKER8OARO' OF PU8LIC AND PRIVATE LANO, WITH
     OWNERSHIP ALTERNATING IN EACH SQUARE MILE(640 ACRES).
  $$SCALE            63360 NOTE- ONE SQUARE INCH EQUALS 640 ACRES
  INCHES PER MILE=  .10000000E+01 ONE CELL=  .21333333E+02 ACRES
   THE FIRST STEP IS TO FILL UP THE EMPTY CELLS WITH COUES
   THE SECONO STEP IS TO MAKE FEDERAL LAND OVERLAY 8Y REMOVING P'S
  $$FILL
FILL INPUT CAROS
  $$CUOES REMOVED         REAOING STOPS WHEN A PAIR OF BLANKS IS ENCOUNTEREO.
REMOVE   7 CODES
99999999999999      99999999999999999999999999999999999999999999               1
99F1F1F1F1F199      99F2F2F2F2F2          F3F3F3F3F3          99               2
99F1F1F1F1F199      99F2F2F2F2F2          F3F3F3F3F3          99               3
99F1F1F1F1F199      99F2F2F2F2F2          F3F3F3F3F3          99               4
99F1F1F1F1F199      99F2F2F2F2F2          F3F3F3F3F3          99               5
99F1F1F1F1F199      99F2F2F2F2F2          F3F3F3F3F3          99               6
99F1F1F1F1F19999999999F2F2F2F2F2          F3F3F3F3F3          99               7
999999999999F4F4F4F4F4          F5F5F5F5F5          F6F6F6F6F699               8
          99F4F4F4F4F4          F5F5F5F5F5          F6F6F6F6F699               9
          99F4F4F4F4F4          F5F5F5F5F5          F6F6F6F6F699              10
          99F4F4F4F4F4          F5F5F5F5F5          F6F6F6F6F699              11
          99F4F4F4F4F4          F5F5F5F5F5          F6F6F6F6F699              12
999999999999F4F4F4F4F4          F5F5F5F5F5          F6F6F6F6F699              13
99F7F7F7F7F7          F8F8F8F8F8          F9F9F9F9F9          99              14
99F7F7F7F7F7          F8F8F8F8F8          F9F9F9F9F9          99              15
99F7F7F7F7F7          F8F8F8F8F8          F9F9F9F9F9          99              16
99F7F7F7F7F7          F8F8F8F8F8          F9F9F9F9F9          99              17
99F7F7F7F7F7          F8F8F8F8F8          F9F9F9F9F9          99              18
99F7F7F7F7F7          F8F8F8F8F8          F9F9F9F9F9          99              19
9999999999999999999999999999999999999999999999999999999999999999              20
  $$ENO
                      BLOCK CODE ACREAGES
  ROW   1 COOES               F1              F2              F3              F4
  CUM.COUNT    4   .63999999F+03   .63999999E+03   .63999999E+03   .63999999E+03
  ROW   2 COOES               F5              F6              F7              F8
  CUM.COUNT    8   .63999999E+03   .63999999E+03   .63999999E+03   .63999999E+03
  ROW   3 COOES               F9              P2              P3              P4
  CUM.COUNT   12   .63999999E+03   .63999999E+03   .63999999E+03   .63999999E+03
  ROW   4 COOES               P5              P6              P7              P8
  CUM.COUNT   16   .63999999E+03   .63999999E+03   .63999999E+03   .63999999E+03
BLOCK ACREAGE=   .10239998E+05
  INPUT-ALL RECORDS  31 ALL MAP RECORDS  20 ALL CONTROL CARDS  11
NO.OF 8AD MAP RECOROS=   0 **ENU OF RUN**
```

B. Availability of Operating Manual

Detailed instructions on how to use MIADS2 and for preparing and processing data by the computer programs are included in an operating manual titled "MIADS2." This manual may be obtained as an interlibrary loan by writing to—

Computer Services Librarian
Pacific Southwest Forest and Range
Experiment Station
P. O. Box 245
Berkeley, California 94701.

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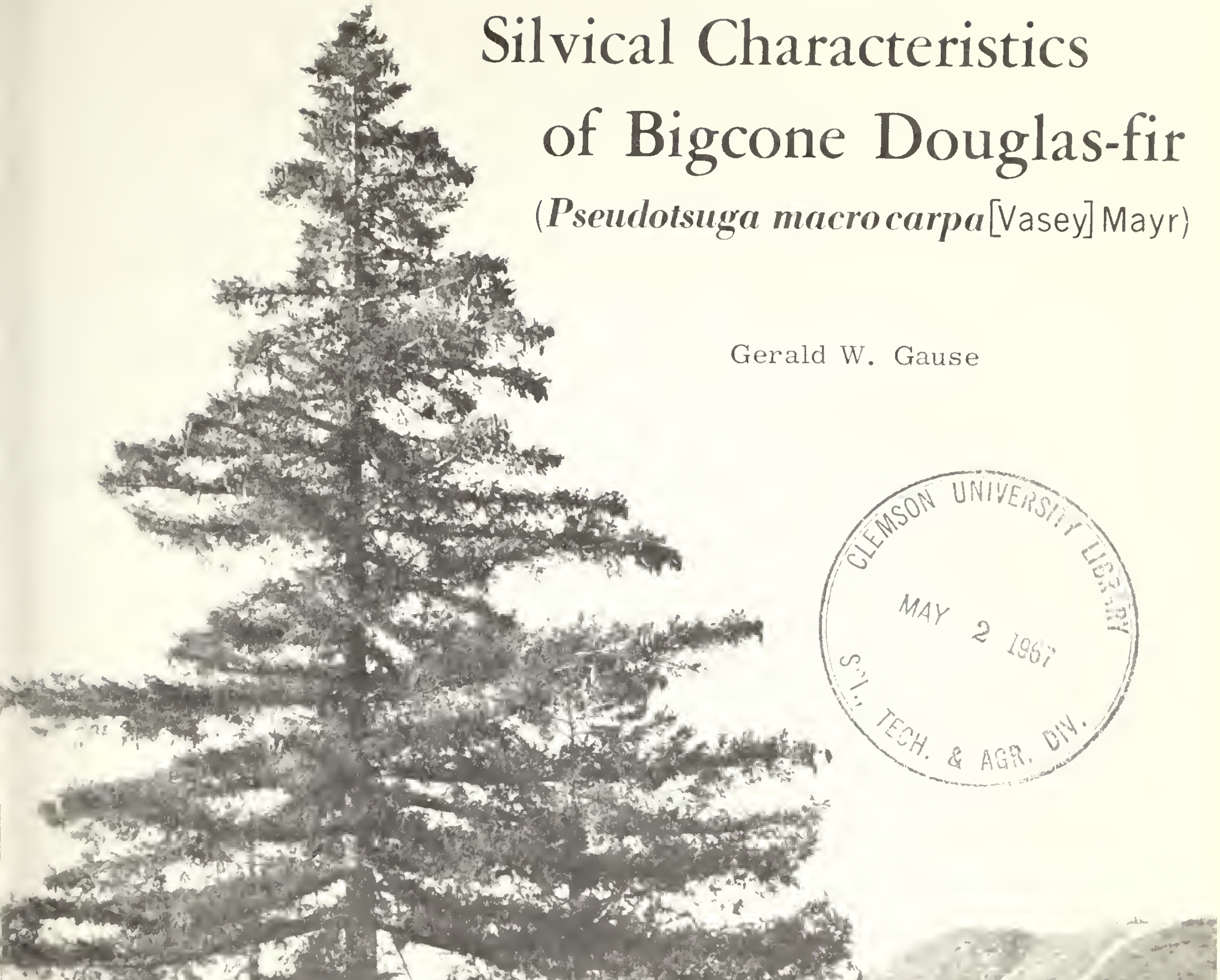
GPO 973-775

Silvical Characteristics of Bigcone Douglas-fir

(***Pseudotsuga macrocarpa*** [Vasey] Mayr)

Gerald W. Gause



S. FOREST SERVICE RESEARCH PAPER PSW-39 1966

Pacific Southwest Forest and Range
Experiment Station - Berkeley, California
rest Service - U. S. Department of Agriculture

Contents

The Author

GERALD W. GAUSE is a botanist, at Glendora, Calif., where he heads the visitor information service, Mt. Baldy Ranger District, Angeles National Forest. Born in Pasadena, Calif., he received an A. A. degree (1960) in forest management at Pasadena City College and a B. A. degree (1963) in botany and physical geography from California State College at Los Angeles. He joined the U. S. Forest Service in 1963.

Acknowledgments

I wish to thank Dr. D. W. Lynch, of the Pacific Southwest Forest and Range Experiment Station, for his guidance in the assemblage and organization of the written material; and Dr. K. K. Ching, of Oregon State University, for providing information on hybridization of the species.

Bigcone Douglas-fir (*Pseudotsuga macrocarpa* [Vasey] Mayr) has been referred to by many common names and by several genera. Common names for this species include desert fir (Jepson 1910), bigcone spruce (Munz 1959), false hemlock (Sargent 1884), and bigcone Douglas-fir (Abrams 1923). According to Jepson (1910) and others, botanical names used in the past include *Abies Douglasii* var. *macrocarpa* Torrey (Ives 1861), *Tsuga macrocarpa* Lemmon (Lemmon 1875), and *Pseudotsuga Douglasii* var. *macrocarpa* Engelmann (Watson 1880). The name bigcone Douglas-fir both describes the species and identifies its close relationship to Douglas-fir (*Pseudotsuga menziesii* [Mirb] Franco).

The species was discovered in 1858 by an expedition led by Lieutenant J. C. Ives, who sighted the tree in San Felipe canyon between Banner and Julian in San Diego County, California (Ives 1861; Jepson 1910). Early botanical writers were perplexed by the similar taxonomic characteristics of bigcone Douglas-fir and Douglas-fir. But growth habits, wood characteristics, and cone size distinguished one species from the other. And no intermediate types have been found (Jepson 1910).

Bigcone Douglas-fir averages about 70 to 80 feet in height. A pyramidal crown composed of long lenticular branches gives it a sparse or thin appearance. The lower branches are long, and bend downward as the trees become older. Short, gray lateral stems or twigs droop downward from the main branches in numerous clusters. The 1-year-old twigs on the trees are red-brown and then become light gray the following year. The bole and lateral branches of the pole trees are gray and sometimes occur with balsam blisters. On mature trees the bark is rusty red-brown, 2 to 5 inches thick, with deep wide furrows and ridges that are irregularly connected (Sudworth 1908).

The dark gray-green needles are ¾ to 1 inch long, somewhat curved with a distinct midrib. They are attached in a spiral around the twig. Needles remain on the tree from 3 to 4 years and then fade during late September, and fall off through October. Five-year-old needles have been observed on some trees at 7,000 feet elevation on the Angeles National Forest, in southern California. The needles have been reported to remain on the trees 5 years or longer (Sudworth 1908).

Habitat Conditions

Unlike Douglas-fir, bigcone Douglas-fir grows under a wide variety of altitudinal conditions and climatic influences.

Climatic

Bigcone Douglas-fir is found in a Mediterranean-type climate. According to Koopen's climatic classification (Haurwitz and Austin 1944), the Mediterranean climate is characterized by long hot summers and short unpredictable winters. Annual rainfall during a 30-year period on a north facing slope at 4,350 feet elevation in the San Gabriel Mountains averaged 24 inches.[1] The lowest recorded for the period was 9.87 inches, and the highest for any year (winter 1957–1958) was 49 inches.[1] Throughout the range of the species, annual rainfall varies between 14 and 30 inches. Summer tropical rain is sparse throughout the range and seldom increases tree growth.

In the mountain ranges of southern California, annual temperatures are considered moderate—and extremes are rare. Annual temperatures average in the high 50's. Temperatures may exceed 100°F.; winter temperatures seldom drop below 10°F.

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[1] Unpublished rainfall data from 1935–1965, San Dimas Experimental Forest, Glendora, California, on file at Pacific SW. Forest & Range Exp. Sta., Glendora, Calif.

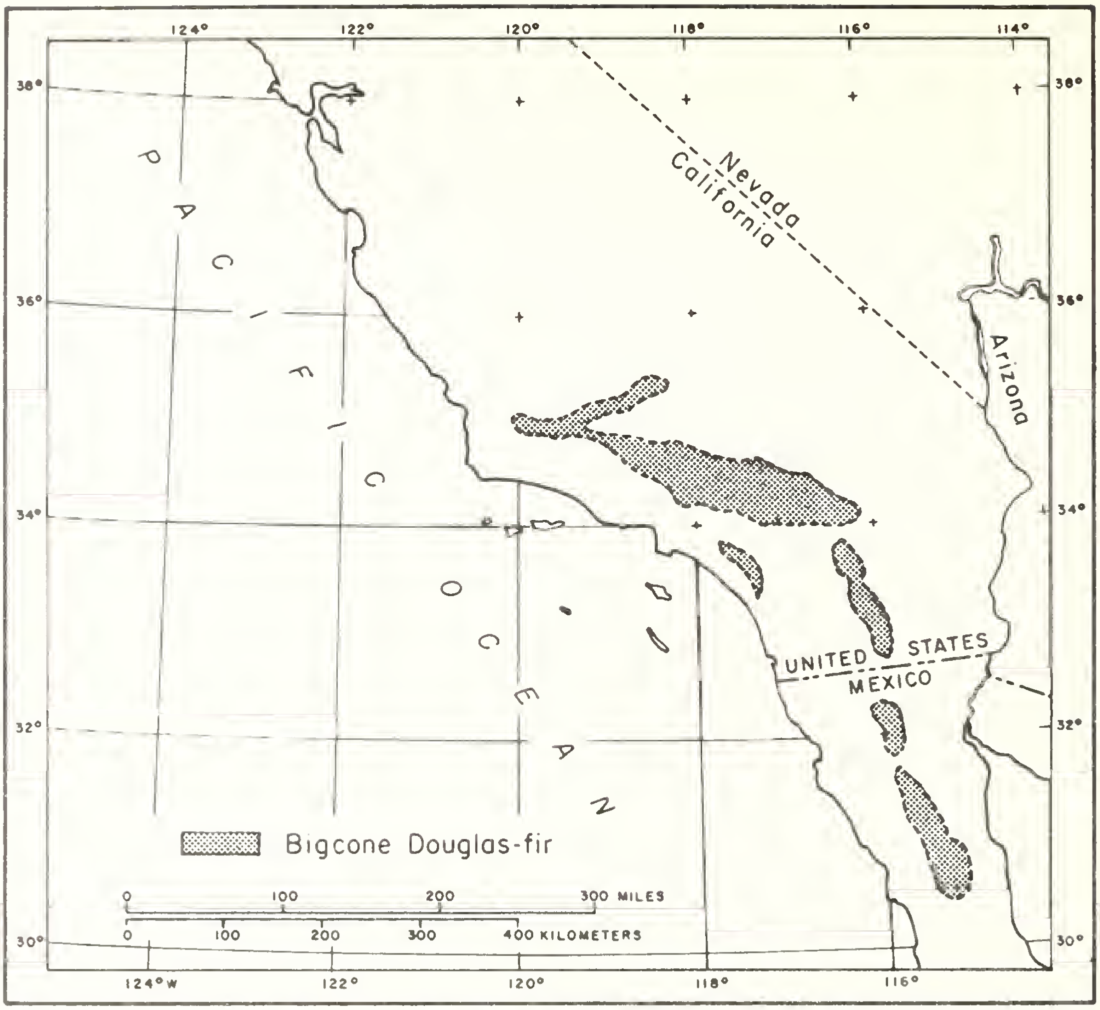

Figure 1. — *Botanical range of bigcone Douglas-fir*

Edaphic

The species grows on a variety of well-drained soils of igneous, metamorphic, and sedimentary origin. The residual soils were developed from a wide range of decomposed granitic rock. They form the major soil types found on all sites throughout the range of this species. Soils of igneous origin[2] include the Wilson, Mixed Wilson, and Red Wilson series.

In the Transverse, Coastal, and Peninsular Ranges, the species grows on the San Gabriel Compromise and Wilson Series.[2] The tree is also found on the Violin Sedimentary soil series in all three ranges.[2]

The more abundant and aggressive stands of pole and sawtimber trees grow on the San Gabri series, mainly along canyon edges and expose ridges on north slopes, where moisture is moı abundant the year around for prolonged growtl The poorest stands are found on soils derive from an anorthosite mineral, where trees appe suppressed and over-aged for their size.

Alluvial soils support numerous isolated stan on terraces or benches well above major strean and riverbeds. Bigcone Douglas-fir is also found soils in riverbottoms on south-facing slopes whe moisture is available.

Physiographic

The northern limits of bigcone Douglas-fir ar 34° 50′ north and 120° 10′ west in the San Rafa Mountains of Santa Barbara County, some 2 miles from the most southerly extension of Dougla fir in California *(fig. 1)* (Griffin 1964). The specie

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[2] Published soil maps of southern California mountain ranges on file at the Pacific Southwest Forest and Range Experiment Station, Glendora, Calif.

is found east of the San Rafael Mountains at the same latitude in the Tehachapi Mountains (Munz 1935). It extends further eastward to 116° 30′ west in the San Bernardino and San Jacinto Mountains. Its southern extension in California is 32° 40′ north and 116° 20′ west near Julian in the southern portion of the Laguna Mountains in San Diego County. In the central part of Baja California, Mexico, it is reported to grow around 30° 00′ north, in association with the same conifers found with it in southern California.[3]

Bigcone Douglas-fir is found at elevations from 900 feet on the north slope of lowland canyons in the chaparral zone to 8,000 feet in a mixed coniferous stand on south slopes—an altitudinal range of some 7,100 feet. The tree grows at the lower elevations under xeric conditions in the chaparral covered canyons on west through north slopes. On south slopes it is found at or above 2,500 feet elevation in both the canyons and exposed ridges. In the Transverse Range, larger stands are found from 3,000 to 5,500 feet elevation on southwest through north slopes, mainly in the upper canyons. The Coastal and Peninsular Ranges support vigorous stands in westerly canyons from 2,400 to 5,000 feet. This condition can be attributed to the persistency of the marine influence throughout the year.

Above 6,000 feet elevation the species grows in the mixed conifer zone in open timberland growing with *Pinus ponderosa* (ponderosa pine), *P. jeffreyi* (Jeffrey pine), *P. lambertiana* (sugar pine), *Libocedrus decurrens* (incense-cedar), and *Abies concolor* (white fir). The species covers some 4.5° of latitude, giving it a north-south range of 315 miles.

Biotic

Bigcone Douglas-fir is found in the upper Sonoran (500 to 2,500 feet), Transition (2,500 to 6,000 feet), and Canadian (6,000 to 9,000 feet) life zones of southern California.

Adaptation of this species to the xeric chaparral brushland and its occurrence in the montane forest regions of southern California show its ability to endure and grow in a variety of ecological settings. Throughout its 315-mile north-south range, the tree occurs with a variety of vegetation. Woody and herbaceous plant associations are as follows:

- From 900 to 3,500 feet on northwest oriented canyons, north and east slopes, and canyons, bigcone Douglas-fir associates with *Heteromeles arbutifolia, Artemesia californica, Quercus agrifolia, Q. dumosa, Ceanothus leucodermis, C. spinosus* var. *palmeri, Dendromecon rigida, Rhus laurina, R. ovata, Yucca whipplei, Cercocarpus betuloides, Adenostoma fasciculatum, Eriogonum fasciculatum, Salvia apiana, S. mellifera, S. leucophylla, Juglans californica, Acer macrophylla,* and *Woodwardia fimbriata.*

- From 3,600 to 5,500 feet from northwest through south and southeast slopes, canyons and ridges, bigcone Douglas-fir associates with *Pinus ponderosa, P. coulteri, P. attenuata, P. lambertiana, P. monophylla, Quercus chrysolepis, Q. kelloggii, Acer macrophylla, Arctostaphylos glauca, A. patula, Ceanothus cuneatus, C. integerrimus, C. spinosus* var. *palmeri, C. leucodermis, C. oliganthus, Fraxinus dipetala, Adenostoma sparsifolium, Pteridium aquilinium* var. *pubescens, Woodwardia fimbriata,* and *Polypodium* sp.

- From 5,600 to 8,000 feet on south and west slopes, bigcone Douglas-fir associates with *Pinus ponderosa, P. lambertiana, P. coulteri, P. monophylla, P. jeffreyi, Libocedrus decurrens, Abies concolor, Quercus chrysolepis, Q. kelloggii, Ceanothus cuneatus, C. crassifolius, Cercocarpus betuloides, C. ledifolius, Castanopsis sempervirens, Arctostaphylos glauca, A. patula, Chrysothamnus nauseosus, Penstemon ternatus, Rhamnus californica, R. crocea, Pellaea compacta,* and *Allium* sp.

At one time more trees grew on the lower and upper ridges in the chaparral zone, but repeated fires have gradually removed them from these sites. In the chaparral zone, canyons or draws support numerous isolated relic stands that have escaped burning. These relic stands consist of partially burned and unburned islands of overmature sawtimber trees, with little or no reproduction present.

From 3,600 to 5,500 feet elevation on shaded slopes, isolated pure stands may grow in association with canyon live oak. Most of the reproduction is found in and around the periphery of oak thickets, where shaded mesic conditions are favorable.

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[3] Bergen 1904; Bowers 1942; Dallimore and Jackson 1948; Ives 1961; Jepson 1910; Sudworth 1908.

Life History

Seeding Habits

Flowering and fruiting.—Flowers on bigcone Douglas-fir are monoecious. Flowering buds form in September and October on the same twig of the current year's leaves. Microsporangiate strobili form on the underside of the twig, subtended by conspicuous involucres of bud scales. Each pollen scale is tipped by an awl-shaped spur (Bergen 1904).

Dark red to yellow green megasporangiate strobili appear just behind the terminal bud or at the end of the branchlets. The scales are concealed by numerous two-lobed, long, pointed bracts. The cone is oblong, 1½ to 2 inches long, and droops from the end of the branch.

At lower elevations, strobili bud swelling and subsequent flush may occur as early as February *(fig. 2)*. Megasporangiate strobili that flush in February are often frozen at the pedicel. The desiccated megasporangiate strobili will often remain on the tree for several months—a phenomenon also reported in Douglas-fir (Isaac and Dimock 1958).

Strobili flush of both sexes occurs in late March and early April. Homogamy seldom occurs on the same branch or the same tree. Microsporangiate strobili flush on the same tree will often burst and shed pollen before megaspronagiate strobili appear. This dichogamy either prevents pollination or allows the subsequent cross-pollination from other trees in the stand.

Pollination lasts 3 to 4 weeks. Staminate strobili become desiccated after pollen dehiscence; the bud scales then fall off. The dried microsporangiate remains on the tree until fall. Fertilized conelets enlarge in mid July and then mature after one full growing season—usually in late September or early October.

Seed production. — Bigcone Douglas-fir trees rarely produce seed until they are 20 years old. Few exceptions may occur on good open sites. Heavy seed crops seldom occur. During four years' observation there was little fluctuation in the amount of seed crop.

When mature in late September and early October, the short stalked ovulate cones vary in size from 4½ to 7 inches long, scales measure 1½ to 2 inches long *(figs. 3, 4)*. The thick concave cones have a purbulant outer covering (Clinton-Baker 1913). Scale bracts are three-toothed, slightly exerted, with broad midribs (Munz 1959). Pitch often is emitted between the cone bracts and scales before ripening. Chocolate brown and shiny on the upper side and gray white on the under side, seeds are large and triangular in shape with a rounded wing ½-inch long.

Seed dissemination occurs at lower elevations during September. Trees at or above the 5,000-foot level disseminate seeds in late September through all of October. Distance of dispersal of wind blown seeds seldom exceeds several tree lengths—except when winds are heavy.

Rodents and birds play a minor role in seed dispersal and in eventual distribution developing beyond an existing stand. The more terrestrial rodents, such as chipmunks (*Eutamias* ssp.) and California ground squirrels (*Citellus* spp.), eat vast amounts of viable seed during the pouching season in fall. The Gray squirrel *(Sciurus griseus)* clips cones in August and September before the cones open. The larval stage of cone insects destroy some of the seed crop on portions of a cone before it matures.

Figure 2. — *Megasporangiate strobili grow behind the terminal bud of the current year's growth. Microsporangiate strobili occur on the underside of the twig.*

Vegetative Reproduction

The tree will not resprout from a cut stump, but has been propagated by grafts (Dallimore and Jackson 1948). Vegetative reproduction on bigcone Douglas-fir occurs after injury. Pole trees and young sawtimber with broken terminal leaders often produce several aggressive stems that compete for apical dominance. When injury is sustained during fire or mechanical processes, numerous sprouts may develop on the bole and lateral branches. Large scale propagation methods other than the use of seed are not known.

Sprouting after fire.—Among native tree species of California, bigcone can be rated second only to redwood *(Sequoia sempervirens)* in its ability to sprout or recover from fire. This ability to recover from fire damage has enabled the species to persist in many locations where renewed fires commonly occur.

Trees completely defoliated by fire will sprout in the middle and upper one-third crown of the tree where soft unhardened woody tissue prevails under the bark. All sprouts arise from the upper surface of the limbs defoliated by the fire, giving a layered appearance to the crown foliage. Seedlings and saplings are normally destroyed by the fire and do not sprout. Larger pole and sawtimber trees defoliated will sprout vigorously. Overmature sawtimber trees seldom sprout, possibly because of a loss or decline in vigor before the fire.

Bigcone Douglas-fir trees damaged by fire usually are free from bark beetle attacks. This condition is in contrast to that found in pines, which often are attacked after a fire.

Figure 3. — *Numerous cones cluster on terminal portion of the branch, 2 months before maturity.*

Sprouting after mechanical damage.—Mechanical damage can be attributed to abrasion on branches or damage caused by windfalls, rock slides, or blasting for roadside construction.

Bole damage is one of the major causes of vegetative sprouting. Buds proliferate and subsequent stems appear profusely around the perimeter of the injured area. Sprouting following mechanical injury only in pole and younger saw-timber

Figure 4. — *Open mature cones of,* left to right, *Pseudotsuga macrocarpa, P. menziesii, and P. Menziesii var. glauca.*

trees seldom occurs on older trees. Resprouting around the injured area can appear within 1 year following mechanical damage. In time, one dominant stem may protrude through the cluster of new twigs.

The apparent cause of resprouting following fire or mechanical injury can be attributed to the activation of dormant adventitious buds under the bark. Injury appears to stimulate the bud cells which eventually connect to the vascular system.

Seedling Development

Establishment.—The time of germination varies from season to season and with elevation and exposure within the stand. Naturally reseeded plots occur in canyons, usually in and around the edge of oak thickets where mineral soil, decompose oak litter, and good drainage prevails. Seed germinating on dry open exposed rocky area normally die the first year. In the lower chaparra zone, germination occurs in late March; whil above 5,500 feet elevation, germination is in lat April and may continue until late May and earl June.

Fire in and around a tree stand appears to hav no effect in helping germination. In most cases blackened exposed slope may impair any poss bilities of successful seed germination.

The ability of the species to produce a long ta root and numerous lateral roots exhibits its er durance to the xeric conditions of the chaparra zone.

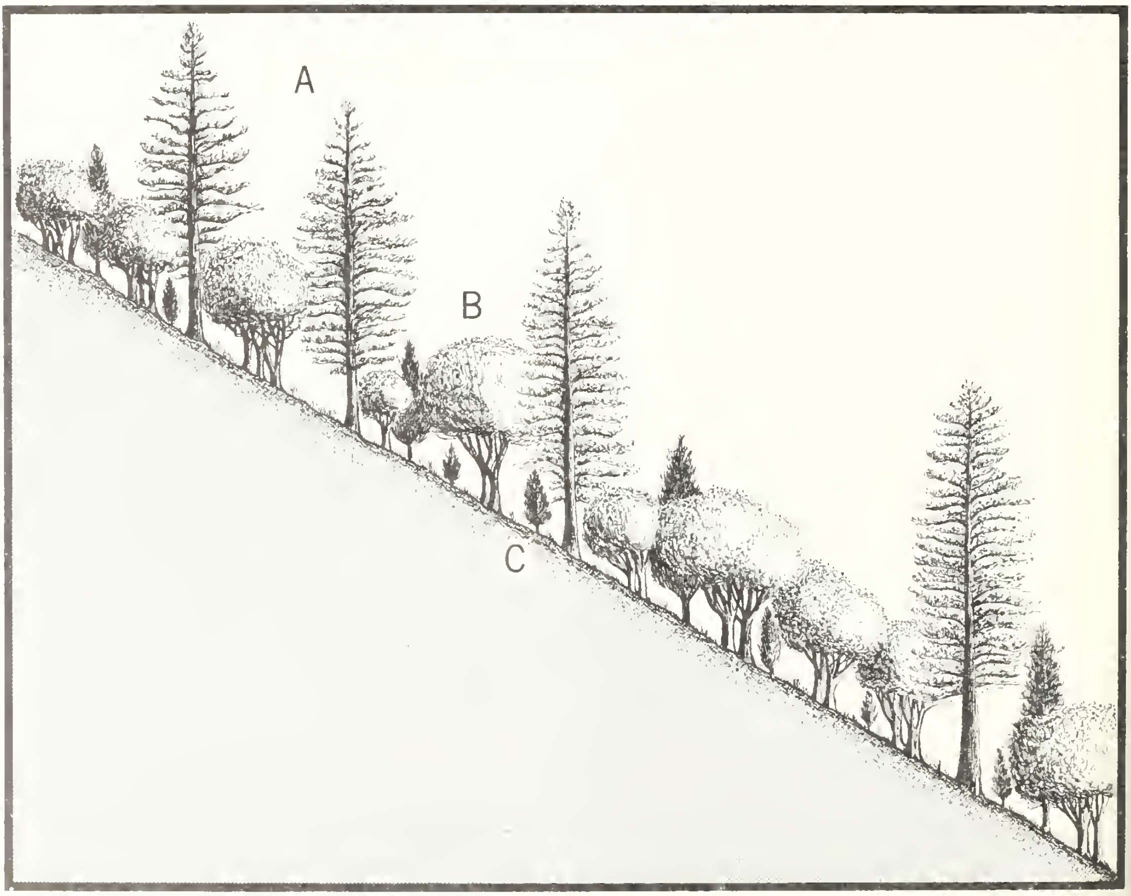

Figure 5.—*Typical profile on an unburned north through east slope, bigcone Douglas-fir:* A, *scattered overmature sawtimber, 24 to 70 inches d. b. h.;* B, *live oak woodland profile, oak crowns coalescent, forming dense shaded overstory 15 to 30 feet high, with few pole trees penetrating oak canopy;* C, *shaded profile, persistent shade, widely scattered under-sized-overaged seedlings and saplings, with a few herbaceous plants.*

Early growth.—If seedlings are growing on north slopes within a thick oak canopy 15 to 30 feet high, they become suppressed because of the almost constant shade. A tree 0.9 inch in diameter at ground level and 40 to 50 years old may be only 24 inches tall.

On slopes of southerly exposure, trees have a much higher growth rate. And seedlings on south through west slopes at higher elevations, where shading is even less, become saplings within 3 to 5 years.

Sapling Stage to Maturity

Reaction to competition.—Among the obstacles to continued growth of bigcone Douglas-fir are lack of sunlight, inadequate moisture, and competition from other species. On unexposed shaded north slopes, saplings show little vigor. The branches of the lower one-third of the crown are usually dead. And annual growth increments can barely be distinguished.

By the time poles are 15 to 30 feet tall and 40 to 70 or more years old, they begin protruding through the thick oak canopy. Their diameter at breast height then ranges from 5 to 8 inches. Continual sunlight on the newly exposed crown and the moist shaded forest floor combine to produce vigorous growth. Once the trees protrude through to full sunlight, there is an annual increment increase of ⅛ to as much as ¼ inch. Terminal growth is also accelerated. Such trees have elongated spaces between the nodes on branches. A tree that has 7 years' elongated terminal growth also has an equal increase of annual increment—dating back for 7 years.

As numerous bigcone Douglas-fir develop to sawtimber size, the canyon live oak trees are gradually shaded from the site and are found mainly on the periphery of the stand *(fig. 5)*. Pure stands of bigcone Douglas-fir found growing on south through northwest ridges and canyons from 3,500 to 5,500 feet elevation and having abundant year-round moisture are tall and aggressive for their age.

Widely spaced canyon live oak decreases competition for moisture and sunlight, thus vigorous fir trees occur with thick buttressed trunks and long lenticular branches from the ground level upward.

Pole-size bigcone Douglas-fir trees grow quickly; their terminal branch growth may exceed 12 inches annually. Saplings vary from 4 to 10 feet tall on open sites, pole trees from 12 to 48 feet. Annual increments are large and uniform in size, showing no effect of dry and wet years. This condition shows that the combination of full exposure and year-around moisture are beneficial for excessive prolonged growth. A decrease in increment size occurs in sawtimber trees that are older than 100 years.

Figure 6. — *Physiological change or disorder causes bigcone Douglas-fir to fade and lose needles. Some trees resprout, mainly along the bole after needles fall.*

From 6,500 up to 8,000 feet, the tree is found only as widely scattered specimens growing in mixed conifer stands from southeast through westerly exposures. Reproduction is scanty in the coniferous zone. At 8,000 feet, where the species fades out, the canyon live oak also rarely appears.

Injurious Agencies

Older trees sometimes fade to an amber color and lose their needles and appear dead *(fig. 6)*. But in 2 years, they appear to sprout with renewed vigor. The cause of the fade is not known, but may be due to some physiological disorder brought on by drought. Larval mines or galleries have not been observed in the faded trees. The tree does not appear to be afflicted by major insect epidemics or diseases on a large scale. But flathead borers *(Melanophila californica)* have been observed on bigcone Douglas-fir growing on the San Bernardino National Forest, near Angeles Camp, in southern California.[4]

Fire usually will not destroy a stand, but ofte reduces its size. After a fire, canyon live oak ar mixed chaparral species often invade the burne over areas of the stand.

The return of bigcone Douglas-fir as the dom nant species on the site may require several hu dred years. The high incidence of fires over tl same areas has eliminated many stands from tl upper ridges and slopes, and reduced their siz

Special Features

Longevity

The age and size of bigcone Douglas-fir vary with site conditions throughout its range. In southern California, trees larger than 40 inches d.b.h. normally are found above 5,000 feet elevation. Bucked-up windfalls, 72 inches d.b.h., may be 450 to 550 years old.

The largest known bigcone Douglas-fir is 91 inches d.b.h. and 173 feet tall. Called "Old Glory," it has a crown spread of about 65 feet,[5] and is estimated to be 600 to 700 years old. The tree is near San Antonio Canyon on the Angeles National Forest, in southern California *(fig. 7)*.

Hybridization

Hybridization of Douglas-fir with bigcone Douglas-fir was achieved in 1956 by Dr. Kim K. Ching, who devised an intensive controlled pollination program (Ching 1959).

The objective of this cross was to develop a hybrid that would have the inate wood characteristics and rapid growth rate of Douglas-fir and have the dry site adaptability of bigcone Douglas-fir. Progenies produced conclusive evidence of a successful cross, having characteristics of both parent trees. The hybrid is characterized by lower seedling mortality, a denser and more fibrous root system, longer needles, and significantly taller trees *(fig. 8)*.

Management Values

Bigcone Douglas-fir can be propagated routinel in nurseries. Collected cones set out in the ope sun will open in 2 to 3 days. They can be ru through a shaker to remove seeds. Dewinging done by rubbing seeds over a 1/6-inch mes screen (U.S. Forest Service 1948). Under ope storage in diurnal room temperatures, seeds will— during a 4-year period — lose their viabilit

Figure 7. — *The largest recorded bigcone Douglas-fir tree stands near San Antonio Canyon, Angeles National Forest.*

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[4] Personal correspondence with Ken Swain, entomologist, San Bernardino National Forest, San Bernardino, Calif., Oct. 6, 1966.

[5] American Forestry Association's Social Register of Big Trees.

Photo courtesy of Dr. K. K. Ching.

Figure 8.—*Nine-year-hybrids of Douglas-fir × bigcone Douglas-fir* (outside rows) *outgrew Douglas-fir control trees* (center row) *by 11 to 19 percent, at the Willamette Valley Plantation, Oregon State University.*

Germination of the species is epigeous. To obtain rapid growth, young seedlings should be transplanted from tar pots into 5-gallon cans and watered often. But trees should not be left in 5-gallon cans more than 1 or 2 years, because roots develop rapidly.

The species has been grown successfully outside the continental United States. It was unknown in Europe until seedlings were raised at Bayfordbury, England in 1910. Trees are also reported growing in Sussex and North Ireland, where they reached heights of more than 60 feet, with a 40-foot spread (Clinton-Baker 1913; Dallimore and Jackson 1948; Royal Horticultural Society 1932).

Since the species grows under a variety of climatic influences, it can be planted for both watershed and esthetic values at sea level up to 7,000 feet in southern California.

The combination of fast growth on fair sites, xerophytic characteristics, no specific soil requirements, and the ability to sprout after fire should be considered when planting this species along new roadside-fill zones, recreation areas, plantations, or mountain recreation residences.

The hybrid of Douglas-fir X bigcone Douglas-fir if introduced into the semiarid parts of southern California may prove to have some potential for more widespread planting in the future.

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Forest Service — U. S. Department of Agriculture

Requirements for New Housing in Hawaii, 1965-70 . . . a Forecast

John D. Zinnikas R. Sidney Boone

U. S. FOREST SERVICE RESEARCH PAPER PSW- 40 1967

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Contents

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The assistance of George D. Frazier, whose insight and experience greatly helped in formulating some of the ideas in this paper, is gratefully acknowledged.

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Housing construction is the largest single market for lumber, plywood, and other wood-base panel products.[1] The major uses of lumber are in structural framing, flooring, siding, concrete forms, millwork, and cabinets. The single most important user of lumber has traditionally been the construction industry. In the United States, this industry in 1962 used nearly three-fourths of all lumber produced *(table 1)*. Housing construction and upkeep and improvements in housing took up about half of all lumber produced. These two uses together accounted for 70 percent of the total lumber used in construction.

How large and important is the housing construction market in Hawaii? What factors affect the demand for new housing? What changes, if any, can be expected in the near future in the demand for housing? Answers to these and related questions would be helpful to the State's timber products industry for planning and management purposes. To obtain answers, this study was made as one of a series examining the present and potential markets for Hawaii-produced timber.

This paper provides estimates of the needs for new housing units in Hawaii during the period 1965–70, and describes the factors that may affect housing construction in the State.

Table 1.--*Lumber consumption in the United States, by end use, 1962*[1]

End use	Billion board feet	Percent of total
Construction:		
Residential, new	14.0	37.5
Non-residential, new	5.0	13.4
Upkeep and improvements	5.4	14.5
Railroads, mines, farms	3.2	8.6
Subtotal	27.6	74.0
Shipping	4.3	11.5
Manufactured products	4.2	11.3
Miscellaneous	1.2	3.2
Total	37.3	100.0

[1] U.S. Forest Service. *The demand and price situation for forest products 1964*. U.S. Dep. Agr. Misc. Publ. 983, p. 6. 1965.

Pattern of Lumber Use

The pattern of lumber demand in Hawaii is probably similar to that for the rest of the United States. Otteson reported that "The primary demand for lumber (in Hawaii) comes from the construction industry. Between 80 and 85 percent of Hawaii's annual lumber imports are consumed by this industry."[2]

A study by Baldridge[3] of demand for lumber in construction also indicates that about 80 percent of the State's lumber imports were used by the construction industry in 1959. Based on these data and Frazier's estimate[4] of average annual consumption for the period 1959–61, it is estimated that between 65 and 75 million board feet of lumber are used annually by the building and construction industry in Hawaii.

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[1] Phelps, R. B. *Wood products used in single-family houses inspected by the Federal Housing Administration, 1959 and 1962*. U.S. Dep. Agr. Stat. Bull. 366, p. 7, 1965.

[2] Otteson, Conner Piper. *A study of lumber distribution in Hawaii*. 1961. (Unpublished master's thesis on file Univ. Hawaii, Honolulu.)

[3] Baldridge, Milton C., Jr. *Markets for materials in construction in Hawaii*. 84 pp. Menlo Park, Calif: Stanford Research Institute. 1959.

[4] Frazier, G. D. *Estimated demand for lumber and plywood in Hawaii by the year 2000*. p. 7. U.S. Forest Serv. Res. Paper PSW-23. Pacific SW. Forest & Range Exp. Sta., Berkeley, Calif. 1965.

Trends in Housing Construction

Residential construction in Hawaii is an important segment of total construction demand. In constant dollars, residential construction value increased almost 3½ times between 1954 and 1962 *(table 2; fig. 1)*.

The decline in private construction activity during World War II left Hawaii with an acute housing shortage. Further, Hawaii did not fully share in the expansion of new housing construction after the war as experienced by the rest of the United States in general. During the immediate post-war years (1946–50), the pent-up demand for housing in Hawaii was counter-balanced by a large cutback in defense expenditures by the Federal Government and the unsettling effect of several major strikes on Hawaii's economy.

These two factors contributed to the most severe contraction in business activity in Hawaii's history and to an actual outflow of people from the Islands in 1951 and 1952. From 1951 to 1954, the value of new residential housing (adjusted to eliminate changes in construction costs) declined from 30

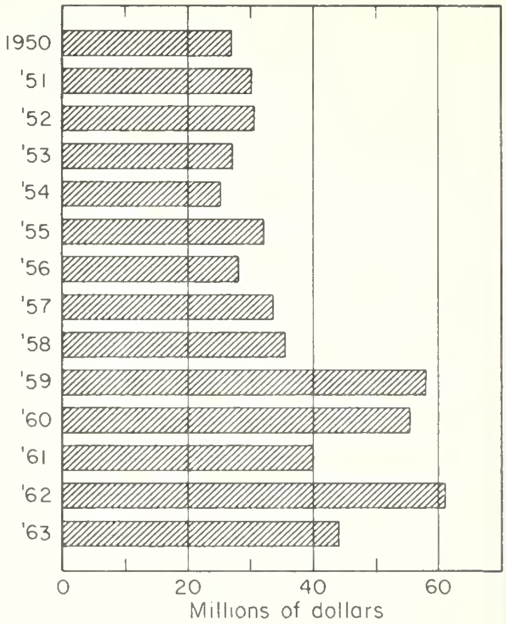

Figure 1.—*Dollar value of new residential housing in Hawaii, adjusted by changes in construction costs for the period 1950–63.*

Table 2.--*Selected economic data for Hawaii, 1951-65*[1]

Year	Population	Value of construction[2,3]	Value of new residential construction (building permit value)[3]
		Millions of dollars	
1951	471,853	99	30
1954	474,391	88	25
1955	491,899	97	36
1956	512,200	110	33
1957	538,296	134	42
1958	560,448	174	48
1959	580,505	216	81
1960	595,024	275	78
1961	612,763	268	60
1962	635,888	268	94
1963	655,546	269	71
1964	674,951	318	80
1965	702,030	343	--

[1] Hawaii Dept. of Health. *Civilian population--State of Hawaii*. 1950-63 (midyear). Rev. Sept. 13, 1963.

[2] Adjusted by an index of construction costs to eliminate changes in the price level.

[3] Bank of Hawaii, Dept. of Business Research. *Annual Reports 1951-65.*
Honolulu Redevelopment Agency. *Redevelopment and housing research.* No. 23, p. 52, July 1963 and No. 25, p. 52, July 1965.
Builders Report Pacific. *Annual index of construction costs 1951-65.*

to 25 million dollars per year.

Begining in 1955 the trend was reversed and Hawaii experienced a revival in housing construction activity which reached record heights in 1965. New housing construction was stimulated not only by the shortage resulting from World War II, but also by (a) a marked increase in defense expenditures and military personnel in Hawaii, (b) the influx of tourists, and (c) the large growth in population over the period.

Factors Affecting Demand for New Housing

Demand for new housing can be closely tied to three factors: (a) population growth and family formation; (b) sufficient disposable income to activate new construction activity; and (c) the age distribution of the existing housing units.

These factors have influenced construction activity in the past and may reasonably be expected to do so in the future. Each of these three factors will be considered separately in forecasting new housing construction.

Population

Hawaii's population increased 39 percent between 1950 and 1963 and 48 percent between 1950 and 1965.[5] This growth has been a factor in the demand for housing, and thus in the demand for lumber. If military personnel are included in the population data, the increase would be even greater. The large influx of people from the mainland, Hawaii's substantial natural increase in population (births over deaths), and the increase of military dependents have all contributed to the State's growth in population.

Predicting the demand for new housing necessitates a prediction of the expected change in population over the period. Numerous forecasts of Hawaii's population are available. The State Department of Planning and Economic Development lists 21 different sets of population projections.[6] Together these studies are characterized by their wide variance in defining population, the time-span covered by the forecast, and different methodologies used. As a result, the population estimates differ substantially among studies.

Among the many published projections of Hawaii's population, four are illustrated in *figure 2*. Although there is discrepancy between these projections in expected numbers, of greater significance is the rate of change in each projection over time. Each estimate differs as to the number of people comprising the population, but the estimates agree on a constant rate of change or

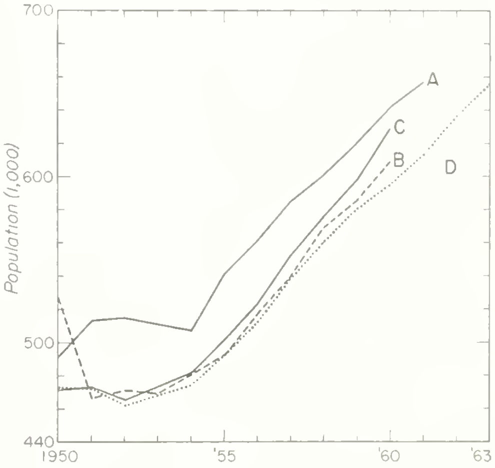

Figure 2.—*Comparison of some population projections for State of Hawaii, 1950–62. Sources:* A. *Statistical abstract of the United States, 1962, table 6, p. 9;* B. *Lucas, Ernesto dela Cruz, "Evaluation of market data as a guide for forest development in Hawaii," 1963, (Unpublished master's thesis on file, Graduate School, Univ. of Hawaii, Honolulu, Hawaii);* C. *Otteson, C. P., "Lumber distribution in Hawaii," 1961. (Unpublished master's thesis on file in Dept. Bus. Admin., Univ. of Hawaii, Honolulu.) (Based on de facto population for July 1 of years shown. Includes visitors and civilian dependents of military personnel, excludes military personnel and residents absent for business or other reasons.)*

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[5] Population estimates are from the Research, Planning, and Statistics Office, Hawaii Department of Health. They include visitors and civilian dependents of military personnel, but exclude military personnel and residents absent for business.

[6] Department of Planning and Economic Development, State of Hawaii. *Research Memorandum 5, annotated bibliography of population projection for Hawaii issued since 1959.* 9 pp. Honolulu, April 27, 1964.

percentage growth in population from an initial base year. After about 1954 the rate of increase for all four series is about the same. This factor is of prime importance for the purpose of forecasting new housing needs.

Total lumber consumption depends to a great extent on new construction, which in turn depends upon the rate of increase in population. If population increases at a constant annual rate, then the amount of lumber used in construction would be relatively constant from year to year. If population increases at an increasing annual rate, then other things being equal, lumber consumption and construction can be expected to increase over time.

This relationship accounts at least in part for the declining per capita consumption of lumber. A constant rate of usage per unit change in population implies a decreasing per capita consumption. In assessing changes in per capita consumption patterns, the relevant measure is the ratio of change in lumber consumption to change in population.

Two additional characteristics of the population affect the level of housing construction. The first is the rate of family formation. The second characteristic is the average household size. Owing to the youthfulness (median age: 24.5 years) of its population, Hawaii can expect a relatively larger rate of family formation in coming years. This expectation will tend to increase housing demand over what it would have been otherwise.

Hawaii has more persons per occupied housing unit than any other state. The average for the United States is 3.0 persons per housing unit.[7] The average number of persons per dwelling unit for Hawaii is now about 3.5 *(table 3)*. This figure is computed by dividing the number of dwelling units into the population. Except for a slight rise in 1965, the State trend since 1950 has been steadily downward. Such a change suggests a shift in housing needs, for as the average declines a larger number of houses are required to meet the needs of a given population.

As of April 1, 1965, the State average rose slightly, to 3.51. The ratio for Oahu (city and county of Honolulu) then was 3.60. From this it appears that the housing inventory is growing at a slower rate than the population of Oahu,[8] but at a faster rate than the population on the neighboring islands.

Table 3.--*Persons per dwelling unit in Hawaii, 1950-1965*[1]

Year	Population per dwelling unit
1950	3.96
1952	3.71
1954	3.57
1956	3.59
1958	3.72
1960	3.57
1962	3.50
1964	3.48
1965	3.51

[1] Honolulu Redevelopment Agency. *Redevelopment and housing research.* July 1964, p. 30 and July 1965, p. 10.

According to the U.S. Bureau of the Census, a housing unit is defined as "A house, an apartment, or other group of rooms, or a single room . . . when it is occupied or intended for occupancy as separate living quarters, that is, when the occupants do not live and eat with any other persons in the structure and there is either (1) direct access from the outside or through a common hall, or (2) a kitchen or cooking equipment for the exclusive use of the occupants of the unit."[9]

Income

Translating housing needs into effective housing demand depends to a great extent on the level of family income. The magnitude of effective housing demand depends mainly on (a) proportion of family income available for housing, and (b) construction costs. For example, while there may exist a need for 10,000 new housing units owing to the dilapidated condition of old substandard housing units, effective housing demand may or may not exist—depending upon the income level of these family units and the replacement cost of new housing in the State.

About 20 percent of families on Oahu now live in substandard housing *(table 4)*. Most of these families fall into the $4,000 to $6,999 income group. In 1962 the median household income on Oahu was $6,883.[10] This relatively modest income would indicate a need for lower priced housing in the lower and middle income ranges. For this

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[7] *Supplemental research notes to the redevelopment and housing research report, July 1963.* p. 5. Honolulu Redevelopment Agency, Honolulu, Hawaii. August and September 1963.

[8] Honolulu Redevelopment Agency. *Redevelopment and housing research.* p. 3. Honolulu, Hawaii. July 1965.

[9] U.S. Bureau of Census. *U.S. Census of housing, 1960 Final report.* p. 14. HC(1)-13. Govt. Printing Office Washington, D.C. 1963.

[10] Honolulu Redevelopment Agency. *Redevelopment an housing research.* p. 50. July 1964.

Table 4.--*Distribution of housing for Oahu, by quality and household income, October 1962*[1]

Annual income before taxes (dollars)	Total	Quality of housing[2]		
		Standard	Substandard	Not reported
	Number			
Less than 4,000	19,200	12,300	6,500	500
4,000 - 6,999	47,200	36,000	10,400	900
7,000 or more	62,700	54,300	7,700	800
All households	129,100	102,600	24,600	2,200

[1] Adapted from Honolulu Redevelopment Agency. *Redevelopment and housing research.* July 1963, p. 42; totals corrected by the author.

[2] Substandard housing is defined as an occupied housing unit that is either dilapidated or with 1.51 or more persons per room.

need to be translated into effective housing demand hinges on the ability of the construction industry to furnish new housing at a price attractive to this income group.

Age Distribution of Houses

The replacement demand for housing can be expected to be related closely to the age distribution of existing housing units. The older the existing housing units, the greater will be the expected replacement demand.

The age of the average housing unit in Hawaii in 1962 was relatively low *(table 5)*. Among existing units, 51.5 percent have been constructed since 1950. Given the high proportion of newly constructed housing in Hawaii, demand for replacement housing in the next 35 to 40 years can be expected to be a relatively small proportion of the total existing housing units.

Table 5.--*Age distribution of houses,*[1] *on Oahu, October 1962*[2]

Year built	Percent
Before 1930	12.2
1930 - 1944	23.3
1945 - 1949	11.2
1950 - 1954	14.7
1955 - 1959	22.6
1960 - later	14.2
Not reported	1.9

[1] Total number of households: 129,200.

[2] Honolulu Redevelopment Agency. *Redevelopment and housing research.* July 1963, p. 18.

Forecasting New Housing Construction

Forecasting construction activity requires evaluation of the factors determining housing demand. The rate of increase in population has an important bearing on housing construction. It is reasonable to expect that new housing needs to accommodate Hawaii's constant rate of growth in population would itself be a relatively constant amount from year to year. This does not mean that actual construction will be constant each year. Rather one would expect actual construction to fluctuate somewhat as the industry adjusts to demand, strikes, and land availability.

The Hawaii Department of Health's population series for the State indicates that the population has grown at an average rate of 4.2 percent per year over the base year of 1954. Projecting this growth rate into the future yields an estimate of 793,200 people in Hawaii by 1970—an increase of about 100,000 persons over the 1965 population. Assuming 3.5 persons to a household, Hawaii will need about 28,500 new housing units between 1965 and 1970. This addition is solely to meet the estimated increase in population *(appendix)*.

In addition to new housing to meet growth in population, new units will be required because of replacement of older existing units. Since Hawaii's housing stock is comparatively young, the replacement demand will probably not be substantial. Nevertheless, assuming a 40-year life for the average house, about 12 percent of today's existing houses can be expected to be replaced by 1970 *(table 5)*. Therefore, the housing replacement demand is estimated to be 15,800 housing units between 1965 and 1970.

Markets for Hawaii Hardwood Lumber in New Single-Family Houses on Oahu, Hawaii

John D. Zinnikas

R. Sidney Boone

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Continued development of Hawaii's timber products industry depends upon identifying markets for those species of wood that are and can be grown in the State. Residential construction provides the major market in Hawaii for both softwood and hardwood lumber, plywood, and other wood products. If Hawaii-grown hardwood timber can penetrate this important market, continued expansion and development of the local industry should follow. An important prerequisite is to have information about the potential size of the market.

This paper reports on a study of the potential market for hardwood lumber and wood products which might be produced in Hawaii for use as residential flooring, house siding, and millwork and cabinets on Oahu. It provides estimates of the total potential volume of lumber and wood products which could have been used in flooring, siding, and interior millwork and cabinets for 1962 and 1963. The total potential volume is projected for lumber and wood products in each of these uses. And some characteristics of Hawaii hardwoods and their ability to replace presently used species are discussed.

Single-Family Housing Construction

The State of Hawaii is characterized by a heavy concentration of people and economic activity on the Island of Oahu. According to the Bank of Hawaii, "with less than one-tenth of the land area of the State, Oahu contains over four-fifths of its population and represents nearly nine-tenths of retail sales, construction, and personal income."[2] Therefore, an investigation of the residential construction market on Oahu would cover a major portion of the total demand for housing and lumber in the State *(table 1)*.

Single-family building permit records for calendar years 1962 and 1963 were obtained from the City and County of Honolulu. From this information the number of permits issued classified by house square footage and the total square feet of living area were determined *(table 3, Appendix B)*.

Table 1.--*Single-family dwelling construction, 1960-1964, determined by building permit*

Year	State	Oahu	On Oahu
			Percent
1960	4,867	4,189	86.1
1961	4,113	3,412	82.9
1962	4,448	3,654	82.1
1963	4,321	3,352	77.6
1964	4,551	3,671	80.7

Source: Redevelopment and Housing Research, Honolulu Redevelopment Agency, July 1965, p. 6.

Also examined were plans and blueprints of houses insured by the U.S. Federal Housing Administration in 1962–63. From these plans we obtained detailed data on the amount of wood used in flooring, siding, and cabinet and millwork in various sizes and designs of houses.

Using these two sources of data, estimates were made of the total possible market for flooring,

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[1] For the purposes of this paper, the terms "City and County of Honolulu" and "Island of Oahu" are used interchangeably.

[2] Department of Business Research, Bank of Hawaii. Annual Economic Report. p. 9. 1964.

siding, and cabinet and millwork for 1962 and 1963 *(tables 4 to 7, Appendix B)*. Also estimated was the total possible market for lumber in single-family house construction for these uses for the period 1965–70.

In 1962, builders put up 3,422 single-famil units on Oahu, representing almost 3.8 millio square feet of living area. In 1963, there were 3 164 units built consisting of 3.5 million squa feet *(table 3, Appendix B)*.[3]

Flooring Market

An estimate of the total potential market for hardwood flooring on Oahu can be derived by reducing the total square feet of living area by the estimated area of bathrooms and kitchens. After adjusting for kitchens and baths, the total potential market on Oahu for wood flooring is about 3 million square feet *(table 4, Appendix B)*. When a 25-percent allowance is made for scraps and tongue and groove overlap, this market probably represents a potential of about 3.75 million board feet of hardwood lumber.

It should be recognized that this estimate is of the total possible market. The use today of many substitutes for wood flooring indicates that the market share for wood is less than the total possible flooring market.

Federal Housing Administration data indicate that about 85 percent of the homes built on Oahu in the past 3 to 5 years have used a concrete slab-type foundation.[4] The principal floor covering in these homes has been asphalt or vinyl tile. Wood flooring can be installed on concrete slab foundations—a common practice in some parts of the mainland—but this is not now being done in Hawaii. A primary reason probably is the in-place price differential. With present construction practices and the high cost of imported hardwood wood is more expensive than tile. In additio there has been some concern over termite damag

It is estimated that 95 percent of the homes bui in Hilo (County of Hawaii) have crawl spac foundation and wood flooring. There were 41 building permits issued in 1963 by the County c Hawaii for single-family dwellings, and 428 i 1964. Using the median calculated living area fc FHA houses in Hawaii (1,041 square feet), th number of dwelling units represents about 435 000 square feet of living area in 1963 and 445,50 square feet in 1964.

These estimates indicate that more new house are built with wood floors in Hilo than in th City and County of Honolulu. In Honolulu, mo houses with wood floors are the larger custon built houses rather than tract homes.

The difference in type of construction seems a tributable to two factors: (a) it has been the cu tom, in Hilo, to build crawl space foundations u to heights of 7 or 8 feet, and (b) most homes thei are built as individual units rather than as tra homes, whereas most homes on Oahu are tra developments.

House Siding Market

An even larger and perhaps more attainable outlet for Hawaii hardwoods is the house siding market. The most common type of house in Hawaii is of single wall construction, with wood siding providing both inner and outer wall area. The material generally used for this vertically orient siding is clear, all-heart redwood in 1- by 8-inc tongue and groove boards.[5]

In 1964 the FHA reported 85.7 percent of tl new single family dwellings in Hawaii had woc siding.[6] The estimated siding market amounted

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[3] Discrepancies in data between table 1 and table 3 (Appendix B) are due to differences in collection procedures.

[4] Data for states and selected areas—1964. Federal Housing Administration, Division of Research and Statistics. Washington, D.C. 1964.

[5] Sharp, William. *Comparison of residential constr tion costs in Hawaii and on the mainland.* College Business Administration, University of Hawaii. p. May 1963.

[6] Federal Housing Administration, *op. cit.*

4.8 million square feet in 1962, and 4.4 million square feet in 1963 *(table 5, Appendix B)*. Allowing 25 percent increase for tongue and groove, and overlap and scrap, the present house siding market represents nearly 6 million board feet of lumber annually.

On the basis of individual units, it is estimated that a 1,000-square-foot house requires 1,688 board feet of siding, a 1,500-square-foot house requires 2,216 board feet, and a 2,000-square-foot house uses 2,722 board feet of siding.

Two other housing studies provide estimates that add some perspective to the ones already cited. The Stanford Research Institute[7] estimated that about 3,000 board feet of siding was required for a 1,000 square foot house in Hawaii in 1963. In a study of lumber requirements for housing in California, Vaux used sampling and regression techniques for estimating wood siding required for frame dwellings.[8] He estimated that siding for a house in the 1,000 to 1,099 class required 958 board feet; in the 1,500 to 1,599 class house, 1,270 board feet of siding; and in the 2,000 to 2,099 class house, 1,581 board feet.[9]

Vaux does not report whether he allowed for a wastage factor in his calculations. If not, this would tend to understate his estimate. The estimates made in this study fall between those of Vaux and of the Stanford Research Institute and include a wastage estimate.

Interior partitions in the single-wall houses are usually of the same material as the siding, i.e., 1- by 8-inch tongue and groove redwood. In the FHA blueprints examined, each house averaged 94 lineal feet of partition, ranging from 75 to 120 lineal feet. While partitions are not included in the estimates on siding, they must be considered as a potential use of siding material.

Kitchen Cabinet Market

Kitchen cabinets require large amounts of lumber and appear to be a reasonable outlet for Hawaii hardwood lumber. The total potential market is estimated to be between 1 and 1¼ million board feet annually, about two-thirds in base cabinets and one-third in wall cabinets *(table 6, Appendix B)*. Since no adjustment was made for wastage, these estimates are understated. Several U.S. mainland cabinet makers have estimated that a 15- to 25-percent allowance should be made for wastage.

The estimates were made with the assumption that the entire cabinet—sides, drawers, doors, framing, etc.—was made of lumber. This is an unrealistic assumption because an important market for plywood and particle board is in counter tops, shelves, drawers, and door fronts. To this extent these estimates are overstated.

Projection of Lumber Demand to 1970

Between 1965 and 1970, an estimated 20,000 to 26,000 new houses are expected to be constructed in Hawaii.[10] Using this forecast, it is possible to estimate the potential market for lumber in flooring, siding, and cabinets *(table 2, Appendix B)*.

The estimate is based on the assumption that the proportion of houses in each size class in 1963 will not change. Table 2 does not adjust for overlap in tongue and groove flooring and siding, nor for wastage. The adjustment factors, e.g., 889,000 square feet per house, were developed from *tables 4–6 (Appendix B)*. For example, the 2.8 million square feet of flooring developed in table 4 was divided by the number of new house permits issued in 1963 to obtain the average square feet of floor area per house. *Tables 3–6 (Appendix B)* are presented in such a manner that the reader can develop his own forecast under chosen assumptions concerning the size distribution of houses and the amount of wood estimated in construction.

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[7] Cited in Sharp, *op. cit.* p. 37.

[8] Vaux, Henry J. *An economic-statistical analysis of lumber requirements for California housing.* Hilgardia. p. 484. March 1950.

[9] The mid-point of each class was used as the permit area in Vaux's equation: MBF of wood siding/structure $= 0.304 + 0.623$ (M sq. ft. total permit area): $R = 0.810$; $SYXK = 0.241$ (standard error of the estimate): $GB = 0.0921$ (standard error of regression coefficient).

[10] Zinnikas, John D., and Boone, R. Sidney. *Requirements for new housing in Hawaii, 1965–1970 . . . a forecast.* U.S. Forest Serv. Res. Paper PSW-40. Pacific SW. Forest & Range Exp. Sta., Berkeley, Calif. 6 pp., illus. 1967.

Market for Hawaii Hardwoods

Frazier has made long-range predictions of hardwood and softwood lumber demand in Hawaii's economy. He forecast that, by the year 2000, hardwood consumption will have increased 2½ times over that in 1965. The estimates were based on the assumption that present consumer tastes and preferences would undergo no radical change. In assessing the growth in consumption, Frazier concludes that

> At the present time Hawaii's forest products industry provides about one-sixth of the hardwood lumber requirements of the State. If the industry only maintains its present share of the market, it will necessitate a growth of over 2½ times its present size of about one million board feet per year. There is no reason to assume that the industry could not undergo even greater growth and develop into a major supplier of Hawaii's hardwood lumber needs.[11]

Entry into the potential markets described in this paper indicates that it is possible to go beyond Frazier's estimates by a large margin. This paper is concerned with estimates of the potential markets for certain lumber products used in new home construction. These products are flooring, siding, cabinets; all three represent potential markets for Hawaii produced hardwoods at the present time.

In assessing the extent to which the lumber industry in Hawaii can share in these markets, an analysis of the species composition of existing hardwoods must be made. The acceptability of locally grown timber depends upon the characteristics inherent in the wood related to its use, the availability of a continuing supply to satisfy consumer demands, and the production costs of Hawaii lumber compared to imports F.O.B. Hawaii.

The siding market appears to offer the best potential outlet for Hawaii hardwoods. Since most houses have a siding exterior and the demand for new houses is expected to be a continuing one, a large and relatively stable demand exists for wood siding. For Hawaii-grown woods to penetrate this market, they will have to compete successfully in both price and quality with imported species. One locally grown species—robusta eucalyptus *(Eucalyptus robusta)*—has many of the characteristics necessary to compete in the siding market. It is heavier and stronger than redwood *(Sequoia sempervirens)* and compares favorably in durability and appearance. There also are enough stands of maturing robusta eucalyptus to satisfy an expected continuing demand. Locally grown woods have one advantage in that the shipping cost is much less than for imports from the mainland. If Hawaii hardwoods can compete in price, then they should be able to capture a portion of the siding market.

As a beginning step, an analysis was made of the species composition or mix in the Hawaii hardwood lumber market *(table 8, Appendix B)*. The results suggest that wood utilization is broadening among many different species, implying the acceptance of new and different hardwood varieties in the market. Noteworthy is the important change in the "other" category. This classification includes such imported species as teak, Japanese ash, and maple. It also includes the more common mainland hardwoods, such as ash, alder, and walnut. This trend is significant, since a continuing broadening of species lines would indicate a favorable outlet for some of Hawaii's introduced hardwood species.

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[11] Frazier, George D. *The estimated demand for lumber and plywood in Hawaii by the year 2000.* U.S. Forest Serv. Res. Paper PSW–23. Pacific SW. Forest & Range Exp. Sta., Berkeley, Calif. p. 8. 1965.

Appendix

A. Calculation of number of board feet of lumber per linear foot of kitchen cabinet

Minimum requirements of the Federal Housing Administration for single family houses in Hawaii specify that shelving must be 11 to 12 inches deep, base cabinets 22 to 24 inches deep *(fig. 1)*. The linear feet of cabinets, shelving, and drawer space varies by the number of bedrooms in the house. In the typical kitchen that meets FHA minimum standards there are 9½ linear feet of wall cabinets and 10 linear feet of base cabinets. From this diagram in *fig. 1*, the number of surface feet can be calculated. Under the assumption that lumber of 1-inch thickness is used, the calculated surface feet is equivalent to board feet.

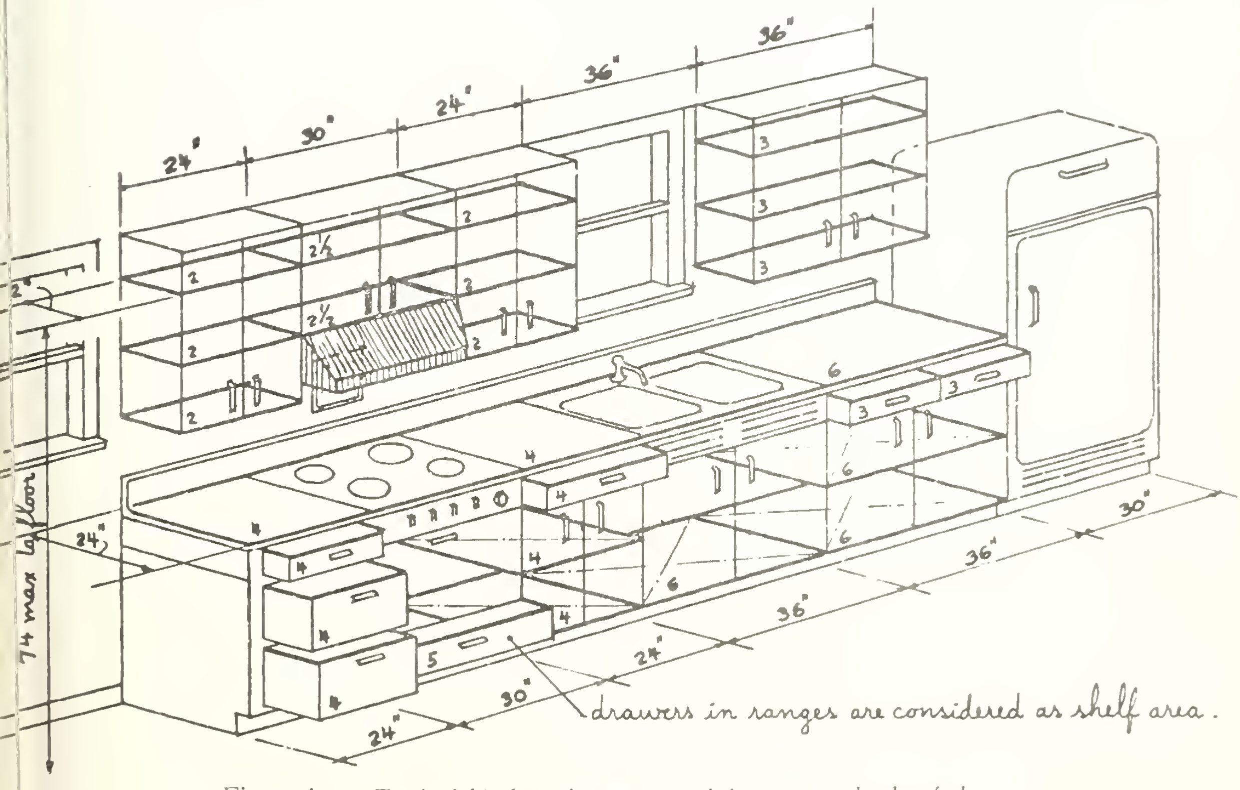
Calculations:

Wall cabinets
(1) shelving
2 × 6 = 12
2.5 × 2 = 5
3 × 3 = 9
——
26 sq. ft.
(2) sides of cabinets
3.5 × 6 = 21 sq. ft.
(3) doors
7 × 2 = 14
10.5 × 1 = 10.5
5 × 1 = 5
——
29.5 sq. ft.
Total = 76.5 sq. ft.

Base cabinets
(1) shelving
4 × 2 = 8
5 × 1 = 5
6 × 3 = 18
——
31 sq. ft.
(2) counter top
4 × 2 = 8
6 × 1 = 6
——
14 sq. ft.

(3) drawers
3 × 2 = 6
4 × 4 = 16
——
22 sq. ft.
(4) sides of drawers
6 × 2 = 12
1 × 6 = 6
——
18 sq. ft.

(5) backs of drawers
6 × 1 = 6
1.5 × 1 = 1.5
1.25 × 1 = 1.25
——
8.75 sq. ft.
(6) front area
6 × 2 = 12
1.25 × 1 = 1.25
9 × 2 = 18
——
31.25 sq. ft.
(7) sides of cabinets
6 × 5 = 30 sq. ft.
Total = 156 sq. ft.



drawers in ranges are considered as shelf area.

Figure 1. — *Typical kitchen that meets minimum standards of the Federal Housing Administration for one and two living units.*

B. Tables

Table 2.--*Estimated total possible market for lumber in single family house construction, 1965-70*

Estimated number of houses	Wood flooring[1]	Siding[2]	Cabinets[3]
	M sq. ft.		*M bd. ft.*
Lower prediction:			
20,000	17,780	27,920	7,320
Upper prediction:			
26,000	23,114	36,296	9,516

[1] 889 square feet per house.

[2] 1,396 square feet per house.

[3] 366 board feet per house.

Table 3.--*Permits issued for single-family houses, by house area, in city and county of Honolulu, 1962 and 1963*

Area of house (sq. ft.)	1962		1963	
	Permits[1]	Total Living area[2]	Permits[1]	Total Living area[2]
	No.	*Sq. ft.*	*No.*	*Sq. ft.*
500- 599	80	46,248	156	87,885
600- 699	229	148,761	290	187,707
700- 799	284	212,814	275	208,809
800- 899	389	333,408	256	217,229
900- 999	620	586,140	351	331,151
1,000-1,099	399	417,209	309	324,986
1,100-1,199	331	379,963	407	462,539
1,200-1,299	288	362,060	336	422,196
1,300-1,399	193	260,407	184	247,961
1,400-1,499	218	317,815	201	292,740
1,500-1,599	103	159,332	91	140,499
1,600-1,699	78	128,315	75	123,649
1,700-1,799	52	90,610	67	117,044
1,800-1,899	38	70,321	43	79,383
1,900-1.999	29	56,390	30	58,326
2,000-2,099	33	67,811	22	45,144
2,100-2,199	14	30,091	20	42,743
2,200-2,299	11	24,660	9	20,073
2,300-2,399	5	11,712	11	25,811
2,400-2,499	2	4,956	5	12,267
2,500 or more	26	79,979	26	81,363
Total	3,422	3,789,002	3,164	3,529,505

[1] In 1962, 71 permits were issued for houses less than 500 square feet. The total area covered by these permits, amounting to 20,196 square feet, was not included in the classification. In 1963, 84 similar permits totaling 31,005 square feet were also not included.

[2] The city and county building permit area has been adjusted to reflect 'inside' living area of each house. Since the city and county data included the area of carports and lanais, these items were eliminated to show actual living area of the house.

Table 4.--*Estimate of total possible market for wood flooring in new single-family houses, in city and county of Honolulu, 1962 and 1963*

Area of house (sq. ft.)	1962			1963		
	Total area of housing	Adjustment for kitchen and bath[1]	Total area available for wood flooring	Total area of housing	Adjustment for kitchen and bath[1]	Total area available for wood flooring
	Sq. ft.					
500- 599	46,248	14,000	32,248	87,885	27,300	60,585
600- 699	148,761	14,220	107,541	187,707	52,200	135,507
700- 799	212,814	52,540	190,274	208,809	50,875	157,934
800- 899	333,408	71,965	261,443	217,229	47,360	169,869
900- 999	586,140	117,800	468,340	331,151	66,690	264,461
1,000-1,099	417,209	79,800	337,409	324,986	61,800	263,186
1,100-1,199	379,963	76,130	303,833	462,539	93,610	368,929
1,200-1,299	362,060	73,440	288,620	422,196	85,680	336,516
1,300-1,399	260,407	53,075	207,332	247,961	50,600	197,361
1,400-1,499	317,815	65,400	252,415	292,740	60,300	232,440
1,500-1,599	159,332	30,900	128,432	140,499	27,300	113,199
1,600-1,699	128,315	23,400	104,915	123,649	22,500	101,149
1,700-1,799	90,610	15,600	75,010	117,044	20,100	96,944
1,800-1,899	70,321	11,400	58,921	79,383	12,900	66,483
1,900-1,999	56,390	8,700	47,690	58,326	9,000	46,326
2,000-2,099	67,811	9,900	57,911	45,144	6,600	38,544
2,100-2,199	30,091	4,200	25,891	42,743	6,000	36,743
2,200-2,299	24,660	3,300	21,360	20,073	2,700	17,373
2,300-2,399	11,712	1,500	10,212	25,811	3,300	22,511
2,400-2,499	4,956	600	4,356	12,267	1,500	10,767
2,500 or more	79,979	7,800	72,179	81,363	7,800	73,563
Total	3,789,002	--	3,026,332	3,529,505	--	2,813,390

[1] Kitchen and bath adjustment developed by averaging area of kitchens and baths computed from blueprints filed with FHA homes in the above size classifications. Lowest two classes (500 and 600 square feet) are estimates, as are houses larger than 1,700 square feet; these comprised only about 15 percent of the total.

Adjustment was separately computed for each class based on measurements taken from model house blueprints filed with FHA corresponding to that particular class. An average was then computed for each class of house. Total adjustment in square feet for each class is product of number of permits issued in that class and the adjustment factor.

Table 5.--*Estimate of total possible market for wood siding in new single-family houses, city and county of Honolulu, 1962 and 1963*[1]

Area of house (sq. ft.)	1962	1963
	Sq. ft.	
500- 599	71,280	138,996
600- 699	226,710	287,100
700- 799	306,720	297,000
800- 899	455,130	299,520
900- 999	781,200	442,260
1,000-1,099	538,650	417,150
1,100-1,199	476,640	586,080
1,200-1,299	440,640	514,080
1,300-1,399	310,923	296,424
1,400-1,499	368,856	340,092
1,500-1,599	182,619	161,343
1,600-1,699	144,612	139,050
1,700-1,799	100,620	129,645
1,800-1,899	76,950	87,075
1,900-1,999	61,074	63,180
2,000-2,099	71,874	47,916
2,100-2,199	31,626	45,180
2,200-2,299	25,740	21,060
2,300-2,399	12,105	26,631
2,400-2,499	5,004	12,510
2,500 or more	66,924	66,924
Total	4,755,897	4,419,216

[1] Computed as product of number of houses constructed in a class times an average computed perimeter for a house in that class times an average height of 9 feet for all houses. Where FHA plans were available (85 percent of the time), perimeters were scaled from plans, giving consideration to glass door walls and windows (carports, garages, and lanais not included). For classes where FHA plans were unavailable, an estimate was made of the perimeter available for siding; estimated perimeter computed as average of a minimum perimeter = four times the square root of class midpoint and a maximum perimeter. Maximum perimeter = 2(L + W) where a minimum width of 15 feet is assumed and area is given as midpoint of class (thus L = area/15).

Table 6.--*Estimate of total possible market for kitchen wood cabinet, in new single-family houses, in city and county of Honolulu, 1962*

Area of house (sq. ft.)	Base cabinets		Wall cabinets		Total market
	Linear feet[1]	*Board feet*[2]	*Linear feet*[1]	*Board feet*[2]	*Board feet*[2]
500- 599	1,040	16,120	800	7,128	23,352
600- 699	2,977	46,144	2,519	20,404	66,845
700- 799	3,692	57,226	3,124	25,304	82,899
800- 899	5,057	78,384	4,279	34,660	113,549
900- 999	8,060	124,930	9,920	80,351	206,090
1,000-1,099	6,384	98,952	6,384	51,710	151,300
1,100-1,199	5,958	92,349	5,627	45,579	138,524
1,200-1,299	5,184	80,352	4,896	39,658	120,528
1,300-1,399	3,474	53,847	3,281	26,576	80,770
1,400-1,499	3,924	60,822	3,706	30,019	91,233
1,500-1,599	1,854	28,737	1,751	14,183	43,105
1,600-1,699	1,404	21,762	1,326	10,741	32,643
1,700-1,799	936	14,508	884	7,160	21,762
1,800-1,899	684	10,602	646	5,233	15,903
1,900-1,999	522	8,091	493	3,993	12,136
2,000-2,099	594	9,207	561	4,544	13,810
2,100-2,199	252	3,906	238	1,928	5,859
2,200-2,299	198	3,069	187	1,515	4,604
2,300-2,399	90	1,395	85	689	2,093
2,400-2,499	36	558	34	275	837
2,500 or more	468	7,254	442	3,580	10,881
Total	52,788	818,215	51,263	415,230	1,238,723

[1] Obtained by multiplying number of permits issued in each class by average linear feet of kitchen cabinets for houses in that particular size class. Linear feet estimates were obtained from FHA blueprints of houses in size classes up to 1,700 square feet. For houses greater than 1,700 square feet, linear feet of kitchen cabinets is established at a constant 18 feet.

[2] Scaled from a model cabinet meeting FHA standards for houses in Hawaii (see appendix A). For wall cabinets there were 8.1 board feet per linear foot, and for base cabinets 15.5 board feet; no allowance made for wastage. Estimates from individual cabinet makers ranged from 15 to 25 percent of lumber used.

Table 7.--*Estimate of total possible market for kitchen wood cabinet, in new single-family houses, in city and county of Honolulu, 1963*

Area of house (sq. ft.)	Base cabinets		Wall cabinets		Total market
	Linear feet[1]	*Board feet*[2]	*Linear feet*[1]	*Board feet*[2]	*Board feet*[2]
500- 599	2,028	31,434	1,716	13,900	45,537
600- 699	3,770	58,435	3,190	25,839	84,651
700- 799	3,575	55,413	3,025	24,503	80,273
800- 899	3,328	51,584	2,816	22,810	74,727
900- 999	4,563	70,727	5,616	45,490	116,673
1,000-1,099	4,944	76,632	4,944	40,046	117,172
1,100-1,199	7,326	113,553	6,919	56,042	170,326
1,200-1,299	6,048	93,744	5,712	46,267	140,616
1,300-1,399	3,312	51,336	3,128	25,337	77,004
1,400-1,499	3,618	56,079	3,417	27,678	84,119
1,500-1,599	1,638	25,389	1,547	12,531	38,084
1,600-1,699	1,350	20,925	1,275	10,328	31,388
1,700-1,799	1,206	18,693	1,139	9,226	28,040
1,800-1,899	774	11,997	731	5,921	17,995
1,900-1,999	540	8,370	510	4,131	12,555
2,000-2,099	396	6,138	374	3,029	9,207
2,100-2,199	360	5,580	340	2,754	8,370
2,200-2,299	162	2,511	153	1,239	3,766
2,300-2,399	198	3,069	187	1,515	4,604
2,400-2,499	90	1,395	85	689	2,093
2,500 or more	468	7,254	442	3,580	10,881
Total	49,694	770,258	47,266	382,855	1,158,081

[1] Obtained by multiplying number of permits issued in each class by average linear feet of kitchen cabinets for houses in that particular size class. Linear feet estimates were obtained from FHA blueprints of houses in size classes up to 1,700 square feet. For houses greater than 1,700 square feet, linear feet of kitchen cabinets is established at a constant 18 feet.

[2] Scaled from a model cabinet meeting FHA standards for houses in Hawaii (see appendix A). For wall cabinets there were 8.1 board feet per linear foot, and for base cabinets 15.5 board feet; no allowance made for wastage. Estimates from individual cabinet makers ranged from 15 to 25 percent of lumber used.

Table 8.--*Hardwood lumber consumption in the State of Hawaii, 1951-61*[1]*, by species*

Year	Phillipine mahogany	Oaks	Koa	Other
	Percent			
1951	76	3	20	1
1952	77	5	17	1
1953	81	4	14	1
1954	81	7	11	1
1955	73	16	9	2
1956	57	30	9	4
1957	53	34	10	3
1958	55	29	11	5
1959	56	21	13	10
1960	54	15	16	15
1961	45	13	19	23

[1] Lucas, Ernesto dela Cruz. *Evaluation of market data as a guide for forest development in Hawaii.* 1963. (Unpublished master's thesis on file, Graduate School, Univ. of Hawaii, Honolulu, Hawaii.)

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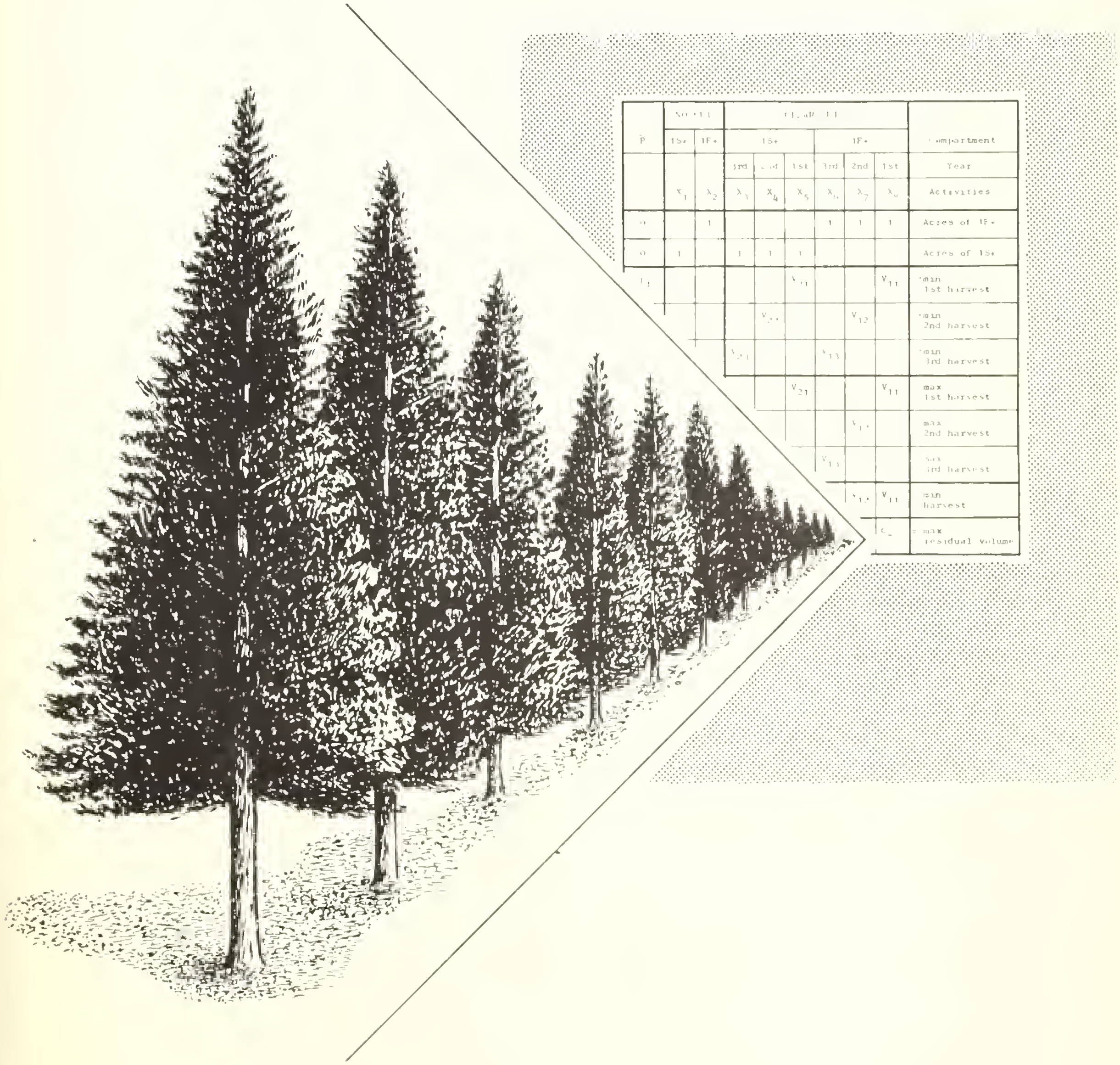
Evaluating Forest Management Policies by Parametric Linear Programing

Daniel I. Navon Richard J. McConnen



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Contents

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A traditional responsibility of management is to evaluate and implement policies. Accounting and mathematical techniques have long been used by managers to perform this task. The development of operations research and electronic computers has ushered in new techniques that make the intensive evaluation of large numbers of alternative policies practical. One of the most powerful of these new techniques is parametric linear programing.

Operations research generally proceeds from analytical or simulation approach. Analytical models are designed to yield an optimal or best solution to a given management situation. Simulation models are simplified versions of management systems which can be "operated" usually with the help of a computer. These models determine the impact of continuously varying conditions on selected components of the system. A simulation model does not yield a solution in the conventional sense, but generates a list of solutions corresponding to different conditions of the system.

Parametric linear programing borrows from both of these approaches. It explores a wide spectrum of alternative conditions, and also devises an optimal management plan for each condition. Thus parametric linear programing qualifies both as an analytical and as a simulation technique.

Several characteristics of parametric linear programing recommend it to managers:

- It is simple to use—requiring only that the users have a grasp of elementary algebra.
- It uses available computer programs.
- It provides information with the rapidity and accuracy typical of computer techniques.
- It generates information which can assist the manager in locating the elements having the greatest impact on the system.

The technique offers additional enticements to natural resource managers, who must often reevaluate policies after unexpected major changes in resources.[1] Computers make it possible to develop quickly new management plans based upon the changed resource inventory. And the revision of the inventory itself can be computerized with the use of existing systems, such as the Map Information Assembly and Display System now in use by land resource managers in the United States and Canada.[2] Management plans, for example, can be revised almost immediately after a fire or storm. Parametric linear programing can then indicate if the previously established goals can still be realized, and then assist the manager in making the necessary adjustments.

This paper describes the parametric linear programing technique, suggests some of its applications to forest management problems, and illustrates its use on a tract of commercial forest land. The primary emphasis has been placed on problems of managing forest land for timber production, but the use of parametric linear programing can be extended to a wide variety of wildland management problems, including the difficult problem of multiple-use management.

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[1] Navon, D. I. **Computer-oriented systems for wildland management.** J. Forestry 65(7):473-479. 1967.

[2] Amidon, Elliot L. **A computer-oriented system for assembling and displaying land management information.** U.S. Forest Serv. Res. Paper PSW-17. Pacific SW. Forest & Range Exp. Sta., Berkeley, Calif. 34 pp., illus. 1964.

Amidon, Elliot L. **MIADS2—An alphanumeric map information assembly and display system for a large computer.** U.S. Forest Serv. Res. Paper PSW-38. Pacific SW. Forest & Range Exp. Sta., Berkeley, Calif. 12 pp., illus. 1966.

[3] Broido, A., O'Regan, W. G., and McConnen, R. J. **Some operations research applications in the conservation of wildland resources.** Manage. Sci. Ser. A 11(9): 802-814, illus. 1965.

McConnen, R. J., Amidon, E. L., and Navon, D. I. **The use of operations research techniques in determining allowable cut.** Proc. Ann. Mtg. Soc. Amer. Foresters 1966, 109-115, illus. 1967.

Linear Programing

Linear programing is an efficient method of selecting the optimum feasible combination of management practices. A combination is feasible if it can be carried out with available resources and does not violate specified policies or goals. These available resources and specified goals are generally referred to as constraints. In forest management, a feasible combination of management practices is optimum if it maximizes profits or some other measure of performance, or in the case of public lands, if it minimizes budgetary expenditures required to achieve a set of specified goals. In many problems, all the goals cannot be incorporated into a single objective function, and some of the goals must be introduced in the program by stating them as constraints.

Problems of resource allocation in which the quantity of the factors of production is given and the policies guiding management have already been determined are often solved by linear programing. The management policies are incorporated in the linear program by setting up a list of constraints, and defining an economic objective and a set of plausible management activities. For example, management policies for a tract of forest land could be formulated as follows: "Maximize the stumpage volume remaining at the end of 10 years subject to constraints on acreage and annual mill deliveries, by carrying out clear- and partial-cutting management activities."

The solution to the linear program accomplishe two aims. First, it specifies the level at which th activities must be operated to maximize—or minimize—the value of the economic objective. In th foregoing example, these activity levels would b the number of acres to be clearcut or partially cu for each of the 10 years.

Second, the solution generates a shadow pric for each constraint. The shadow price of a give constraint can be interpreted as the margina change in the economic objective caused by unit change in the level of this constraint. Th shadow price of the constraint specifying the leve of the first-year mill delivery indicates the decreas in the volume of the residual stumpage whic would result from a unit increase in this constrain level. This change is referred to as marginal because it is known to be correct only for smal changes in the neighborhood of the original constraint level. Therefore only small changes in constraint levels can be evaluated with assurance b these shadow prices. For example, shadow price could not be used to assess the impact of a 10-per cent increase in the first year mill delivery constraint on the volume of the residual stumpage The obvious solution is to solve the linear program again after adjusting the constraint to th contemplated level. But this procedure rapidl becomes burdensome as the number of contemplated levels increases, unless a special algorithr such as parametric programing is used.

Parametric Linear Programing

Parametric linear programing computes a series of solutions which determine the relationship between the economic objective and any one of the constraints over the entire range of levels which these constraints can assume in the program.

Let us assume that the minimum acceptable delivery at the mill is 10 MMBF per year. The linear program is then solved initially with the annual delivery constraint at the level of 10 MMBF: the initial linear program solution would indicate the maximum residual stumpage corresponding to this delivery schedule. Parametric linear programing could then be used to assess the impact of increasing the level of the "annual delivery constraint" on the volume of the residual stumpage.

For example, consider the results of four hype thetical parametric solutions *(fig. 1)*. As annua deliveries increase, the liquidation volume decreases until it reaches zero. The mathematica structure of parametric linear programing is suc that the relation between the liquidation volum and annual deliveries is known to be linear between any two adjacent parametric solution Hence, by joining the solution points with straig line segments, the maximum liquidation volume co responding to an annual delivery level falling between solutions can be read directly from th graph *(fig. 1)*. The relation between the economi objective "maximize the liquidation volume" an the constraint on annual mill delivery has been e tablished over the entire range of levels the constraint can assume in the program. If management prescriptions are required for an annual mill delivery level falling between parametric solutions, the program must be solved independently of the parametric linear program. In most cases the parametric linear program will provide enough solutions to afford a sound basis for management decisions, without requiring additional computations.

Once the parametric linear program has been solved, the policy decision consists of selecting the constraint levels and the corresponding value of the economic objective. This decision may be based on a purely quantitative criterion, but the complexity of most operational situations will require the use of some intuitive judgment.

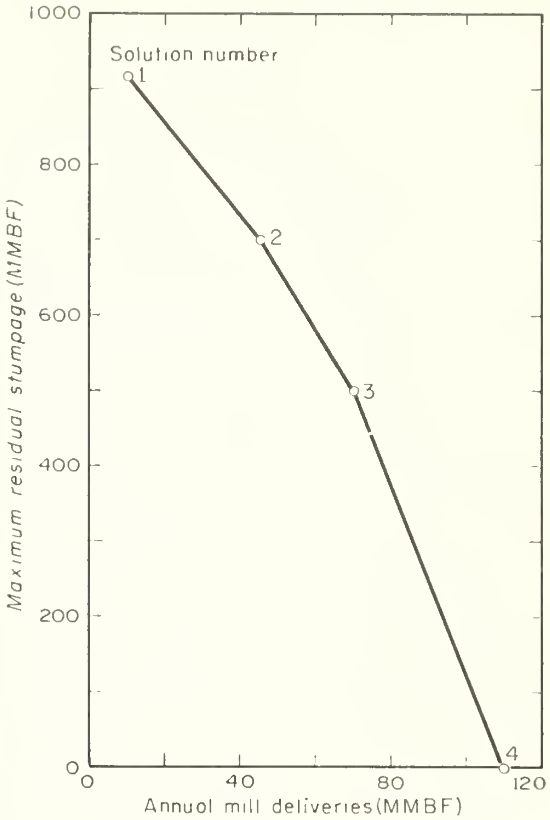

Figure 1—*Parametric relation between volume of annual mill deliveries and maximum residual stumpage.*

A Study in Commercial Forestry

In the following study, parametric linear programing is used to explore increasingly complex policy alternatives in the management of a tract of commercial forest land. The forest manager needs to select a schedule of annual mill deliveries that will leave vigorous and well-stocked stands at the end of 10 years. The greater the annual deliveries, the lower will be the maximum "liquidation" value of the remaining standing timber. The manager must then use his judgment to select the combination of mill delivery schedule and liquidation value which meets the management goals not incorporated explicitly into the program.

Consider a tract of commercial forest covering 1,804 acres. This tract is classified into 17 evenaged stand classes. The timber of each stand class s assumed to be homogeneous with respect to all elevant economic and silvicultural characteristics. Eight of the 17 classes are stocked predominantly with sugar and ponderosa pine; nine with white r, Douglas-fir, and cedar. The 17 stand classes are grouped into the following four "timber management" categories:

I. Poorly stocked old-growth.
II. Poorly stocked mature-growth.
III. Well stocked old-growth.
IV. Well stocked mature- and young-growth.

One or more management practices can be applied to each category *(table 1)*. Note that for category

Table 1.--*Management practices allowed*

Category	Clear cut	Partial cut	No cut
I. Poorly stocked old-growth	X	--	--
II. Poorly stocked mature-growth	X	--	X
III. Well stocked old-growth	X	X	X
IV. Well stocked mature- and young-growth	--	X	X

I only clearcutting is allowed; hence these stands must be completely clearcut by the end of the 10-year period. Note also that clearcutting is not permitted for Category IV. The broad intent of these prescriptions is to insure that the commercial forest remaining at the end of the 10 years is reasonably vigorous and well stocked. Only a short management period is considered in this illustration. However, the general long-term policy of the company is reflected by the set of management practices allowed by table 1. If, for example, the general long-term policy had been one of "cut out and get out," clearcutting activities would have been permitted in all four timber management categories.

The manager has a broad range of policy alternatives. Clearcutting only the poorly stocked very old stands will produce the desired vigorous forest and result in the highest liquidation value realizable. The annual harvest will necessarily be small. Clearcutting and partial cutting all the timber allowed will still produce the desired type of forest but at the cost of a much lower liquidation value compensated by relatively high annual yields. The range between these extremes is explored systematically by a series of parametric linear programs reflecting increasingly complex policy alternatives.

The first step in developing a policy is to determine the range of available alternatives. In the context of a parametric linear program, this procedure requires the determination of the range of values which the constraints can be made to assume.

In the following illustrations, two groups of constraints are defined:

1. Constraints expressing the number of acres in each stand. In the short run, no change in acreage is contemplated, hence, these resource constraints are treated as fixed.

2. Mill delivery constraints specifying the value —or volume— of timber to be delivered annually over the 10-year management period. It is the range of values which can be assumed by these constraints that is explored by the parametric program.

Simple Policy Alternatives

Let us assume that all annual harvests must be equal. The level of the total harvest will then determine the annual mill delivery schedule.

The management problem can now be defined as a standard linear program, and a related parametric program. The linear program is:

Maximize the liquidation value of the forest at the end of a 10-year period subject to the following constraints.

1. Realize a total harvest of a given level—all annual harvest being equal;

2. Operate within a broadly specified forest improvement policy, i.e., clearcut poorly stocked, old-growth, etc.; and

3. Do not exceed the available resources.

And the related parametric program states:

1. Increase continuously the total harvest up to the highest possible level, i.e., until all allowable timber is cut, and

2. Compute the solutions required to define precisely the relation between the total harvest level and the liquidation value of the forest.

To solve the linear program, the initial acreage and the following rates per acre must be available for each stand:

- (A) Yield from clear and partial cutting;
- (B) Annual growth;
- (C) Annual growth after partial cutting; and
- (D) Annual salvage value.

These rates—originally expressed in thousands of board feet (MBF) — were converted to dollar value on the basis of current 1965 stumpage prices of each species and grade. Stumpage prices are likely to change substantially during a 10-year period, but it was assumed that the value relative to grade and species would remain fairly constant.[1] Thus only the absolute amount of the liquidation value would be affected; the management plan itself would remain unchanged.

Fifty-seven parametric solutions were computed, corresponding to total harvest levels ranging from $0.85 million to $5.48 million.

A good approximation to the relation between liquidation value and minimum total harvest was obtained by plotting only 5 of the 57 solutions *(fig. 2)*. The relation was nearly linear over the range of total harvests likely to be selected—$0.85 million to $5.5 million. An increase in total harvest reduced the liquidation value by almost the same amount. The nature of this relationship emerged more precisely when the aggregate timber value—the sum of total harvest and liquidation value—was plotted against the total harvest level *(fig. 3)*. Aggregate timber value was highest when the total harvest level was set at $1.44 million.

A perceptive analyst might have deduced tha the maximum aggregate value would not b

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[1] The data used are available on request to the Director, Pacific Southwest Forest and Range Experiment Station, P. O. Box 245, Berkeley, California 94701.

Solution summary for figures 2 and 3

Solution number	Liquidation value	Aggregate timber value	Total harvest
	Million dollars		
1	8.97	9.82	.85
27*	8.64	10.08	1.44
44	7.03	10.03	3.0
49	4.76	9.84	5.08
57	4.24	9.73	5.49

*See figure 4.

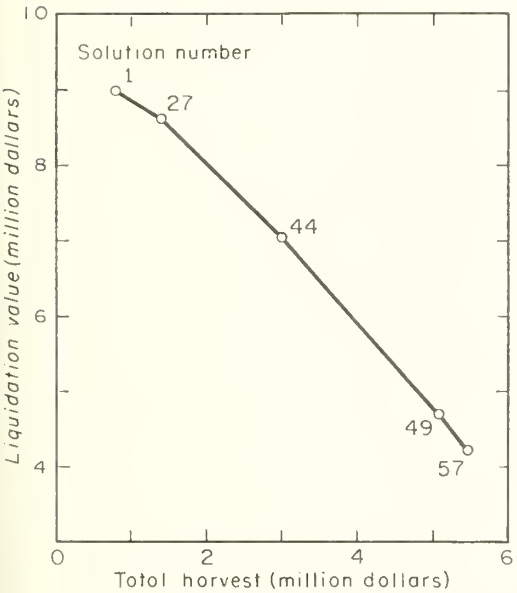

Figure 2—*Parametric relation between liquidation value and total harvest value.*

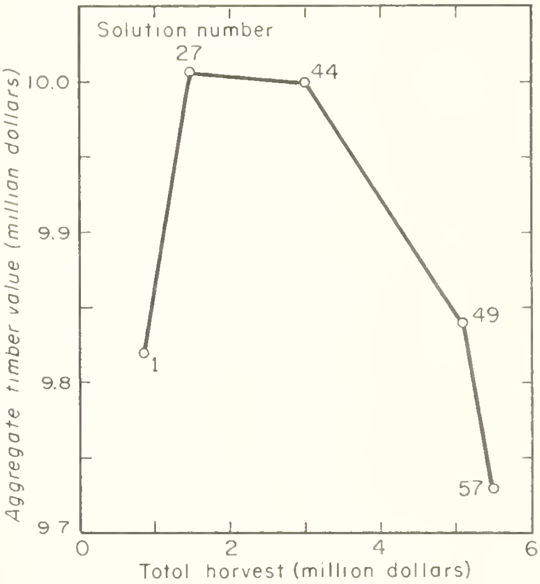

Figure 3—*Parametric relation between aggregate timber value and total harvest value.*

realized at the lowest total harvest level. However, he determination of this optimum without paranetric linear programing would require complex and tedious computations. The actual location of he maximum aggregate value is readily explained y analyzing changes in the cutting activity patern of the parametric solutions. This analysis is ased on inspection of the activity levels precribed by the parametric management plan preared by the program for each of the 57 parametic solutions. As the annual harvest level is inreased, the poorly stocked very old stands cannot neet the demand for timber, and the well stocked oung growth and eventually the well stocked old rowth must be partially cut. This maximum paral cutting pattern yields the maximum aggregate alue. Partial cutting here acts essentially as a mber stand improvement practice. As annual harvest is further increased, clearcutting must be substituted for partial cutting. The loss of annual growth on clearcut acres causes the aggregate value to decline.

Aggregate value can be used as a quantitative criterion to evaluate the policy decision on the level of the total harvest. The decision to harvest a total of $5 million worth (solution 49, *fig. 3*)—rather than $1.44 million (solution 27)—would cost $240,000—the difference in the corresponding aggregate timber values. Lowering total harvest to $3 million (solution 44) would reduce this loss to $50,000. In this particular situation, parametric programing affords the policy maker a simple criterion for evaluating his selection of a minimum acceptable total harvest.

This analysis is based on the assumption that the discount rate is zero. More complex criteria based on nonzero rates of interest are considered below. Even then, the parametric linear program solutions are unlikely to provide a completely adequate basis for decision making. Careful consideration of the assumptions underlying the system and an intuitive assessment of factors not explicitly included in the system must be introduced in the decision process.

Providing Management Prescriptions

Parametric linear programing also provides additional valuable information to the policy maker. Each solution provides a set of detailed management prescriptions required to attain specified annual harvest levels at maximum liquidation value. These prescriptions have been translated by the computer into the management plan illustrated *(fig. 4)*. The management plan corresponding to the optimal combination of liquidation value and total harvest may prove to be impractical because of topographical considerations or because the number of acres cut fluctuates too much from year to year. It is likely that some considerations left out in the initial formulation will subsequently appear crucial. Other considerations may be too complex and subtle to be expressed algebraically. The policy-maker can search among the parametric solutions for a management plan which meets the considerations not included in the program, or he can modify the management plan devised by the parametric program. The modified management plan, at best, will yield the same liquidation value. In most cases, deviations from the parametric plan will result in a reduction of the liquidation value.

The program also computes a shadow price corresponding to each of the constraints of the program. The shadow price of each stand acreage constraint indicates the increase in liquidation value which would result from increasing the area of that stand by one acre. Parametric variation of the annual harvest level will induce changes in the resource shadow prices. The "history" of each shadow price for the range of parametric solutions reflects the changes in the value of each stand over the parametric range. For example, as the annual harvest level is increased the shadow price of well stocked old-growth pine may rise above the market price. The purchase of additional acres of old-growth pine would then be profitable. Shadow prices should be used with caution because they are likely to be accurate only for small changes about the constraint level.

The objective in evaluating the range of alternatives is not to have parametric linear programs make decisions but rather, as Novick states:

> . . . to improve the basis for decision making. One step is improvement in the methods of framing the problems and in organizing the available data. A second and perhaps more important step is more effective analysis of the information needed to produce better plans or recommendations. The product of these efforts will facilitate the reason, judgment, experience, and intuition of the decision maker.[5]

Range of Complex Policy Alternatives

In the preceding case, the annual harvests were assumed to be equal. In many cases, the annual harvest level can be allowed to fluctuate within a specified range. The parametric linear program can easily be modified to reflect this requirement.

In the following illustrations, the annual harvest requirements are expressed as a range of allowable harvests. Each year the amount—or the value—of the timber harvested must not exceed some maximum but must be at least as great as some minimum. The basic structure of the model has not been changed; the delivery schedule for a given year, previously defined by a single constraint, is now defined by an upper bound constraint and a lower bound constraint. To focus the analysis on the parametric manipulation of the bounds, the problem was simplified by reducing the number of resource constraints to seven. This was accomplished by aggregating some of the old stands and excluding the young stands. The problem was further simplified by allowing only clearcut activities.

In the next section, parametric programing is used to explore the impact of changes in total harvest on the liquidation value and on the pattern of annual mill deliveries. Then in the following section parametric variations of the bounds themselves are investigated.

Parametric Variation of Total Harvest with Fixed Bounds

The bounds within which annual harvests were allowed to vary were fixed at $340,000 and $570,000 for all 10 annual harvests. The lowest total harvest consistent with this constraint was therefore 10 times the lower annual bound or $3.4 million. The alternatives available to the policy maker were determined by increasing the minimum

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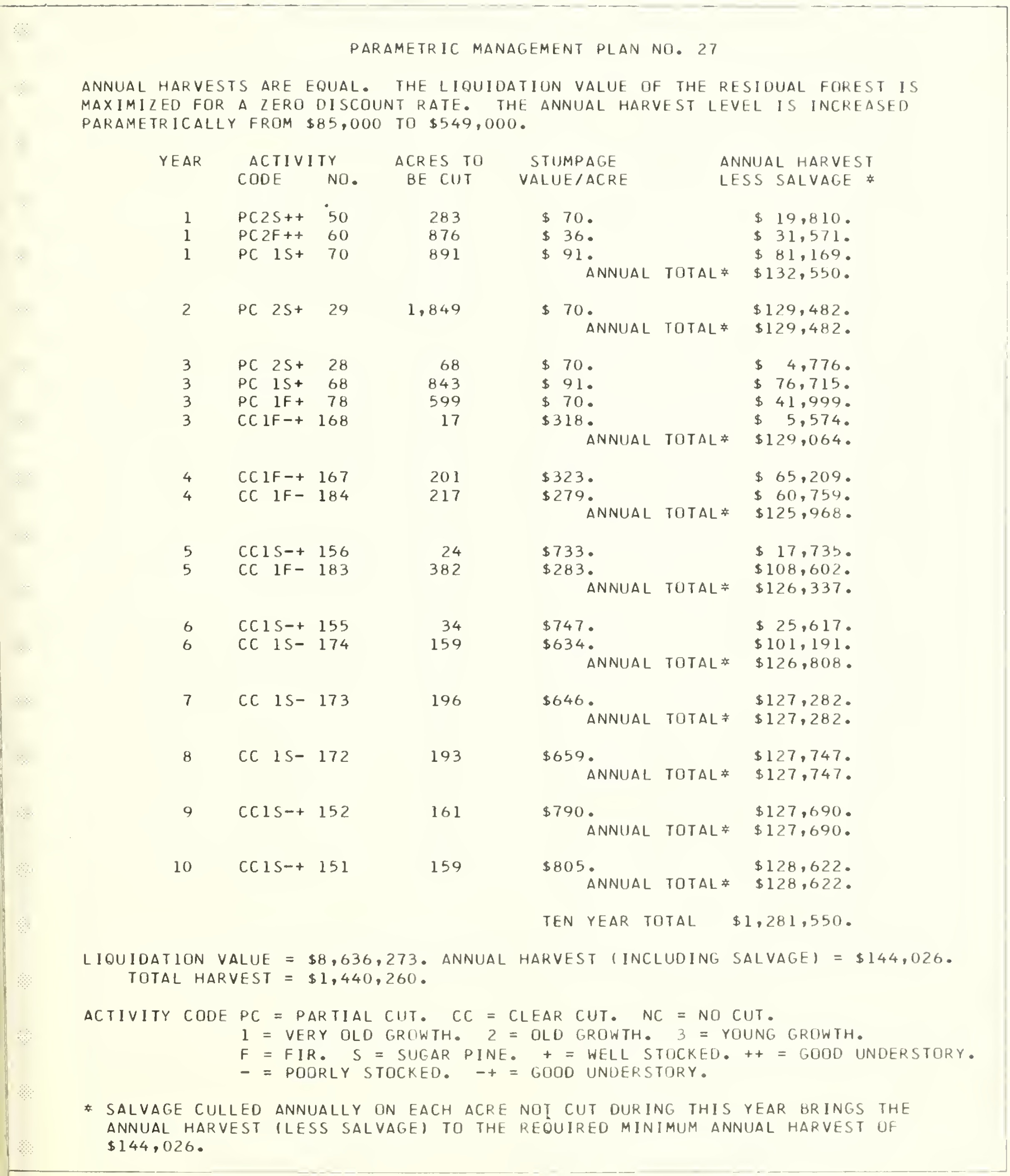
[5] Novick, David, ed. **Program budgeting . . . program analysis and the Federal budget.** U.S. Govt. Printing Office, Washington, D.C., 236 pp. illus. 1965.



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                        PARAMETRIC MANAGEMENT PLAN NO. 27

ANNUAL HARVESTS ARE EQUAL.  THE LIQUIDATION VALUE OF THE RESIDUAL FOREST IS
MAXIMIZED FOR A ZERO DISCOUNT RATE.  THE ANNUAL HARVEST LEVEL IS INCREASED
PARAMETRICALLY FROM $85,000 TO $549,000.

     YEAR     ACTIVITY      ACRES TO    STUMPAGE          ANNUAL HARVEST
             CODE    NO.     BE CUT    VALUE/ACRE         LESS SALVAGE *

       1     PC2S++   50       283        $ 70.                $ 19,810.
       1     PC2F++   60       876        $ 36.                $ 31,571.
       1     PC 1S+   70       891        $ 91.                $ 81,169.
                                             ANNUAL TOTAL*     $132,550.

       2     PC 2S+   29     1,849        $ 70.                $129,482.
                                             ANNUAL TOTAL*     $129,482.

       3     PC 2S+   28        68        $ 70.                $  4,776.
       3     PC 1S+   68       843        $ 91.                $ 76,715.
       3     PC 1F+   78       599        $ 70.                $ 41,999.
       3     CC1F-+  168        17        $318.                $  5,574.
                                             ANNUAL TOTAL*     $129,064.

       4     CC1F-+  167       201        $323.                $ 65,209.
       4     CC 1F-  184       217        $279.                $ 60,759.
                                             ANNUAL TOTAL*     $125,968.

       5     CC1S-+  156        24        $733.                $ 17,735.
       5     CC 1F-  183       382        $283.                $108,602.
                                             ANNUAL TOTAL*     $126,337.

       6     CC1S-+  155        34        $747.                $ 25,617.
       6     CC 1S-  174       159        $634.                $101,191.
                                             ANNUAL TOTAL*     $126,808.

       7     CC 1S-  173       196        $646.                $127,282.
                                             ANNUAL TOTAL*     $127,282.

       8     CC 1S-  172       193        $659.                $127,747.
                                             ANNUAL TOTAL*     $127,747.

       9     CC1S-+  152       161        $790.                $127,690.
                                             ANNUAL TOTAL*     $127,690.

      10     CC1S-+  151       159        $805.                $128,622.
                                             ANNUAL TOTAL*     $128,622.

                                          TEN YEAR TOTAL    $1,281,550.

LIQUIDATION VALUE = $8,636,273. ANNUAL HARVEST (INCLUDING SALVAGE) = $144,026.
    TOTAL HARVEST = $1,440,260.

ACTIVITY CODE PC = PARTIAL CUT.  CC = CLEAR CUT.  NC = NO CUT.
              1 = VERY OLD GROWTH.  2 = OLD GROWTH.  3 = YOUNG GROWTH.
              F = FIR.  S = SUGAR PINE.  + = WELL STOCKED. ++ = GOOD UNDERSTORY.
              - = POORLY STOCKED.  -+ = GOOD UNDERSTORY.

* SALVAGE CULLED ANNUALLY ON EACH ACRE NOT CUT DURING THIS YEAR BRINGS THE
  ANNUAL HARVEST (LESS SALVAGE) TO THE REQUIRED MINIMUM ANNUAL HARVEST OF
  $144,026.
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Figure 4—*Linear programing solution is translated into a management plan in this computer-produced printout.*

tal harvest from $3.4 million until the liquida- on value for these old-growth stands was forced zero at $4.8 million. For each parametric solution the program selected the annual harvest schedule which maximized the liquidation value of the forest.

The liquidation value corresponding to the 15 parametric solutions computed by the program decreased from $1.45 million to zero at the maximum total harvest level of $4.8 million. The aggregate timber value also decreased as minimum total harvest increased. These relations are almost inversely proportional *(fig. 5)*.

As could be expected, the 10-year harvest schedule corresponding to a minimum total harvest of $3.4 million requires the clearcutting of the minimum harvest allowed each year *(fig. 6)*. As the minimum total harvest is increased, a consistent pattern of changes emerges in the annual harvest schedules. To take full advantage of growth, annual harvests are kept at the lower bound as long as the total harvest requirements permit. The harvests for the tenth year, the ninth year, the eighth year, etc., are then pushed successively to the upper bound as the minimum total harvest requirement increases *(fig. 6)*. At the highest minimum total harvest, $4.79 million, the annual harvests for years 10 to 5 are at the upper bound ($566,000), the fourth year of harvest has been pushed to $380,000, and the annual harvests for the first 3 years are still at the lower bound *(fig. 6)*.

These results reflect the obvious. If the objective is to maximize the undiscounted liquidation value, cutting must be delayed as long as possible. What is not obvious, except in very simple problems, is what cutting schedule will assure the longest delay. The management plan devised by the parametric program solves this problem.

In the harvest schedules prepared by the parametric program, the shift from the "low" to the "high" harvest schedule occurs occasionally in a single year. Production and market considerations may require that this increase be spread over several years. This additional restriction can easily be introduced into the program by defining special constraints specifying the maximum allowable change in successive harvest levels.

If providing enough timber to keep the mill operating at capacity were required, the annual harvest levels and the economic objective could be expressed in volume units. No changes in the structure of the program would be necessary. The yield coefficients and the constraint levels would simply be converted from dollar values to volume units such as thousand board feet. This conversion was performed for parametric solution No. 12 *(fig. 6)*. The annual and total harvest constraints were divided by 22.66. This is the average value of a thousand board feet of timber weighted by the total volume of each species.

The order in which the timber classes are cut is essentially the same for both the liquidation value and volume maximization programs *(table 2)*. The jump from the lower to the upper bound occurs in both programs from the fifth to the sixth year. However, the number of acres to be clearcut annually varies considerably. The value maximization program required the cutting of 373 acres the first year, but the volume maximization program required only 231 acres. This decrease in the number of acres to be cut reflects the low value of fir compared to that of pine.

Parametric Changes in Bounds

In the two preceding cases, parametric linear programing was used to relate total harvest and liquidation value. In the first case, all annual harvests were equal; in the second case, the annual harvest schedule was selected within specified bounds, as the minimum total harvest was increased parametrically. These bounds defined the range of acceptable values from which the parametric linear program could select, and hence affected the corresponding level of the economic objective being maximized.

The effect of systematic changes in the location of these upper and lower bounds on the value of the economic objective can also be studied. To focus the analysis on changes in the location of the bounds, it will be assumed initially that the minimum total harvest level has already been fixed at 200 MMBF. Then, we will lift this restriction and explore the effects of simultaneous parametric variation in the minimum total harvest and in the location of the bounds.

The location of the upper and lower bounds can be varied in an infinite number of ways. The decision maker must therefore define some patterns of change that are relevant to his problem and that can be investigated with parametric linear programing.[6]

The simplest pattern is obtained by reducing uniformly the range of allowable harvests. The an-

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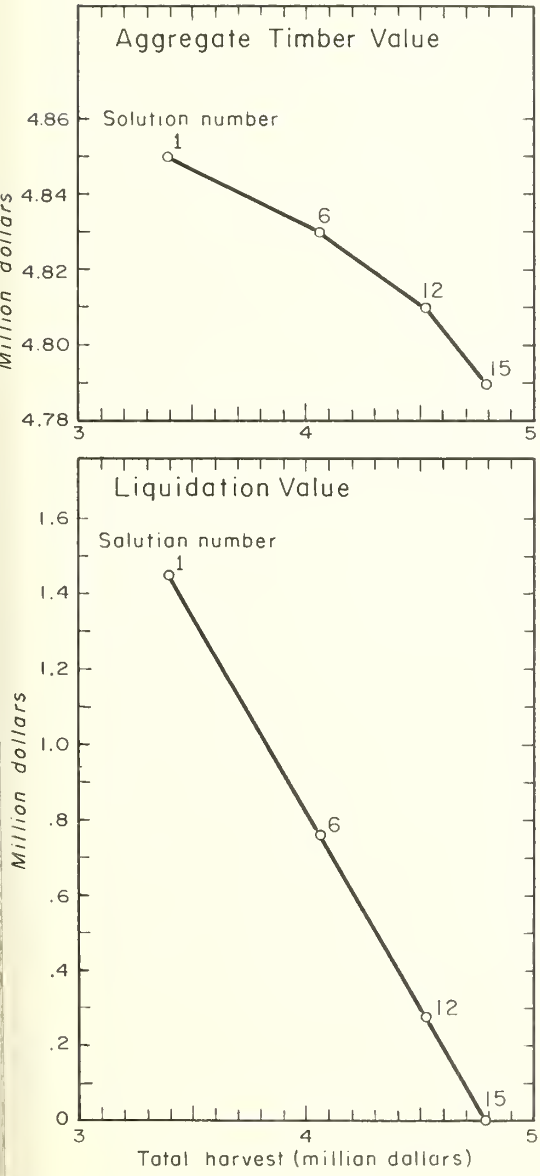
[6] The restrictions on the pattern of changes in the bounds imposed by parametric programing and a discussion of theoretical and technical considerations are included in a separate appendix to this paper. It is available upon request to the Director, Pacific Southwest Forest and Range Experiment Station, P. O. Box 245, Berkeley, California 94701.

Solution summary for figures 5 and 6

Solution number	Liquidation value	Aggregate timber value	Total harvest
	Million dollars		
1	1.45	4.85	3.40
6	.76	4.83	4.07
12	.28	4.81	4.53
15	0	4.79	4.79



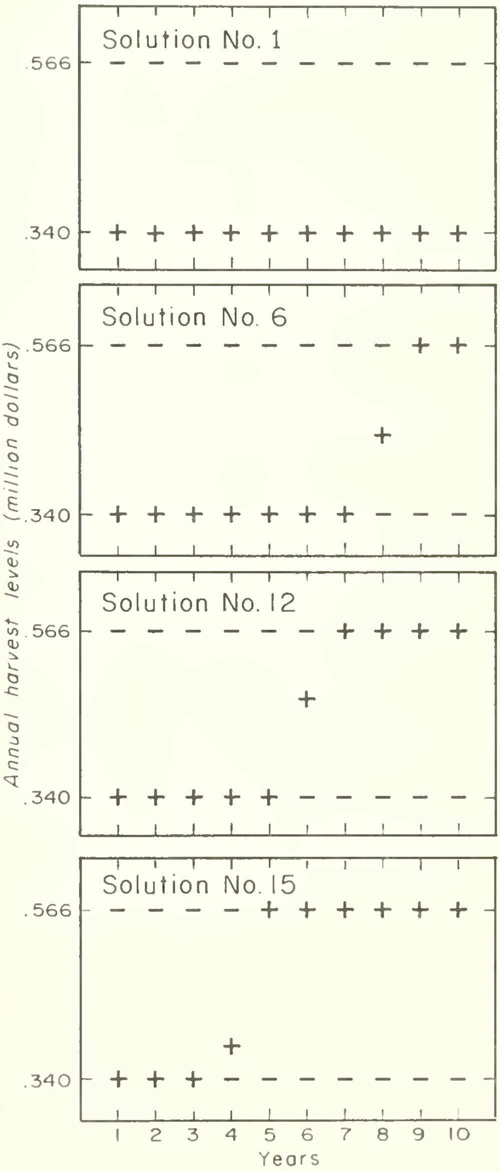


Figure 5—*Parametric relation between aggregate timber value, liquidation value, and total harvest value when annual harvests are allowed to vary between fixed upper and lower bounds.*

Figure 6—*Alternative schedules for annual harvest.* – *indicates fixed upper and lower bounds between which annual harvests can fluctuate.* + *indicates optimum level for each year of harvest.*

Table 2.--*A comparison of parametric solutions based on stumpage value and stumpage volume data, for similar annual harvest constraint levels*

Year	Stand[1]	Clearcut activities		Annual harvest	
		Value LP	Volume LP	Value LP	Volume LP
		Acres	*Acres*	*Dollars*	*MMBF*
1	$1F^{+}$	373	231	340,000	15
2	$1S^{++}$	72	--	--	--
2	$1F^{+}$	227	229	340,000	15
3	$1S^{++}$	183	80	340,000	15
3	$1F^{++}$	--	141	--	--
4	$1S^{++}$	181	208	340,000	15
5	$1S^{++}$	181	206	342,000	15
6	$1S^{++}$	297	340	566,000	25
7	$1S^{++}$	294	337	566,000	25
8	$1S^{++}$	291	334	566,000	25
9	1F-	87	95	--	--
9	1F-$^{+}$	220	220	--	--
9	$1S^{++}$	236	230	566,000	25
10	1F-	513	--	--	--
10	1S-	550	550	--	--
Total harvest				4,531,000	200
Residual stumpage				278,000	12.6

[1] Symbols used:
1 very old growth F = fir S = sugar pine.

nual mill delivery bounds are set initially at 15 and 25 MMBF. The upper and lower bounds are then brought closer together until they meet at the midrange annual harvest of 20 MMBF *(fig. 7).*

The parametric linear program mapped this pattern of change in three solutions *(fig. 8).* As the range of allowable harvests was narrowed, maximum liquidation volume fell proportionately from 12.6 MMBF to 11.3 MMBF. The loss of liquidation volume amounted to 10 percent of the initial volume or 1.3 MMBF. The cause of this loss can be deduced from *figure 7.* As the bounds approached each other, the loss of growth from the rising lower bound exceeded the gain from the falling upper bound. The net result was a decrease in the liquidation volume. When the range was reduced to 0.8 MMBF the level of annual cut remained at the lower bound for the first 5 years and then jumped to the upper bound for the remaining 5 years.

The maximum liquidation volume corresponding to any range up to 10 MMBF can be computed by simple interpolation. If a management plan is also required, an additional solution can be computed for the desired range.

Some situations may require the investigation of nonuniform changes in the bounds. Parametric programing can be used to perform this analysis subject to the restriction that the changes in the bounds must be proportional. For the preceding example this restriction is roughly equivalent to keeping all the upper and the lower bounds on separate straight lines. These lines can be independently raised, lowered, or rotated about any point on their initial locations. Still more complex patterns of change can be investigated by parametric linear programing.

Because parametric programing can be used to change the slope as well as the level of upper and lower bounds, it can be used to investigate a wide spectrum of planning situations. In the following example, the upper and lower bounds were made to converge over time until the tenth-year range of allowable harvests was forced to zero. This was accomplished in four parametric solutions by tilting the upper bound downward, and the lower bound upward *(fig. 9).* Here again, maximum liquidation volume levels corresponding to intermediate bound locations can be calculated by interpolation. The maximum liquidation volume was

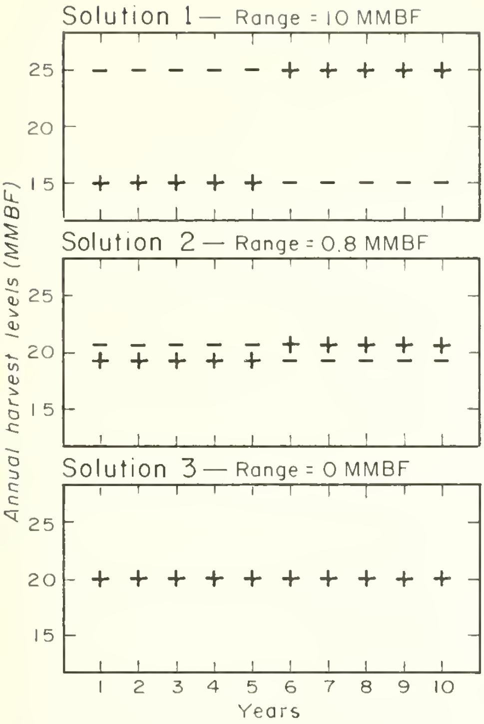


Figure 7—*Alternative schedules for annual harvest. Minimum total harvest is fixed at 200 MMBF. − indicates variable upper and lower bounds between which annual harvests can fluctuate. + indicates optimum level for each year of harvest.*

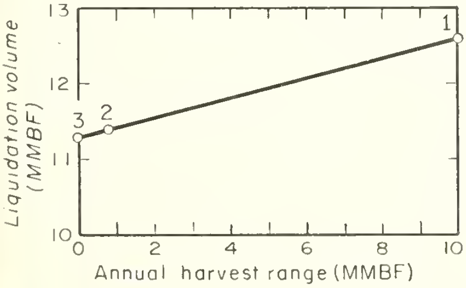


Figure 8—*Parametric relation between the range for annual harvests and the optimal liquidation volume of the forest.*

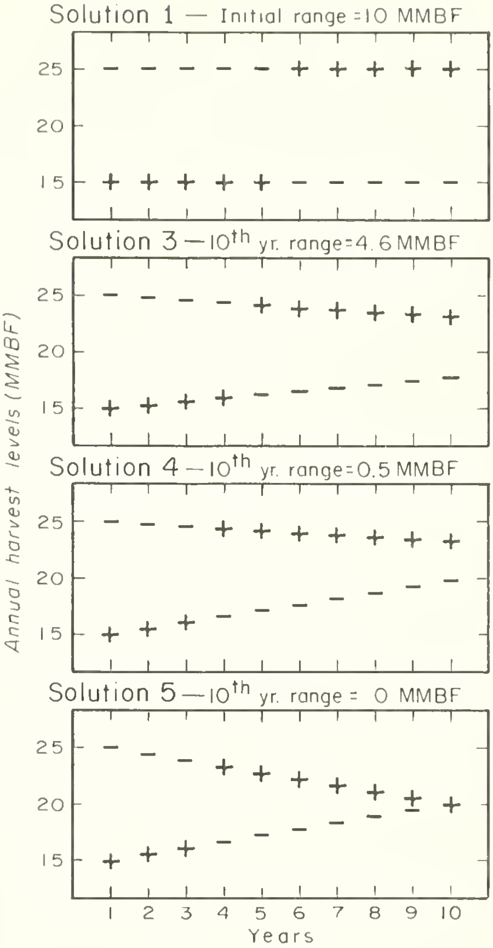


Figure 9—*Alternative schedules for annual harvest. Variable upper and lower bounds converge over time. Minimum total harvest is fixed at 200 MMBF. − indicates bounds between which annual harvests can fluctuate. + indicates optimum level for each year of harvest.*

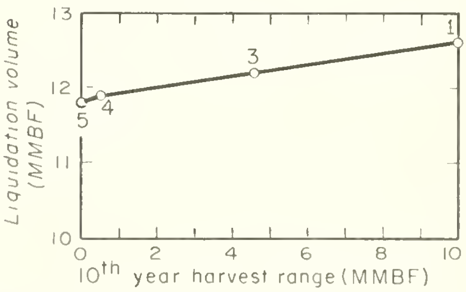


Figure 10—*Parametric relation between alternative pattern of annual harvests and liquidation volume of the forest. Minimum total harvest remains fixed.*

reduced by 0.8 MMBF as the bounds converged on the tenth year *(fig. 10)*. The program was forced to select annual harvests at the upper bound earlier as the bounds converged, causing an accelerated decrease in the maximum liquidation volume. Alternative patterns of convergence may be explored parametrically. For example, only one of the bounds could be pivoted, or the bounds could be pivoted at different rates.

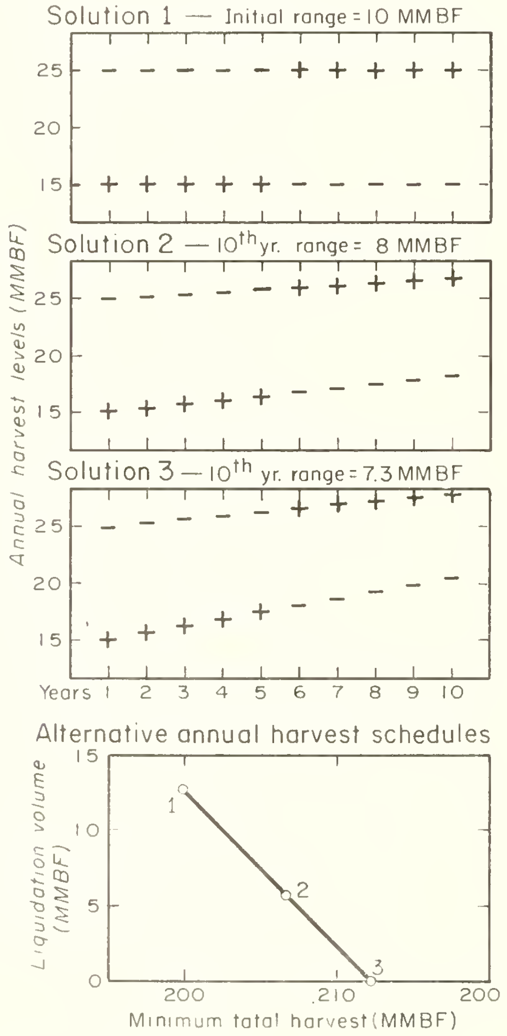


Figure 11—*Alternative schedules for annual harvest. Variable minimum total harvest. Variable upper and lower bounds converge over time.* — *indicates bounds between which levels of annual harvests can fluctuate.* + *indicates optimum level for each year of harvest.*

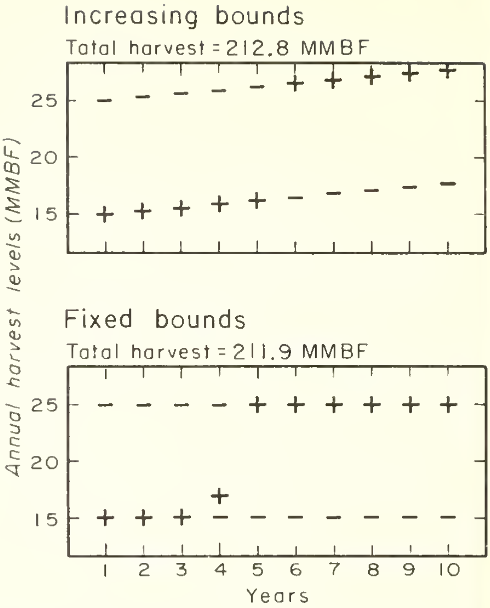


Figure 12—*Alternative schedules for annual harvest at zero liquidation value.*

Simultaneous changes in the minimum total harvest and in the bounds can be programed and the consequences on the economic objective assessed. If the upper and lower bounds are raise at different rates *(fig. 11)*, the liquidation volum is reduced to zero at a minimum acceptable tot harvest of 212.17 MMBF. With the bounds fixe at the initial levels, the minimum acceptable tot harvest corresponding to zero liquidation volume only 211.92 MMBF. An increase of more tha 200 MBF was realized by exploring parametricall changes in the location of the bounds defining a lowable cut. This increase is readily explained b the cutting schedules of the two programs corre ponding to zero liquidation volume *(fig. 12)*. Wi the bounds "tilted upward" the program can dela until the sixth year increasing the cut to the upp bound. The resulting additional growth more tha compensates for the increase in cut for the begi ning years.

In the last cases the economic objective was t maximize the liquidation volume of the forest This analysis provided the decision maker wit information on the production possibilities of th forest. Parametric linear programing can also b used to explore financial possibilities, such as pres ent value of the residual timber and of the inte mediate harvests.

To obtain this additional information, it is onl necessary to change the coefficients of the objec tive functions from thousand board feet to dollar

To obtain the present value of a stream of goods, the market value at various points in the future must be discounted to the present. Two alternate discount rates were investigated: 5 and 6 percent per annum. Each rate was assumed to endure throughout the planning period. At a minimum total harvest of 200 MMBF, a uniform reduction of the range of allowable harvests from 10 MMBF to zero resulted in a decrease in the present liquidation value of $31,254 for a discount rate of 5 percent, and of $42,466 for a discount rate of 6 percent. The management plans for the two discount rates were similar. Both discount rates exceeded the average rate of increase of the timber value attributable to growth, hence the program consistently selected as many early harvests at the lower bound as possible in order to minimize the net loss imposed by the discount rates.

Summary and Conclusions

Decision-making in commercial forest management is a complex process that seldom focuses exclusively on maximizing profit.[7] Rather, annual harvest levels are more likely to be influenced by consideration of sustained yield than by financial maturity. Accommodating preferred buyers or satisfying the raw material needs of its own processing plants may far outweigh a firm's incentive to maximize its profits.

The realization of profits nevertheless determines the viability of private and—perhaps to a lesser extent—publicly owned enterprises. The decision maker must therefore be able to evaluate the economic implications of the policies that govern his decisions. This evaluation can be efficiently performed by parametric linear programing. The solutions it generates also detail the land management activities necessary to realize the specified policies and economic objective. Parametric linear programing can also determine the precise level at which policies become inconsistent with the fixed resources available. For example, parametric linear programing can readily locate the maximum sustained yield level of a timber holding. It can also determine whether the management policies are consistent. The information provided by parametric linear programing does not diminish the value of sound judgment, but can increase its effectiveness.

The application in this paper of parametric linear programing to a simple but real timber management problem demonstrates its versatility. Policy alternatives of increasing complexity can be realistically evaluated within the linearity restriction of parametric programing.

Many timber management problems can be cast as linear programs. This casting requires a thorough study of the structure of the management problem which will lead to better management even if, in the last analysis, the linear programing formulation is not adopted.

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[7] Casamajor, Paul, Teeguarden, Dennis E., and Zivnuska, John A. **Timber marketing and land ownership in Mendocino County.** Calif. Agr. Exp. Sta. Bull. 772. 55 pp., illus. 1960.

Teeguarden, Dennis E., Casamajor, Paul, and Zivnuska, John A. **Timber marketing and land ownership in the central Sierra Nevada region.** Calif. Agr. Exp. Sta. Bull. 774. 71 pp., illus. 1960.

Forest Service - U.S. Department of Agriculture

Soil Wettability and Wetting Agents...

our current knowledge of the problem

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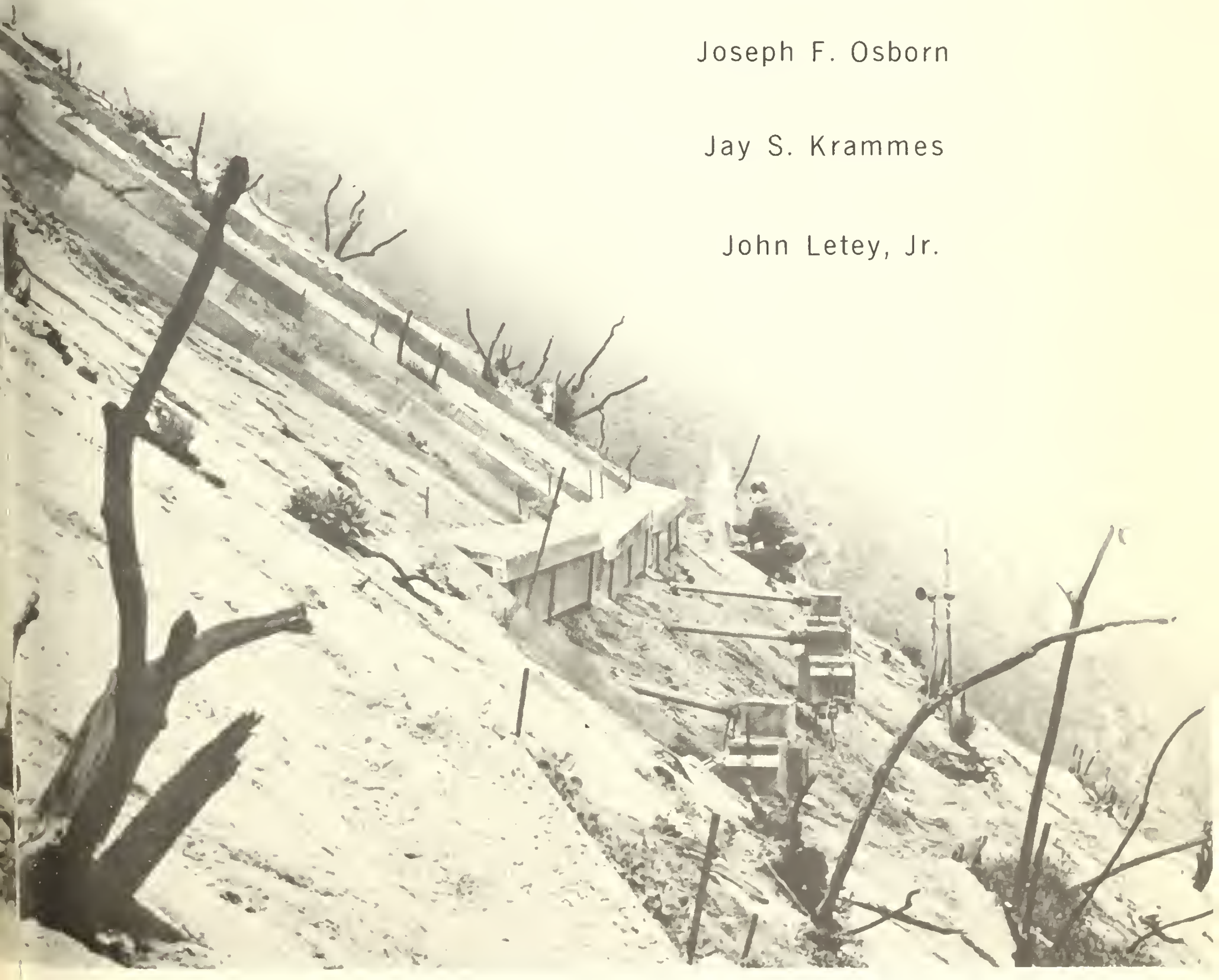
John Letey, Jr.



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Contents

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Since the early 1960's, researchers have been studying a novel soil property — one considered important in the hydrology of watersheds in southern California brushlands. These watersheds have some soils that are hydrophobic, water-resistant, or—as we call it in this paper—non-wettable.

Until now, studies of soil non-wettability have been concerned with (a) factors responsible for its formation, (b) methods for quantitatively characterizing it in soils and plant materials, (c) its effect on moisture movement during infiltration and evaporation, (d) remedial treatments for reducing it, and (e) its effects and that of wetting agents on vegetation establishment. This paper summarizes some of the most significant findings to date on the problem of soil non-wettability.

Problem of Soil Non-Wettability

In the past, researchers at the San Dimas Experimental Forest, near Glendora, Calif., were puzzled by their "dusty tracks in the mud" as they trudged across freshly burned watersheds after fall and winter rains. They attached little significance to their observations for a number of years until researchers at the University of California, Los Angeles, became concerned with the problem of water-resistant soils. The research staff consisted of Arthur Pillsbury, John Letey, Jr., Joseph Osborn, and Robert Pelishek. This group was first concerned with developing a method of measuring the non-wettable property of various "problem soils." These scientists demonstrated that a large variety of soils can become resistant to wetting.

The recognition of soil non-wettability leads to a plausible explanation for the earlier observations made at the Experimental Forest. A closer examination of the soil profile on burned watersheds after rainstorms revealed that the soil wetted unevenly. The soil at or near the surface could be saturated, but present a few inches downward was an air-dry layer. Below the air-dry layer was another damp or moist layer. In some places, this layered arrangement was continuous over extended areas, while in others it occurred in patchy irregular patterns. When water droplets were placed on soil material taken from the air-dry layer, the droplets did not penetrate, but instead "balled-up" *(fig. 1)*. These observations provided an explanation of the "dusty tracks in the mud." Researchers reasoned that the mud collecting on their boots came from the wet upper soil layers, while the dusty footprints represented the exposed portions of a non-wettable soil layer.

Figure 1.—*Water droplets on a non-wettable soil showing their "balled-up" appearance.*

Soil non-wettability appears to be widespread throughout wildland areas in the Western United States. It has been detected in California, Utah, Arizona, and Colorado. Its areal distribution outside of southern California has not as yet been fully determined. Non-wettable soils have also been reported in Florida (Jamison 1946), New Zealand (Van't Woudt 1959), and Australia (Bond 1964; Bond and Harris 1964). The problem seems particularly acute in chaparral brushlands of southern California. For example, a survey of the brushland areas on the San Dimas Experimental Forest and nearby areas suggested that 60 percent of the areas sampled had non-wettable soils (Krammes and DeBano 1965).

Resistance to wetting can be found on both burned and unburned watershed areas, although it is more pronounced on burned areas. Since 1963, several freshly burned brushland areas in southern California extending from Santa Barbara to San Diego have been studied for non-wettable soils. Non-wettability of various degrees were found in soils in each of these areas. In some areas, non-wettability occurred in rather irregular patterns which corresponded to a former sparse vegetation canopy and was most readily detectable near the charred remnants of brush stems.In other areas, a more uniform layer of non-wettable soil could be detected.

The widespread occurrence of soil non-wettability in chaparral brushlands represents a problem affecting thousands of acres in southern California. Wieslander and Gleason (1954) estimated that southern California has about 3.8 million acres of chaparral brushland areas. If between 1/60 and 1/30 of this acreage burns each year, then potentially 38,000 to 76,000 acres of non-wettable soils could be produced annually. This estimate assumes that 60 percent of the burned chaparral watersheds are characterized by non-wettable soils. The degree of non-wettability in these brushlands probably varies according to vegetation species, fire history, physical and chemical properties of the soil, and numerous interrelated environmental factors.

Effect of Hydrophobic Substances

The presence of water repellency in soils affects the wetting properties of the soil. The impedance to wetting has important effects on moisture movement and the subsequent hydrology of watersheds. The most apparent hydrologic effects involve (a) the reduction of infiltration which induces erosion by overland flow, and (b) modified evaporation of water from the soil profile.

Wetting Phenomena in Soils

Soil scientists generally agree that porous materials, such as soils, have a high absorptive capacity for water. Usually, when water is applied to coarse textured soils either as natural rainfall or irrigation, it will readily penetrate and infiltrate into the soil. In the non-wettable soil, however, this rapid penetration does not occur. Instead, if a water droplet is placed on the surface of these non-wettable soils, it will not be absorbed but will "ball-up" and remain on the soil surface *(fig. 1)*. How long the water droplet remains on the soil surface before being absorbed depends upon the degree of soil non-wettability. In a slightly non-wettable soil, the water droplet is impeded only for a short time before being absorbed by the soil. If non-wettability is extreme, however, then the water droplet may never penetrate the soil surface but instead may evaporate.

The affinity or repellency of a surface for water originates from the attractive forces between water and solid surfaces. If the attraction between water and a solid surface, such as that of a soil particle, is greater than the attraction between individual water molecules, then water will spread out and be adsorbed on the solid surface. In a wettable soil, a strong affinity exists between soil particles and water. When the soil particles repel water, however, the attraction between water molecules are greater than that between the water and the solid surface. And the water will "ball-up" rather than penetrate the soil. The latter effect is apparent in the non-wettable soils described in this paper.

The angle between a water droplet and a solid surface has been used to characterize soil non wettability. This characteristic is commonly refer red to as the wetting angle. When a water drople is placed on a hydrophobic surface the wetting angle is larger than the angle made on a hydro philic surface *(fig. 2)*. In soils literature, the angl is also called the liquid-solid contact angle. I porous media, the wetting angle is calculated from

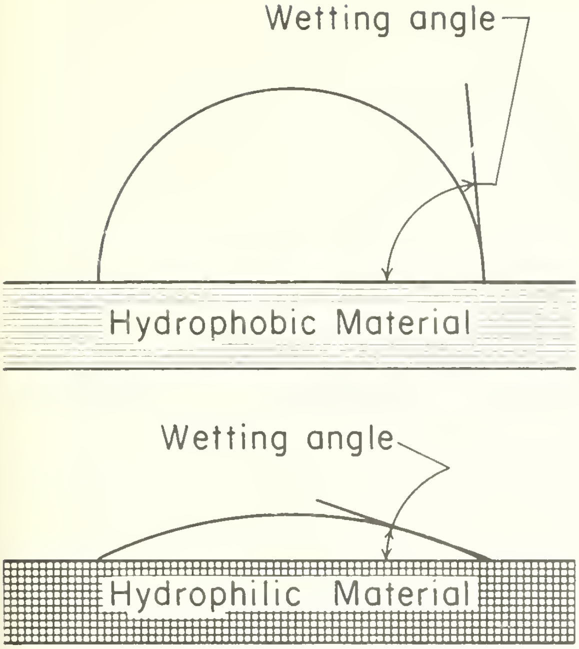

Figure 2.—*The wetting angle, or angle between a water droplet and a solid surface, is much greater on hydrophobic surfaces than on hydrophilic surfaces.*

a capillary tube model and refers to the apparent angle the water meniscus makes with the pore wall. The literature on soil-water systems usually assumes that the liquid-solid contact angle is zero. But work by Letey *et al.* (1962a, 1962b) indicates that even in a wettable soil, the angle can be much larger than zero. For non-wettable soils, larger angles up to and exceeding 90 degrees have been measured.

Moisture Movement

The movement of water through soil generally occurs by two processes: saturated and unsaturated flow. Saturated flow occurs when the entire soil pore space is filled with water. Water flows through a soil in response to differences in water potentials. The nature of the solid surface affects saturated flow primarily by frictional resistance developed between the moving water and the particle surface. Saturated flow is regulated chiefly by the geometry of the saturated pores and by the liquid properties of the solution passing through the soil.

In unsaturated soils, water flows in response to the attraction forces between the soil particles and the water molecules. This attractive force is sometimes cast in terms of free energies. Thermodynamically, soil moisture moves from regions of high free-energy to those of low free energy. The attraction forces between the water and the soil can be represented by the apparent wetting angle. Therefore, because the attractive forces between the hydrophobic particle surfaces and the water molecules are less, flow rate is consequently reduced.

Evaporation

Hydrophobic substances tend to reduce evaporation from soils and sands. For example, a wettable sand made non-wettable by ammonium hydroxide extracts of chaparral litter lost 45 percent of its water after 400 hours of evaporation. In contrast, an untreated wettable sand lost 60 percent of its water during the same period (Letey, *et al.* 1962a). Both the wettable and the non-wettable sands were saturated before evaporation was started. A dry mulch layer forming at the surface was believed responsible for the lower evaporation.

Recent studies of a sandy loam on the San Dimas Experimental Forest have substantiated that non-wettable substances reduce the rate of evaporation. We obtained a non-wettable soil by using the less-than-2 mm. fraction of a naturally occurring non-wettable soil collected from a burned area of the San Gabriel Mountains. A similar textured wettable soil was prepared by heating the water-resistant soil in a muffle furnace to destroy the substances producing non-wettability. Evaporation was allowed to occur in the laboratory from soil columns packed with either wettable or non-wettable soil.

Cumulative evaporation was less from columns packed with non-wettable soil than from those filled with wettable soil *(fig. 3)*. Water loss was less from non-wettable soil at the start, and the difference in evaporation became greater with time. Soil moisture distribution after the 109 days of evaporation *(fig. 4)* could explain the differences in evaporation rates. In the columns containing only wettable soil, moisture was withdrawn from all depths. In contrast, in those with non-wettable soil, the moisture was depleted primarily from the upper part of the soil column. These moisture profiles indicate that moisture moves slowly in the non-wettable soil, and water cannot be readily transmitted to the surface where it is evaporated.

Infiltration

Infiltration is also reduced by the presence of hydrophobic substances. The reduction is particularly pronounced in soils containing a non-wettable

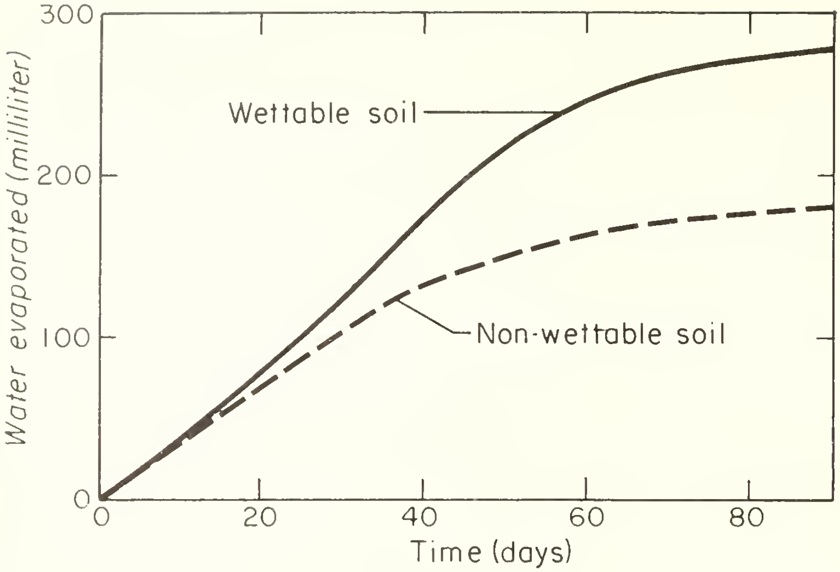

Figure 3.—*Cumulative evaporation over time from soil columns containing only wettable or non-wettable soil.*

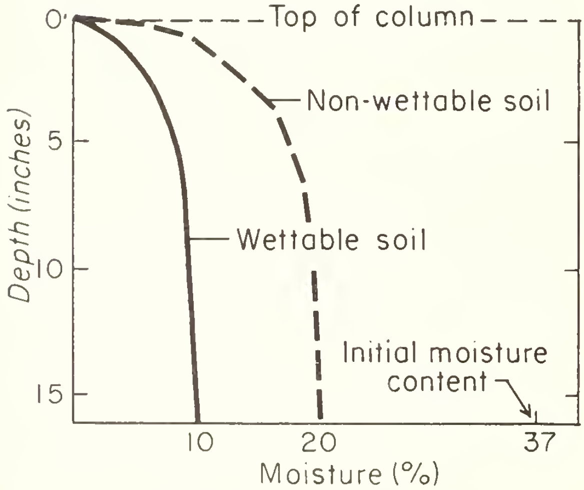

Figure 4.—*Soil moisture distribution in soil columns containing only wettable or non-wettable soil after evaporating for 109 days.*

layer below the soil surface. The effect of a non-wettable layer on infiltration can be illustrated by the results obtained from one of our laboratory infiltration experiments *(fig. 5)*. One set of plastic columns was packed with only wettable soil. A second set was packed with only non-wettable soil. The third set was packed with wettable soil but had a 6 cm. layer of non-wettable soil at 7 to 13 cm. below the top of the column. The data show that the infiltration rates in the layered columns and in those containing wettable soil only were similar until the wetting front approached a depth

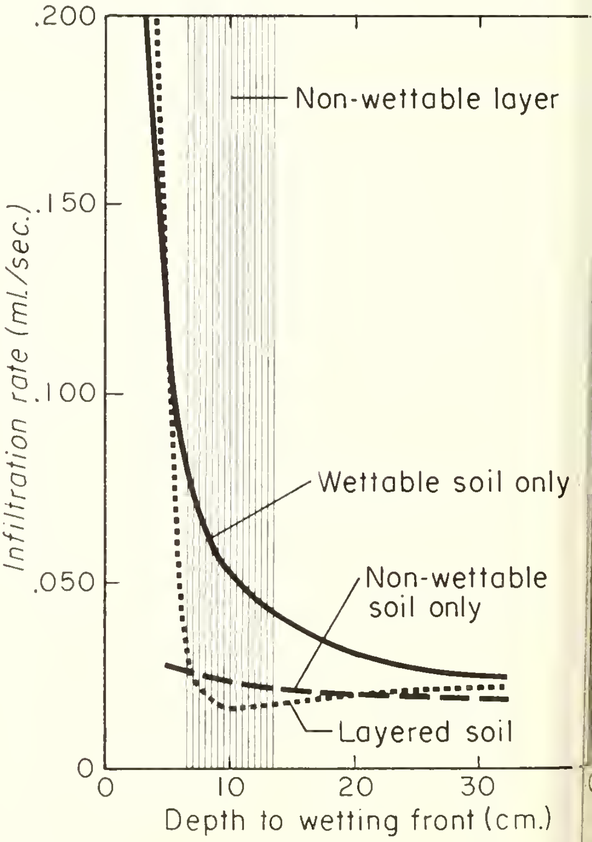

Figure 5.—*Infiltration rate when the wetting front approached different depths in soil columns packed with only wettable soil, non-wettable soil, or layered soils.*

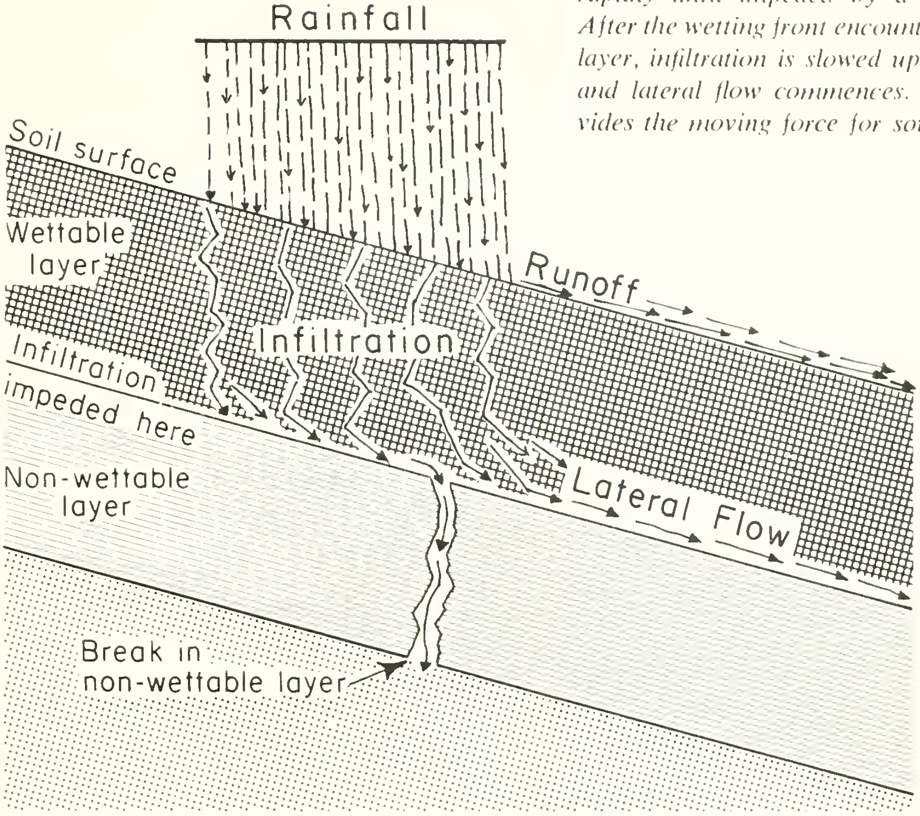

Figure 6.—*Rain falling on the soil surface infiltrates rapidly until impeded by a non-wettable layer. After the wetting front encounters the non-wettable layer, infiltration is slowed up, and surface runoff and lateral flow commences. Surface runoff provides the moving force for soil erosion.*

of 6 cm. When the wetting front approached the non-wettable layer in the layered columns (at about 6 cm.), the infiltration rates dropped below the infiltration rates in the columns packed only with non-wettable soil. When the wetting front had passed below the non-wettable layer, infiltration rates increased slightly and maintained a rate similar to that in the non-wettable soil, although the wetting front was again in wettable soil. These results suggest that the non-wettable layer decreased infiltration after the wetting front has passed through the non-wettable layer and was moving through the underlying wettable soil.

The results of the laboratory experiment probably represent the relationship which could be expected in field soils having a non-wettable soil layer. The degree of impedance of the non-wettable layer probably depends upon both the degree of non-wettability and the thickness of the non-wettable layer. In case of extreme non-wettability, it is possible that infiltration could stop completely when the wetting front encountered the non-wettable layer.

Brushland Hydrology and Erosion

Runoff and Debris Movement

The presence of a non-wettable soil layer could be partly responsible for the high surface runoff and erosion which occur during fall rains on freshly burned areas in southern California. The soils may be of particular importance where high surface runoff and debris movement occur after relatively small amounts of rainfall. High debris movement on freshly burned areas resulting from small rainstorms is a common phenomenon in southern California. Associated with the large debris movement are many rills on the eroded surface.

We can offer a plausible hypothesis on the effect of soil non-wettability on runoff *(fig. 6)*. Incoming rainfall infiltrates only a very short distance before the wetting front reaches the non-wettable layer. For example, if the upper part of the non-wettable layer is 2 inches below the soil surface and the overlying wettable layer holds a maximum of 30 percent of moisture before becoming saturated, then less than 1 inch of percipitation is needed before runoff would occur if the wetting front was impeded by a non-wettable layer. After downward infiltration has stopped or been impeded, both lateral flow as well as surface runoff occurs. The runoff and lateral movement from this upper layer along with portions of non-wettable material removed by runoff could be an important source of debris production from freshly burned areas.

Recent research indicates that the debris production can be reduced by remedial treatments with wetting agents. The studies showed debris movement was reduced after storms as large as 6.16 inches with intensities up to 1.35 inches per 20 minutes.

Dry-Creep Erosion

The material accumulating in debris cones is usually non-wettable. Fairly coarse textured and sandy, it moves primarily under the influence of gravity during the summer months and extended dry periods between winter storms.

This dry-creep phenomenon may be related to a less dense packing density of the non-wettable soil. Our laboratory studies show that materials treated with hydrophobic materials to make them non-wettable do not pack as dense as before treatment. In general, the greater the degree of non-wettability produced, the less dense the air-dry material will pack under similar packing procedures, with a mechanical packing machine.

Further, densities recorded in the field have shown that non-wettable soils are less dense than comparable wettable soils from the same area. The difference in bulk densities between wettable and non-wettable soils on the sloping hillsides may be important in dry-creep erosion. A reduction in surface density would imply less individual particle contact at the surface and therefore less resistance to surface movement. On slopes approaching the angle of repose, a lower resistance to surface movement in a non-wettable soil may lower the angle at which dry creep occurs. This reduction in the angle of repose may be small, but on the steep mountainous topography of southern California the acreage and amount of debris involved could be quite large.

Some investigators have noted that non-wettable soils appear to "fluff up" after rainfall. These non-wettable soil particles do not draw together upon evaporation as do the wettable particles. As the moisture evaporates, the cohesive and adhesive forces of the water and a wettable surface tend to draw one to the other. But such is not the case between water and non-wettable surfaces because adhesive forces between the water and non-wettable surface are low. Therefore, rainfall or misting may in fact increase dry creep patterns where non-wettable soil particles are present and reduce dry creep on wettable surfaces.

Moisture Disposition

Our laboratory studies have indicated soil non-wettability may affect the disposition of moisture in the soil. These studies were concerned with the effects of non-wettability on infiltration into layered soils and evaporation from columns filled with only wettable or non-wettable soil. In the columns packed with only wettable or non-wettable soil, evaporation was less in the non-wettable soils. Likewise infiltration was impeded by the presence of a non-wettable layer located below a layer of wettable soil.

In nature, soil non-wettability is found in a layered arrangement. It is possible that this layered condition could either increase or decrease evaporation under field conditions. There is probably a decrease when moisture movement is impeded by the non-wettable layer.

In contrast, a non-wettable layer could increase evaporation under certain climatic conditions. For example, consider the case in which precipitation occurs in increments of 2 inches or less, and the rains are interspersed by periods of warm weather conducive to evaporation. This is a common sequence in southern California during winter when Santa Ana wind conditions follow rainstorms. In a soil having a non-wettable layer within a few inches of the soil surface, the water may be held near the soil surface rather than percolate downward in the soil profile. This situation produces a nearly saturated soil layer at the surface. And when the layer is exposed to highly evaporative conditions, it is conducive to large soil moistur losses. Therefore, larger evaporation losses woul be expected than if this layer were not present s that the water could move downward and distribute itself deeper in the soil profile. In the latte situation the surface soil would contain less wate and should therefore lose less by surface evaporation.

The application of wetting agents as remedi treatments complicates the possible evaporatio relationships we have suggested. Wetting agent should increase capillarity in the non-wettable soi and thereby improve moisture transmission throug the non-wettable layer. The end result should be a increase in evaporation. But preliminary labor tory experiments suggest that this may not be th ease. In columns filled with non-wettable soil, those treated with wetting agents did not evaporate more than those left untreated. In contrast, wetting agents can reduce evaporation in wettable soils. The reduced evaporation in wettable soils is similar to that produced by such evaporation suppressants as hexadeconal. The results would indicate that from the standpoint of evaporation, the application of wetting agents may be desirable.

If an area has a high proportion of wettable soil, the benefits from evaporation may be outweighed by the reported drop in infiltration into wettable soil treated with wetting agents (Pelishek, *et al.* 1962). But the full effects of wetting-agent treatments cannot be determined accurately until more detailed research is done on the effects of such treatments on evaporation and infiltration in both wettable and non-wettable soils.

Factors Affecting Non-Wettability

Soil non-wettability is probably produced by a number of soil, climatic and vegetation factors, although not all of them have been isolated. Our research to date has been concerned with only a few factors. At present, the two factors best understood are vegetation and fire.

Vegetation

The primary source of non-wettable substances appears to be organic substances produced by brush species. These substances apparently coat soil particles and render them non-wettable. Substances responsible for producing non-wettability have been extracted from both plant litter and plant parts. For example, Letey *et al.* (1962a, 1962b) reported that extracts (both water and ammonium hydroxide) of chaparral litter can produce non-wettability in formerly wettable sands. In their studies, samples of wettable sand were treated with extracts of organic litter material. When dried, the treated sand demonstrated a marked resistance to wetting. Experiments at San Dimas have confirmed that extracts from plants as well as from non-wettable soil samples can induce non-wettability in sands. In general the extracts were obtained from soil samples which contained large amounts of organic material.

Work in Australia (Bond 1964; Bond and Harris 1964) indicated that fruiting bodies of actinomycetes contain hydrophobic substances. Microbial processes may also be involved in the decomposition of the organic plant material and the subsequent formation of non-wettable substances in our area. But the dry semi-arid conditions existing in southern California probably are not conducive to high rates of microbial activity.

In studies at San Dimas, we found that non-wettable substances originate from both fresh plant material and decomposition products of litter. We are seeking to develop a system for rating species according to their potential for producing non-wettable substances. The procedure involves extracting a given weight of plant material with 0.1N NH_4OH solution and then saturating a wettable sand with this extract. After the material has dried, data on capillary rise in the sand are used to determine wetting angle of water in the treated sand. The wetting angle is then used to rank the various plants and plant parts according to their potential for producing non-wettability.

Preliminary results indicate that chamise *(Adenostoma fasciculatum)*—specifically leaf material—contains large amounts of hydrophobic materials *(table 1)*. In general, the leaves of all species tested—except sugar bush *(Rhus ovata)* plants—produced a greater degree of non-wettability than did the stems.

Fire

Soil non-wettability appears closely related to fire temperatures. DeBano and Krammes (1966) found that soil non-wettability may be intensified or destroyed by heating soil samples at different

Table 1.--*Plants ranked, in descending order, according to potential for producing non-wettability, as determined by wetting angle of water in treated sand*

Plant	Part	Wetting angle
		Degrees
Chamise (*Adenostoma fasciculatum*)	Leaves Stems	82 79
Mountain mahogany (*Cercocarpus betuloides*)	Leaves Stems	80 77
Scrub oak (*Quercus dumosa*)	Leaves Stems	76 75
Deer brush (*Ceanothus* spp.)	Leaves Stems	72 73
Sugar bush (*Rhus ovata*)	Leaves Stems	60 67

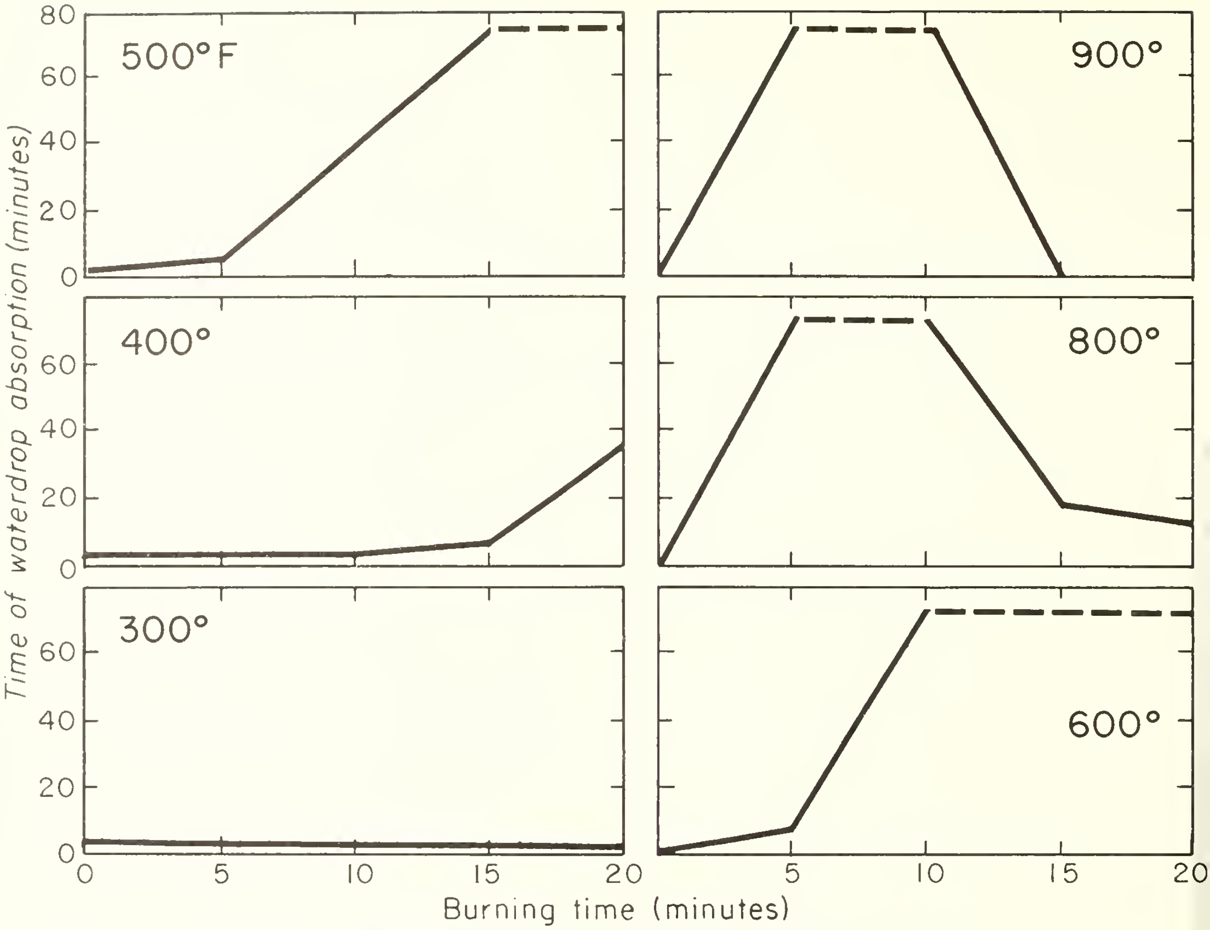

Figure 7.—*The relationship between soil non-wettability and burning time at six burning temperatures.*

temperatures for various periods of time *(fig. 7)*. The soil used in their experiment was slightly non-wettable and resisted the penetration of a water droplet for about 2 minutes. The burning treatment consisted of heating a sample in a muffle furnace at different temperatures for various times.

At the lowest temperatures (300° F.), non-wettability was unaffected by burning time. When the temperature was increased to 400° F., non-wettability increased slightly at 15-minute burning times and substantially at 20 minutes. Higher temperatures at 500 and 600° F. for 10 to 15 minutes produced a soil which was completely water repellent. This water-repellent state was termed the impenetrable condition. In contrast, temperatures of 800 and 900° F. began destroying the non-wettable property after 10 minutes; in fact, the soil sample burned at 900° F. for 15 minutes was completely wettable.

The relationship between heat regime and non-wettability suggested a hypothesis that may explain the non-wettable soil layer found on burned watersheds: When fire burns an area, soil non-wettability is destroyed near the soil surface; below the wettable soil surface layer, non-wettability is not destroyed but intensified; this zone where soil non-wettability is intensified corresponds to the water-resistant layer observed in the field.

The intensification of non-wettable substance in the subsurface layer can result from two processes. First, heat *per se* may intensify incipient non-wettability in place at various depths below the soil surface, and hence non-wettability is formed *in situ*. This process precludes the movement of hydrophobic substances within the soil profile. If the process occurs, then creation of a non-wettable layer depends only on the presence of incipient non-wettability at a particular depth and the thermal regime existing during a fire. Second, the vapors and other gaseous material containing hydrophobic substances may distill from the hot soil surface and condense in the underlying cool layers

The vaporization and condensation process has been demonstrated by other experiments (DeBano 1966). Material was burned in a 22-inch-deep asbestos container that was heated from the top by muffle furnace coils. The container was filled with a wettable sand to within 1½ to 2 inches of the top. The remaining depth of the container was filled with non-wettable soil material in one experiment and with a decomposed *Ceanothus crassifolius* litter in a second experiment. After the soil, plant, and sand material were packed into the container, a heat source preheated to 1400° F. was applied to the top of the soil container. The heat source was allowed to remain on the surface of the soil container until the upper part of the sand layer reached 250 to 300° F. (1½ to 2 inches below the top of the soil container). The heat source was then removed and the column allowed to cool.

After cooling, the burned soil and plant material as well as the underlying sand were tested for non-wettability. Non-wettability was not present in the upper ½ to 1 inch of the burned soil or plant material. The non-wettable substances in this upper layer had apparently been vaporized by the applied heat treatment. In the lower part of the burned soil and plant material, non-wettability was more intense than before burning. The upper layers of the underlying test sand also demonstrated a marked resistance to wetting. The presence of non-wettable substances in the formerly wettable soil indicated that hydrophobic substances had distilled downward and condensed on the sand particles. Therefore, it appears that vaporization and condensation may be an important process in the production of a non-wettable soil layer below the soil surface in areas where a source of hydrophobic material is present.

Summary of Vegetation and Fire Hypothesis

In southern California, a number of chaparral brush species produce organic substances that can make soil non-wettable. During the years between fires, leachate from the brush and decomposing plant parts accumulate in the upper part of the soil profile *(fig. 8a)*. In the unburned condition, the maximum concentration of non-wettable substances lies in the upper part of the soil profile immediately below the litter layer. The area corresponds roughly to the transition between the A_0 and A_1 horizons. Smaller amounts may be moved below this layer by infiltrating water. In addition, some of the substances may remain in the undecomposed plant litter. The most severe soil non-wettability in this unburned situation probably results from a particle coating and intermixing of partially decomposed plant parts with the mineral soil. The accumulation of hydrophobic substances tends to build up over time, and its intensity depends upon the particular plant species occupying the area and time between fires. The average interval between fires in brush areas is about 25 years. Most likely, the multitude of interacting environmental conditions governing litter build-up, and removal plays various roles in the induced soil non-wettability.

In a fire, the native chaparral cover and underlying litter layer may be partially or wholly consumed *(fig. 8b)*. Temperatures above the soil surface may soar as high as 2,000° F. (Countryman 1964). Temperatures at the soil surface are much less, and may not exceed 1,200° F. Within the soil, the temperature drops rapidly because of the low heat conductivity of soil *(fig. 8b)*. At 2 inches below the soil surface maximum temperatures of 350 to 550° F. have been reported (Bentley and Fenner 1958; Sampson 1944). The temperatures existing at different depths may intensify incipient non-wettability at the various depths. More important, however, are the large temperature gradients existing in the upper few inches of the soil that cause vapor and gases containing hydrophobic substances to move downward in the soil profile where they condense on soil particles.

After the fire has swept through the area, the soil possesses a non-wettable layer *(fig. 8c)*. Depth and thickness of the layer depend on the intensity of fire and the nature and amount of vegetation litter present. Under burning conditions where the surface temperatures are not high, the layer might be at or near the soil surface. Where a hot fire had burned, non-wettability could show up in deeper layers. The soil physical properties and water content of the soil would also probably affect the movement of these hydrophobic substances.

The relationship between the temperature regime existing during a fire and the extent and degree of non-wettability in the underlying layer are

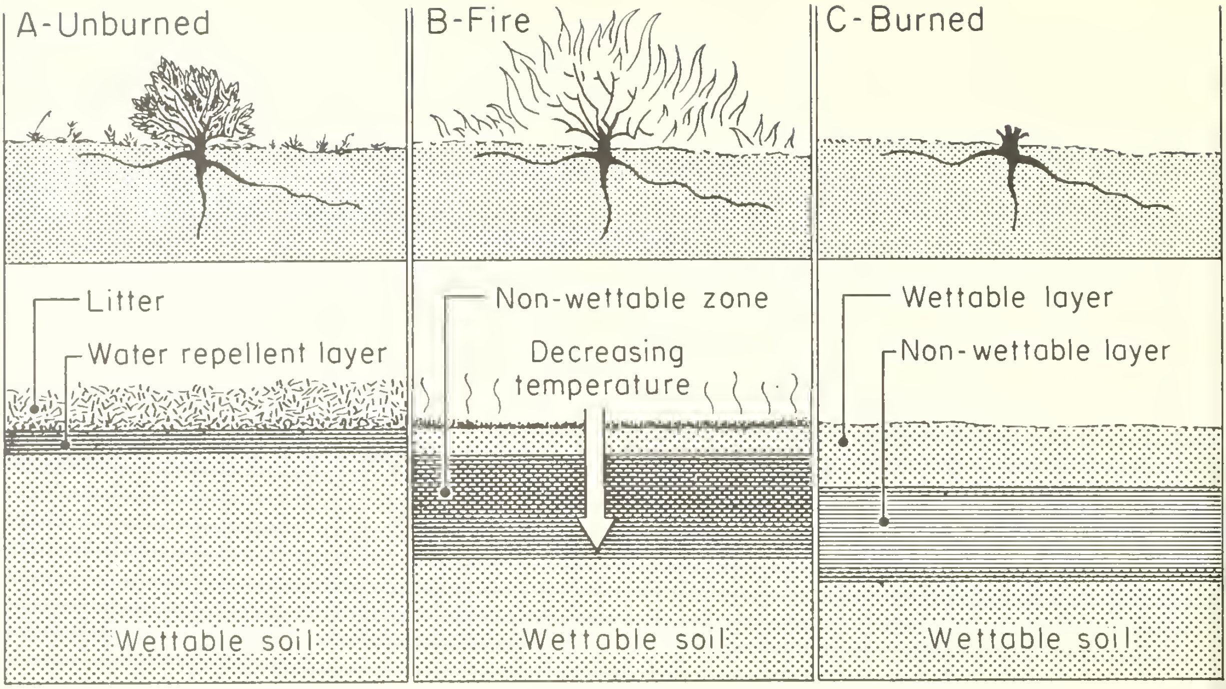

Figure 8.—*Soil non-wettability before, during, and after fire. (a) Before fire, the non-wettable substances accumulate in litter layer and mineral soil immediately beneath it; (b) fire burns vegetation and litter layer, causing non-wettable substances to move downward along temperature gradients; (c) after a fire, non-wettable substances are located below and parallel to soil surface on burned area.*

not completely understood. We need more precise measurements of temperature profiles at the soil surface and immediately below it to obtain more precise data on the amounts of hydrophobic materials that move during wildfire conditions. Furthermore, the susceptibility of different soil particles and clay minerals being rendered non-wettable under fire conditions remains obscure.

Remedial Treatments: Wetting Agents

Among the treatments being studied to overcome non-wettability in soils, the most promising to date are organic compounds known as "wetting agents." The large number of wetting agents commercially available share a common characteristic: their effect on the wetting angle of water entering water-repellent soils. Wetting agents reduce the surface tension and thereby reduce the wetting angle between the solution and the material being wetted. The reduced wetting angle allows water to enter porous media and provide a faster and more complete wetting.

Wetting agents are available in either liquid or powdered form and in either concentrated or diluted form. The common denominator is the amount of active ingredient in the product. Tests suggest that the different types of wetting agents differ only slightly when compared on a unit-active ingredient basis (Letey, *et al.* 1963).

Increasing Infiltration

Wetting agents can be used to increase infiltration of water into hydrophobic soil (Letey, *et al.* 1961). According to the general capillary laws governing wetting in soils, reducing the surface tension decreases capillarity. In contrast, decreasing the wetting angle increases capillary attraction (Pelishek, *et al.* 1962). These capillary forces are important factors in unsaturated moisture movement during infiltration. Therefore, a delicate balance exists during infiltration between the limitations of decreasing surface tension and the benefits arising from decreasing the wetting angle. If the benefits from a decrease in wetting angle exceeds the limitations of decreasing surface tension, then infiltration will be increased.

In non-wettable soils having large wetting angle, the reduction in surface tension is overcome by the decrease in wetting angle, and infiltration as a whole is increased. In contrast, in a wettable soil the wetting angle is originally low, and wetting agents do not reduce it significantly. Therefore, the reduction in capillarity brought about by a reduction in surface tension is not compensated for by a lower wetting angle, which results in a lower infiltration rate. It appears that wetting agents can either increase or decrease infiltration depending upon the initial water repellency of the soil. In non-wettable soils, the wetting angle is usually large, and in most cases application of a wetting agent increases infiltration.

Controlling Soil Erosion

The premise that wetting agents increase infiltration in non-wettable soil led to field testing of wetting agents as a treatment to control soil erosion on burned watersheds (Osborn, *et al.* 1964). The tests were carried out on small plots next to the San Dimas Experimental Forest that had been burned by a wildfire. Six plots, 10 feet wide and 40 feet long, extending down slope were established; three were treated with a liquid wetting agent and the remainder were left untreated. Surface runoff and debris were measured. Through the first rainy season after the fire the treated plots yielded 0.47 cu. ft. of debris as compared to 6.52 cu. ft. from the untreated plots. The reduction in debris was attributed to the wetting agent application. In addition, the treated plots produced four times more grass than the untreated plots.

Applying Wetting Agents

The method of applying wetting agents becomes critical if broadscale applications prove desirable as a post-fire remedial treatment. In southern California, large scale watershed treatments are usually confined to aerial application. Most brushland watersheds occupy topography too steep and rugged to permit application by land-borne machinery or implements.

The aerial application of concentrated liquid olutions is probably prohibitive both logistically nd economically. A satisfactory distribution of small amounts of wetting agents by aerial means requires that the concentrated liquid form be diluted manyfold with water. The cost of transporting large quantities of water to obtain this dilution makes this treatment economically unfeasible.

Attempts have been made to absorb liquid wetting agent on dry carrier substances (Pelishek, *et al.* 1964). The concentration of the wetting agent in this powder can be varied by using different dilutions of wetting agent when saturating the carrier. The use of carriers would have the advantage of diluting the wetting agent and allowing easier aerial distribution of various concentrations of wetting agent. Because the powder material used as a carrier would be light, there is no need to transport heavy dilution material.

A study made in winter of 1964–65 on an area burned by the Coyote Fire, near Santa Barbara, California, pointed to a difficulty when using powdered wetting agents. One treatment in the study was a powdered form of wetting agent. The study did not yield any additional information on the effectiveness of wetting agents as an erosion measure, but it did point out that severe winds can blow the powdered wetting agent off the study plots. Therefore, powdered wetting agents may have to be modified to solve the problem of wind dispersion before their use can be recommended.

The residual properties of wetting agents are important when the effectiveness of remedial treatments are judged. On burned watersheds in southern California, the greatest benefits from wetting agents would come during the first rainy season after a fire, when rain falls on relatively bare soil exposed by the fire. This period probably corresponds to the most impermeable condition of a non-wettable soil layer. Later, when vegetation becomes established, some roots undoubtedly penetrate the non-wettable layer. Root penetrations provide passageways through the layer, allowing water to infiltrate. Therefore, a prime prerequisite is that the wetting agent should be effective for at least 1 year through this critical recovery period.

Present indications are that wetting agents last for at least 1 year. An earlier study had indicated that wetting agents were effective through at least two irrigations (Letey, *et al.* 1961). A more recent leaching study[1] showed that the residual effects of a wetting agent were still detectable after 8 inches

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[1] Krammes, J. S., and DeBano, L. F. *Longevity of a wetting agent treatment for water resistant soils.* 1967. (Ms. submitted to Soil Sci. Soc. Amer.)

of water passed through the samples. Under rainfall conditions in southern California, this condition would represent the leaching potential of 16 to 32 inches of rainfall.

Establishing Grass

Results from a plot study (Osborn, *et al.* 1964) suggest that wetting agents may stimulate grass establishment on non-wettable soil.

A subsequent laboratory study using wettable and non-wettable soil showed that non-wettability can have a significant effect on both germination and establishment (Osborn, *et al.* 1967). Soil containers were either maintained at a level position or inclined at 30-degree slope. Half of them were treated with wetting agents; the remainder, untreated. No germination occurred on the inclined containers with the untreated non-wettable soil. Good germination occurred on the same containers treated by a wetting agent. In contrast, in the level position small differences in germination occurred between the treated and untreated containers. Germination in the inclined position was poor, probably because water ran off the containers and was not available for seed germination Subsequent seed establishment showed the same trends in the sloping containers as in the germination trials; that is, establishment was good on non-wettable soils treated with wetting agents, but failed on the sloping non-wettable soils. On the level plots, however, establishment was low on untreated non-wettable soils. During establishment on the untreated plots, many plants died. Apparently enough moisture was available for germination but not for subsequent survival and establishment.

Summary and Prospects

Since the early 1960's a substantial amount of information has been collected on the problem of non-wettable soils. An important relationship which has been partially solved is the effect of fire temperatures on the degree of non-wettability. Test results strongly suggest that a non-wettable layer below the soil surface forms when hydrophobic substances volatize and then condense. This formation seems to be related to the large temperature gradients near the soil surface produced by extremely high temperatures at the soil surface, such as during wildfires. The extent and amounts of hydrophobic substances distilling downward under different temperature gradients have not been fully defined. And future research should be directed toward expanding knowledge of the transfer of hydrophobic substances during fire. When these relationships are better defined, it will be necessary to correlate them with temperature profiles developing in the upper few inches of the soil during wildland fires.

Preliminary findings strongly suggest that plant species vary in their potential for inducing non-wettability in soils. The relative amounts of hydrophobic substances in the plant material, underlying litter layer, and associated soil profile have not been established. The few samples of plant material analyzed to date indicate chamise has more hydrophobic materials than other chaparral brush species. The rate that these substances accumulate in the soil over time between fires is still an unknown. Field samplings suggest that between fires they accumulate in the litter layer and mineral soil immediately beneath it. These accumulated materials are moved downward by temperature gradients existing during a fire. Additional studies of the relative hydrophobicity of different plant and litter components should increase our understanding o the distribution of hydrophobic substances in the plant-soil system.

The problem of grass establishment on non wettable soils should be carefully considered whe burned watersheds are to be reseeded. Our earl experiments suggest that wetting agent treatment applied to non-wettable soils may improve mois ture relationship during germination and establish ment. Therefore, this remedial treatment may deter mine whether reseedings succeed or fail on area having non-wettable soils.

The nature of moisture movement—particularl unsaturated flow—remains an important problem The large difference in unsaturated flow betwee wettable and non-wettable systems points to a pos sible difference in the type of moisture flow in volved. For example, the extremely slow move ment of water in the non-wettable system suggest the principal mechanism involved may be vap diffusion phenomena. In contrast, more rapi movement by viscous flow may be important in wettable soil. Before the effects of wetting agent on flow can be determined, we need better quantitative data on the mechanisms involved.

Another perplexing problem concerns the possible relationship between the textural and mineralogical nature of soils with non-wettability. For example, we have consistently observed the difficulty of inducing non-wettability in fine-textured soils with a high clay content. This resistance may be related to their specific surface. This relationship suggests that because clay soils have a greater specific area than sandy textured soil, a given quantity of hydrophobic substances may coat a smaller proportion of the available particle surface in the clay soil. The proportion of the total surface area of soil particles coated with hydrophobic materials could be an important factor in determining the degree of water repellency acquired by soils. The mineralogical make-up of the colloidal soil fraction probably also enters into this relationship.

And finally, a more practical question has to do with amount and method of treatment for remedying non-wettable soils. To date, not enough basic information is available to recommend specific techniques of treating entire watersheds with wetting agents. Fundamental research in the laboratory followed by field plot studies could fill this gap in our knowledge of soil non-wettability.

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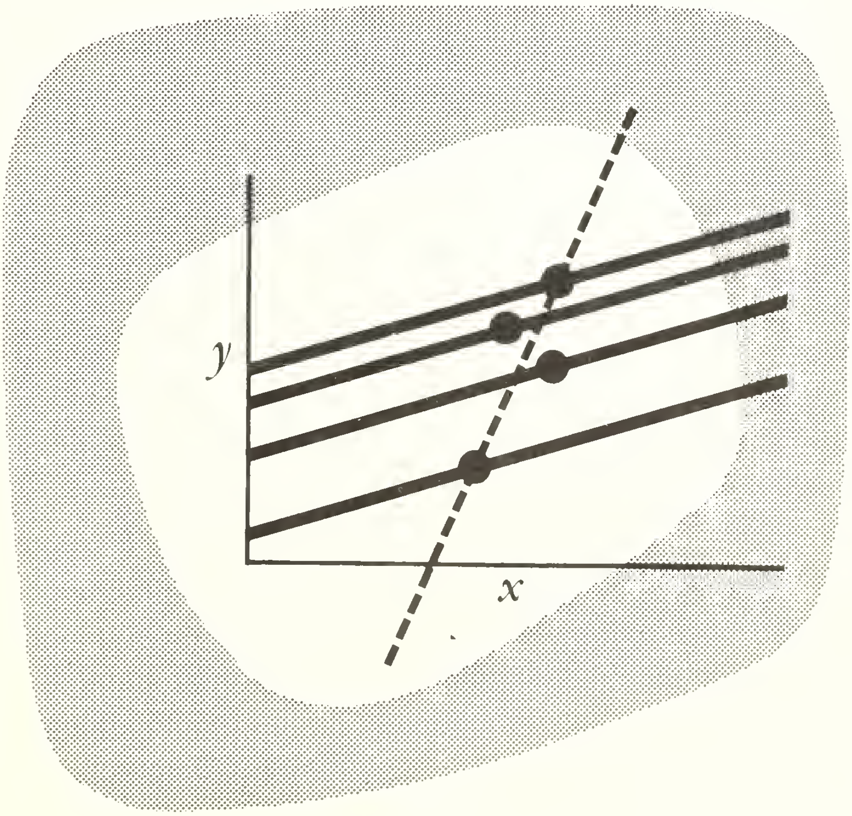
REX -- FORTRAN - 4 SYSTEM

for combinatorial screening or conventional analysis of multivariate regressions



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THIS COMPUTER-PRODUCED PUBLICATION IS AN EXPERIMENTAL EFFORT TO PUBLISH (MORE RAPIDLY AND MORE EFFICIENTLY) INFORMATION ON COMPUTER-ORIENTED THEORIES AND TECHNIQUES.

AT THE SAME TIME, WE ARE TRYING TO IMPROVE SUSCEPTIBILITY OF THE INFORMATION TO AUTOMATED SEARCH AND RETRIEVAL. THE INITIAL SUMMARY AND THE ENTIRE TEXT OF THE PAPER ARE IMMEDIATELY SUITABLE FOR COMPUTER SEARCH BY VIRTU OF ALREADY BEING ON PUNCHED CARDS. AN IDENTIFIER AT THE TOP OF EACH PAGE SERVES TO MATCH IT WITH ITS PARENT DOCUMENT IN CASE OF SEPARATION OR MIXUPS.

FINALLY, COMPUTER-PROCESSED TEXT IS EASILY REVISED AND REPUBLISHED. THIS IS AN IMPORTANT CONSIDERATION IN FIELDS WHERE CHANGES AND NEW DEVELOPMENT ARE OCCURRING SO RAPIDLY.

THE COMPUTER PROGRAM 'PRN', WRITTEN BY THE AUTHOR IN FORTRAN-4 LANGUAGE, WAS USED TO PRINT THIS RESEARCH PAPER AS WELL AS EARLIER U.S. FOREST SERVICE RESEARCH PAPERS PSW-13 AND PSW-21.

PROGRAM LISTING AND SOURCE DECKS FOR 'REX' CAN BE MADE AVAILABLE TO INTERESTED ORGANIZATIONS HAVING ACCESS TO A SUITABLE LARGE COMPUTER.

REX--FORTRAN-4 SYSTEM FOR COMBINATORIAL SCREENING OR CONVENTIONAL ANALYSIS OF MULTIVARIATE REGRESSIONS

BY

L. R. GROSENBAUGH

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I FOREST AND RANGE EXPERIMENT STATION.              I
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FOREST SERVICE, U.S.DEPARTMENT OF AGRICULTURE

REX -- FORTRAN-4 SYSTEM FOR COMBINATORIAL SCREENING OR CONVENTIONAL ANALYSIS OF MULTIVARIATE REGRESSIONS.

L.R.GROSENBAUGH

SUMMARY

'REX' IS AN EXPANSIBLE COMPUTERIZED SYSTEM THAT PROVIDES DATA NEEDED IN REGRESSION OR COVARIANCE ANALYSIS OF AS MANY AS 50 VARIABLES, 8 OF WHICH MAY BE DEPENDENT. ALTERNATIVELY, IT CAN SCREEN VARIOUSLY GENERATED COMBINATIONS OF INDEPENDENT VARIABLES TO FIND THE REGRESSION WITH THE SMALLEST MEAN-SQUARED-RESIDUAL, WHICH WILL BE FITTED IF DESIRED. USERS CAN EASILY PROGRAM ADDITIONAL PROCESSING.

THE SYSTEM WILL ACCEPT INPUT IN THE FORM OF WEIGHTED OR UNWEIGHTED OBSERVATION VECTORS THAT CAN BE REARRANGED, TRANSFORMED, OR TRANSGENERATED. IT WILL ALSO ACCEPT MATRIX INPUT IN THE FORM OF THE COMPACT UPPER TRIANGLE OF A SYMMETRIC MOMENT MATRIX AND WILL CORRECT THE MATRIX FOR MEANS, IF THIS ACTION IS DESIRED. ALTERNATIVELY, IF REGRESSION THROUGH ORIGIN IS DESIRED DESPITE INPUT OF A CORRECTED MATRIX, THE SYSTEM WILL 'UNCORRECT' THE MATRIX. IN ANY CASE, THE COMPACT UPPER TRIANGLE OF THE FULL RESULTANT MATRIX CAN BE PUNCHED FOR LATER USE IF DESIRED.

REGRESSION ANALYSIS MAY INVOLVE THE FULL MATRIX OR ONLY SELECTED ELEMENTS. OUTPUT MAY INCLUDE MOMENT AND/OR CORRELATION MATRICES OF SELECTED ELEMENTS, WITH OR WITHOUT THE INVERSE MATRICES. STANDARDIZED REGRESSION COEFFICIENTS ARE AVAILABLE AS WELL AS CONVENTIONAL REGRESSION COEFFICIENTS, MEANS, VARIANCES, AND ANALYSIS OF SOURCES OF VARIATION. IF OBSERVATION VECTORS HAVE BEEN INPUT, COMPARISONS OF PREDICTIONS WITH OBSERVATIONS CAN BE PRINTED, ALONG WITH CORRESPONDING ERRORS.

WHERE COMBINATORIAL SCREENING HAS BEEN SPECIFIED AND THE NUMBER OF GENERATED COMBINATIONS OF VARIABLES EXCEEDS MAXIMUM MACHINE OR PROGRAM CAPABILITY, THE USER HAS SEVERAL METHODS AT HIS DISPOSAL FOR BRINGING THE GENERATED NUMBER DOWN TO SOME TOLERABLE NUMBER.

============ REGRESSION FITTING, SCREENING, AND ANALYSIS ============

PROBLEM SIZE-LIMITS FOR EACH APPLICATION APPEAR ON THE FIRST PAGE OF OUTPUT INVOLVING THAT APPLICATION. HOWEVER, MAXIMUM NUMBER OF INDEPENDENT VARIABLES THAT CAN BE FITTED TO ONE DEPENDENT VARIABLE IS CURRENTLY 49, WHILE MAXIMUM NUMBER OF VARIABLES THAT CAN BE COMBINED LINEARLY IN ALL POSSIBLE WAYS FOR PREDICTION OF ONE DEPENDENT VARIABLE IS CURRENTLY 13. BY FIXING OR FORCING VARIABLES, COMBINING THEM INTO SETS AND GROUPS, OR LIMITING THE MAXIMUM NUMBER OF OF SETS ALLOWED IN COMBINATION, THIS LATTER LIMIT CAN BE EXTENDED UPWARDS. BY EMPLOYING LESS THAN MAXIMUM NUMBER OF INDEPENDENT VARIABLES, AS MANY AS 8 DEPENDENT VARIABLES CAN BE PROCESSED AT ONCE. WHEN PARAMETERS EXCEED LIMITS HANDLED BY PROGRAM, A MESSAGE OR ASTERISK FLAGGING THE OFFENDER IS PRINTED OUT ON THE FIRST PAGE, AND NO FURTHER COMPUTATIONS ARE PERMITTED.

THE ABOVE LIMITS ASSUME AVAILABILITY OF 32K WORDS OF HIGH-SPEED STORAGE. IF 280K WORDS ARE AVAILABLE, CHANGING A FEW PARAMETERS AND DIMENSIONS WILL ALLOW EXPLORING ALL POSSIBLE LINEAR COMBINATIONS OF 30 INDEPENDENT VARIABLES TAKEN 1,2,3...,17 AT A TIME. THE PROGRAM CURRENTLY REQUIRES USE OF 'OVERLAY' (AN IMPROVED TYPE OF CHAIN EXECUTION) TO AVOID EXCEEDING AVAILABLE STORAGE. TWO BINARY SCRATCH TAPES 'JW' AND 'JX' (NOT NEEDED BY 'OVERLAY') MUST BE SPECIFIED IN BLOCK DATA SUBROUTINE 'BLRM', AND UNNEEDED BUFFERS MUST BE ELIMINATED BY SOME DEVICE SIMILAR TO SUBROUTINE 'BUFK'. APPENDIX A ILLUSTRATES DECK ARRANGEMENTS AND MODIFICATIONS NEEDED BY A NUMBER OF DIFFERENT COMPUTERS.

FIVE CONTROL CARDS MUST BE PROVIDED TO INITIATE PROCESSING OF EACH PROBLEM. THESE MUST BE FOLLOWED BY DATA VECTORS OF QUANTITIES OBSERVED IN ASSOCIATION OR BY A DATA MATRIX OF SUMMED SQUARES AND CROSSPRODUCTS UNLESS INPUT FROM EARLIER PROBLEM HAS BEEN SPECIFIED ON SECOND CONTROL CARD. IF OBSERVATION VECTORS NEED TO BE TRANSFORMED, TRANSGENERATED, OR REARRANGED, SUBROUTINE TRNX CAN BE MODIFIED APPROPRIATELY. THE SIMPLEST WAY OF DOING THIS IS TO USE THE '*ALTER' PROCEDURE AVAILABLE ON THE IBM 7090-7094 (ILLUSTRATED IN APPENDIX B), BUT ANOTHER METHOD AVAILABLE ON ANY COMPUTER IS TO REPLACE 'TRNX' CARDS NUMBERED 18, 19, 20, 21 WITH A GREATER OR LESS NUMBER OF CARDS SPECIFYING THE DESIRED FORTRAN MANIPULATION.

ARRANGEMENT OF VARIABLES IS CRITICAL ONLY IN SCREENING, WHEN IDENTIFICATION OF BEST-FITTING REGRESSIONS IS BEING ATTEMPTED. THEN 'TRNX' MUST ARRAY VARIABLES SO THAT FIXED VARIABLES OCCUR BEFORE ANY NONFIXED VARIABLES, AND ALL DEPENDENT VARIABLES MUST OCCUR CONSECUTIVELY IN A TERMINAL STRING. VARIABLES IN SAME SET AND SETS IN SAME GROUP MUST ALSO BE CONSECUTIVE, WHILE 'TRNX' SHOULD IGNORE UNNECESSARY VARIABLES.

A CARD PUNCHED 'DONE' IN COLUMNS 1-4 MUST FOLLOW LAST OBSERVATION VECTOR OR LAST CARD OF MATRIX ELEMENTS (OR LAST CONTROL CARD WHERE EARLIER DATA WILL BE USED) OF EACH PROBLEM.

A CARD PUNCHED 'DONE DONE DONE....' STARTING IN COLUMN 1 SHOULD FOLLOW THE 'DONE' CARD OF THE LAST PROBLEM TO RETURN CONTROL TO THE MONITOR BEFORE ENCOUNTERING END-OF-FILE.

AFTER READING THE 'DONE DONE DONE....' CARD FOLLOWING A 'DONE' CARD, 'REX' PRINTS NUMBER OF SUCCESSFUL COMPLETIONS AND TOTAL NUMBER OF PROBLEMS ATTEMPTED, THEN RETURNS CONTROL TO SYSTEM.

'REX' SHOULD RUN ON ANY COMPUTER WITH FULL FORTRAN-4 CAPABILITY, WORD-LENGTH OF AT LEAST 4 CHARACTERS, 'OVERLAY' OR 'CHAIN' CAPABILITY, AND AT LEAST 32K WORDS OF MEMORY. THIS INCLUDES IBM 7040-7044, 7090-7094, 360/65, ETC., AND CDC 6400-6600. WHERE MONITORS OCCUPY EXCESSIVE SPACE, DIMENSIONS OF 'A'IN 'SKRN' MUST BE SHRUNK BY CHANGING CARDS NUMBERED SKRN 11, PALM 63, PALM 284 (SEE CDC IN APPENDIX A).

SINCE MAJOR PROCESSING OPTIONS 0 AND 1 OFTEN INVOLVE NULL OR NEARLY NULL MATRICES, IT IS IMPERATIVE THAT USERS SET SYSTEM SUBROUTINES SO THAT UNDERFLOW IS RESET TO NORMAL ZERO WITHOUT ERROR MESSAGES OR ERROR TRACE.

FIRST CONTROL CARD --

COL. 1- 4 --- ALWAYS BLANK
COL. 5-72 --- BCD PROBLEM IDENTIFICATION
COL. 73-76 --- LABEL FOR OPTIONAL INITIAL MATRIX PUNCHOUT

SECOND CONTROL CARD (FIELDS MUST BE RIGHT-JUSTIFIED) ----------------

COL. 1- 8 --- NUMBER OF OBSERVATION VECTORS = NOB
COL. 11-12 --- NUMBER OF RAW VARIABLES TO BE READ-IN BEFORE TRANSFORMATION OR MATRIX FORMATION = NVR (BLANK IMPLIES SAME AS COL. 15-16)
COL. 15-16 --- MAXIMUM SIZE OF MATRIX AVAILABLE = NVS (EXCLUDES VECTOR OF TOTALS AND WEIGHT)
COL. 17 --- 'W' IF WEIGHTED REGRESSION IS DESIRED, ELSE 'BLANK' OR ANY CHARACTER BUT 'W'
COL. 19-20 --- LIMIT CN NUMBER OF SETS OF NONFIXED INDEPENDENT VARIABLES TO BE INCLUDED IN LARGEST COMBINATORIAL REGRESSION = LM (BLANK OR ZERO IMPLIES NO LIMIT)

THE 5 PRECEDING FIELDS CAN BE OMITTED COMPLETELY WHEN DATA FROM EARLIER PROBLEM ARE BEING USED.

SIX GROUPS OF PROCESSING OPTIONS ARE CONTROLLED BY COLUMNS 67-72.

COL. 67 --- MAJOR PROCESSING ALTERNATIVES
0 = IDENTIFICATION OF BEST FITTING REGRESSIONS
1 = SAME AS 1 PLUS FITTING OF BEST REGRESSIONS
2 = FITTING OF SPECIFIED REGRESSIONS
3-9 ARE AVAILABLE FOR USER-PROGRAMMED OPTIONS

SECOND CONTROL CARD (CONTINUATION) ------------------------------------

COL. 68 --- DATA DESCRIPTION, USE (**CORRECTED OR UNCORRECTED)

0 = OBSERVATION VECTOR INPUT,
TO BE **CORRECTED BEFORE USE
1 = OBSERVATION VECTOR INPUT,
TO BE USED UNCORRECTED
2 = UNCORRECTED MATRIX INPUT,
TO BE **CORRECTED BEFORE USE
3 = UNCORRECTED MATRIX INPUT,
TO BE USED UNCORRECTED
4 = **CORRECTED MATRIX INPUT,
TO BE USED **CORRECTED
5 = **CORRECTED MATRIX INPUT,
TO BE UNCORRECTED BEFORE USE
6 = UNCORRECTED MATRIX FROM EARLIER PROBLEM,
TO BE **CORRECTED BEFORE USE
7 = UNCORRECTED MATRIX FROM EARLIER PROBLEM,
TO BE USED UNCORRECTED
8 = **CORRECTED MATRIX FROM EARLIER PROBLEM,
TO BE USED **CORRECTED
9 = **CORRECTED MATRIX FROM EARLIER PROBLEM,
TO BE UNCORRECTED BEFORE USE

EVEN NUMBERS IMPLY REGRESSION THROUGH MEAN.
ODD NUMBERS IMPLY REGRESSION THROUGH ORIGIN.

WITH OBSERVATION VECTOR INPUT, NVR RAW ELEMENTS ARE AUTOMATICALLY READ INTO VECTOR D AND ARE AVAILABLE TO 'TRNX'. THESE MAY BE COMBINED OR TRANSFORMED, BUT IN ADDITION TO SUCH ACTIONS, THE USER MUST MODIFY 'TRNX' SO THAT RESULTANT QUANTITIES ARE STORED IN DESIRED ORDER AS THE NVS ELEMENTS OF VECTOR X. ALSO, 'TRNX' MUST SET W EQUAL TO AN APPROPRIATE WEIGHT IF WEIGHTING HAS BEEN SPECIFIED ON CONTROL CARDS.

'TRNX' IS BYPASSED WHEN MATRICES ARE INPUT, BUT DATA MUST CONFORM TO FORMAT (4E16.8), AND ORDER MUST CONFORM TO THAT DESCRIBED BELOW FOR MATRIX PUNCHOUT.

CODE NUMBER APPROPRIATE TO USE OF DATA ALREADY IN STORAGE FROM EARLIER PROBLEM IS 4 GREATER THAN THE CODE NUMBER REQUIRED TO INPUT AND SIMILARLY USE THE SAME MATRIX CURRENTLY.

EARLIER-STORED DATA (CODES 6-9) CANNOT BE USED WITH SCREENING (MAJOR ALTERNATIVE 0 OR 1), WITH FIRST PROBLEM OF ANY RUN, OR IMMEDIATELY AFTER ANY PROBLEM THAT HAS FAILED TO RUN.

SECOND CONTROL CARD (CONTINUATION) ------------------------------------

COL. 69 --- PUNCHED-CARD OUTPUT
0 = NONE
1 = MAXIMUM MATRIX AVAILABLE
AFTER TRANSFORMATIONS AND /OR CORRECTION
BUT BEFORE SPECIFICATION OF ELEMENTS

CARDS WILL BE LABELLED AS SPECIFIED ON FIRST CONTROL CARD, WITH 0 OR 1 APPENDED TO SHOW WHETHER THE MOMENTS ARE ABOUT MEAN (CORRECTED) OR ABOUT ORIGIN (UNCORRECTED).

ROW ELEMENTS OF COMPACT UPPER TRIANGULAR MATRIX APPEAR SUCCESSIVELY, IMMEDIATELY FOLLOWED BY VECTOR OF SUMS OF WEIGHTED X'S OR Y'S. SUM OF WEIGHTS IS LAST. ALL MATRIX ELEMENTS HAVE BEEN MULTIPLIED BY FACTOR NEEDED TO MAKE SUM OF WEIGHTS EQUAL NUMBER OF OBSERVATION VECTORS.

COL. 70 --- MATRIX PRINTOUT AFTER SPECIFICATION OF ELEMENTS
0 = NONE
1 = MOMENT MATRIX
2 = CODED MATRIX (CORRELATION IF ABOUT MEAN)
3 = BOTH MATRICES

COL. 71 --- INVERSE MATRIX PRINTOUT AFTER SPECIFICATION
0 = NONE
1 = MOMENT MATRIX INVERSE
2 = CODED (CORRELATION) MATRIX INVERSE
WITH (STANDARDIZED) REGRESSION COEFF.
3 = BOTH MATRICES

COL. 72 --- PREDICTIONS, OBSERVATIONS, AND ERRORS
0 = NO COMPUTATION OR PRINTOUT
1 = COMPLETE COMPUTATION AND PRINTOUT, ALONG
WITH SUM OF WEIGHTED ERRORS AND
SUM OF WEIGHTED SQUARED ERRORS

THIS OPTION IS AVAILABLE ONLY WITH CURRENT/OR EARLIER INPUT OF DATA IN FORM OF OBSERVATION VECTORS, NOT WITH MATRIX INPUT. INTERVENING MATRIX INPUT OR FAILURE OF PROBLEM WIPES OUT AVAILABILITY OF EARLIER DATA.

SUM OF WEIGHTED ERRORS SHOULD APPROXIMATE ZERO WHEN REGRESSION IS THROUGH MEAN.

SUM OF WEIGHTED SQUARED ERRORS SHOULD ALWAYS EQUAL ERROR SUM OF SQUARES IN EARLIER TABLE, EXCEPT FOR ROUNDING ERRORS.

THIRD CONTROL CARD FOR MAJOR PROCESSING ALTERNATIVES 0 AND 1
(IDENTIFICATION OF BEST FITTING REGRESSIONS)

COL. 1 --- 'BLANK' IMPLIES G'S PUNCHED IN THIS AND ALL FOLLOWING COLUMNS UNTIL THE FIRST 'Y' OCCURS.

ANY COL.--- 'S' IN A COLUMN IMPLIES THAT THE ORDINAL OF THAT COLUMN IS THE SUBSCRIPT OF THE FIRST INDEPENDENT VARIABLE IN A SET. WHEN THE 'S' OCCURS BEFORE ANY 'G', MEMBERS OF THE SET ARE TREATED AS FIXED (I.E., THEY WILL ALWAYS BE INCLUDED IN ANY REGRESSION TESTING COMBINATIONS OF NONFIXED VARIABLES). MEMBERS OF SETS OCCURRING AFTER A 'G' HAS APPEARED ARE TREATED AS NONFIXED, AND ARE INCLUDED IN REGRESSIONS ONLY WHEN CALLED FOR BY SPECIFIC COMBINATORIAL RULES. ORDINALS OF BLANK COLUMNS FOLLOWING AN 'S' DENOTE SUBSCRIPTS OF OTHER INDEPENDENT VARIABLES BELONGING TO THE SET. ALL MEMBERS OF A GIVEN SET ARE SIMULTANEOUSLY PRESENT OR ABSENT IN ANY PARTICULAR COMBINATION.

WHEN SEVERAL S'S OCCUR BEFORE ANY 'G', THEY WILL BE FITTED CUMULATIVELY (NOT INDIVIDUALLY), SO THAT A SPECIFIC PATH OF FIT CAN BE EXPLORED AND OBSERVED AT EACH SUCCESSIVE STAGE.

'G' IN A COLUMN IMPLIES THAT THE ORDINAL OF THAT COLUMN IS THE SUBSCRIPT OF THE FIRST INDEPENDENT VARIABLE IN THE FIRST NONFIXED SET OF A GROUP CONSISTING OF ONE OR MORE SETS.

NOT MORE THAN ONE SET FROM A GIVEN GROUP WILL APPEAR IN THE SAME REGRESSION UNDER COMBINATORIAL CONTROL (I.E., THEY ARE MUTUALLY EXCLUSIVE). BLANK COLUMNS IMMEDIATELY AFTER ANY 'G' DENOTE (BY COLUMN ORDINALS) SUBSCRIPTS OF INDEPENDENT VARIABLES BELONGING TO THE FIRST SET IN THAT GROUP, WHILE EACH SUBSEQUENT 'S' BELONGS TO THE 'G' THAT STARTED THE SEQUENCE OF SETS IN WHICH THE 'S' OCCURS.

'Y' IN A COLUMN IMPLIES THAT THE ORDINAL OF THAT COLUMN IS THE SUBSCRIPT OF A DEPENDENT VARIABLE THAT IS TO BE PREDICTED BY VARIOUS LINEAR COMBINATIONS OF INDEPENDENT VARIABLES.
'Y' MUST APPEAR IN SUCCESSIVE COLUMNS AFTER ITS FIRST APPEARANCE, TERMINATING WITH THE COLUMN WHOSE ORDINAL CORRESPONDS TO THE NUMBER 'NVS' PUNCHED IN COLUMNS 15-16 OF SECOND CONTROL CARD. THE CHARACTER FOLLOWING THE LAST 'Y' MUST BE SAME AS IN COLUMN 17 OF SECOND CONTROL CARD ('W' REQUIRES WEIGHTING, ALL OTHER CHARACTERS AND BLANKS IMPLY UNIT WEIGHTS).

THIRD CONTROL CARD FOR MAJOR PROCESSING ALTERNATIVE 2 ---------------
(FITTING OF SPECIFIED REGRESSIONS) ----------------------------------
----

ANY COLUMN WHOSE ORDINAL DOES NOT EXCEED THE NUMBER 'NVS' (PUNCHED OR IMPLIED IN COLUMNS 15-16 OF SECOND CONTROL CARD) MAY CONTAIN AN 'X' OR 'Y' TO SHOW THAT THE VARIABLE WITH SUBSCRIPT INDICATED IS TO BE CONSIDERED AS AN INDEPENDENT OR DEPENDENT VARIABLE IN A PARTICULAR REGRESSION TO BE FITTED BY LEAST SQUARES. THE SAME CHARACTER MUST APPEAR IN COLUMN (NVS+1) OF 3RD CONTROL CARD AS IN COLUMN 17 OF 2ND CARD ('W' REQUIRES WEIGHTING, ANYTHING ELSE IMPLIES UNIT WEIGHTS).

FOURTH AND FIFTH CONTROL CARDS (MUST BE PRESENT THO OFTEN BLANK) -----

THESE CARDS ARE FOR OBJECT-TIME SPECIFICATION OF VARIABLE FORMAT NEEDED FOR DATA INPUT IN FORM OF OBSERVATION VECTORS. NO FORMAT SPECIFICATION IS NEEDED FOR MATRIX INPUT, WHICH MUST BE IN FORMAT (4E16.8). THUS, THESE TWO CONTROL CARDS CAN BE LEFT BLANK EXCEPT WHERE COLUMN 68 OF SECOND CONTROL IS PUNCHED 0 OR 1, BUT THE TWO CARDS MUST ALWAYS BE PRESENT.

WHEN USER ELECTS TO FIT AND ANALYZE A SPECIFIC REGRESSION, MINIMUM SUCCESSFUL OUTPUT WILL CONSIST OF ONE PAGE LISTING IMPLICIT OR EXPLICIT PARAMETERS OF PROBLEM, ONE PAGE OF REGRESSION COEFFICIENTS WITH THEIR VARIANCES ON THE FOLLOWING PAGE, ONE PAGE FOR QUANTITIES NEEDED IN REGRESSION-COVARIANCE ANALYSIS, AND ONE PAGE GIVING MEANS AND VARIANCES OF ALL VARIABLES INVOLVED IN THE SPECIFICATION OF VARIABLES ON THE THIRD CONTROL CARD.

WHEN USER ELECTS IDENTIFICATION OF BEST FITTING REGRESSIONS, MINIMUM SUCCESSFUL OUTPUT WILL CONSIST OF ONE PAGE LISTING IMPLICIT OR EXPLICIT PARAMETERS OF PROBLEM, AND ONE OR MORE PAGES OF RELATIVE MEAN SQUARED RESIDUALS FOR EACH REGRESSION GENERATED BY THE SPECIFIC COMBINATORIAL MODEL ESTABLISHED BY THE SECOND AND THIRD CONTROL CARDS. THESE RELATIVE MEAN SQUARED RESIDUALS (RELATIVE TO SIMPLE VARIANCE ABOUT MEAN Y) ARE IDENTIFIED AS TO COMPONENT COMBINATORIAL SETS INVOLVED. ALL FIXED SETS ARE IMPLICITLY INCLUDED IN ANY COMBINATORIAL REGRESSION. COMBINATORIAL REGRESSIONS HAVING MINIMUM VARIANCES ARE IDENTIFIED IN TABLE ON LAST PAGE.

THE COEFFICIENT OF COLLINEARITY, A MEASURE OF RELATIVE NULLITY OF THE MATRIX OF INDEPENDENT VARIABLES, IS ALSO LISTED AT THE LEFT OF THE RELATIVE MEAN SQUARED RESIDUALS. A ZERO OR NEAR-ZERO COEFFICIENT (WITH NEGATIVE EXPONENT MORE THAN DOUBLE THE NUMBER OF INDEPENDENT VARIABLES INVOLVED) WARNS OF NULL OR NEARLY NULL MATRIX WHOSE INVERSE MIGHT NOT BE COMPUTABLE BY SUBROUTINE CBXR, USUALLY BECAUSE OF HIGH CORRELATION AMONG INDEPENDENT VARIABLES. COMPLETELY ORTHOGONAL VARIABLES WOULD BE INDICATED BY A COEFFICIENT OF UNITY, SINCE IT IS MERELY THE RATIO OF THE DETERMINANT OF THE UNCORRECTED MOMENT MATRIX (ABOUT ORIGIN) OF INDEPENDENT VARIABLES TO THE CONTINUING PRODUCT OF THE MATRIX DIAGONALS. REGRESSIONS THROUGH THE MEAN CONSIDER THE VECTOR OF VARIABLE SUMS AND AGGREGATE WEIGHTS AS AUGMENTING THE BASIC UNCORRECTED MATRIX, BUT OTHERWISE THE COMPUTATION IS THE SAME.

A COEFFICIENT FOR THE IMPLIED CONSTANT PSEUDO-VARIABLE 'UNITY' IS ALWAYS COMPUTED WHEN A PARTICULAR REGRESSION THROUGH MEAN IS SPECIFIED. THIS CONSTANT IS ALSO KNOWN AS THE INTERCEPT (ON THE Y AXIS) AND IS SUBSCRIPTED 'U' FOR UNITY. IT IMMEDIATELY FOLLOWS THE COEFFICIENT FOR THE LAST REAL VARIABLE, AS DOES ITS VARIANCE ON THE NEXT PAGE. SIMILARLY, A FINAL COLUMN OF ELEMENTS C(I,U) FOR THE MOMENT MATRIX INVERSE IS ALWAYS COMPUTED WHEN REGRESSION THROUGH MEAN IS SPECIFIED. THIS IS THE IDENTICAL COLUMN OF ELEMENTS THAT WOULD BE COMPUTED LESS ACCURATELY IF REGRESSION THROUGH ORIGIN WERE SPECIFIED AND TERMINAL PSEUDO-VARIABLE OF UNITY WERE PROGRAMMED IN SUBROUTINE 'TRNX'. THE LATTER PROCEDURE RESULTS IN AUGMENTING THE UNCORRECTED MOMENT MATRIX BY A TERMINAL VECTOR OF SIMPLE TOTALS, AN UNDESIRABLE PROCEDURE EXCEPT FOR ITS CONVENIENCE IN COVARIANCE ANALYSIS.

ALTHOUGH SCREENING OF REGRESSIONS BY THE CONVENTIONAL STEPWISE PROCEDURE WILL ORDINARILY NOT LEAD TO AS GOOD REGRESSIONS AS THE COMBINATORIAL APPROACH DESCRIBED EARLIER, SOMETIMES THE USER MAY WISH TO VIEW THE BEHAVIOR OF THE MEAN SQUARED RESIDUAL AS VARIABLES ARE ADDED ALONG A SPECIFIC PATH OF FIT. THIS CAN BE DONE BY CHOOSING MAJOR PROCESSING ALTERNATIVES 0 OR 1 AND PUNCHING 'S' IN THE FIRST COLUMN OF THE SECOND CONTROL CARD, AND IN SUBSEQUENT COLUMNS WHERE A CUMULATIVE VALUE FOR THE MEAN SQUARED RESIDUAL IS DESIRED. ALTHOUGH NO 'BEST' REGRESSION ALONG THIS PATH WILL BE PROGRAM-SELECTED, THE USER CAN EASILY LOCATE IT BY INSPECTION. THE COMPLETE REGRESSION CONTAINING ALL VARIABLES ALONG THE PATH WILL NOT BE FITTED, EVEN WITH MAJOR PROCESSING ALTERNATIVE 1, UNLESS THE LAST SPECIFIED SET IS PUNCHED 'G'.

======================== COVARIANCE ANALYSIS ========================

THE SIMPLEST METHOD FOR ANALYZING COVARIANCE DOES NOT REQUIRE ORTHOGONAL DUMMY VARIABLES OR WEIGHTING INVERSELY ACCORDING TO GROUP SIZE, ALTHOUGH SUCH DEVICES IMPROVE ACCURACY WHEN MATRICES ARE ILL-CONDITIONED. IF (G) IS THE NUMBER OF GROUPS INTO WHICH OBSERVATIONS CAN MEANINGFULLY BE DIVIDED, AND IF (K) IS THE NUMBER OF INDEPENDENT VARIABLES, THEN 'REX' CAN EASILY ANALYZE COVARIANCE IN CASES WHERE (G+1)*(K+1) DOES NOT EXCEED 49, AND CAN HANDLE SLIGHTLY LARGER PROBLEMS WITH A BIT MORE TROUBLE.

USER MUST MODIFY SUBROUTINE 'TRNX' SO THAT AN ENLARGED OBSERVATION VECTOR IS DEFINED WITH (G+1) SETS OF (K+1) INDEPENDENT VARIABLES AND WITH ONE OR MORE DEPENDENT VARIABLES. THE (K) ACTUAL INDEPENDENT VARIABLES ARE PLACED IN THE FIRST (K) ELEMENTS, WHILE UNITY IS PLACED IN THE (K+1)TH ELEMENT. THIS SAME SET OF (K+1) VARIABLES IS ALSO PLACED IN THE SUBSEQUENT SET OF ELEMENTS WHOSE ORDINAL IS ONE GREATER THAN THAT FOR THE GROUP. ALL OTHER INDEPENDENT VARIABLES MUST BE EQUATED TO ZERO.

THREE REGRESSIONS MUST NOW BE SPECIFIED TO OBTAIN ALL NEEDED DATA. ALTHOUGH THEY ARE NOMINALLY SPECIFIED TO PASS THROUGH THE ORIGIN, THE CONSTANT DUMMY FORCES THEM TO PASS THROUGH THE MEAN. THE SAME MAXIMUM MATRIX SERVES ALL 3. THE FIRST, CALLED A1, REPRESENTS UNGROUPED DATA. THE SECOND, CALLED B1, ALLOWS DIFFERENT INTERCEPTS FOR EACH GROUP BUT REQUIRES POOLED SLOPES. THE THIRD ALLOWS EACH GROUP TO HAVE ITS OWN REGRESSION.

THE THIRD CONTROL CARDS FOR THESE REGRESSIONS WOULD APPEAR AS FOLLOWS WHERE THERE WERE 6 GROUPS WITH 3 INDEPENDENT AND 2 DEPENDENT VARIABLES, AS IN THE LAST EXAMPLE OF INPUT IN APPENDIX B -----

```
A1'S CARD ===XXXX                        YY=
B1'S CARD ===XXX    X   X   X   X   X   XYY=
C1'S CARD ===    XXXXXXXXXXXXXXXXXXXXXXXXYY=
```

FROM THE 3 OUTPUTS THUS SECURED, THE DEGREES OF FREEDOM (DFS) AND SUMS OF SQUARES (SS) ATTRIBUTABLE TO REGRESSION (R) AND TO ERROR (E) CAN BE OBTAINED, ALONG WITH THE MEAN SQUARED RESIDUALS (MSQR) OR ERROR VARIANCES. NEXT (A1E MINUS B1E) AND (B1E MINUS C1E) ARE COMPUTED BY HAND, BOTH FOR DFS AND FOR SS. LASTLY, CORRECTION TERMS MUST BE SUBTRACTED FROM B1R (BOTH DFS AND SS). THE APPROPRIATE SUBTRACTION IN THE CASE OF B1R DFS IS UNITY, WHILE IN THE CASE OF B1R SS, IT IS (SQUARED MEAN Y)*(NUMBER OF OBSERVATIONS).

AN ANALYSIS OF COVARIANCE USUALLY DETERMINES THE FOLLOWING (DEGREES OF FREEDOM FOR 'F' CAN BE INFERRED FROM SS OR MSQR) ---

F = (CORRECTED B1R SS)/((B1E MSQR)*(CORRECTED B1R DFS))
FOR SIGNIFICANCE OF POOLED REGRESSION COEFFICIENTS

F = (B1E SS MINUS C1E SS)/((C1E MSQR)*(B1E DFS MINUS C1E DFS))
FOR SIGNIFICANCE OF DIFFERENCES AMONG SLOPES OF INDIVIDUAL GROUP REGRESSIONS

F = (A1E SS MINUS B1E SS)/((B1E MSQR)*(A1E DFS MINUS B1E DFS))
FOR SIGNIFICANCE OF DIFFERENCES AMONG GROUP INTERCEPTS WHEN SLOPES ARE POOLED (TEST OF DIFFERENCES AMONG ADJUSTED MEANS)

GENERALLY, THERE IS LITTLE USE IN CONDUCTING THE SECOND AND THIRD TESTS UNLESS THE FIRST SHOWS SIGNIFICANCE. SIMILARLY, THE THIRD TEST IS USUALLY OMITTED EXCEPT WHERE A SIGNIFICANT FIRST TEST AND A NONSIGNIFICANT SECOND TEST HAVE OCCURRED.

POOLED SLOPE COEFFICIENTS AND INDIVIDUAL GROUP INTERCEPTS MAY BE READ DIRECTLY FROM THE OUTPUT OF REGRESSION B1, WHILE INDIVIDUAL GROUP REGRESSION SLOPES AND INTERCEPTS OCCUR IN SETS OF (K+1) ENTITIES IN THE OUTPUT OF REGRESSION C1. THE VARIANCES OF THESE COEFFICIENTS ARE DERIVED FROM THE POOLED SUM OF SQUARED RESIDUALS FROM INDIVIDUAL REGRESSIONS RATHER THAN FROM SUM FOR JUST THE PARTICULAR GROUP, BUT OTHERWISE HAVE VALIDITY. THE OUTPUT OF MEANS AND VARIANCES FOR C1 REQUIRES SOME DECODING TO PLACE THEM ON AN INDIVIDUAL GROUP BASIS, BUT COMPUTATIONS ARE SIMPLE AND OBVIOUS.

AN ANALOGOUS PROCEDURE CAN BE FOLLOWED WITH ORTHOGONAL DUMMY VARIABLES SECURED FROM DELURY'S TABLES (*2) IF ALL 3 REGRESSIONS ARE SPECIFIED TO PASS THROUGH THE MEAN INSTEAD OF THE ORIGIN. HOWEVER, EACH GROUP MUST BE CHARACTERIZED BY (G-1) DUMMIES AND THEIR SUITABLY LOCATED CROSSPRODUCTS WITH THE (K) REAL VARIABLES, INSTEAD OF SIMPLY BY THE LOCATION OF A SECOND SET OF THE REAL VARIABLES AND UNITY. THESE DUMMIES MUST BE DIVIDED BY GROUP SIZE UNLESS ALL GROUPS CONTAIN THE SAME NUMBER OF OBSERVATIONS. ALTHOUGH NO CORRECTION IS NEEDED FOR THE SECOND REGRESSION (A0, B0, C0 WILL BE USED TO DISTINGUISH REGRESSIONS THROUGH THE MEAN HAVING ORTHOGONAL DUMMY VARIABLES), EACH GROUP INTERCEPT AND INDIVIDUAL GROUP COEFFICIENT MUST BE CALCULATED AS THE SEPARATE SUM OF (G) QUANTITIES, (G-1) OF WHICH ARE SECURED AS THE PRODUCT OF A DUMMY COEFFICIENT MULTIPLIED BY A DUMMY VARIABLE APPROPRIATE TO THAT PARTICULAR GROUP. PROBLEMS WHERE (G*(K+1)-1) DOES NOT EXCEED 49 CAN BE SIMPLY HANDLED BY THIS TECHNIQUE. LARGER PROBLEMS WILL REQUIRE GETTING THE C0 OR C1 REGRESSION COMPONENTS FROM SUMMING QUANTITIES SECURED BY SEPARATING DATA INTO GROUPS AND FITTING EACH GROUP REGRESSION INDIVIDUALLY. EXAMPLES A0RX, B0RX, C0RX IN APPENDIX B ILLUSTRATE COVARIANCE INPUT USING ORTHOGONAL POLYNOMIALS.

THE SIMPLER COVARIANCE PROCEDURE (USING UNITY AS A DUMMY VARIABLE WITH THE SAME RAW INPUT DATA) IS ILLUSTRATED BY EXAMPLES A1RX, B1RX, C1RX IN APPENDIX B. FORMAL REQUIREMENT THAT THE REGRESSIONS PASS THROUGH ORIGIN IS EFFECTIVELY CANCELLED BY USE OF UNITY AS A DUMMY VARIABLE.

IT CAN BE SEEN THAT THERE ARE 6 GROUPS, EACH CONTAINING 5 SETS OF OBSERVATIONS. ALTERATIONS TO 'TRNX' SHOW THAT THE GROUP CODE IS READ AS RAW VARIABLE D(2), AND THAT RAW VARIABLES D(3), D(6), D(10) SERVE AS FINAL VARIABLES X(1), X(2), X(3), WITH X(4) ALWAYS BEING UNITY. ADDITIONALLY, EXACTLY THE SAME SET OF VARIABLES IS STORED IN A SEQUENCE OF 4 X'S APPROPRIATE TO THE OBSERVED GROUP CODE. THE OTHER SUPERFLUOUS GROUPS OF 4 X'S ARE SET TO ZERO, WHILE THE 2 DEPENDENT VARIABLES ORIGINALLY READ AS D(11) AND D(12) ARE MOVED TO X(29) AND X(30) AT THE END OF THE 7 SEQUENCES OF 4 X'S RESERVED FOR THE POOLED REGRESSION AND 6 INDIVIDUAL GROUP REGRESSIONS. FROM THE SUBSEQUENT OUTPUT THAT REX PRODUCES, QUANTITIES APPEARING IN THE MULTIPLE COVARIANCE ANALYSIS BELOW ARE EASILY OBTAINED.

SOURCE	DFS	29Y SS	30Y SS	29Y MSQR	30Y MSQR
A1E	26	2187.50	1173.59		
B1E	21	28.80	731.73	1.371	34.84
C1E	6	21.94	71.64	3.657	11.94
B1R(+)	9	9426.20	4074.27		
(UNCORRECTED LINE ABOVE NEEDS CORRECTION TERMS BELOW)					
CORR.(-)	1	7207.50	3456.13		
B1R=B1R(+)-CORR.	8	2218.70	618.14		
AB = A1E-B1E	5	2158.70	441.87		
BC = B1E-C1E	15	6.86	660.09		

TO TEST SIGNIFICANCE OF DIFFERENCES OF POOLED REGRESSION COEFFICIENTS FROM ZERO --

F=(B1R SS)/((B1R DFS)*(B1E MSQR))=202.2** FOR 29Y.
= 2.22 FOR 30Y.
DFS= 8/21

TO TEST SIGNIFICANCE OF DIFFERENCES OF INDIVIDUAL GROUP REGRESSION COEFFICIENTS FROM POOLED REGRESSION COEFFICIENTS --

F= (BC SS)/((BC DFS)*(C1E MSQR))= .13 FOR 29Y.
= 3.69 FOR 30Y.
DFS=15/6

TO TEST SIGNIFICANCE OF DIFFERENCES AMONG INDIVIDUAL GROUP MEANS ADJUSTED BY POOLED REGRESSION COEFFICIENTS (INTERCEPT DIFFERENCES) --

F= (AB SS)/((AB DFS)*(B1E MSQR))=314.8** FOR 29Y.
= 2.54 FOR 30Y.
DFS= 5/21

================ BACKGROUND AND DEVELOPMENT OF SYSTEM ================

PROGRAM LOGIC IS BRIEFLY AS FOLLOWS. 'REX' IS THE EXECUTIVE ROUTINE (OR ZERO LINK IN THE OVERLAY STRUCTURE) THAT CONTROLS ALL OTHER SUBROUTINES. 'PALM' INTERPRETS CONTROL CARDS 2 AND 3. THEN 'MATX' WITH 'TRNX' HANDLE DATA INPUT, TRANSFORMATIONS, CORRECTIONS TO CURRENT OR EARLIER DATA INPUT, AND WHATEVER PUNCHED-CARD OUTPUT THE USER MAY HAVE SPECIFIED. THEN, DEPENDING ON USER'S CHOICE OF MAJOR PROCESSING OPTIONS, CONTROL PASSES EITHER TO 'SKRN', TO 'SKRN' FOLLOWED BY 'CBXR', TO 'CBXR' ALONE, OR TO SOME USER-SUPPLIED SET OF SUBROUTINES WHICH MAY INCLUDE 'SKRN' AND/OR 'CBXR'. FINALLY, CONTROL RETURNS TO 'REX' FOR STARTING ON THE NEXT PROBLEM IN THE STACK.

THE BROAD OUTLINE FOR 'REX' WAS CONCEIVED BY THE AUTHOR AS A RESULT OF HIS EXPERIENCE IN DESIGNING AND USING A GROUP OF REGRESSION PROGRAMS FOR THE IBM 704 IN THE PERIOD 1957-60, THE FIRST OF WHICH WAS DESIGNATED G2-TV-REM (SHARE DISTRIBUTION AGENCY NUMBER 822). THIS WAS THE FIRST COMBINATORIAL APPROACH TO REGRESSION SCREENING, MADE POSSIBLE BY THE REVOLUTIONARY SPEEDS OF NEW ELECTRONIC COMPUTERS (*4). 'REM' WAS SOON SUPPLEMENTED BY 'REA' FOR MATRIX INPUT, 'XXR' FOR ACCUMULATION OF LARGER CORRELATION MATRICES, AND 'CBY' AND 'CBZ' FOR FITTING PARTICULAR REGRESSIONS BY THE MODIFIED FISHER-DOOLITTLE METHOD.

IN CONTRAST TO THE COMBINATORIAL APPROACH WHICH EXPLORES ALL POSSIBLE LINEAR COMBINATIONS OF VARIABLES WITHIN CERTAIN CONSTRAINTS IMPOSED TO KEEP THE DIMENSIONS OF THE PROBLEM WITHIN COMPUTABLE LIMITS, THE MORE WIDELY KNOWN STEPWISE APPROACH ADDS OR DELETES ONE VARIABLE AT A TIME TO SOME PREVIOUSLY SELECTED GROUP OF VARIABLES. UNFORTUNATELY, THIS PROCESS IS NOT CAPABLE OF FINDING THE COMBINATION OF INDEPENDENT VARIABLES THAT BEST EXPLAINS THE VARIATION OF THE DEPENDENT VARIABLE (EXCEPT IN THE TRIVIAL CASE INVOLVING NO MORE THAN 2 VARIABLES), AND MOST TESTS OF SIGNIFICANCE APPLIED TO REJECTION OR ACCEPTANCE OF VARIABLES FOR A GIVEN STEP ARE INVALID.

IT WAS THE AUTHOR'S DISSATISFACTION WITH THE MORE POPULAR STEPWISE PROCEDURE WHICH CAUSED HIM TO EXPLORE THE COMBINATORIAL APPROACH. HE EARLY DISCOVERED THAT SUMS OF SQUARES OR MULTIPLE CORRELATION COEFFICIENTS WERE NOT GOOD CRITERIA FOR DETERMINING THE 'BEST' REGRESSION FOR A PARTICULAR SET OF OBSERVATIONS, BECAUSE THEY INCREASED OR DECREASED MONOTONICALLY AS THE NUMBER OF VARIABLES INCREASED. HOWEVER, THE MEAN SQUARED RESIDUAL (OR VARIANCE OF THE REGRESSION ESTIMATE) IS NOT A MONOTONIC FUNCTION, BUT FLUCTUATES IN AN UNPREDICTABLE MANNER CEPENDING ON BOTH SUMS OF SQUARES AND DEGREES OF FREEDOM. IT IS A FIGURE OF MERIT WHOSE MINIMUM FLAGS A 'BEST BET'.

THE FIRST EXAMPLE IN APPENDIX B ('ABST') HAS OUTPUT FROM MAJOR OPTION 1 SHOWN IN APPENDIX C, AND ILLUSTRATES A SITUATION WHERE THE COMBINATORIAL APPROACH SUCCEEDS IN FINDING THE 'BEST' REGRESSION (INVOLVING VARIABLES 5, 6, 7).

STARTING WITH EXACTLY THE SAME DATA, NEITHER THE ASCENDING NOR THE DESCENDING STEPWISE REGRESSION ANALYSIS CAN REACH THE CORRECT ANSWER, SINCE THEIR SELECTION OF PATHS IS IRREVOCABLY LIMITED BY INITIAL INCLUSION OF VARIABLES 1 AND 2 OR BY INITIAL DELETION OF VARIABLES 5, 6, AND 7.

ALTHOUGH NO ONE CAN SAY WITH ASSURANCE THAT ANY VARIANCE IS A GLOBAL MINIMUM UNLESS ALL POSSIBLE COMBINATIONS HAVE BEEN TRIED, EXPERIENCE HAS SHOWN THAT THE 'BEST' COMBINATION FROM A LARGE NUMBER OF VARIABLES USUALLY DOES NOT INVOLVE MORE THAN 3 TO 7 VARIABLES. HENCE, THE INTRODUCTION OF SOME SUCH MODERATE LIMIT TO KEEP THE PROBLEM WITHIN CAPABILITIES OF THE PROGRAM USUALLY WILL NOT CHANGE THE OUTCOME.

THE PRESENT PROGRAM REFLECTS THE FOREGOING AS WELL AS A NUMBER OF ADDITIONAL IMPROVEMENTS STEMMING FROM THE AUTHOR'S EXPERIENCE. THERE ARE SEVERAL MAJOR IMPROVEMENTS FOR WHICH OTHERS SHOULD BE CREDITED, HOWEVER.

FURNIVAL (*3) REALIZED THAT RESIDUALS FROM REGRESSION COULD BE COMPUTED BY DETERMINANTS (METHOD OF SINGLE DIVISION) MUCH MORE EASILY THAN BY THE USUAL METHOD INVOLVING MATRIX INVERSION, IF OTHER REGRESSION STATISTICS WERE SACRIFICED. THIS MADE THE COEFFICIENT OF COLLINEARITY CHEAPLY AVAILABLE AS A BYPRODUCT. HE ALSO DEVISED AN INGENIOUS COMPUTATIONAL SEQUENCE TO MINIMIZE DETERMINANTAL ARITHMETIC, AND RECOGNIZED THAT SET AND GROUP CONSTRAINTS MIGHT BE USEFUL TOOLS FOR KEEPING PROBLEM DIMENSIONS WITHIN REASONABLE BOUNDS. THESE IMPROVEMENTS HAVE BEEN EMBODIED IN SUBROUTINE 'SKRN'.

THE AUTHOR ORIGINALLY FELT THAT ACCUMULATION OF THE MATRIX OF SUMS OF SQUARES AND CROSSPRODUCTS FROM OBSERVATION VECTORS COULD BE MOST ACCURATELY AND EFFICIENTLY ACHIEVED BY INTEGER ARITHMETIC WITH MULTIPLE PRECISION, AS HE DID IN 'XXR'. RODDEN (*7) LATER SUPPORTED THIS VIEW, BUT THE AUTHOR DECIDED AGAINST IT IN 'REX' BECAUSE ASSEMBLY LANGUAGE WOULD BE REQUIRED IN AN OTHERWISE ALL-FORTRAN PROGRAM.

WELFORD'S TECHNIQUE (*9) INVOLVING USE OF SINGLE-PRECISION, FLOATING-POINT, PROGRESSIVE AVERAGES WAS EMPLOYED INITIALLY, BUT ITS NOTICEABLE INACCURACY ON SMALL TEST PROBLEMS WAS A DISAPPOINTMENT. NEELY (*6) LATER DOCUMENTED SIMILAR EXPERIENCE.

FINALLY, THE STRAIGHTFORWARD USE OF A SINGLE PASS WITH DOUBLE-PRECISION FLOATING-POINT ARITHMETIC SEEMED PREFERABLE TO THE USE OF TWO PASSES WITH SINGLE-PRECISION FLOATING-POINT ARITHMETIC (FIRST PASS TO COMPUTE MEANS, SECOND PASS TO CODE DEVIATIONS AND FORM CROSSPRODUCTS). HENCE, FORMATION OF MATRIX AND ITS SUBSEQUENT CORRECTION FOR MEANS (IF SPECIFIED) ARE PERFORMED WITH DOUBLE-PRECISION, BUT THE FINAL MATRIX IS STORED WITH SINGLE-PRECISION.

RECENT IMPROVEMENTS IN HIGH-SPEED COMPUTERS HAVE MADE THE SQUARE-ROOT METHOD OF MATRIX INVERSION MUCH MORE ATTRACTIVE THAN THE MODIFIED JORDAN ELIMINATION METHOD FOR SYMMETRIC MATRICES, ESPECIALLY IF THEY HAPPEN TO BE ILL-CONDITIONED. BODEWIG (*1) POINTS THIS OUT, ALTHOUGH DWYER AND OTHERS SURMISED THE SAME THING PRIOR TO THE AVAILABILITY OF MODERN COMPUTERS. CONSEQUENTLY, THE AUTHOR WROTE A DOUBLE-PRECISION FORTRAN-4 MATRIX INVERTER FOR 'REX' THAT USES THE SQUARE-ROOT METHOD.

THUS, REX EMPLOYS DOUBLE-PRECISION ARITHMETIC FOR ACCUMULATION AND CORRECTION OF MOMENT MATRIX, FOR MATRIX INVERSION BY THE SUPERIOR SQUARE-ROOT METHOD, AND FOR COMPUTATION OF MOST OF THE IMPORTANT REGRESSION STATISTICS. HENCE, 'REX' RETAINS MORE SIGNIFICANT DIGITS THAN DO LEAST-SQUARES PROGRAMS TESTED BY LONGLEY (*5), WHICH EMPLOYED SINGLE-PRECISION ARITHMETIC AND LESS ACCURATE INVERSION METHODS.

REGRESSION STATISTICS FOR 'REX' ARE COMPUTED BY THE MODIFIED FISHER-DOOLITTLE METHOD DESCRIBED IN (*8). HOWEVER, STANDARDIZED REGRESSION COEFFICIENTS ARE NOT CALCULATED UNLESS REQUESTED. CODING OF MATRIX ELEMENTS PRIOR TO MATRIX INVERSION IS ALWAYS BY DIVISION BY SQUARE-ROOT OF PRODUCT OF DIAGONAL ELEMENTS WITH SUBSCRIPTS INVOLVED, SO THE MATRIX DOES NOT BECOME A TRUE CORRELATION MATRIX EXCEPT WHERE REGRESSION THROUGH MEAN HAS BEEN SPECIFIED. RSQUARED THEREFORE, IS MERELY THE RATIO OF TWO SUMS OF SQUARES WHEN REGRESSION THROUGH ORIGIN HAS BEEN SPECIFIED. THE MAIN ARGUMENT IN FAVOR OF SUCH CODING IS THAT IT IMPROVES MATRIX CONDITION.

THE AUTHOR CONSIDERED USING HIS COMBINATORIAL GENERATOR DEVELOPED FOR ANALYSIS OF VARIANCE PROGRAM G4-BC-ANV (SHARE DISTRIBUTION AGENCY NUMBER 3337), WHICH COULD HAVE HANDLED AN UNLIMITED NUMBER OF GROUPS COMBINATORIALLY WITHOUT ANY PRACTICAL STORAGE LIMITATION, BUT MATRIX OPERATIONS AFTER EACH GENERATION WOULD START ANEW, WHICH INVOLVED A CONSIDERABLE EXTRA EXPENDITURE OF TIME, SO THE IDEA WAS DISCARDED. PERSONS INTERESTED IN MASSIVE COMBINATORIAL ANALYSES MIGHT STILL WISH TO EMPLOY THIS ALTERNATIVE BY MODIFYING THE PRESENT VERSION OF 'SKRN'.

IN VIEW OF THE RELIABILITY OF THIRD-GENERATION SOLID-STATE COMPUTERS, THE ELABORATE SUM AND PRODUCT CHECKS OF 'REM', 'XXR'. 'CBY', AND 'CBZ' HAVE BEEN DISCARDED. NO CHECKS AT ALL HAVE BEEN PROVIDED FOR THE SIMPLE SCREENING OPTION (MAJOR PROCESSING ALTERNATIVE 0), BUT MOST MACHINE ERRORS WOULD CAUSE OUTPUT FIELD OVERFLOW FLAGGED BY MONITOR. MAJOR PROCESSING ALTERNATIVE 1 HAS RMSQR OF BEST REGRESSIONS COMPUTED BY 2 INDEPENDENT PROCEDURES. MAJOR PROCESSING ALTERNATIVES 1 AND 2 (WITH PREDICTIONS) HAVE SUM OF SQUARED RESIDUALS COMPUTED BY 2 INDEPENDENT PROCEDURES, AND IF REGRESSION IS THROUGH MEAN, THE SUM OF RESIDUALS SHOULD APPROXIMATE ZERO FOR AN ADDITIONAL CHECK.

DYNAMIC MODIFICATION OF FORMATS STORED AS BCD ARRAYS SAVES SPACE AND HAS BEEN USED FREELY, ALTHOUGH THE AUTHOR ATTEMPTED TO MAINTAIN COMPATIBILITY BETWEEN MACHINES INCAPABLE OF HANDLING FORMATS BIGGER THAN A4 (IBM 360, CDC 3500) AND THOSE CAPABLE OF HANDLING A6 (SUCH AS THE IBM 7040-7044, 7090-7094, CDC 6400-6600).

=========== AIDS FOR USERS MODIFYING OR EXPANDING SYSTEM ===========

'REX' HAS BEEN DESIGNED AS AN OPEN-ENDED SYSTEM RATHER THAN AS A SINGLE PROGRAM. HENCE, USERS WISHING TO EXPAND IT CAN CALL ON OTHER MAJOR PROCESSING OPTIONS OF THEIR OWN. THIS WOULD MERELY INVOLVE PUNCHING AN APPROPRIATE INTEGER (FROM 3 THROUGH 9) IN COLUMN 67 OF OF THEIR SECOND CONTROL CARD AND REPLACING CORRESPONDING FORTRAN STATEMENT NUMBERED 300 THROUGH 900 IN 'REX' BY AN APPROPRIATE 'CALL'.

WITH A LITTLE ADDITIONAL PROGRAMMING, SUCH EXPANSIONS CAN EMPLOY 'PALM', 'MATX', AND 'TRNX' FOR INPUT PROCESSING AND ACCUMULATIONS, AND 'CBXR' FOR INTERMEDIATE CALCULATIONS. LOCATIONS OF RESULTS OBTAINED AND PRESERVED BY 'CBXR' ARE GIVEN BELOW.

ELEMENTS OF THE MOMENT MATRIX INVERSE (AUGMENTED BY C(I,U) WHERE APPROPRIATE) ARE STORED DOUBLE-PRECISION IN UPPER TRIANGLE OF A(I,J). B(I,K),THE MATRIX OF REGRESSION COEFFICIENTS, IS STORED SINGLE-PRECISION IN VB(I,K) AND DOUBLE-PRECISION IN B(I,K), WITH B(U,K) FOLLOWING THE LAST REAL COEFFICIENT WHERE APPROPRIATE. VB(51,K) CONTAINS RSQUARED, WHILE B(51,K) AND V(51,K) EACH CONTAIN THE VARIANCE OF THE REGRESSION ESTIMATE. VARIANCES OF THE REGRESSION COEFFICIENTS ARE STORED SINGLE-PRECISION IN V(I,K).

IT SHOULD BE NOTED THAT NEITHER OF THE DOUBLE-PRECISION ARRAYS 'A' AND 'B' IS IN COMMON STORAGE CURRENTLY. USERS WOULD HAVE TO DECLARE THEM AS LABELLED COMMON IF THEY ARE TO BE MADE AVAILABLE TO TO ANY OTHER SUBROUTINE THAN 'CBXR' IN THE SAME LINK AS 'CBXR'.

MNC(K) CONTAINS THE NUMBER OF INDEPENDENT VARIABLES INVOLVED, AND SUBSCRIPTS OF BOTH INDEPENDENT AND DEPENDENT VARIABLES ARE STORED IN KX(I). H(K,1) CONTAINS RSQUARED, H(K,2) CONTAINS (1-RSQUARED), AND H(K,3) CONTAINS TOTAL SUM OF SQUARED DEVIATIONS ABOUT MEAN Y OR ABOUT ORIGIN, ALL SINGLE-PRECISION. U(K) CONTAINS 'RMSQR', THE SINGLE-PRECISION VARIANCE OF REGRESSION ESTIMATE RELATIVE TO VARIANCE ABOUT MEAN.

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(*3) FURNIVAL, G.M. 1965. MORE ON THE ELUSIVE FORMULA OF BEST FIT. PROCEEDINGS SOC. AMER. FORESTERS MEETING SEPT. 27-OCT. 1, 1964, DENVER, COL. (WASHINGTON, D. C.), PP. 201-207.

(*4) GROSENBAUGH, L.R. 1958. THE ELUSIVE FORMULA OF BEST FIT -- A COMPREHENSIVE NEW MACHINE PROGRAM. U. S. FOREST SERV. SOUTH. FOREST EXPT. STA. OCCAS. PAPER 158, NEW ORLEANS, LA. 9 PP.

(*5) LONGLEY, J. W. 1967. AN APPRAISAL OF LEAST SQUARES PROGRAMS FOR THE ELECTRONIC COMPUTER FROM THE POINT OF VIEW OF THE USER. JOUR. AMER. STATIS. ASSOC. 62, PP. 819-829.

(*6) NEELY, P. M. 1966. COMPARISON OF SEVERAL ALGORITHMS FOR COMPUTATION OF MEANS, STANDARD DEVIATIONS AND CORRELATION COEFFICIENTS. COMMUNICATIONS OF THE ACM 9, PP. 496-499.

(*7) RODDEN, B. E. 1967. ERROR-FREE METHODS FOR STATISTICAL COMPUTATIONS. COMMUNICATIONS OF THE ACM 10, PP. 179-180.

(*8) WALKER, H. M., AND J. LEV. 1953. STATISTICAL INFERENCE. HENRY HOLT AND CO., NEW YORK CITY. 510 PP.

(*9) WELFORD, B. P. 1962. NOTES ON A METHOD FOR CALCULATING CORRECTED SUMS OF SQUARES AND PRODUCTS. TECHNOMETRICS 4, PP. 419-420.

APPENDIX A

'REX' SOURCE DECK ARRANGEMENTS AND MODIFICATIONS NEEDED BY DIFFERENT COMPUTERS

ARRANGEMENT OF PROGRAM DECKS FOR INPUT WITH APPROPRIATE OVERLAY CONTROL CARDS FOR USE ON IBM 7090-7094 UNDER IBSYS

```
=======================================================================================
```

```
$JOB   XX      5,150,800            GROSENBAUGH-59.REX
$IBJOB REX     MAP
$IBFTC TRNXHH  DECK                                                     TRNX     0
$IBMAP BUFK    DECK                                                     BUFK     0
$IBMAP UNO4    DECK                                                     UNO4     0
$IBMAP UNO8    DECK                                                     UNO8     0
$IBFTC REX     DECK                                                     REX      0
$IBFTC BLRM    DECK                                                     BLRM     0
      DATA MRE/ 5/,MPR/ 6/,MPU/ 7/,JW/ 4/,JX/ 8/,MEOF/0/                BLRM    44
   (ASSIGNMENTS APPROPRIATE TO INSTALLATION I/O CONFIGURATION)
$ORIGIN        ABLE
$IBFTC PALMHH  DECK                                                     PALM     0
$IBFTC MATXHH  DECK                                                     MATX     0
$ORIGIN        ABLE,REW
$IBFTC SKRNHH  DECK                                                     SKRN     0
$ORIGIN        ABLE,REW
$IBFTC CBXRHH  DECK                                                     CBXR     0
$ENTRY         REX
$DATA
   (FOLLOWED BY APPROPRIATE DATA DECK)
$EOF
```

ARRANGEMENT OF PROGRAM DECKS FOR INPUT WITH APPROPRIATE CHAIN CONTROL CARDS AND CHANGES FOR USE ON IBM 7040-7044 UNDER IBSYS

```
$JOB        T        592026        GROSENBAUGH-8   18  20REXSKN          26
$*SCRATCH       L2 AND L3
$OPEN           S.SU02=I01,S.SU03=I02
$IBJOB REX      MAP
$CHAIN REX      U04
$NAME           SJXIT=S.JXIT
$IBFTC TRNXHH   DECK                                                 TRNX    0
$IBMAP BUFK     DECK                                                 BUFK    0
$IBFTC BLRM     DECK                                                 BLRM    0
      DATA MRE/ 5/,MPR/ 6/,MPU/ 7/,JW/ 2/,JX/ 3/,MEOF/0/             BLRM   44
   (ASSIGNMENTS APPROPRIATE TO INSTALLATION I/O CONFIGURATION)
$IBFTC REX      DECK                                                 REX     0
      CALL CHAIN(1)                                                  REX    67
      CALL CHAIN(1)                                                  REX    70
      CALL CHAIN(2)                                                  REX    75
  200 CALL CHAIN(1)                                                  REX    83
  250 CALL CHAIN(3)                                                  REX    85
 1000 CALL SJXIT                                                     REX   102
$ENTRY          REX
$LINK  LINK1
$IBFTC PALMHH   DECK                                                 PALM    0
C     SUBROUTINE PALM                                                PALM    1
   231(NONFIXED) REGRESSIONS (CURRENTLY MUST NOT EXCEED LPP= 8200/(NY+1)PALM  63
  200 LPP= 8200/NYY                                                  PALM  284
      CALL CHNXIT                                                    PALM  375
$IBFTC MATXHH   DECK                                                 MATX    0
$ENTRY
$LINK  LINK2
$IBFTC SKRNHH   DECK                                                 SKRN    0
C     SUBROUTINE SKRN                                                SKRN    1
     1A( 8200),ORD( 2),RMS( 2),OFS( 2),VOL( 2),DEN(6)                SKRN   11
      CALL CHNXIT                                                    SKRN  337
$ENTRY
$LINK  LINK3
$IBFTC CBXRHH   DECK                                                 CBXR    0
C     SUBROUTINE CBXR                                                CBXR    1
  261 CALL CHNXIT                                                    CBXR  308
$ENTRY
$ENDCH
   (FOLLOWED BY APPROPRIATE DATA DECK)
$IBSYS
```

ARRANGEMENT OF PROGRAM DECKS FOR INPUT WITH APPROPRIATE OVERLAY CONTROL CARDS AND CHANGES FOR USE ON CDC 6400-6600 UNDER SCOPE 3.0

```
JXXXXAA,7,300,55000.XXXX,GROSENBAUGH-51.REX
RUN(P,55000,,,,,12000,1,1)
LGO.
EXIT.
DMP(101,3336)
DMP(3336,6062)
CDC RECORD SEPARATOR CARD, WITH 7,8,9 PUNCHED IN COLUMN ONE.
      OVERLAY(REXO,0,0)
     OPROGRAM REX(INPUT,OUTPUT,PUNCH,TAPE5=INPUT,TAPE6=OUTPUT,
     1TAPE7=PUNCH,TAPE4,TAPE8)
$IBFTC REX      DECK                                                    REX     0
      CALL OVERLAY(4HREXO,1,0,6HRECALL)                                 REX    67
      CALL OVERLAY(4HREXO,1,0,6HRECALL)                                 REX    70
      CALL OVERLAY(4HREXO,2,0,6HRECALL)                                 REX    75
  200 CALL OVERLAY(4HREXO,1,0,6HRECALL)                                 REX    83
  250 CALL OVERLAY(4HREXO,3,0,6HRECALL)                                 REX    85
$IBFTC BLRM     DECK                                                    BLRM    0
      DATA MRE/ 5/,MPR/ 6/,MPU/ 7/,JW/ 4/,JX/ 8/,MEOF/0/                BLRM   44
   (ASSIGNMENTS APPROPRIATE TO PROGRAM CARD I/O EQUIVALENCES)
$IBFTC TRNXHH   DECK                                                    TRNX    0
      OVERLAY(1,0)
$IBFTC PALMHH   DECK                                                    PALM    0
C     SUBROUTINE PALM                                                   PALM    1
   231(NONFIXED) REGRESSIONS (CURRENTLY MUST NOT EXCEED LPP= 8200/(NY+1)PALM   63
  200 LPP= 8200/NYY                                                     PALM  284
$IBFTC MATXHH   DECK                                                    MATX    0
      REAL             SS(1326),Z(51)                                   MATX    6
      OVERLAY(2,0)
$IBFTC SKRNHH   DECK                                                    SKRN    0
C     SUBROUTINE SKRN                                                   SKRN    1
     1A( 8200),ORD(2),RMS(2),OFS(2),VOL(2),DEN(6)                       SKRN   11
      OVERLAY(3,0)
$IBFTC CBXRHH   DECK                                                    CBXR    0
C     SUBROUTINE CBXR                                                   CBXR    1
     OREAL             A(51,51),B(51,8),DD(51),XX(51),YY(8),P,PP,PPP,QQ,CBXR   10
     4DZ/.0E 00/,D1/.1E 01/                                             CBXR   54
      DD(I)= SQRT (DD(I))                                               CBXR  152
      YY(JJ)= SQRT (DD(I))                                              CBXR  160
      A(J,J)= SQRT (A(J,J)-P)                                           CBXR  277
CDC RECORD SEPARATOR CARD, WITH 7,8,9 PUNCHED IN COLUMN ONE.
   (FOLLOWED BY APPROPRIATE DATA DECK)
CDC END-OF-FILE CARD, WITH 6,7,8,9 PUNCHED IN COLUMN ONE.
```

ARRANGEMENT OF PROGRAM DECKS FOR PART SOURCE AND PART BINARY INPUTS TO CDC 6400-6600 UNDER SCOPE 3.0

```
JXXXXAA,7,300,55000.XXXX,GROSENBAUGH-51.REX
RUN(S,55000,,,,,12000,1,1)
LOAD(INPUT)
LOAD(LGO)
LOAD(INPUT)
EXECUTE,REX.
CDC RECORD SEPARATOR CARD, WITH 7,8,9 PUNCHED IN COLUMN ONE.
$IBFTC TRNXHH  DECK (TRANSGENERATION SOURCE PROGRAM SUPPLIED BY USER)   TRNX   0
CDC RECORD SEPARATOR CARD, WITH 7,8,9 PUNCHED IN COLUMN ONE.
   (FOLLOWED BY BINARY DECKS FOR ALL OF 'REX' LINK (0,0) EXCEPT 'TRNX')
CDC RECORD SEPARATOR CARD, WITH 7,8,9 PUNCHED IN COLUMN ONE.
   (FOLLOWED BY BINARY DECKS FOR ALL OF 'REX' LINKS (1,0),(2,0),(3,0))
CDC RECORD SEPARATOR CARD, WITH 7,8,9 PUNCHED IN COLUMN ONE.
   (FOLLOWED BY APPROPRIATE DATA DECK)
CDC END-OF-FILE CARD, WITH 6,7,8,9 PUNCHED IN COLUMN ONE.
```

ARRANGEMENT OF PROGRAM DECKS FOR INPUT WITH APPROPRIATE CONTROL CARDS AND CHANGES FOR USE WITH IBM 360 UNDER OPERATING SYSTEM 360

```
//JYYYYRX  JOB  (YYYY,50,50,1000),GROSENBAUGH,MSGLEVEL=1
//CLG  EXEC  FORTGCLG,PARM.FORT='DECK,LOAD,SOURCE,BCD,NAME=REX',          X1
//              PARM.LKED='XREF,LET,LIST,OVLY',COND.GO=(16,LT)             2
//FORT.SYSIN  DD  *
 (USE DECKS DENOTED BY FOLLOWING LABELS, BUT DELETE ALL $IBMAP AND $IBFTC CARDS)
C REX--REGRESSION EXECUTIVE PROGRAM (GROSENBAUGH 05-01-67)               REX    1
      BLOCK DATA                                                        BLRM   1
      DATA MRE/ 5/,MPR/ 6/,MPU/ 7/,JW/ 4/,JX/ 8/,MEOF/0/                BLRM  44
   (ASSIGNMENTS APPROPRIATE TO INSTALLATION I/O CONFIGURATION AND DD CARDS)
      SUBROUTINE TRNX                                                   TRNX   1
      SUBROUTINE PALM                                                   PALM   1
   231(NONFIXED) REGRESSIONS (CURRENTLY MUST NOT EXCEED LPP= 8200/(NY+1)PALM  63
  200 LPP= 8200/NYY                                                     PALM 284
      SUBROUTINE MATX                                                   MATX   1
      SUBROUTINE SKRN                                                   SKRN   1
     1A( 8200),ORD(2),RMS(2),OFS(2),VOL(2),DEN(6)                       SKRN  11
      SUBROUTINE CBXR                                                   CBXR   1
/*
//LKED.SYSIN  DD  *
  OVERLAY ABLE
  INSERT PALM#,MATX#
  OVERLAY ABLE
  INSERT SKRN#
  OVERLAY ABLE
  INSERT CBXR#
  ENTRY REX
/*
//GO.FT04F001  DD  DSNAME=&TAPE4,UNIT=SYSSQ,SPACE=(CYL,(20,20)),          X1
//               DISP=(NEW,DELETE)                                         2
//GO.FT08F001  DD  DSNAME=&TAPE8,UNIT=SYSSQ,SPACE=(CYL,(20,20)),          X1
//               DISP=(NEW,DELETE)                                         2
//GO.SYSIN  DD  *
        (FOLLOWED BY INPUT DATA DECK PUNCHED ACCORDING TO EBCDIC CODE)
/*
//
```

COND.GO=(16,LT) ON EXEC CARD IS NEEDED ONLY BECAUSE OF BUG IN IBM LINKEDITOR. IN THE EVENT THAT 131K-BYTE COMPILER IS UNABLE TO COMPILE SUBROUTINE CBXR, IT CAN BE COMPILED ON A LARGER MACHINE AND OBJECT DECK OBTAINED. OBJECT DECKS FOR THE REDUCED VERSION OF REX SHOWN ABOVE WILL RUN ON A 131K-BYTE COMPUTER. PARENS AND PLUS SIGN MAY NOT PRINT PROPERLY UNLESS EBCDIC SOURCE DECKS ARE USED.

APPENDIX B

EXAMPLES OF INPUT DATA THAT TEST 'REX' PROCESSING AND OUTPUT OPTIONS

MODIFICATION TO SUBROUTINE TRNX NEEDED BY TEST PROBLEMS 'ABST' THROUGH 'HCBW'
FITTING SPECIFIC REGRESSIONS AND COMPARING RELATIVE GOODNESS OF FIT
(TEST PROBLEMS 'ABST' THRO 'HCBW' CAN USE SAME VERSION OF 'TRNX')

```
      *ALTER  18,21                                                   TRNX
C  KEEPS VARIABLES AND SEQUENCE UNCHANGED WITH WEIGHT(IF ANY) FOLLOWING TRNX   18
     DO   1 J=1,NVS                                                   TRNX   19
   1 X(J)=D(J)                                                        TRNX   20
     W=D(NVR)                                                         TRNX   21
      *ENDAL                                                          TRNX
```

```
    EXAMPLE OF FAILURE OF STEPWISE PROCEDURE TO FIND BEST REGRESSION   ABST 1
      30       8=                                                 100111ABST 2
       Y=                                                               ABST 3
(8F4.0)                                                                 ABST 4
                                                                        ABST 5
  -2   0   0   2   0   0   1  -2                                        01  ABST
  -2   0   0   2   0   0   1   2                                        02  ABST
   6  -2   0   0   0   0   4   2                                        03  ABST
   6  -2   0   0   0   0   4   6                                        04  ABST
   8   0   0   0   0   0   8   6                                        05  ABST
   8   0   0   0   0   0   8  10                                        06  ABST
  10   2  50 -50   0   0  12  10                                        07  ABST
  10   2 -50  50   0   0  12  14                                        08  ABST
  16   0   0   0   0   0  16  14                                        09  ABST
  16   0   0   0   0   0  16  18                                        10  ABST
   7   2   0   0   0   9   0   7                                        11  ABST
   7   2   0   0   0   9   0  11                                        12  ABST
  19   0  -3   0   0  16   0  14                                        13  ABST
  19   0  -3   0   0  16   0  18                                        14  ABST
  23   2   0   0   0  25   0  23                                        15  ABST
  23   2   0   0   0  25   0  27                                        16  ABST
  46 -10   0   0   0  36   0  34                                        17  ABST
  46 -10   0   0   0  36   0  38                                        18  ABST
  34   2   0   0   0  36   0  34                                        19  ABST
  34   2   0   0   0  36   0  38                                        20  ABST
  29   0   0  -4  25   0   0  23                                        21  ABST
  29   0   0  -4  25   0   0  27                                        22  ABST
  14   2 -50  50  16   0   0  14                                        23  ABST
  14   2  50 -50  16   0   0  18                                        24  ABST
  27  -2   0   0  25   0   0  23                                        25  ABST
  27  -2   0   0  25   0   0  27                                        26  ABST
  34   2   0   0  36   0   0  34                                        27  ABST
  34   2   0   0  36   0   0  38                                        28  ABST
  42   2   5   0  49   0   0  47                                        29  ABST
  42   2   5   0  49   0   0  51                                        30  ABST
DONE                                                                    31  ABST
```

```
    TV-REM REGRESSION TEST DATA (REVISED) WITH PART PROCESSING BY REX   AREX   1
      30   12  12=                                                100331AREX   2
GSG GG    YY=                                                           AREX   3
(12F4.0)                                                                AREX   4
                                                                        AREX   5
   1   0   0   0   0   0   0   0   0   0   2   9                    01  AREX
   2   0   1   0   0   1   0   0   0   1   1  23                    02  AREX
   3   0   2   0   0   4   0   0   0   8   4  17                    03  AREX
   4   0   3   0   0   9   0   0   0  27   3   5                    04  AREX
   5   0   4   0   0  16   0   0   0  64   6   8                    05  AREX
   6   1   0   0   1   0   0   0   0   0   5   9                    06  AREX
   7   1   1   1   1   1   1   1   1   1   8   8                    07  AREX
   8   1   2   2   1   4   2   4   4   8   7   5                    08  AREX
   9   1   3   3   1   9   3   9   9  27  10  15                    09  AREX
  10   1   4   4   1  16   4  16  16  64   9   2                    10  AREX
  11   2   0   0   4   0   0   0   0   0  12   3                    11  AREX
  12   2   1   2   4   1   4   2   4   1  11   3                    12  AREX
  13   2   2   4   4   4   8   8  16   8  14   7                    13  AREX
  14   2   3   6   4   9  12  18  36  27  13   4                    14  AREX
  15   2   4   8   4  16  16  32  64  64  16   9                    15  AREX
  16   3   0   0   9   0   0   0   0   0  15   7                    16  AREX
  17   3   1   3   9   1   9   3   9   1  18  11                    17  AREX
  18   3   2   6   9   4  18  12  36   8  17   7                    18  AREX
  19   3   3   9   9   9  27  27  81  27  20   4                    19  AREX
  20   3   4  12   9  16  36  48 144  64  19  18                    20  AREX
  21   4   0   0  16   0   0   0   0   0  22   9                    21  AREX
  22   4   1   4  16   1  16   4  16   1  21   5                    22  AREX
  23   4   2   8  16   4  32  16  64   8  24  11                    23  AREX
  24   4   3  12  16   9  48  36 144  27  23  14                    24  AREX
  25   4   4  16  16  16  64  64 256  64  26  23                    25  AREX
  26   5   0   0  25   0   0   0   0   0  25   7                    26  AREX
  27   5   1   5  25   1  25   5  25   1  28  18                    27  AREX
  28   5   2  10  25   4  50  20 100   8  27  13                    28  AREX
  29   5   3  15  25   9  75  45 225  27  30  19                    29  AREX
  30   5   4  20  25  16 100  80 400  64  29  29                    30  AREX
DONE                                                                    31  AREX
```

```
    UNCORRECTED MATRIX INPUT USED CORRECTED (THRO MEAN)                      BREX    1
      30        12                                                     120000BREX    2
GSG GG    GYY                                                                BREX    3
                                                                             BREX    4
                                                                             BREX    5
  0.94550000E 04  0.160000C0E C4  0.99000000E 03  0.33500000E 04             BREX1   1
  0.64500000E 04  0.30300C00E 04  0.13450000E 05  0.10200000E 05             BREX1   2
  0.40900000E 05  0.10224000E C5  0.94400000E 04  0.55990000E 04             BREX1   3
  0.27500000E 03  0.15000000E C3  0.55000000E 03  0.11250000E 04             BREX1   4
  0.45000000E 03  0.22500000E 04  0.16500000E 04  0.67500000E 04             BREX1   5
  0.15000000E 04  0.15970000E 04  C.91000000E 03  0.18000000E 03             BREX1   6
  0.45000000E 03  0.55000000E 03  0.60000000E 03  0.16500000E 04             BREX1   7
  0.15000000E 04  0.5500C000E 04  0.21240000E 04  0.99000000E 03             BREX1   8
  0.72700000E 03  0.16500000E 04  0.22500000E 04  0.15000000E 04             BREX1   9
  0.67500000E 04  0.55000C00E 04  0.22500000E 05  0.53100000E 04             BREX1  10
  0.33440000E 04  0.22570000E 04  0.48950000E 04  0.16500000E 04             BREX1  11
  0.97900000E 04  0.67500000E 04  0.29370000E 05  0.55000000E 04             BREX1  12
  0.64350000E 04  0.37080000E 04  0.21240000E 04  0.55000000E 04             BREX1  13
  0.53100000E 04  0.19470000E 05  0.78000000E 04  0.30300000E 04             BREX1  14
  0.22810000E 04  0.29370000E 05  0.22500000E 05  0.97900000E 05             BREX1  15
  0.19470000E 05  0.134200C0E 05  0.93130000E 04  0.19470000E 05             BREX1  16
  0.79650000E 05  0.195000C0E 05  0.10170000E 05  0.74030000E 04             BREX1  17
  0.34656600E 06  0.71500000E 05  0.40750000E 05  0.30619000E 05             BREX1  18
  0.29340000E 05  0.10224000E C5  0.78910000E 04  0.94550000E 04             BREX1  19
  0.56190000E 04  0.48060000E 04  0.46500000E 03  0.75000000E 02             BREX1  20
  0.60000000E 02  0.15000CC0E C3  0.27500000E 03  0.18000000E 03             BREX1  21
  0.55000000E 03  0.45000C00E 03  0.16500000E 04  0.60000000E 03             BREX1  22
  0.46500000E 03  0.322000C0E 03  0.30000000E 02                             BREX1  23
DONE                                                                         BREX1  24
```

```
    CORRECTED MATRIX INPUT USED CORRECTED WITH MAX. NO. SETS PUT AT 5    CREX   1
      30      12    5                                               140000CREX   2
          YY                                                             CREX   3
                                                                         CREX   4
                                                                         CREX   5
  0.22475000E 04  0.43750000E 03  0.60000000E 02  0.10250000E 04         CREXO  1
  0.21875000E 04  0.24000000E 03  0.49250000E 04  0.32250000E 04         CREXO  2
  0.15325000E 05  0.92400000E 03  0.22325000E 04  0.60800000E 03         CREXO  3
  0.87500000E 02 -0.00000000E-38  0.17500000E 03  0.43750000E 03         CREXO  4
 -0.00000000E-38  0.87500000E 03  0.52500000E 03  0.26250000E 04         CREXO  5
 -0.00000000E-38  0.43450000E 03  0.10500000E 03  0.60000000E 02         CREXO  6
  0.15000000E 03 -0.00000000E-38  0.24000000E 03  0.55000000E 03         CREXO  7
  0.60000000E 03  0.22000000E 04  0.92400000E 03  0.60000000E 02         CREXO  8
  0.83000000E 02  0.90000000E 03  0.87500000E 03  0.60000000E 03         CREXO  9
  0.40000000E 04  0.32500000E 04  0.14250000E 05  0.23100000E 04         CREXO 10
  0.10190000E 04  0.64700000E 03  0.23741667E 04 -0.00000000E-38         CREXO 11
  0.47483333E 04  0.26250000E 04  0.14245000E 05 -0.00000000E-38         CREXO 12
  0.21725000E 04  0.75633333E 03  0.10440000E 04  0.22000000E 04         CREXO 13
  0.26100000E 04  0.95700000E 04  0.42000000E 04  0.24000000E 03         CREXO 14
  0.34900000E 03  0.19286667E 05  0.14250000E 05  0.67650000E 05         CREXO 15
  0.84700000E 04  0.48950000E 04  0.34096667E 04  0.12720000E 05         CREXO 16
  0.54900000E 05  0.10500000E 05  0.31950000E 04  0.25730000E 04         CREXO 17
  0.25581600E 06  0.38500000E 05  0.15175000E 05  0.12909000E 05         CREXO 18
  0.17340000E 05  0.92400000E 03  0.14510000E 04  0.22475000E 04         CREXO 19
  0.62800000E 03  0.13498667E 04  0.46500000E 03  0.75000000E 02         CREXO 20
  0.60000000E 02  0.15000000E 03  0.27500000E 03  0.18000000E 03         CREXO 21
  0.55000000E 03  0.45000000E 03  0.16500000E 04  0.60000000E 03         CREXO 22
  0.46500000E 03  0.32200000E 03  0.30000000E 02                         CREXO 23
DONE                                                                     CREXO 24
```

```
    CALCULATING PARTICULAR REGRESSION FROM LARGER MATRIX (MAX. NO. Y'S) DREX    1
      30  18  18=                                                 200000DREX    2
 XXXXXXXXXYYYYYYYYY=                                                    DREX    3
(18F4.0)                                                                DREX    4
                                                                        DREX    5
   1   0   0   0   0   0   0   0   0   0   9   2   2   2   2   2   2   2  01DREX
   2   0   1   0   0   1   0   0   0   1  23   1   1   1   1   1   1   1  02DREX
   3   0   2   0   0   4   0   0   0   8  17   4   4   4   4   4   4   4  03DREX
   4   0   3   0   0   9   0   0   0  27   5   3   3   3   3   3   3   3  04DREX
   5   0   4   0   0  16   0   0   0  64   8   6   6   6   6   6   6   6  05DREX
   6   1   0   0   1   0   0   0   0   0   9   5   5   5   5   5   5   5  06DREX
   7   1   1   1   1   1   1   1   1   1   8   8   8   8   8   8   8   8  07DREX
   8   1   2   2   1   4   2   4   4   8   5   7   7   7   7   7   7   7  08DREX
   9   1   3   3   1   9   3   9   9  27  15  10  10  10  10  10  10  10  09DREX
  10   1   4   4   1  16   4  16  16  64   2   9   9   9   9   9   9   9  10DREX
  11   2   0   0   4   0   0   0   0   0   3  12  12  12  12  12  12  12  11DREX
  12   2   1   2   4   1   4   2   4   1   3  11  11  11  11  11  11  11  12DREX
  13   2   2   4   4   4   8   8  16   8   7  14  14  14  14  14  14  14  13DREX
  14   2   3   6   4   9  12  18  36  27   4  13  13  13  13  13  13  13  14DREX
  15   2   4   8   4  16  16  32  64  64   9  16  16  16  16  16  16  16  15DREX
  16   3   0   0   9   0   0   0   0   0   7  15  15  15  15  15  15  15  16DREX
  17   3   1   3   9   1   9   3   9   1  11  18  18  18  18  18  18  18  17DREX
  18   3   2   6   9   4  18  12  36   8   7  17  17  17  17  17  17  17  18DREX
  19   3   3   9   9   9  27  27  81  27   4  20  20  20  20  20  20  20  19DREX
  20   3   4  12   9  16  36  48 144  64  18  19  19  19  19  19  19  19  20DREX
  21   4   0   0  16   0   0   0   0   0   9  22  22  22  22  22  22  22  21DREX
  22   4   1   4  16   1  16   4  16   1   5  21  21  21  21  21  21  21  22DREX
  23   4   2   8  16   4  32  16  64   8  11  24  24  24  24  24  24  24  23DREX
  24   4   3  12  16   9  48  36 144  27  14  23  23  23  23  23  23  23  24DREX
  25   4   4  16  16  16  64  64 256  64  23  26  26  26  26  26  26  26  25DREX
  26   5   0   0  25   0   0   0   0   0   7  25  25  25  25  25  25  25  26DREX
  27   5   1   5  25   1  25   5  25   1  18  28  28  28  28  28  28  28  27DREX
  28   5   2  10  25   4  50  20 100   8  13  27  27  27  27  27  27  27  28DREX
  29   5   3  15  25   9  75  45 225  27  19  30  30  30  30  30  30  30  29DREX
  30   5   4  20  25  16 100  80 400  64  29  29  29  29  29  29  29  29  30DREX
DONE                                                                      31DREX
```

```
    SPECIFIC REGRESSION WITH NONTERMINAL Y, USING DATA INPUT EARLIER    EREX   1
                                                                  280000EREX   2
YXXXXXXXXX         =                                                    EREX   3
                                                                        EREX   4
                                                                        EREX   5
DONE                                                                    EREXLAST
```

```
    MINIMUM WEIGHTED REGRESSION TEST FOR REX (OLD XXR-CBY, THRO ORIGIN) FCBW    1
       10    5    4W                                                 110000FCBW    2
  YYW                                                                      FCBW    3
(5F4.0)                                                                    FCBW    4
                                                                           FCBW    5
  82 -17  82    5    2                                                     01   FCBW
  85 -17  75    5    2                                                     02   FCBW
  89 -13  62    4    2                                                     03   FCBW
  98 -15  62    4    2                                                     04   FCBW
  77 -15  50    3    2                                                     05   FCBW
  62 -13  49    3    2                                                     06   FCBW
 133 -17  94    6    2                                                     07   FCBW
 114 -15  89    6    2                                                     08   FCBW
 110 -14  87    6    2                                                     09   FCBW
  80 -14  79    5    2                                                     10   FCBW
DONE                                                                       11   FCBW
```

```
    WEIGHTED UNCORRECTED MATRIX INPUT USED CORRECTED BY REX (THRO MEAN) GCBW   1
      10       4W                                                 120000GCBW   2
  YYW                                                                   GCBW   3
                                                                        GCBW   4
                                                                        GCBW   5
  0.90432000E 05 -0.14058C0CE 05  0.70119000E 05  0.45420000E 04        GCBW1  1
  0.22720000E 04 -0.11049000E 05 -0.71200000E 03  0.55505000E 05        GCBW1  2
  0.35930000E 04  0.23300000E 03  0.93000000E 03 -0.15000000E 03        GCBW1  3
  0.72900000E 03  0.47000000E 02  0.10000000E 02                        GCBW1  4
DONE                                                                    GCBW1  5
```

```
   WEIGHTED CORRECTED MATRIX INPUT USED UNCORRECTED (THRO ORIGIN)      HCBW   1
    10       4W                                                  050000HCBW   2
SGYYW                                                                  HCBW   3
(4E16.8)                                                               HCBW   4
                                                                       HCBW   5
  0.39420000E 04 -0.10800000E 03  0.23220000E 04  0.17100000E 03       HCBWO  1
  0.22000000E 02 -0.11400000E 03 -0.70000000E 01  0.23609000E 04       HCBWO  2
  0.16670000E 03  0.12100000E 02  0.93000000E 03 -0.15000000E 03       HCBWO  3
  0.72900000E 03  0.47000000E 02  0.10000000E 02                       HCBWO  4
DONE                                                                   HCBWO  5
DONE DONE DONE DONE DONE DONE DONE DONE DONE DONE DONE DONE DONE DONE DONE DONE
```

MODIFICATION TO SUBROUTINE TRNX NEEDED BY TEST PROBLEMS 'AORX' THROUGH 'CORX'
COVARIANCE ANALYSIS USING ORTHOGONAL POLYNOMIALS
(TEST PROBLEMS 'AORX' THRO 'CORX' CAN USE SAME VERSION OF 'TRNX')

```
       *ALTER  18,21                                                    TRNX
C   COVARIANCE (6 GROUPS, 3 X'S, 2 Y'S, CORRECTED MATRIX, ORTHO. POLY.)
      X(1)=D(3)
      X(2)=D(6)
      X(3)=D(10)
      X(24)=D(11)
      X(25)=D(12)
      IF (D(2) .NE. 0.0) GO TO 20
      X(4)=-5./5.
      X(5)=+5./5.
      X(6)=-5./5.
      X(7)=+1./5.
      X(8)=-1./5.
      GO TO 70
   20 IF (D(2) .NE. 1.0) GO TO 30
      X(4)=-3./5.
      X(5)=-1./5.
      X(6)=+7./5.
      X(7)=-3./5.
      X(8)=+5./5.
      GO TO 70
   30 IF (D(2) .NE. 2.0) GO TO 40
      X(4)=-1./5.
      X(5)=-4./5.
      X(6)=+4./5.
      X(7)=+2./5.
      X(8)=-10./5.
      GO TO 70
   40 IF (D(2) .NE. 3.0) GO TO 50
      X(4)=+1./5.
      X(5)=-4./5.
      X(6)=-4./5.
      X(7)=+2./5.
      X(8)=+10./5.
      GO TO 70
   50 IF (D(2) .NE. 4.0) GO TO 60
      X(4)=+3./5.
      X(5)=-1./5.
      X(6)=-7./5.
      X(7)=-3./5.
      X(8)=-5./5.
      GO TO 70
```

```
60 X(4)=+5./5.
   X(5)=+5./5.
   X(6)=+5./5.
   X(7)=+1./5.
   X(8)=+1./5.
70 K=8
   DO  75 J=1,3
   DO  75 I=1,5
   K=K+1
   L=I+3
75 X(K)=X(J)*X(L)
    *ENDAL                                                      TRNX
```

```
    COVARIANCE (6 GROUPS, 3 X'S, 2 Y'S)  REAL                           AORX   1
      30  12  25=                                                 200000AORX   2
XXX                    YY=                                              AORX   3
(12F4.0)                                                                AORX   4
                                                                        AORX   5
   1   0   0   0   0   0   0   0   0   0   2   9                        01  AREX
   2   0   1   0   0   1   0   0   0   1   1  23                        02  AREX
   3   0   2   0   0   4   0   0   0   8   4  17                        03  AREX
   4   0   3   0   0   9   0   0   0  27   3   5                        04  AREX
   5   0   4   0   0  16   0   0   0  64   6   8                        05  AREX
   6   1   0   0   1   0   0   0   0   0   5   9                        06  AREX
   7   1   1   1   1   1   1   1   1   1   8   8                        07  AREX
   8   1   2   2   1   4   2   4   4   8   7   5                        08  AREX
   9   1   3   3   1   9   3   9   9  27  10  15                        09  AREX
  10   1   4   4   1  16   4  16  16  64   9   2                        10  AREX
  11   2   0   0   4   0   0   0   0   0  12   3                        11  AREX
  12   2   1   2   4   1   4   2   4   1  11   3                        12  AREX
  13   2   2   4   4   4   8   8  16   8  14   7                        13  AREX
  14   2   3   6   4   9  12  18  36  27  13   4                        14  AREX
  15   2   4   8   4  16  16  32  64  64  16   9                        15  AREX
  16   3   0   0   9   0   0   0   0   0  15   7                        16  AREX
  17   3   1   3   9   1   9   3   9   1  18  11                        17  AREX
  18   3   2   6   9   4  18  12  36   8  17   7                        18  AREX
  19   3   3   9   9   9  27  27  81  27  20   4                        19  AREX
  20   3   4  12   9  16  36  48 144  64  19  18                        20  AREX
  21   4   0   0  16   0   0   0   0   0  22   9                        21  AREX
  22   4   1   4  16   1  16   4  16   1  21   5                        22  AREX
  23   4   2   8  16   4  32  16  64   8  24  11                        23  AREX
  24   4   3  12  16   9  48  36 144  27  23  14                        24  AREX
  25   4   4  16  16  16  64  64 256  64  26  23                        25  AREX
  26   5   0   0  25   0   0   0   0   0  25   7                        26  AREX
  27   5   1   5  25   1  25   5  25   1  28  18                        27  AREX
  28   5   2  10  25   4  50  20 100   8  27  13                        28  AREX
  29   5   3  15  25   9  75  45 225  27  30  19                        29  AREX
  30   5   4  20  25  16 100  80 400  64  29  29                        30  AREX
DONE                                                                    31  AREX
    COVARIANCE (6 GROUPS, 3 X'S, 2 Y'S)  REAL+DUMMY                     BORX   1
                                                                  280000BORX   2
XXXXXXXX               YY=                                              BORX   3
                                                                        BORX   4
                                                                        BORX   5
DONE                                                                    BORXLAST
    COVARIANCE (6 GROUPS, 3 X'S, 2 Y'S)  REAL+DUMMY+INTERACTION         CORX   1
                                                                  280000CORX   2
XXXXXXXXXXXXXXXXXXXXXXXYY=                                              CORX   3
                                                                        CORX   4
                                                                        CORX   5
DONE                                                                    CORXLAST
DONE DONE DONE DONE DONE DONE DONE DONE DONE DONE DONE DONE DONE DONE DONE DONE
```

MODIFICATION TO SUBROUTINE TRNX NEEDED BY TEST PROBLEMS 'A1RX' THROUGH 'C1RX'
COVARIANCE ANALYSIS USING DUMMY UNITY VARIABLES
(TEST PROBLEMS 'A1RX' THRO 'C1RX' CAN USE SAME VERSION OF 'TRNX')

```
      *ALTER  18,21                                                        TRNX
C    COVARIANCE (6 GROUPS, 3 X'S, 2 Y'S, UNCORRECTED MATRIX, UNITY VAR.)
      X(1)=D(3)
      X(2)=D(6)
      X(3)=D(10)
      X(4)=1.
      X(29)=D(11)
      X(30)=D(12)
      DO    5 I=5,28
    5 X(I)=0.0
      K=4.0*(D(2)+1.)
      DO   6 I=1,4
      J=K+I
    6 X(J)=X(I)
      *ENDAL                                                               TRNX
```

```
    COVARIANCE (6 GROUPS, 3 X'S, 2 Y'S)  UNGROUPED (SINGLE TOTAL REGR.) A1RX   1
      30  12  30=                                                 210000A1RX   2
XXXX                        YY=                                         A1RX   3
(12F4.0)                                                                A1RX   4
                                                                        A1RX   5
   1   0   0   0   0   0   0   0   0   0   2   9                        01  AREX
   2   0   1   0   0   1   0   0   0   1   1  23                        02  AREX
   3   0   2   0   0   4   0   0   0   8   4  17                        03  AREX
   4   0   3   0   0   9   0   0   0  27   3   5                        04  AREX
   5   0   4   0   0  16   0   0   0  64   6   8                        05  AREX
   6   1   0   0   1   0   0   0   0   0   5   9                        06  AREX
   7   1   1   1   1   1   1   1   1   1   8   8                        07  AREX
   8   1   2   2   1   4   2   4   4   8   7   5                        08  AREX
   9   1   3   3   1   9   3   9   9  27  10  15                        09  AREX
  10   1   4   4   1  16   4  16  16  64   9   2                        10  AREX
  11   2   0   0   4   0   0   0   0   0  12   3                        11  AREX
  12   2   1   2   4   1   4   2   4   1  11   3                        12  AREX
  13   2   2   4   4   4   8   8  16   8  14   7                        13  AREX
  14   2   3   6   4   9  12  18  36  27  13   4                        14  AREX
  15   2   4   8   4  16  16  32  64  64  16   9                        15  AREX
  16   3   0   0   9   0   0   0   0   0  15   7                        16  AREX
  17   3   1   3   9   1   9   3   9   1  18  11                        17  AREX
  18   3   2   6   9   4  18  12  36   8  17   7                        18  AREX
  19   3   3   9   9   9  27  27  81  27  20   4                        19  AREX
  20   3   4  12   9  16  36  48 144  64  19  18                        20  AREX
  21   4   0   0  16   0   0   0   0   0  22   9                        21  AREX
  22   4   1   4  16   1  16   4  16   1  21   5                        22  AREX
  23   4   2   8  16   4  32  16  64   8  24  11                        23  AREX
  24   4   3  12  16   9  48  36 144  27  23  14                        24  AREX
  25   4   4  16  16  16  64  64 256  64  26  23                        25  AREX
  26   5   0   0  25   0   0   0   0   0  25   7                        26  AREX
  27   5   1   5  25   1  25   5  25   1  28  18                        27  AREX
  28   5   2  10  25   4  50  20 100   8  27  13                        28  AREX
  29   5   3  15  25   9  75  45 225  27  30  19                        29  AREX
  30   5   4  20  25  16 100  80 400  64  29  29                        30  AREX
DONE                                                                    31  AREX
    COVARIANCE (6 GROUPS, 3 X'S, 2 Y'S)  POOLED COEFF., MULTIPLE LEVELS B1RX   1
                                                                  270000B1RX   2
XXX    X   X   X   X   X    XYY=                                        B1RX   3
                                                                        B1RX   4
                                                                        B1RX   5
DONE                                                                    B1RXLAST
    COVARIANCE (6 GROUPS, 3 X'S, 2 Y'S)  SEPARATE GROUP REGRESSIONS     C1RX   1
                                                                  270000C1RX   2
    XXXXXXXXXXXXXXXXXXXXXXXXYY=                                         C1RX   3
                                                                        C1RX   4
                                                                        C1RX   5
DONE                                                                    C1RXLAST
DONE DONE DONE DONE DONE DONE DONE DONE DONE DONE DONE DONE DONE DONE DONE DONE
```

==========
APPENDIX C
==========

ILLUSTRATIVE OUTPUT FROM INITIAL INPUT (PROBLEM LABELLED 'ABST')
USING 'REX' MAJOR PROCESSING OPTION 1
(PRINTOUT SLIGHTLY CONDENSED TO SAVE SPACE)

===

```
===     EXAMPLE OF FAILURE OF STEPWISE PROCEDURE TO FIND BEST REGRESSION    ABST
===       30  -0   B= -0                                               100111====
===        Y=                                                  ========================

PARAMETER NUMBERS SPECIFIED IMPLICITLY OR EXPLICITLY BY CONTROL CARDS 2,3.
PARENTHESIZED ALLOWABLE LIMITS HAVE BEEN EXCEEDED WHEN PARAMETER NUMBERS BELOW ARE ASTERISKED.
A BLANK COLUMN ONE ON THIRD CONTROL CARD IS INTERPRETED AS MEANING ALL X'S ARE PUNCHED WITH G'S.

(3,NOB,  NOB)        30 = NUMBER OF OBSERVATIONS
(2,NVR,   51)         8 = NUMBER OF RAW VARIABLES (ALL TYPES INCLUDING WEIGHT IF NOT UNITY)
(2,NVS,   50)         8 = NUMBER OF FINAL VARIABLES (Y'S AND ALL X'S, BUT NOT INCLUDING WEIGHT)
(1,NY,     8)         1 = NUMBER OF DEPENDENT VARIABLES (Y'S)
(1,NXX,   49)         7 = TOTAL NUMBER OF INDEPENDENT VARIABLES (X'S IMPLIED BY ANY G, S, OR BLANK PRIOR TO FIRST Y)
(0,NXA,   49)         7 = NUMBER OF NONFIXED X'S (OCCURRENCE GOVERNED BY COMBINATORIAL RULES)
(0,NFA,   49)         0 = NUMBER OF FIXED X'S (ALWAYS INCLUDED WITH EACH COMBINATION OF NONFIXED X'S)
(1,NSET,  47)         7 = TOTAL NUMBER OF SETS OF X'S (G OR S STARTS SET, AND MEMBERS APPEAR OR DISAPPEAR TOGETHER)
(0,NXS,   30)         7 = NUMBER OF SETS OF NONFIXED X'S (ANY G, OR S AFTER OCCURRENCE OF FIRST G, STARTS SET)
(0,NF,    17)         0 = NUMBER OF SETS OF FIXED X'S (ANY S PRIOR TO OCCURRENCE OF FIRST G STARTS SET)
(0,NGX,   17)         7 = NUMBER OF GROUPS OF NONFIXED SETS (G STARTS GROUP, COMBINATIONS LIMITED TO ONE SET PER GROUP)
(0,LM,   NGX)         7 = ARBITRARY MAXIMUM OR LIMITING NUMBER OF GROUPS OR SETS ALLOWED IN COMBINATION)
(0,LGK,  LPP)       127 = TOTAL NUMBER OF GENERATED (NONFIXED) REGRESSIONS (CURRENTLY MUST NOT EXCEED LPP=16400/(NY+1))
(MX,NXX,  MX)           MACHINE ERROR--SORT OR SUM
(MS,NSET, MS)           MACHINE ERROR--SORT OR SUM

GROUP LETTER   A  B  C  D  E  F  G
SET ORDINALS   1  2  3  4  5  6  7
X SUBSCRIPTS   1  2  3  4  5  6  7

DATA INPUT FORMAT
(8F4.0)


LISTING OF FIRST TWO OBSERVATION VECTORS (AFTER TRANSFORMATIONS, IF ANY).

-0.2000000E 01 0.0000000E-38 0.0000000E-38 0.2000000E 01 0.0000000E-38 0.0000000E-38 0.1000000E 01-0.2000000E 01
 0.1000000E 01

-0.2000000E 01 0.0000000E-38 0.0000000E-38 0.2000000E 01 0.0000000E-38 0.0000000E-38 0.1000000E 01 0.2000000E 01
 0.1000000E 01

LISTING OF LAST OBSERVATION VECTOR---IF ABSENT, DATA CARDS ARE INCONSISTENT WITH NUMBER OF OBSERVATIONS
                        ON SECOND CONTROL CARD (OR WRONG FORMAT HAS BEEN USED).

 0.4200000E 02 0.2000000E 01 0.5000000E 01 0.0000000E-38 0.4900000E 02 0.0000000E-38 0.0000000E-38 0.5100000E 02
 0.1000000E 01
```

```
===     EXAMPLE OF FAILURE OF STEPWISE PROCEDURE TO FIND BEST REGRESSION     ABST
===       30   8   8=  7                                                 100111====
===GGGGGGGY=                                            =========================

COEFFICIENT OF COLLINEARITY AND RATIOS OF MEAN SQUARED RESIDUALS FROM VARIOUS
'YI' REGRESSIONS TO MEAN SQUARED RESIDUALS FROM CORRESPONDING MEAN 'YI',
WITH ORDINALS OF NONFIXED SETS INVOLVED (ALL FIXED ARE IMPLICIT)

                                   ORDINALS
NO.            RMSQR.              OF  SETS
SETS C.OF C.    YI                 INVOLVED

 1   0.30E 00 0.0975  1
 1   0.10E 01 1.0283  2
 1   0.10E 01 1.0339  3
 1   0.10E 01 1.0355  4
 1   0.71E 00 0.6075  5
 1   0.72E 00 0.8871  6
 1   0.77E 00 0.8926  7

 2   0.27E 00 0.0436  1  2
 2   0.30E 00 0.1009  1  3
 2   0.30E 00 0.1011  1  4
 2   0.15E 00 0.0772  1  5
 2   0.17E 00 0.0938  1  6
 2   0.20E 00 0.1011  1  7
 2   0.10E 01 1.0644  2  3
 2   0.10E 01 1.0661  2  4
 2   0.68E 00 0.5741  2  5
 2   0.62E 00 0.9160  2  6
 2   0.76E 00 0.9220  2  7
 2   0.11E-01 1.0057  3  4
 2   0.71E 00 0.6299  3  5
 2   0.72E 00 0.9174  3  6
 2   0.77E 00 0.9239  3  7
 2   0.71E 00 0.6300  4  5
 2   0.72E 00 0.9196  4  6
 2   0.77E 00 0.9254  4  7
 2   0.43E 00 0.1131  5  6
 2   0.47E 00 0.6045  5  7
 2   0.49E 00 0.8488  6  7

 3   0.27E 00 0.0452  1  2  3
 3   0.27E 00 0.0453  1  2  4
 3   0.10E 00 0.0434  1  2  5
 3   0.14E 00 0.0448  1  2  6
 3   0.18E 00 0.0452  1  2  7
 3   0.32E-02 0.0723  1  3  4
 3   0.15E 00 0.0801  1  3  5
 3   0.17E 00 0.0973  1  3  6
 3   0.20E 00 0.1048  1  3  7
```

```
  3   0.15E 00 0.0801  1   4   5
  3   0.17E 00 0.0974  1   4   6
  3   0.20E 00 0.1050  1   4   7
  3   0.17E-01 0.0665  1   5   6
  3   0.95E-01 0.0796  1   5   7
  3   0.11E 00 0.0969  1   6   7
  3   0.11E-01 1.0297  2   3   4
  3   0.67E 00 0.5961  2   3   5
  3   0.62E 00 0.9486  2   3   6
  3   0.76E 00 0.9556  2   3   7
  3   0.67E 00 0.5961  2   4   5
  3   0.62E 00 0.9509  2   4   6
  3   0.76E 00 0.9572  2   4   7
  3   0.37E 00 0.1174  2   5   6
  3   0.44E 00 0.5804  2   5   7
  3   0.42E 00 0.8792  2   6   7
  3   0.68E-02 0.6520  3   4   5
  3   0.76E-02 0.8524  3   4   6
  3   0.82E-02 0.8874  3   4   7
  3   0.43E 00 0.1174  3   5   6
  3   0.47E 00 0.6276  3   5   7
  3   0.49E 00 0.8791  3   6   7
  3   0.43E 00 0.1174  4   5   6
  3   0.47E 00 0.6277  4   5   7
  3   0.49E 00 0.8811  4   6   7
  3   0.20E 00 0.0245  5   6   7

  4   0.28E-02 0.0252  1   2   3   4
  4   0.10E 00 0.0451  1   2   3   5
  4   0.14E 00 0.0465  1   2   3   6
  4   0.18E 00 0.0470  1   2   3   7
  4   0.10E 00 0.0451  1   2   4   5
  4   0.14E 00 0.0465  1   2   4   6
  4   0.18E 00 0.0470  1   2   4   7
  4   0.97E-02 0.0436  1   2   5   6
  4   0.65E-01 0.0448  1   2   5   7
  4   0.87E-01 0.0466  1   2   6   7
  4   0.14E-02 0.0641  1   3   4   5
  4   0.17E-02 0.0722  1   3   4   6
  4   0.21E-02 0.0750  1   3   4   7
  4   0.17E-01 0.0691  1   3   5   6
  4   0.95E-01 0.0827  1   3   5   7
  4   0.11E 00 0.1006  1   3   6   7
  4   0.17E-01 0.0692  1   4   5   6
  4   0.95E-01 0.0827  1   4   5   7
  4   0.11E 00 0.1007  1   4   6   7
  4   0.37E-02 0.0254  1   5   6   7
  4   0.64E-02 0.6163  2   3   4   5
  4   0.65E-02 0.8848  2   3   4   6
  4   0.81E-02 0.9137  2   3   4   7
  4   0.37E 00 0.1220  2   3   5   6
  4   0.44E 00 0.6035  2   3   5   7
```

```
 4   0.42E 00 0.9120  2   3   6   7
 4   0.37E 00 0.1221  2   4   5   6
 4   0.44E 00 0.6036  2   4   5   7
 4   0.42E 00 0.9141  2   4   6   7
 4   0.17E 00 0.0255  2   5   6   7
 4   0.41E-02 0.1199  3   4   5   6
 4   0.44E-02 0.6475  3   4   5   7
 4   0.51E-02 0.8154  3   4   6   7
 4   0.20E 00 0.0255  3   5   6   7
 4   0.20E 00 0.0255  4   5   6   7

 5   0.97E-03 0.0262  1   2   3   4   5
 5   0.14E-02 0.0262  1   2   3   4   6
 5   0.18E-02 0.0262  1   2   3   4   7
 5   0.97E-02 0.0454  1   2   3   5   6
 5   0.65E-01 0.0467  1   2   3   5   7
 5   0.87E-01 0.0484  1   2   3   6   7
 5   0.97E-02 0.0454  1   2   4   5   6
 5   0.65E-01 0.0467  1   2   4   5   7
 5   0.87E-01 0.0484  1   2   4   6   7
 5   0.95E-03 0.0264  1   2   5   6   7
 5   0.15E-03 0.0588  1   3   4   5   6
 5   0.88E-03 0.0668  1   3   4   5   7
 5   0.11E-02 0.0745  1   3   4   6   7
 5   0.37E-02 0.0265  1   3   5   6   7
 5   0.37E-02 0.0265  1   4   5   6   7
 5   0.35E-02 0.1248  2   3   4   5   6
 5   0.41E-02 0.6222  2   3   4   5   7
 5   0.44E-02 0.8487  2   3   4   6   7
 5   0.17E 00 0.0265  2   3   5   6   7
 5   0.17E 00 0.0265  2   4   5   6   7
 5   0.18E-02 0.0264  3   4   5   6   7

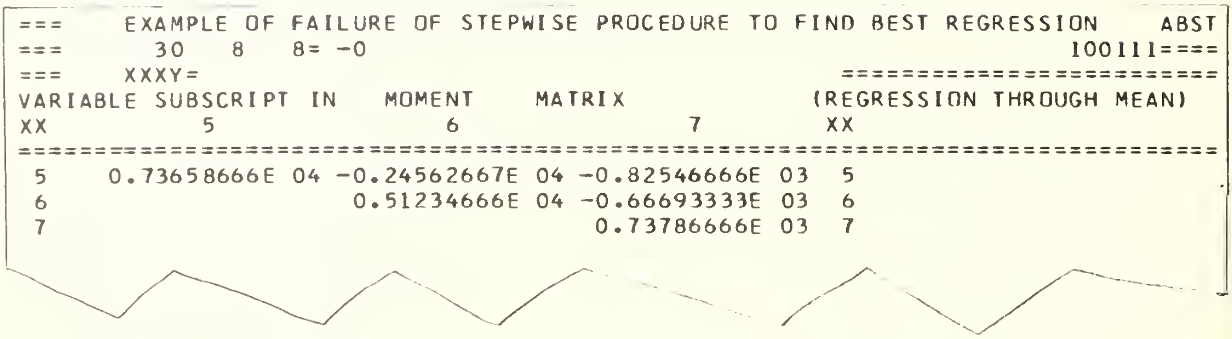
 6   0.84E-04 0.0274  1   2   3   4   5   6
 6   0.60E-03 0.0274  1   2   3   4   5   7
 6   0.88E-03 0.0274  1   2   3   4   6   7
 6   0.94E-03 0.0276  1   2   3   5   6   7
 6   0.95E-03 0.0276  1   2   4   5   6   7
 6   0.22E-04 0.0276  1   3   4   5   6   7
 6   0.15E-02 0.0276  2   3   4   5   6   7

 7   0.88E-07 0.0286  1   2   3   4   5   6   7

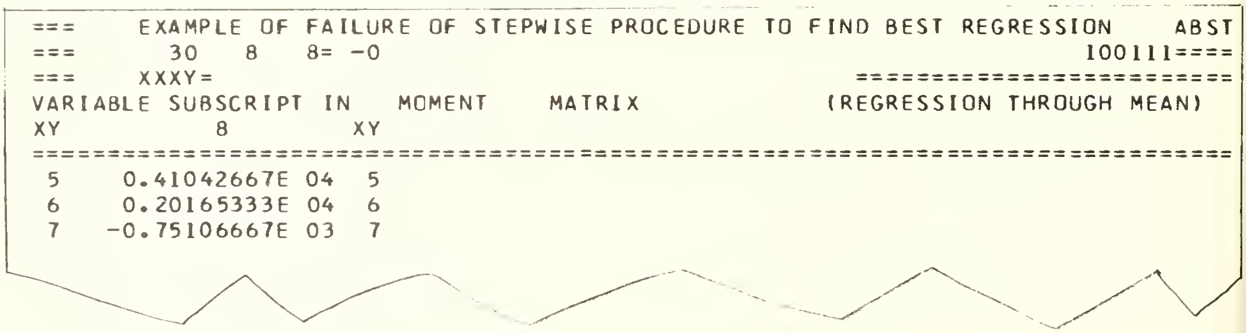
   ORDINALS OF SETS IN REGRESSION WITH SMALLEST RELATIVE MEAN SQUARED RESIDUAL

Y1   0.20E 00 0.0245    5   6   7

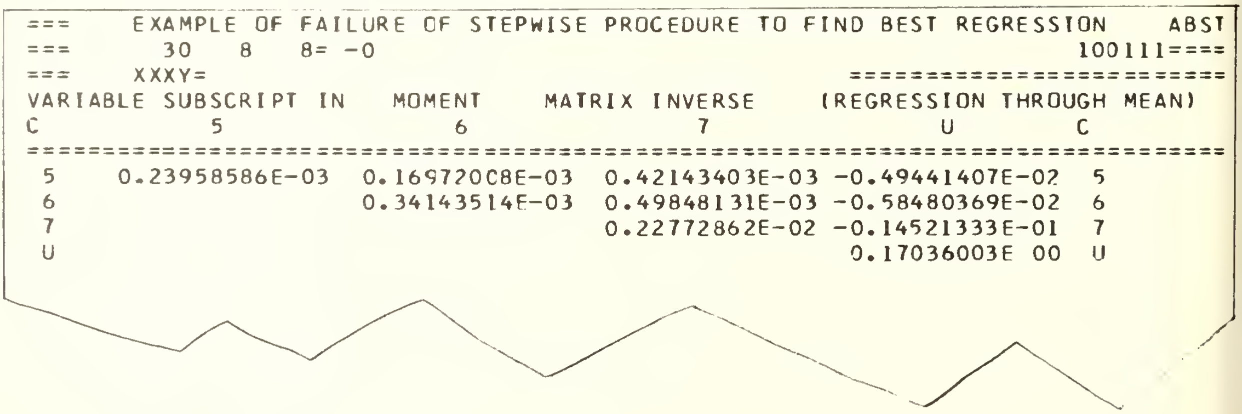
MSQR ABOUT MEAN Y1= 0.19074023E 03
MEAN Y1           = 0.20866667E 02
```



```
===     EXAMPLE OF FAILURE OF STEPWISE PROCEDURE TO FIND BEST REGRESSION    ABST
===       30    8    8= -0                                                100111====
===     XXXY=                                                  =========================
VARIABLE SUBSCRIPT IN    MOMENT     MATRIX                  (REGRESSION THROUGH MEAN)
XX           5                6                7         XX
=====================================================================================
 5     0.73658666E 04 -0.24562667E 04 -0.82546666E 03  5
 6                     0.51234666E 04 -0.66693333E 03  6
 7                                     0.73786666E 03  7
```



```
===     EXAMPLE OF FAILURE OF STEPWISE PROCEDURE TO FIND BEST REGRESSION    ABST
===       30    8    8= -0                                                100111====
===     XXXY=                                                  =========================
VARIABLE SUBSCRIPT IN    MOMENT     MATRIX                  (REGRESSION THROUGH MEAN)
XY           8          XY
=====================================================================================
 5     0.41042667E 04   5
 6     0.20165333E 04   6
 7    -0.75106667E 03   7
```



```
===     EXAMPLE OF FAILURE OF STEPWISE PROCEDURE TO FIND BEST REGRESSION    ABST
===       30    8    8= -0                                                100111====
===     XXXY=                                                  =========================
VARIABLE SUBSCRIPT IN    MOMENT     MATRIX INVERSE     (REGRESSION THROUGH MEAN)
C            5                6                7                U         C
=====================================================================================
 5     0.23958586E-03  0.169720C8E-03  0.42143403E-03 -0.49441407E-02  5
 6                     0.34143514E-03  0.49848131E-03 -0.58480369E-02  6
 7                                     0.22772862E-02 -0.14521333E-01  7
 U                                                     0.17036003E 00  U
```

```
===    EXAMPLE OF FAILURE OF STEPWISE PROCEDURE TO FIND BEST REGRESSION    ABST
===      30   8   8= -0                                                100111====
===    XXXY=                                           ========================
VARIABLE SUBSCRIPT  IN REG. COEFF. MATRIX             (REGRESSION THROUGH MEAN)
B           8        B
===============================================================================
 5    0.10090454E 01  5
 6    0.10106991E 01  6
 7    0.10244881E 01  7
 U   -0.31167755E 00  U
```

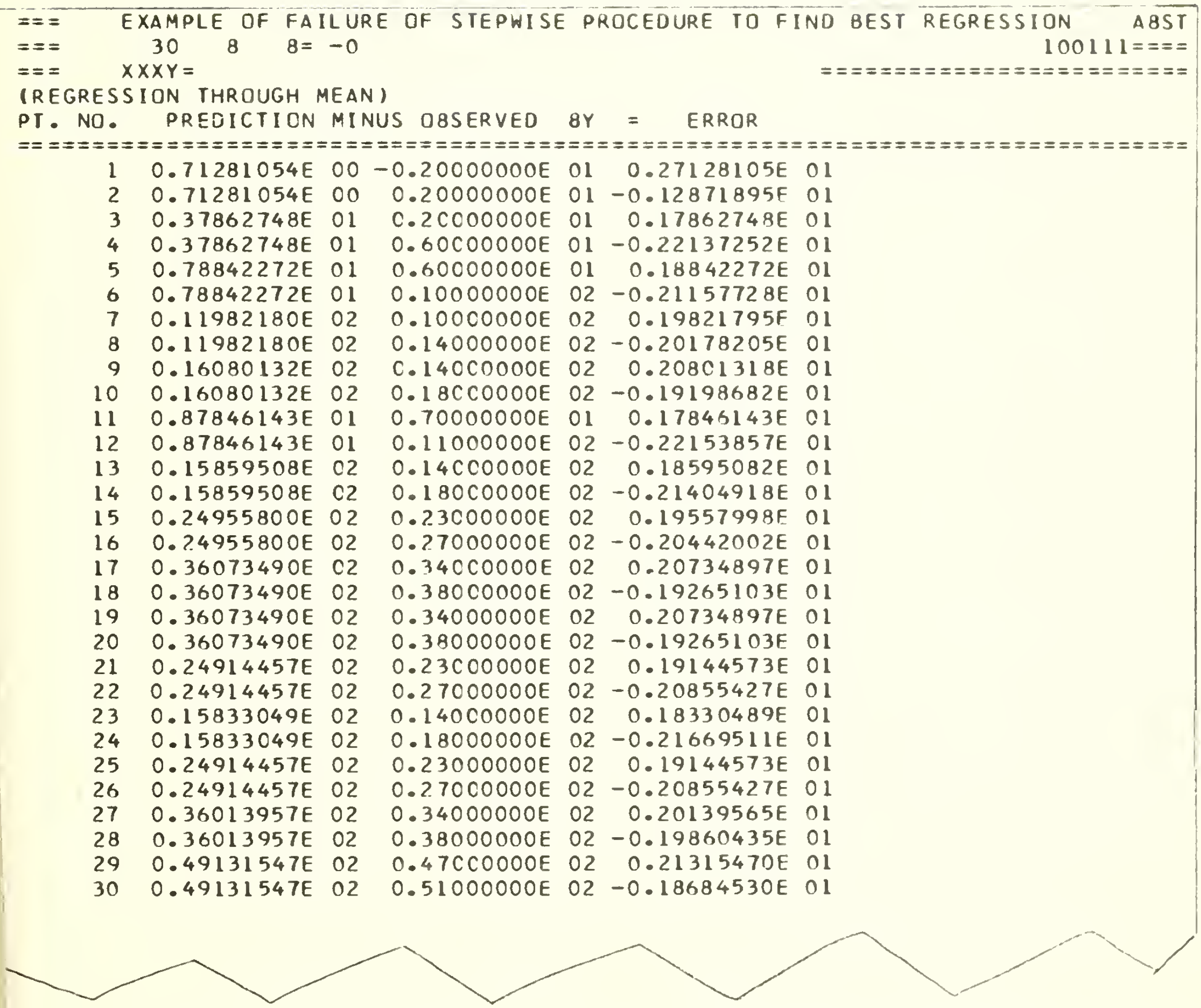
```
===    EXAMPLE OF FAILURE OF STEPWISE PROCEDURE TO FIND BEST REGRESSION    ABST
===      30   8   8= -0                                                100111====
===    XXXY=                                           ========================
VARIABLE SUBSCRIPT  IN B-VARIANCE  MATRIX             (REGRESSION THROUGH MEAN)
VB          8        VB
===============================================================================
 5    0.11189170E-02  5
 6    0.15945749E-02  6
 7    0.10635411E-01  7
 U    0.79561761E 00  U
```

```
===    EXAMPLE OF FAILURE OF STEPWISE PROCEDURE TO FIND BEST REGRESSION     ABST
===      30    8    8= -0                                                 100111====
===    XXXY=                                               =========================
(REGRESSION THROUGH MEAN)

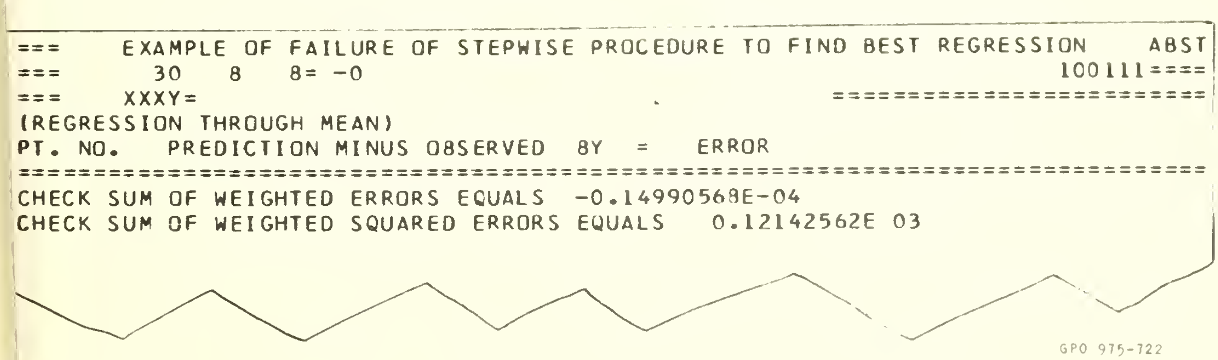
 SOURCE OF  I DEG. OF I   SUMS OF SQUARED Y DEVIATIONS
 VARIATION  I FREEDOM I         8Y
================================================================================
REGRESSION         3     0.54100410E 04
  ERROR           26     0.12142554E 03
--------------------------------------------------------------------------------
TOTAL             29     0.55314666E 04
================================================================================
================================================================================


MEAN SQUARED RESIDUAL OF PREDICTION MINUS MEAN Y
=VAR. OF REG. ESTIMATE          8Y
=MSQR (ABBREVIATION)=    0.46702130E 01
================================================================================
  RMSQR=MSQR/(VAR. Y) =      0.0245
      1-RSQUARED             0.0220
       RSQUARED              0.9780
--------------------------------------------------------------------------------
```

```
===    EXAMPLE OF FAILURE OF STEPWISE PROCEDURE TO FIND BEST REGRESSION     ABST
===      30    8    8= -0                                                 100111====
===    XXXY=                                               =========================
(REGRESSION THROUGH MEAN)
 I    MEAN X OR Y     VARIANCE X OR Y
================================================================================
 5    0.10066667E 02    0.25399540E 03
 6    0.81333333E 01    0.17667126E 03
 7    0.27333333E 01    0.25443678E 02
 8    0.20866667E 02    0.19074023E 03
```



```
===    EXAMPLE OF FAILURE OF STEPWISE PROCEDURE TO FIND BEST REGRESSION    ABST
===      30    8    8= -0                                              100111====
===    XXXY=                                              =======================
(REGRESSION THROUGH MEAN)
PT. NO.    PREDICTION MINUS OBSERVED  BY  =   ERROR
==============================================================================
      1  0.71281054E 00 -0.20000000E 01  0.27128105E 01
      2  0.71281054E 00  0.20000000E 01 -0.12871895E 01
      3  0.37862748E 01  0.20000000E 01  0.17862748E 01
      4  0.37862748E 01  0.60000000E 01 -0.22137252E 01
      5  0.78842272E 01  0.60000000E 01  0.18842272E 01
      6  0.78842272E 01  0.10000000E 02 -0.21157728E 01
      7  0.11982180E 02  0.10000000E 02  0.19821795E 01
      8  0.11982180E 02  0.14000000E 02 -0.20178205E 01
      9  0.16080132E 02  0.14000000E 02  0.20801318E 01
     10  0.16080132E 02  0.18000000E 02 -0.19198682E 01
     11  0.87846143E 01  0.70000000E 01  0.17846143E 01
     12  0.87846143E 01  0.11000000E 02 -0.22153857E 01
     13  0.15859508E 02  0.14000000E 02  0.18595082E 01
     14  0.15859508E 02  0.18000000E 02 -0.21404918E 01
     15  0.24955800E 02  0.23000000E 02  0.19557998E 01
     16  0.24955800E 02  0.27000000E 02 -0.20442002E 01
     17  0.36073490E 02  0.34000000E 02  0.20734897E 01
     18  0.36073490E 02  0.38000000E 02 -0.19265103E 01
     19  0.36073490E 02  0.34000000E 02  0.20734897E 01
     20  0.36073490E 02  0.38000000E 02 -0.19265103E 01
     21  0.24914457E 02  0.23000000E 02  0.19144573E 01
     22  0.24914457E 02  0.27000000E 02 -0.20855427E 01
     23  0.15833049E 02  0.14000000E 02  0.18330489E 01
     24  0.15833049E 02  0.18000000E 02 -0.21669511E 01
     25  0.24914457E 02  0.23000000E 02  0.19144573E 01
     26  0.24914457E 02  0.27000000E 02 -0.20855427E 01
     27  0.36013957E 02  0.34000000E 02  0.20139565E 01
     28  0.36013957E 02  0.38000000E 02 -0.19860435E 01
     29  0.49131547E 02  0.47000000E 02  0.21315470E 01
     30  0.49131547E 02  0.51000000E 02 -0.18684530E 01
```



```
===    EXAMPLE OF FAILURE OF STEPWISE PROCEDURE TO FIND BEST REGRESSION    ABST
===      30    8    8= -0                                              100111====
===    XXXY=                                              =======================
(REGRESSION THROUGH MEAN)
PT. NO.    PREDICTION MINUS OBSERVED  BY  =   ERROR
==============================================================================
CHECK SUM OF WEIGHTED ERRORS EQUALS  -0.14990568E-04
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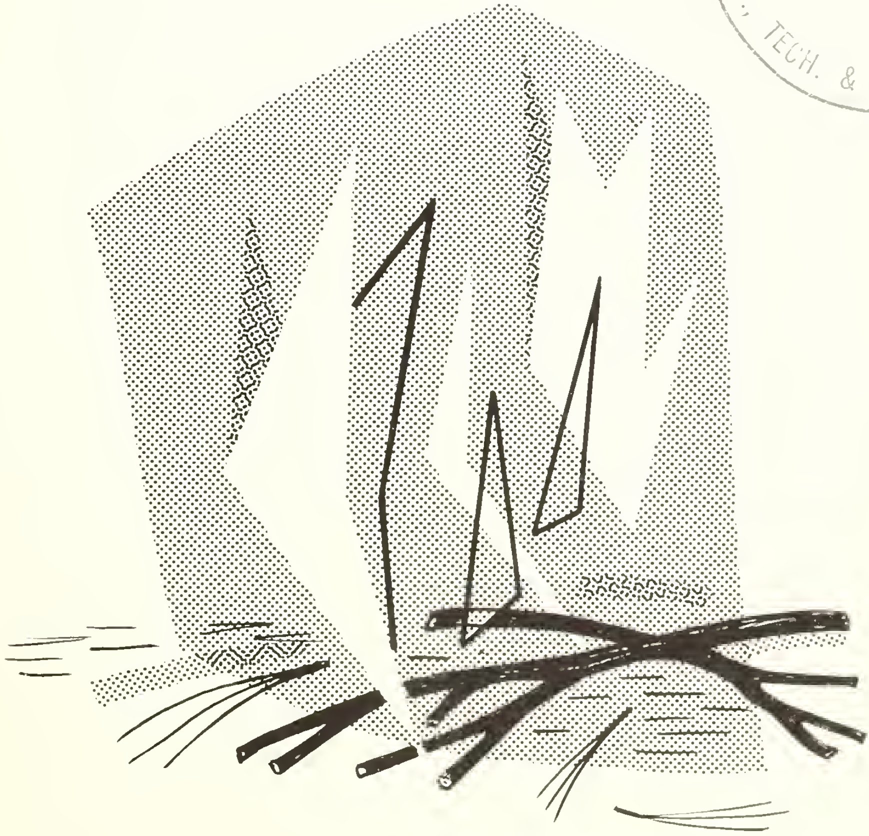
Forest Service - U.S. Department of Agriculture

Prescribed Burning in the Interior Ponderosa Pine Type of Northeastern California . . .

a preliminary study

Donald T. Gordon



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Contents

The Author

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Acknowledgments

I thank Craig C. Chandler for assistance with the fire phases and meteorological monitoring reported; and personnel of the Lassen National Forest—particularly those on the Bogard Ranger District—for their assistance in these experiments.

Perhaps nowhere else has the subject of prescribed burning aroused more debate than in California. For it was here that the controversy had its origin in 1920, when *Sunset* published Stuart E. White's article on "Paiute Forestery."[1] White's advocacy of light burning touched off a cascade of words on the subject. As early as 1924, a cursory literature review yielded more than 30 articles totaling more than 75,000 words on the topic of light burning in California timber stands.

It would seem that in the more than 40 years since the debate on broadcast burning began, nearly every facet of the subject has been exhaustively explored—that no new argument, pro or con, has not been advanced. Yet the use of prescribed burning as a silvicultural or as a fire control tool remains as controversial as ever in California.

What then do we hope to gain by adding an account of a modest set of experiments to an already overflowing literature? Simply that from these experiments we have accrued a reasonable body of objective data from which certain deductions can logically be drawn. Furthermore, detailed descriptions of the trials can add significantly to the data base that must be accumulated before any truly objective analysis of prescribed broadcast burning in California's timber types will be possible. Only rarely in the published results of past experiments has there been enough details on weather conditions, fuel conditions, fire behavior, fire effects, and costs to enable an objective observer to evaluate the practical worth of this management technique.

This paper reports on three experimental prescribed burns in the interior ponderosa pine type on the Blacks Mountain Experimental Forest, northeastern California. Purpose of these trials was fuel hazard reduction or thinning. Information on weather and fuel moisture conditions, timber stands, and results obtained is included.

Blacks Mountain Experimental Forest

The Blacks Mountain Experimental Forest is typical of the interior ponderosa pine type (Society of American Foresters Forest Cover Type 237),[2] with some inclusions of Jeffrey pine (Cover Type 247). This forest type, locally called eastside pine, occupies about 4 million acres of the northeastern plateau of California. Most of the timbered area has a wealth of advance reproduction. Site quality ranges from medium to poor. Elevations of the test plots varied from 5,800 to 6,150 feet. Precipitation averages about 20 to 25 inches annually. In summer, temperatures usually reach 80° to 85°F. in the afternoon, but drop to about 40°F. by early morning.

Because weather during spring and fall may vary considerably from day to day, it is notably difficult to predict accurately. Relative humidity during summer afternoons may fall as low as 10 percent, and often does not rise above 60 or 70 percent at night. In winter, snow blankets the ground most of the time. In this environment, forest fuels decay slowly—especially where they do not touch the soil.

Merchantable timber volume on the uncut Experimental Forest averaged about 18,000 bd. ft. (Scribner) per acre on 10,000 acres, in 1934. Nearly all the young-growth, much of it in dense sapling and pole groups, is at least 75 years old. Stagnation, and suppression by overstory, has been commonplace. Most of the understory is believed to have originated soon after the vast herds of sheep stopped grazing the land. Presumably the sheep helped prepare a good seedbed by severely reducing the amount of low forms of competitive vegetation. A fire exclusion policy has been in effect since the early 1900's, when the area was placed under the U.S. Forest Service. No evidence of previous fire damage was observed in any of the young-growth in this study. Nor has there been any slash treatment.

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[1] White, Stuart E. *Woodsmen, spare those trees!* Sunset. pp. 23–26, 108, 110, 112, 114–116, illus. Mar. 1920.

[2] Society of American Foresters. *Forest cover types of North America.* Washington, D.C. 67 pp., illus. 1962.

Three Prescribed Burns

Our investigative work was intended to be preliminary. We had hoped it would lead to a larger program which would study the possible uses of fire to create fuel-breaks, reduce dangerous fuel accumulations, eliminate undesirable vegetation, and thin over-dense young stands. We wanted to observe what occurred during and after burning. As we progressed, our data collection methods were changed to obtain more complete records of results. Our experience in the three burns changed our hopes and limited our actual program.

The data reported apply to four areas; one area was not burned, and half of one was burned a second time. In all but one case, we kept records for a comparative unburned area.

First Burn

The aim of the first burn was to kill abundant and unwanted incense-cedar (*Libocedrus decurrens* Torr.) seedlings and saplings beneath a mature stand of ponderosa pine (*Pinus ponderosa* Laws.). To achieve the desired result, personnel with fire experience prescribed a hot, clean litter burn. A period during fall was judged to be the most satisfactory time to attempt the burn.

The week of September 28, 1959, was tentatively scheduled for the trial. Weather data were recorded continuously during the field season at the Experimental Forest headquarters (about 6 miles distant from the burn site). During the week of September 14, 0.43 inches of rain fell; by the time of the burn—October 2—any practical effects of the storm had pretty much disappeared. Moisture content of pine needles in litter adjacent to the burned area was determined immediately before and after the fire by the xylene distillation technique:

	Moisture Content *In sun* (percent)	Moisture Content *In shade* (percent)
Before fire	5.5	9.7
After fire	5.2	8.2

Air temperature at ignition time (2:30 p.m.) was 64°F. and burning conditions[3] were as follows:

Fuel stick moisture content 8 vs. Relative humidity 14 = Fine fuel moisture factor 4

Fine fuel moisture factor 4 vs. Wind speed 3–5 = Spread factor 13

Fuel stick moisture content 8 vs. Buildup 47 = Intensity factor 63

Intensity factor 63 vs. Spread factor 13 = *Timber burning index* 10

The perimeter was ignited with a drip torch, lee side first. Some unexpected gusts of wind, perhaps 10–15 m.p.h., caused the fire to burn hotter than desired at times. The hottest areas had to be cooled with water to contain the fire. This fire was secured at 5:30 p.m. On the following day about 2,000 gallons of water were used to douse the smouldering litter and duff.

We obtained the following results:

1. The primary objective — elimination of unwanted cedar reproduction — was accomplished; the understory was reduced from 1,031 to 16 live trees (*fig. 1*).
2. The overstory was reduced from 31 to 26 live trees. Only small trees (8 to 14 inches d.b.h.) were killed.
3. Total fuel hazard in the area was reduced, but fuels were not measured in this instance.
4. Inflammable dry cedar bark, small pitchy fire scars on some pines, and gusts of wind were responsible for the fire escalating into crowns of a few mature trees.

We concluded that future burning of any kind under such severe conditions would be out of the question. Only the timely and repeated application of water by an alert fire crew kept this experiment from becoming a serious fire.

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[3] All expressions of burning conditions in this paper are in terms usable with the *California Fire Danger Rating* (1958), developed by the California Division of Forestry, U.S. Weather Bureau, California Region of the U.S. Forest Service, and California (now Pacific Southwest) Forest and Range Experiment Station. "Fuel stick moisture content" is percent moisture in an assembly of four ½- by 19-inch sugar pine dowels. "Buildup" is an index derived daily from fuel stick moisture content and precipitation data. Basically, buildup increases with days since last precipitation and with progressively lower fine fuel moisture content.

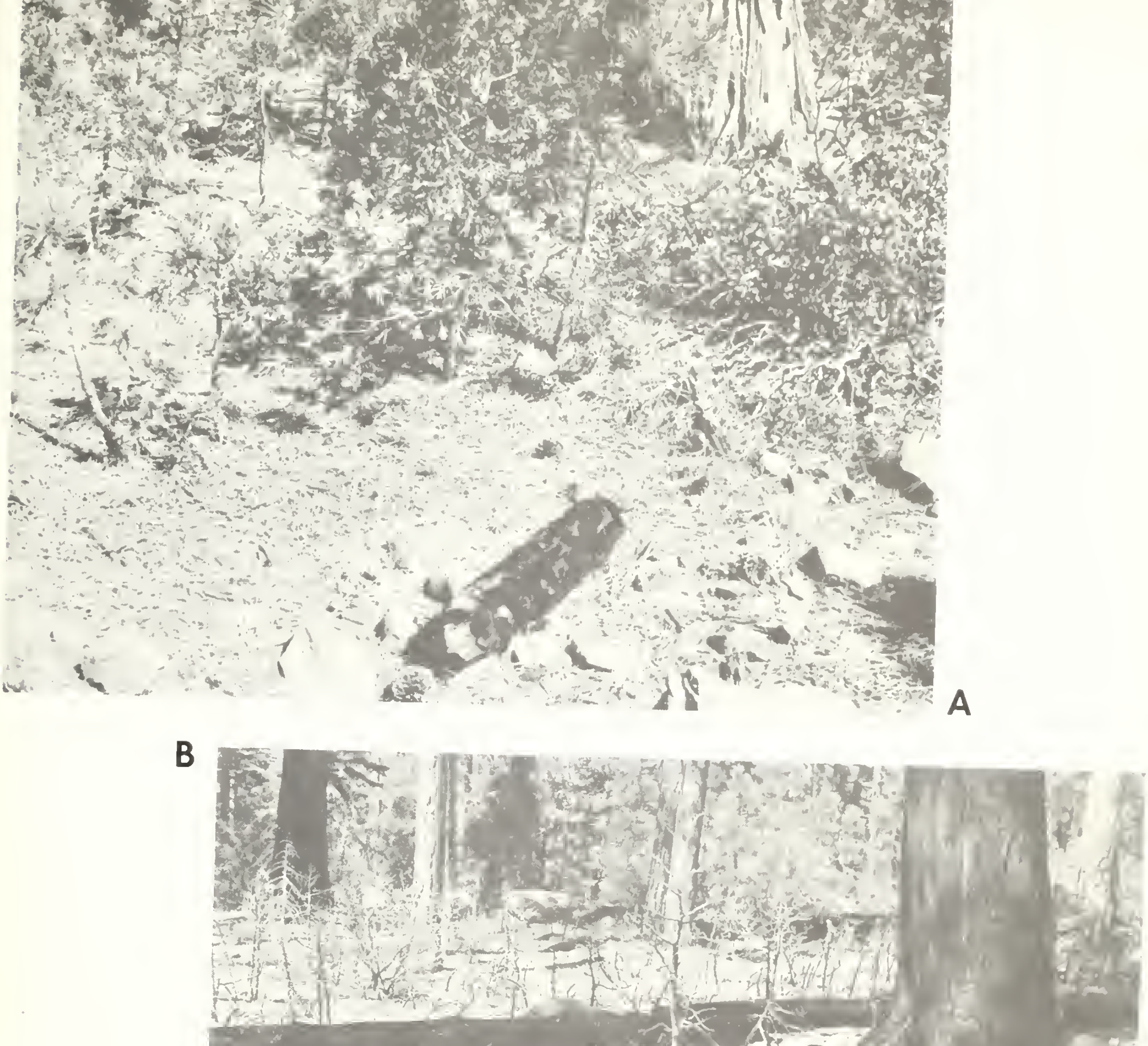

Figure 1. — *First burn, October 2, 1959, Blacks Mountain Experimental Forest. A portion of the area before and 1 year after the burn;* A, *before;* B, *after burn.*

Second Burn

A stand type prevalent in the Experimental Forest consists of dense groups of pine poles. Under the canopy of a closed pole stand, litter—chiefly needles—builds up rapidly, in places to depths of 3 or 4 inches. Also laying on the forest floor, in greatly varying stages of decay, are large dead stems and limbs from the overmature stand which existed when the poles became established.

We decided to try burning for fuel hazard reduction in such a stand. The intent was to secure a light surface burn by backing a fire against a light wind when the surface litter was dry enough to carry fire but when the deeper duff layer was too wet to burn. If this technique succeeded, we thought we would repeat it on the same area—perhaps annually.

The area to be burned was 0.88 acre. Within this uniformly-stocked stand we established a square 1/10-acre sampling unit. The number of trees in each diameter class by crown class and species was tallied *(table 1)*. Stems per acre totaled about 1,200.

Additional trees were sampled within and outside the area to be burned: 20 sets of trees, with four matched individuals in each set. Each set of four trees was picked to be as similar as possible in diameter and crown class; one tree of each set was outside the area to be burned. The 20 sets were chosen to sample the range of diameters and crown classes. All trees were tagged, measured, and described.

Within the burn site, protective treatments were randomly assigned to each of the three trees within a set. One tree was protected by a 3-foot high, .019-inch thick, sheet aluminum collar, with a diameter at least 2 inches greater than that of the tree. Around the second tree, litter was scraped back from the bole for a distance of 6 inches. The third tree received no protection.

When weather and fuel approached the prescribed burning condition *(table 2)*, detailed instrumentation began. A fire weather observation trailer was placed next to the intended burn area. A combination of recording and manual instruments recorded data for 3 days before, and during the early part of the burn.

Fuel samples were collected and "canned" at 1830 hours, a half hour before the burn. Fuel moisture contents determined by solvent distillation techniques were as follows:

Fuel type:	*Moisture content* (percent)
Surface litter	10.4
Duff at half-inch depth	30.2
Half-inch twigs on surface	10.3
Half-inch dead branches on live trees	14.0
Two-inch limbs on surface	19.2
Four-inch limbs on surface	23.6
Six-inch limbs on surface	25.6

Table 1.-*Distribution of trees, by diameter classes, dominance, and species, 1/10-acre plot, second burn, Blacks Mountain Experimental Forest, 1960*

D.b.h.	Dominant		Codominant		Intermediate		Suppressed		Total		All
(inches)	Pine	White fir	Pine	White fir	Pine	White fir	Pine	White fir	Pine	White fir	species
	Number										
1	0	0	0	0	0	0	1	3	1	3	4
2	0	0	0	0	0	0	7	3	7	3	10
3	0	0	0	0	0	0	14	2	14	2	16
4	0	0	0	0	3	0	15	0	18	0	18
5	0	0	0	0	7	0	12	0	19	0	19
6	0	0	2	0	7	0	1	0	10	0	10
7	0	0	0	0	8	0	0	0	8	0	8
8	4	0	10	0	6	0	0	0	20	0	20
9	2	0	4	0	0	0	0	0	6	0	6
10	5	0	0	0	0	0	0	0	5	0	5
11	2	0	0	0	0	0	0	0	2	0	2
12	3	0	0	0	0	0	0	0	3	0	3
13	1	0	0	0	0	0	0	0	1	0	1
Total	17	0	16	0	31	0	50	8	114	8	122

Table 2.--*Trends of weather, fuel moisture conditions, and timber burning index, second burn, Blacks Mountain Experimental Forest, 1960*

Date and time	Location	Air temperature	Relative humidity	Fuel stick moisture	Wind speed	Fine fuel moisture index	Spread factor	Buildup	Intensity factor	Timber burning index
		°F.	*Percent*	*Percent*	*M.p.h.*					
May 13:										
1430	Shelter[1]	52	26	8.0	4	5	11	004.1	39	5
	Ground[2]	48	27	9.5	--	--	--	--	--	--
1930	Shelter	49	32	8.0	1	6	7	004.1	39	3
	Ground	45	40	9.5	--	--	--	--	--	--
2015	Shelter	44	40	--	--	--	--	--	--	--
May 14:										
0715	Shelter	27	70	9.5	--	--	--	--	--	--
	Ground	22	90	11.0	--	--	--	--	--	--
1530	Shelter	60	25	7.5	3	5	11	004.5	39	5
	Ground	57	28	8.5	--	--	--	--	--	--
1810	Shelter	59	28	--	--	--	--	--	--	--
	Ground	56	31	--	--	--	--	--	--	
1930	Shelter	53	30	--	2	--	--	--	--	--
	Ground	52	35	--	--	--	--	--	--	--
2400	Shelter	36	59	--	--	--	--	--	--	--
	Ground	32	79	--	--	--	--	--	--	--
May 15:										
0800	Shelter	--	--	10.0	--	--	--	--	--	--
	Ground	--	--	10.5	--	--	--	--	--	--
1600	Shelter	56	33	8.0	4	6	9	004.9	39	4
	Ground	54	45	9.5	--	--	--	--	--	--
1930	Shelter	49	43	--	2	--	--	--	--	--
	Ground	45	60	--	--	--	--	--	--	--
2200	Shelter	44	64	--	--	--	--	--	--	--
	Ground	39	92	--	--	--	--	--	--	--
May 16:										
0800	Shelter	--	--	12.5	--	--	--	--	--	--
	Ground	--	--	13.0	--	--	--	--	--	--
1200	Shelter	50	13	--	--	--	--	--	--	--
	Ground	44	30	--	--	--	--	--	--	--
1530	Shelter	54	12	8.5	3	4	13	005.3	35	6
	Ground	51	22	10.0	--	--	--	--	--	--
1930	Shelter	46	23	8.0	1	5	8	005.3	39	3
	Ground	42	38	9.5	--	--	--	--	--	--

[1] Recording instruments in shelter 4.5 feet above ground, moisture stick at 9 inches, wind at 20 feet.
[2] Recording instruments at ground level, moisture stick on litter.

The accumulated fuel moisture and weather information indicated that burning would be appropriate at about 1900 hours, when the relative humidity was just beginning a steep rise from its afternoon low. An hour later, wind velocity could be expected to drop.

At 1930 hours, early in the burn, pertinent conditions were as follows:

Air temperature	46°F
Relative humidity	23 percent
Fuel stick moisture	8 percent
Wind speed	1 m.p.h.
Timber burning index	3

The area was fired by a drip torch at 1900 hours, May 16, 1960. The lee side of the perimeter was ignited slowly so that fire behavior could be observed and projected. Strip firing was required immediately to produce enough heat for a continuous burn—even in the surface layer of needles. Therefore, the remainder of the area was fired rapidly by igniting strips 5 to 10 feet apart. Even so, burning was extremely spotty. In many places the fire died by itself, and an unburned strip was left between two torch lines. On the other hand, a few large poles were damaged where fire climbed ladder-like from adjacent smaller trees with low-hanging crowns.

The fire flared up when it reached a prone dead top near the windward edge of the burn. This top was a remnant from logging 2 years previously. It burned hot enough to ignite the crowns of the surrounding trees for 10 or 15 feet. This fire started a crown run that became the most prominent feature of the burn. Embers from the crown fire started numerous smouldering spot fires outside the burned area. All spot fires were extinguished quickly by patrolmen.

The area cooled about an hour after ignition. The fire was watched and allowed to smoulder the following day and night. That this smouldering could go on for several days, at least, became obvious. Pressure of other work required that the fire be secured. Mopup was accomplished on May 18–19, using a 1,100-gallon tanker.

In our estimation, almost ideal conditions existed for this prescribed burn. The top layer of litter was dry, and some of the deeper litter and duff was shiny with free water. A small snowbank still existed on a small part of the area. Weather conditions were good, yet the prescribed burn was disappointing for several reasons. First, litter burned poorly in many places. Second, the major crown fire was an unexpected development. Third, large, rotten, wet fuels were able to carry heat for such a prolonged period that their extinguishment would be a costly necessity.

Part of the crown fire overlapped a portion of the area with the tagged-tree sets. A short time after the fire, when scorched needles had become dry and contrasted with the green, crown damage to all those tagged trees was estimated to the nearest 5 percent of total needle complement. These data were grouped by crown damage classes to reflect certain or probable mortality *(table 3)*. Estimation of the possibility of mortality was based solely on results of a study[4] which found a mortality rate of 52 percent for trees when 75 percent of the live crowns were pruned. We had no comparable data for fire-damaged trees in this area.

For several reasons, the protective effect of aluminum shields and litter raking can be only partially evaluated. First, the crown-out killed some trees which might otherwise have been used in the evaluation. Second, hot but slowly smouldering areas had to be mopped up 2 to 3 days after the main burning period; therefore, the fire could not run its natural course. Third, the surface burn in the crown-out area was hotter than elsewhere; in fact, it was hot enough to melt two of the aluminum collars, but the collars did prevent all bark scorching for the 3-foot height.

In spite of these three shortcomings, some treatment effects are discernible *(table 4)*.

Proportionately more trees were subject to hot basal burns within the crown-out area than outside that area. Within the crown-out area, there was more than twice as much hot basal burning around untreated trees as there was around trees having aluminum collars or basal cleaning. Contrarily, outside the crown-out area there was twice as much hot basal burning around trees with basal cleaning as around trees with other treatments.

Most of the tagged trees were in the crown-out area; the others were next to it. Because ground fuels generally did not burn well during the main burning period—except in the crown-out area—some of this basal injury undoubtedly was caused by heat generated in the above-average accumulation of fuel at tree bases. These shield-shaped accumulations (or the messes created at fringes of basal cleaning) probably were elevated enough so that the upper portions were drier than surrounding areas; wherever progressive smouldering reached such accumulations during the 2 or 3 days before mopup was completed, combustion became more intense.

While mopping-up we were impressed by the number of large, flattened, decayed old stems which had been hidden by the litter. This material, although seemingly saturated with water, continued to smoulder hotly. Obviously, material like this left within a large burn in the spring would create delayed fire outbreaks as fuels become drier.

Growth measurements were not attempted on the matched tree sets because two-thirds of the tagged trees on the burned area were killed.

Insect activity after this small burn created no problem. Turpentine beetles (*Dendroctonus valens* Lec.) moved into many of the dead and dying trees almost immediately, but did not spread to nearby trees. A number of borers moved into the burned trees. Neither *Ips* nor other *Dendroctonus* beetles made attacks in the vicinity.

Although we thought the prescription and actual burning conditions provided an excellent chance to achieve our objective—fuel hazard reduction—we obtained no generally beneficial results. Our fuel sampling scheme for this fire was inadequate and partly destroyed, so the main evidence of results became a series of before-and-after black-and-white photographs and colored slides. However, we could plainly see that fuels had been reduced only slightly, except in the crown-out area. In-

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[4] Hallin, William E. *Pruning ponderosa and Jeffrey pine.* U.S. Forest Serv. Calif. Forest & Range Exp. Sta. Res. Note 115, 4 pp. 1956.

Table 3.--*Crown damage to tagged trees, second burn, Blacks Mountain Experimental Forest, 1960*

Crown damage (percent)	Amount of trees			
	In crown-out area		Not in crown-out area	
	Number	*Percent*	*Number*	*Percent*
85-100	39	95.2	1	5.3
35-80	0	--	0	--
5-30	1	2.4	6	31.6
0	1	2.4	12	63.1
Total	41	100.0	19	100.0

Table 4.--*Incidence of hot basal burns*[1] *in litter and duff around sample trees, second burn, Blacks Mountain Experimental Forest, 1960*

Tree location	Trees in sample area	Trees having hot basal burns when treatment was--			
		Untreated	Basal cleaning	Aluminum collar	All
	Number	*Percent*			
In crown-out area	41	31.7	14.6	12.2	58.5
Not in crown-out area	19	5.3	10.5	5.3	21.1
Total sample area	60	--	--	--	--

[1] 'Hot basal burn' means that litter and duff were completely or mostly consumed by fire; white ash present. Heat which preceded this condition probably caused death of stem cambium and or shallow roots. During mopup, soil under this observable condition was sometimes still hot enough to turn cold water violently to steam.

stead of reducing the hazard, we had created a large amount of standing dead fuel.

During the first fall and winter, many dead needles fell to the ground. In succeeding winters since the burn, increasing numbers of dead trees have fallen. Forbs and grasses have become established in the opening created by the crown-out. These plants have created a competitive environment unfavorable to the establishment and growth of pine reproduction[5,6] *(fig. 2)*.

From this experiment we learned that if we were to control a fire within reasonable bounds in dense pole-size timber, we had to keep it out of the crowns. Furthermore, we had to use more intensive sampling methods to get better measurements of the many possible results of a burn.

Third Burn

The term "third burn" refers to a particular area where more than an acre was burned in 1961, and about half an acre reburned in 1962. To simplify the presentation of data and comments, the sequence of events at this area will be described first.

The purpose of the third burn was fuel hazard reduction in a pole stand. Selection of the site was based on relative uniformity of the stand. The area

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[5] Baron, Frank J. *Effects of different grasses on ponderosa pine seedling establishment.* U.S. Forest Serv. Pacific SW. Forest & Range Exp. Sta. Res. Note 199, 8 pp., illus. 1962.

[6] Roy, D. F. *Effects of ground cover and class of planting stock on survival of transplants in the eastside pine type of California.* U.S. Forest Serv. Calif. Forest & Range Exp. Sta. Res. Note 87, 6 pp. 1953.

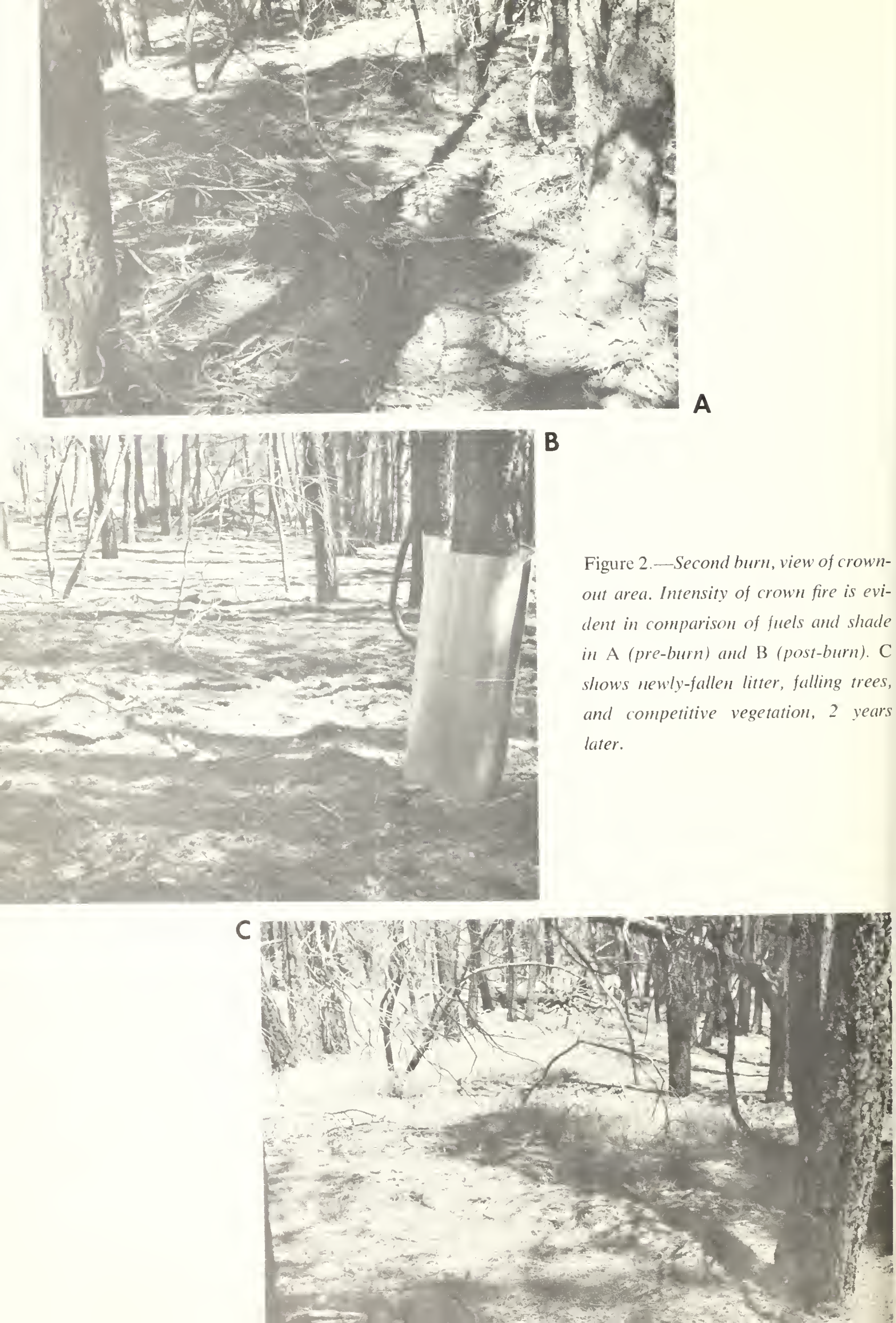

Figure 2.—*Second burn, view of crown-out area. Intensity of crown fire is evident in comparison of fuels and shade in* A *(pre-burn) and* B *(post-burn).* C *shows newly-fallen litter, falling trees, and competitive vegetation, 2 years later.*

comprised 1.50 acres, part of which was used as an unburned check.

The entire area was given a pre-burn treatment designed to keep fire out of the crowns, and in addition to protect bases of selected crop trees. First, potential crop trees were marked. Litter and duff then were scraped from bases of these trees for a distance of 6 to 8 inches. Live and dead limbs were removed to a height of 5 or 6 feet from all but exceptionally short seedlings. In a few instances, small groups of saplings were thinned. In a few places, concentrations of old logging slash were loosely bunched in minor openings with a small bulldozer.

Sampling was by randomly-located 1/100-acre plots, which contained milacre and square-foot sub-plots. Data in Meyer's[7] yield tables indicated that 20 plots would adequately sample trees in the area to be burned (1.10 acres), and that five plots would be necessary in the unburned area (0.40 acre).

On each 1/100-acre plot, crown classes of all trees were recorded. One-foot height classes were used to measure trees up to 10 feet tall; diameter at breast height for trees more than 10 feet tall. Distance from ground level to dead limbs and live limbs was recorded for each tree separately. After burns, fire-killed crown was estimated to the nearest 10 percent of total needle complement. Fire damage to stems (severe bark scorching or worse) was recorded to the nearest 1/10-square foot of external area after measuring with a transparent grid. Only one tree with obviously badly-burned bark was examined in detail. Trees were always tallied as being live or dead. If a tree had any green needles it was considered "live."

We placed a line transect across the middle of each plot. At the surface, condition of soil, rocks, vegetation, and fuel-size classes was recorded to the nearest 1/10-foot. At 18 and 48 inches above the ground transect, additional data were recorded, including vegetation and "overhead" fuels.

Within each 1/100-acre plot, a milacre plot was staked in a specified corner; within each milacre, a 1-foot square litter basket was placed in a specified corner. Each of these sampling units was the area basis for determining weight of a single size-class of fuel.

Fuel weights were recorded by these three size classes: (a) litter—less than 1 inch in diameter; (b) medium—1 to 4 inches in diameter; and (c) large—more than 4 inches in diameter.

Table 5.--*Weather, fuel moisture conditions, and timber burning index, third burn, June 6-8, 1961,*[1] *Blacks Mountain Experimental Forest*

Date and time	Temperature	Relative humidity	Fuel stick moisture[2]	Wind speed	Fine fuel index	Spread factor	Buildup	Intensity factor	Timber burning index
	°F.	*Percent*	*Percent*	*M.p.h.*					
June 6:									
1200	66	37	10.0	4	6	9	000.5	23	3
1400	68	38	8.5	5	6	9	.5	26	3
1600	65	39	9.5	5	6	9	.5	26	3
2000	56	67	10.5	0	11	3	.5	23	1
June 7:									
1200	68	32	11.0	3	7	8	.7	23	2
1400	71	34	9.5	3	6	9	.7	26	3
1500	74	37	9.5	3	6	9	.7	26	3
1700	68	45	9.0	4	7	8	.7	26	2
2000	60	65	10.5	2	11	3	.7	23	1
June 8:									
1200	66	33	9.5	3	6	9	.9	26	3
1330	69	29	9.0	4	6	9	.9	26	3
1600	67	38	9.0	4	6	9	.9	26	3

[1] Hygrothermograph in shelter 4.5 feet above ground, wind at 20 feet, fuel stick moisture at 9 inches.

[2] A fuel moisture stick on litter consistently read one to two percent lower for three days.

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[7] Meyer, W. H. *Yield of even-aged stands of ponderosa pine.* U.S. Dept. Agr. Tech. Bull. 630, 60 pp., illus. 1938.

1

FINE FUEL MOISTURE

Fuel Stick Moisture Content	Relative Humidity																		
	0 6	7 9	10 12	13 15	16 20	21 27	28 34	35 41	42 48	49 53	54 58	59 63	64 68	69 72	73 76	77 82	83 87	88 92	93 100
1-4.5	1.5	1.5	2	2.5	3	4	5	5	6	7	8	8	9	10	11	12	15	16	18+
5-10	2	2.5	3	4	4	5	6	6	7	8	9	10	10	11	12	14	16	18	18+
11-15	3	4	4	5	5	6	7	7	8	9	10	11	11	12	13	15	17	18+	18+
16-20	4	5	5	6	6	7	8	8	9	10	11	12	12	13	14	16	18	18+	18+
21-25	5	6	6	7	7	8	9	9	10	11	12	13	13	14	15	17	18+	18+	18+
26-30	6	7	7	8	8	9	10	10	11	12	13	14	14	15	16	18	18+	18+	18+
31-35	7	8	8	9	9	10	11	11	12	13	14	15	15	16	17	18+	18+	18+	18+
36-40	8	9	9	10	10	11	12	12	13	14	15	16	16	17	18	18+	18+	18+	18+
41-45	9	10	10	11	11	12	13	13	14	15	16	17	18	18	18+	18+	18+	18+	18+
46+	10	11	11	12	12	13	13	14	15	16	17	17	18	18+	18+	18+	18+	18+	18+

2

SPREAD FACTOR

Fine fuel moisture	Wind speed (m.p.h.)																	
	0-2	3-5	6-7	8-9	10	11	12	13	14	15	16	17	18	19	20	21	22-23	24+
1.5	14	19	23	28	33	37	40	43	47	51	55	61	66	70	74	83	89	100
2	13	17	21	26	30	34	37	40	43	47	51	56	61	65	70	77	82	92
2.5	12	15	20	24	28	32	35	38	41	44	47	52	56	61	67	72	77	86
3	11	14	18	22	26	29	32	34	38	41	44	48	52	57	62	67	73	81
4	10	13	16	20	23	26	29	31	34	37	39	43	47	51	56	60	64	72
5	8	11	14	17	20	22	25	28	30	33	35	38	41	45	49	53	57	62
6	7	9	12	14	17	19	21	24	26	28	30	33	35	39	44	47	49	54
7	6	8	10	12	15	17	19	21	22	24	26	29	31	33	39	42	44	46
8	5	7	9	11	13	14	16	17	19	20	22	25	26	29	33	36	38	41
9	5	6	7	8	10	11	13	14	16	17	18	21	22	25	28	30	32	36
10	4	5	6	7	8	9	10	12	13	15	16	17	19	20	24	25	27	29
11	3	4	5	6	7	8	9	9	11	12	12	13	15	16	19	20	22	24
12	2	3	3	4	5	6	6	7	8	9	9	10	11	13	14	15	16	18
13	1	2	2	3	3	4	4	4	5	6	6	7	8	9	10	11	12	13
14	0	0	0	0	0	1	1	2	3	3	4	4	5	6	7	7	8	8
15	0	0	0	0	0	0	0	0	0	0	1	1	1	2	3	4	4	5
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	2	2
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
18+	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
II 41-60%	0-1	2-4	5-6	7	8	9	10	11	12	13	14	15	16	--	17	18	19	20+
III 61%+	0	1-2	3-4	5-6	7	8	--	9	10	11	12	--	13	14	15	16	--	17+
Slope Class	Wind speed (m.p.h.)																	

3

INTENSITY FACTOR--Timber Fuels

Fuel Stick Moisture Content	Buildup										Fuel Stick Moisture Content
	0-1.9	2-3.9	4-6.9	7-10.9	11-16.9	17-25.9	26-39.9	40-61.9	62-99.9	100+	
1.0	57	62	67	71	76	81	86	90	95	100	1.0
1.5	54	60	64	68	73	78	83	87	92	97	1.5
2.0	51	56	61	65	70	75	80	85	89	94	2.0
2.5	49	53	58	63	67	72	77	82	87	91	2.5
3.0	46	51	56	60	65	70	75	79	84	89	3.0
3.5-4.0	44	49	53	58	62	67	72	77	82	86	3.5-4.0
4.5-5.0	40	44	49	54	58	63	68	73	78	82	4.5-5.0
5.5-6.0	36	40	45	50	54	59	64	69	74	78	5.5-6.0
6.5-7.0	32	37	42	46	51	56	61	65	70	75	6.5-7.0
7.5-8.0	30	34	39	44	48	53	58	63	68	72	7.5-8.0
8.5-9.5	26	31	35	40	45	49	54	59	64	69	8.5-9.5
10-12	23	27	32	37	41	46	51	56	61	65	10-12
13-16	19	24	28	33	38	42	47	52	57	62	13-16
17-20	16	20	25	30	34	39	44	49	54	58	17-20
21+	13	17	22	27	31	36	41	46	51	55	21+

4

TIMBER BURNING INDEX

Intensity Factor	Spread Factor																							
	0 2	3 4	5 6	7 8	9 10	11 12	13 14	15 16	17 19	20 22	23 25	26 28	29 31	32 34	35 39	40 44	45 49	50 54	55 60	61 67	68 74	75 81	82 90	91 100
0-12	0	0	1	1	1	1	2	2	2	2	3	3	4	4	5	5	6	6	7	8	9	9	10	11
13-19	0	1	1	2	2	2	3	3	4	4	5	5	6	7	7	8	9	10	12	13	14	15	17	19
20-26	0	1	1	2	3	3	4	4	5	6	6	7	8	9	10	11	13	14	16	17	19	21	23	26
27-32	1	1	2	3	3	4	5	5	6	7	8	9	10	12	13	14	16	18	20	22	24	27	30	33
33-36	1	1	2	3	4	5	6	6	7	8	10	11	12	14	15	17	19	21	24	26	29	32	35	39
37-39	1	2	2	3	4	5	6	7	8	9	11	12	14	15	17	19	21	23	26	29	32	35	39	43
40-42	1	2	3	4	5	6	7	8	9	10	12	13	15	16	18	21	23	25	28	31	35	38	42	47
43-46	1	2	3	4	5	6	7	8	10	11	13	14	16	18	20	22	25	28	31	34	37	41	45	50
47-49	1	2	3	4	5	6	8	9	10	12	14	15	17	19	21	24	27	30	33	36	40	44	49	54
50-52	1	2	3	5	6	7	8	9	11	13	15	16	18	20	23	26	29	32	35	39	43	48	52	58
53-56	1	2	4	5	6	7	9	10	12	14	16	18	20	22	24	27	31	34	38	42	46	51	56	62
57-59	1	2	4	5	7	8	9	11	12	14	17	19	21	23	26	29	32	36	40	44	49	54	59	66
60-62	1	3	4	5	7	8	10	11	13	15	18	20	22	24	27	31	34	38	42	47	52	57	63	69
63-66	1	3	4	6	7	9	10	12	14	16	18	21	23	25	28	32	36	40	44	49	55	60	66	73
67-69	1	3	4	6	8	9	11	13	15	17	19	22	24	27	30	34	38	42	47	52	58	63	70	77
70-72	1	3	5	6	8	10	11	13	15	18	20	23	26	28	32	36	40	44	49	54	60	66	73	81
73-76	1	3	5	7	8	10	12	14	16	18	21	24	27	29	33	37	41	46	51	56	62	69	76	84
77-79	1	3	5	7	9	11	12	14	17	19	22	25	28	31	34	38	43	48	53	59	65	72	79	87
80-82	1	3	5	7	9	11	13	15	17	20	23	26	29	32	36	40	45	50	55	61	68	75	83	91
83-86	2	3	5	7	9	11	13	15	18	21	24	27	30	33	37	42	47	52	58	64	71	78	86	95
87-89	2	4	6	8	10	12	14	16	19	22	25	28	31	34	38	43	49	54	60	67	74	81	89	99
90-92	2	4	6	8	10	12	15	17	20	23	26	29	32	36	40	45	51	56	62	69	76	84	93	100
93-96	2	4	6	8	11	13	15	17	20	24	27	30	33	37	42	47	53	58	64	72	79	87	96	100
97-100	2	4	6	9	11	13	16	18	21	24	28	31	35	38	43	49	55	60	67	74	82	90	100	100

TIMBER TABLES

Table 6.--*Burning conditions, prescribed (blocked) and actual (circled), third burn on June 8, 1961; prescription prepared in early May 1961.*

Large fuels on the 1/100-acre plots were measured to the nearest inch of diameter and foot of length. The data were later converted on a volume basis to ovendry weight of ponderosa pine, using a factor of 25 pounds per cubic foot. In fall 1964, all dead trees on the plots were picked up or cut at ground level. Their parts were placed on a tarpaulin, separated into the three fuel size classes, and weighed or measured. Samples of these fuels were ovendried to obtain correction factors for field weights.

Medium fuels were sampled on the milacre plots. They were weighed to the nearest half-pound and put back in their original positions. Samples of similar material off-plot were oven-dried to obtain field weight correction factors. Milacre plots were also used to estimate to the nearest 10 percent that part of the surface of each milacre that had actually burned.

A wire basket 1-foot square by 2-inches deep was used to sample changes in litter weights. Foot-square cores of litter and duff were cut to mineral soil with a square core-cutter or flat spade, lifted intact, and placed in the baskets. Baskets of litter were weighed to the nearest half-ounce and carefully placed so that the cores could be returned to their original positions. During weighing, off-plot fuel samples were collected for ovendrying, to obtain fuel weight correction factors. Litter depth in each basket was measured. After a burn, we also noted whether any litter in a basket had burned. We found no evidence that the litter basket screen inhibited burning.

For about 3 weeks before the burn, fuel moisture was sampled at intervals. When it seemed appropriate, a fire weather observation trailer was installed next to the test area.

As soon as data established the diurnal weather and fuel moisture pattern *(table 5)*, we decided to burn in early afternoon. It was estimated that fire then would accomplish the most fuel hazard reduction under the burning prescription *(table 6)*.

The Weather Bureau provided a special forecast for the area on the morning of June 8, covering June 8 and 9. Weather and fuel conditions one-half hour before the burn were as follows:

Temperature	69°F.
Relative humidity	29 percent
Fuel stick moisture	9 percent
Wind speed	4 m p.h.
Timber burning index	3

Moisture in fuel samples collected a half-hour before the burn varied widely—from 6.2 percent for litter in the sun to 78.6 percent for a rotten log. Actual fuel moisture content determined by the solvent distillation technique was as follows:

Fuel type:	*Moisture* (percent)
Green needles	110.0
Lopped needles (from pre-burn treatment)	75.2
Litter in sun	6.2
Litter in shade	10.8
Rotten log	78.6
Twigs (¼–½ inch)	7.8
Twigs (½–1 inch)	9.0
Twigs (1–2 inches)	26.8

The area was strip-fired by drip torch according to plans, beginning at 1400 hours, June 8, 1961. Surface litter appeared to burn well. Fire also became established in almost all of the down logs, stumps, and other heavy debris. Flames rose about 12 inches above the ground, but in occasional flareups in small concentrations of slash, flames sometimes reached a height of 3 to 5 feet. Tree crowns near these flareups were sometimes scorched, but nowhere did the fire crown, and there was no difficulty in containing the fire. No spotting was noted.

Relative humidity approached 100 percent by midnight and stayed at that level for the rest of the night. By 0600 hours there were no more than 25 smokes still showing. In most cases, fire which had burned in heavy fuels had gone out by itself during the night. The burned area was patrolled at intervals on June 9 and 10. Mopup consisted mainly of eliminating hot spots on June 11 and 12.

Litter and medium fuels had burned well. Large fuels burned moderately well, considering their relatively high moisture content. There had been no crowning and little evidence of basal scorching, but roughly half of all trees on burned plots were dead by the following spring. No such rate of mortality occurred on unburned plots. Ground fuels had been reduced, but a new condition of standing dead fuels had been created.

Because of this new condition, we decided to reburn about half the area a year later. By so doing we would be able to compare observations of phenomena on adjacent plots burned once and twice.

Weather conditions in spring of 1962 were drier than in the preceding year. Heavy fuels, therefore, had a chance to dry rather well. Our burning prescription was the same as that in 1961. Although we would have preferred a hotter burn, we felt that a higher burning index would result in crown fires becoming started through ignition of dead foliage on trees killed in the previous year.

In 1962 we repeated the 1961 early-season pattern of periodic weather and fuel moisture observations. Subsequently, on May 8, detailed instrumentation at the site began with use of a weather observation trailer *(table 7)*. The data established the immediate weather and fuel moisture pattern, and substantiated our judgment of an approaching burning period which would fit our prescription. Weather and fuel conditions immediately before the burn were as follows:

Temperature	48°F
Relative humidity	31 percent
Fuel stick moisture	8.5 percent
Wind speed	2 m.p.h.
Burning index	3

Strip firing of the burn began at 1745 hours on May 10, 1962. The fire did not spread well through the litter, mainly because the amount of litter had been reduced by the burn of the previous year. However, the fire became well-established in heavy fuels. Flames reached 12 inches high, with occasional flareups in concentrations of heavy fuels. Crown-scorching from below was not noted, nor did fire flare through any crowns.

We had planned to allow this reburn to smoulder for 2 or 3 days. However, mopup had to be undertaken the following afternoon when the weather changed abruptly and unexpected higher air temperature and wind velocity (above predicted data) created a hazardous condition. The condition was so obvious that Ranger District personnel appeared, without being called, to assist us with the work.

To describe results of fires on this "third burn" area, we have grouped data various ways. In some instances, data for 20 plots before and after one burn may be compared with five unburned plots. Or, 11 plots, burned and reburned, may be compared with nine plots burned once only, as well as with five unburned plots.

As expected, dominant and codominant trees were least affected by the fires *(fig. 3)*. Intermediate and suppressed trees suffered heaviest mortality, probably because of smaller and generally lower live crowns, and thinner bark.

This experiment was accomplished during a 3-year drought which was ended by the Columbus Day storm of 1962. During the drought, foresters in the eastside pine type noticed an increasing but moderate amount of mortality of seedling- and sapling-size pines. Also a study within the three plot groupings in the third burn area showed that trees on the unburned area were slightly smaller and more numerous than trees on the burned and reburned areas. One would therefore expect "natural" mortality on the unburned plots to be greater than that on burned plots. For these reasons, any attempt at a direct comparison of "natural" mortality by plot groups would to a certain degree be misleading.

Table 7. --*Weather, fuel moisture conditions, and timber burning index, reburn of third burn, Blacks Mountain Experimental Forest, 1962*[1]

Date and time	Temperature	Relative humidity	Fuel stick moisture	Wind speed	Fine fuel index	Spread factor	Buildup	Intensity factor	Timber burning index
	°F.	*Percent*	*Percent*	*M.p.h.*					
May 8:									
1500	55	38	--	--	--	--	--	--	--
May 9:									
1300	53	28	10.0	5	6	9	004.6	32	3
1530	54	17	8.5	3	4	13	004.6	35	6
May 10:									
1130	52	17	10.0	4	4	13	004.8	32	5
1600	51	25	8.5	3	5	11	004.8	35	5
1730	48	31	8.5	2	6	7	004.8	35	3
1915	44	38	9.0	1	6	7	004.8	35	3

[1] Hygrothermograph in shelter 4.5 feet above ground, wind at 20 feet, moisture stick at 9 inches.

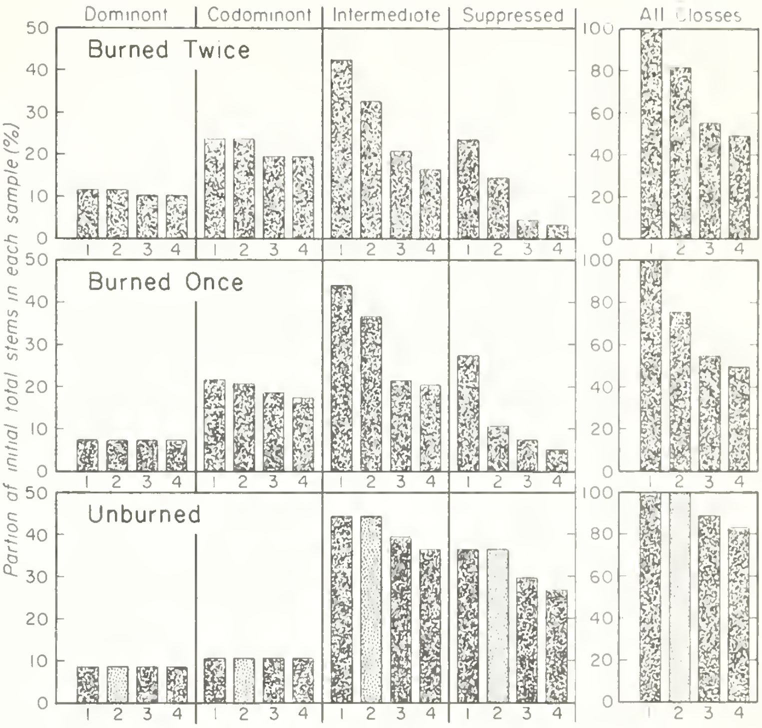

Figure 3. — *Live trees by crown classes on burned and unburned plots, third burn. Numbers below the bars refer to date when plots were examined: 1 = May, 1961 (before first burn); 2 = June, 1961 (after first burn); 3 = May, 1962; 4 = May, 1964 (3 years after first burn). Bar 2 for unburned plots is assumed — no examination.*

Table 8.--*Crown-killing caused by fire, by crown classes, third burn, Blacks Mountain Experimental Forest, 1961*

Portion of crown killed (percent)	Damaged trees by crown classes				
	Isolated (1)[1]	Dominant (27)	Codominant (67)	Inter-mediate (122)	Suppressed (71)
			Percent		
0	0	66.7	55.2	46.7	24.0
10	0	14.8	8.9	8.2	1.4
20	0	7.4	3.0	4.9	1.4
30	0	3.7	10.4	4.1	2.8
40	100.0	3.7	6.0	.8	0
50	0	3.7	3.0	2.5	8.4
60	0	0	4.5	0	1.4
70	0	0	1.5	.8	2.8
80	0	0	1.5	2.5	0
90	0	0	4.5	14.8	9.9
100	0	0	1.5	14.7	47.9
Total	100.0	100.0	100.0	100.0	100.0

[1] Numbers in parentheses equal total trees in each crown class.

The susceptibility of small trees to the effects of fire was demonstrated in the burn. Where pine pole stands have too many stems, killing the small trees could be considered a modest benefit from the standpoint of competition. And if the smallest trees were of a less desirable species—white fir or incense-cedar, for example—some additional gain could be counted. On the other hand, when all young trees are small (seedlings and saplings), and of a single desired species, total or heavy losses are undesirable.

Total or partial crown-killing by fire occurred during the first burn only *(table 8)*. This condition again illustrates vulnerability of small trees to fire—even when they have been afforded some protection by low pruning.

On the burned areas, the effects of fire raised the average base of live crowns about 2 feet above pruned level *(fig. 4)*. On the unburned plots, live crown bases remained steady at their pruned level. Data on dead limbs probably reflect these factors: (a) more killed limbs at low levels, (b) downward-curling effect of fire on dead limbs, (c) variation in the amount of down-curl caused by differences in moisture content of the limbs at different observation times, and (d) fewer live trees during later examinations.

The lowering of the average level of overhead fuel resulting from killed trees was not measured. But dead poles soon began to bend toward the ground *(fig. 5)*. A significant mass of dry fuel then comes closer to the ground, where it could be ignited easily by accidental fires and carry heat upward to live crowns.

At the beginning of this experiment there were 45 potential crop trees within the 25 1/100-acre plots. Average diameter of these trees was 7.1 inches. After the second burn, four crop trees on the burned plots were dead. A basal scar was found on only one tree. This injury measured 2.8 square feet. A hot-burning log near the tree caused the damage. The tree later died.

These results show that, silviculturally, fire improved the pole stand—but at a cost. The slightly increased supply of moisture afforded the dominant trees should increase their growth rate—at least moderately.

Only traces of wet (green) fuels on the ground were recorded at the first measurement. These were trimmings from the preburn treatment. Fuels on the unburned area were not remeasured after the first burn. Nor were ground fuels in the over 4-inch class remeasured in the final examination because no measurable change should be expected.

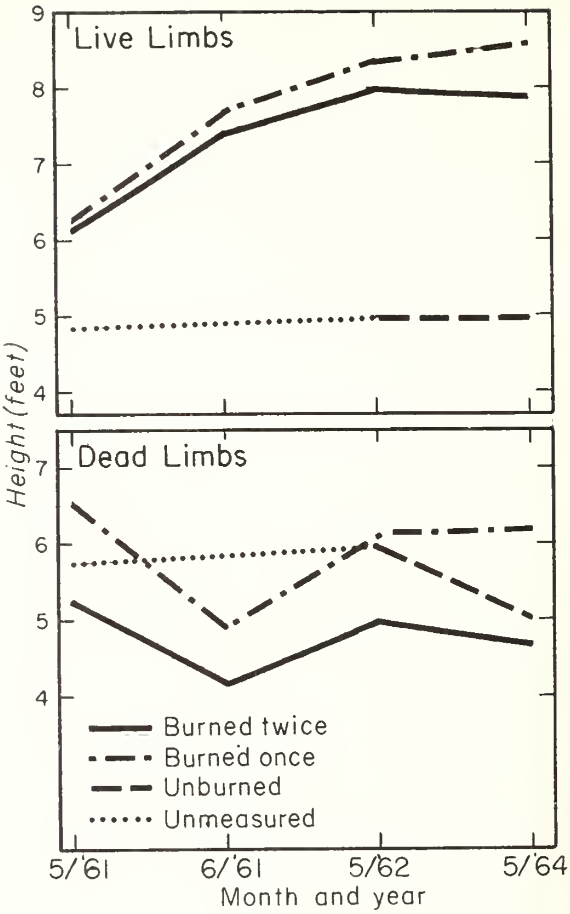

Figure 4.—*Average heights above ground of dead and live limbs at times indicated, for live trees only, third burn.*

The first burn achieved the most over-all fuel reduction. But it also caused most of the mortality which created new fuels *(fig. 6)*. The most striking reduction of fuel occurred in the litter class. Initial litter weight was reasonably comparable between plot groups.

Potential rate of fire spread on the area was therefore at a lower level immediately after the first burn, and was decreased slightly more by the second burn. Description of fire behavior during the reburn supports this judgment.

Medium and large fuels were distributed unevenly over the area, as indicated by grouped plot data in figure 6. Reduction of those original fuels on the burn-reburn area was encouraging, because potential fire intensity was lowered.

Figure 5. — *Site of the third burn as it appeared in 1964. Killed trees bend toward the ground. Forester segregates and weighs fuels.*

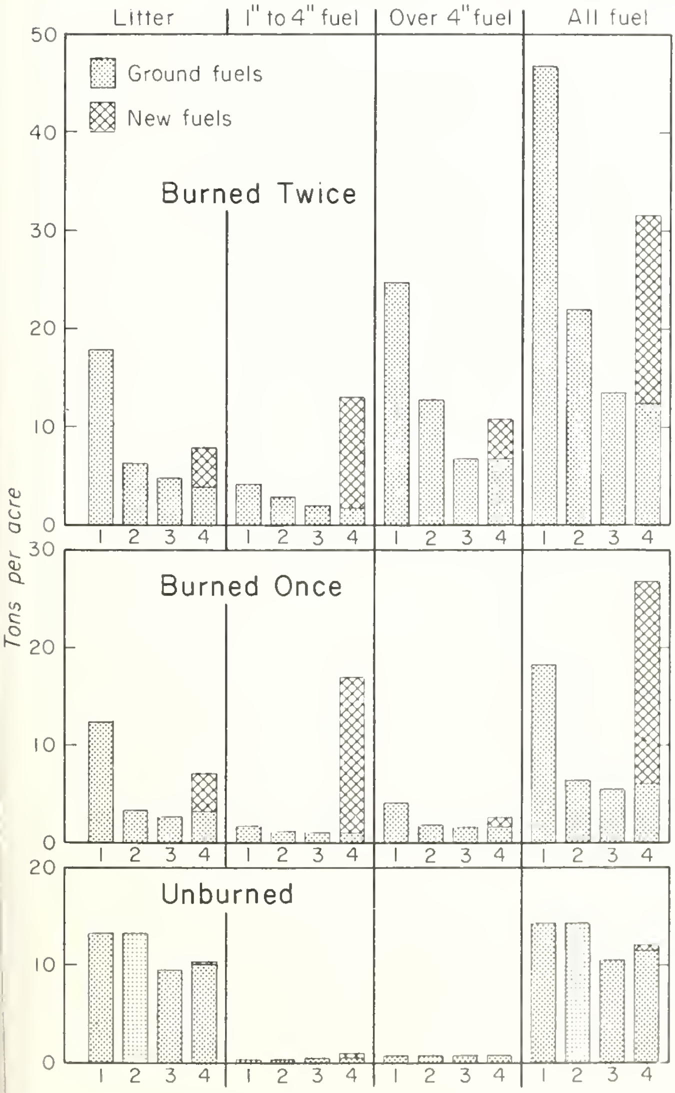

Figure 6. — *Third burn — fuel weights (oven-dry), by fuel size classes and plot groups. Numbers below bars refer to date when trees examined: 1 = May 1961 (before first burn); 2 = June 1961 (after first burn); 3 = May 1962 (after second burn); 4 = May 1964 (3 years after first burn). Bar 2 for unburned plots is assumed — no examination. The upper part of the fourth bar in each fuel class represents dead fuels which were cut, segregated by size, and weighed or measured at the last examination.*

Table 9.--*Line intercept class relationships, by plot groups at successive examinations, Blacks Mountain Experimental Forest*

Intercept class and level	11 plots burned twice, examined...				9 plots burned once, examined...				5 plots unburned, examined[1]...		
	Pre-burn May 1961	After first burn June 1961	After second burn May 1962	Final May 1964	Pre-burn May 1961	After first burn June 1961	After second burn May 1962	Final May 1964	Pre-burn May 1961	After second burn[2] May 1962	Final May 1964
	Percent[3]										
Ground level:											
Tree	1.2	1.2	0.9	1.0	0.4	0.4	0.3	0.2	1.9	1.2	1.3
Forbs	5.7	3.8	1.4	1.0	2.4	1.9	1.2	.2	1.9	.1	.1
Grass	.8	.2	.6	1.1	1.3	1.0	.3	1.2	1.0	2.4	1.7
Sedge	.3	.2	.1	.2	.1	.1	.8	.5	0	0	.4
Sage	3.4	3.2	.4	.2	3.8	2.8	.8	0	4.8	2.6	.4
Other brush	0	0	0	0	0	0	.1	0	0	4.7	1.9
Rock	3.3	3.3	3.6	5.4	11.1	11.1	11.3	14.0	3.6	5.6	4.1
Mineral soil	1.9	1.9	5.4	3.6	2.9	2.9	2.1	3.1	3.6	.8	.9
Litter	76.4	34.6	59.2	82.5	77.4	29.9	77.3	80.5	82.8	82.1	88.4
Charred litter	0	44.8	24.0	0	0	49.3	4.7	0	0	0	0
Bark	.4	.2	0	.3	0	0	0	0	0	0	0
1" - 4" dry fuel	2.9	2.9	1.9	2.4	.4	.4	1.1	.3	0	.5	.8
1" - 4" wet fuel	.1	.1	0	.3	.2	.2	0	0	.4	0	0
Over 4" dry fuel	3.6	3.6	2.5	2.0	0	0	0	0	0	0	0
18-inch level:											
Tree	.2	.2	1.2	.9	.1	.1	.4	.5	5.4	1.3	1.3
Sage	.4	0	2.9	1.3	4.8	3.8	3.6	.4	3.2	6.3	2.3
Other brush	0	0	0	0	.4	.4	.3	.7	0	1.1	0
1" - 4" dry fuel	0	0	0	0	0	0	0	.4	0	0	.4
Over 4" dry fuel	0	0	1.1	0	0	0	0	0	0	.6	0
"Overhead" fuel, fine, live or dead	.6	.2	0	.9	1.5	1.5	.8	2.2	0	2.2	1.6
Air	98.8	99.6	94.8	96.9	93.2	94.2	94.9	95.8	91.4	88.5	94.4
48-inch level:											
Tree	0	0	.8	.9	.4	.3	1.0	.7	.2	.6	1.0
Sage	0	0	0	0	0	0	.3	.1	0	1.3	.6
Other brush	0	0	0	0	0	0	0	.2	0	0	0
1" - 4" dry fuel	0	0	.1	.4	0	0	0	.4	0	0	0
"Overhead" fuel, fine, live or dead	1.8	1.8	.8	.6	5.1	5.1	2.1	2.0	3.1	3.2	3.9
Air	98.2	98.2	98.3	98.1	94.5	94.6	96.6	96.6	96.7	94.9	94.5

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[1] No examination made after first burn, June 1961.

[2] Four plots only.

[3] Percent of total line sample in each plot group. Basis: burned twice--229.9 feet; burned once--188.1 feet; unburned--104.5 feet.

The greatest increase in post-burn dead fuel, however, was in the 1- to 4-inch class. The potential future effect of this fuel is unknown and open to conjecture. Previous mention was made of the early bending of dead saplings and poles so that fine twigs in the crown become close to the ground. Within a few years, these small trees will fall into a jackstraw mass on, and slightly elevated above, the ground. When this occurs, enough annual needle cast from the live stand may accumulate to bring about a condition in which fire—intentional or accidental—would again encounter conditions favorable to high rate of spread and high intensity. And the resistance of the jackstraw mass to fire line construction would be considerable.

Almost as much dead fuel was found on the area at the end of the study as before the burns *(fig. 6)*. Tonnage represented by new fuels is, of course, additive to the remaining part of the original ground fuel. For a rough comparison, fuel weight for areas burned both once and twice was simply averaged on an acre basis. At the beginning of the study, fuels aggregated 32.6 tons. At the end, they totaled 29.2 tons, consisting of 9.2 tons of ground fuel and 20 tons of new fuel. We accomplished, then, a net fuel reduction of about 3.4 tons per acre — 10 percent.

In the 1961 burn, only 42 percent of the ground surface area actually burned. A comparable figure for the second burn was 14 percent. These results illustrate that, under the prescribed conditions used, (a) fire was not a very efficient clean-up tool on an area basis, but (b) the heaviest concentrations of litter must have been reduced significantly.

Estimates of portion of area burned based on milacres and on line transects *(table 9)*, were reasonably comparable. The milacre-based estimate for the first burn was 42 percent, compared to 47 percent estimated from line transects. The intercept class named "charred litter" was used for the latter estimate, this being the only fuel class which reflected a reduction.

Probably only a few general trends can be inferred from the data in table 9 which relate to low vegetation. Where low plants are scarce and scattered, I question the accuracy with which our technique could measure and remeasure them in a study of this size. For example, plant growth, the effects of animal browsing or trampling, and the action of the snow pack in bending small brush in a possible different direction each year, all could contribute significantly to sampling errors. Sampling in May 1961, 1962, and 1964 is believed to have been accomplished at about the same pheno-

Table 10.--*Work input and costs*[1] *associated with prescribed burns, acre basis, Blacks Mountain Experimental Forest, 1962*

Activity	Third burn		Reburn of third burn	
	Labor or equipment	Cost	Labor or equipment	Cost
	Hours	*Dollars*	*Hours*	*Dollars*
Crop tree selection and litter removal	7.11	14.22	--	--
Rough pruning	8.78	17.56	--	--
Slash bunching:				
Labor	.30	.60	--	--
Bulldozer	.30	1.35	--	--
Firing	1.06	2.12	.85	1.70
Patrolling fire	5.76	11.34	5.08	10.16
Mopping up fire:				
Labor	.91	1.96	13.69	27.38
Pumper	.23	2.76	2.54	30.48
Total	--	51.91	--	69.72

[1] Hourly cost rates: labor $2.00, bulldozer $4.50, pumper $12.00.

logical stages for low vegetation. Sampling in June 1961 followed that of May by only 10 days. But slight changes would probably have occurred in broad-leaved vegetation. These changes would further be confounded by effects of the first burn. In the third burn, there was a scarcity of low vegetation beneath this pole stand: only 8 to 9 percent of the ground surface was covered by living plants before the burn. On the other hand, about 80 percent of the surface was covered with dry fuel of all classes.

The general lack of fuel in the space from ground level to the 48-inch sampling level testifies to the effectiveness of the preburn "pruning" treatment.

Time-cost data require some comment *(table 10)*. First, nothing is shown for planning, supervision, or fire trail construction. Nor is there a charge for standby of fire crew and pumper during the main burning period. Time-cost data for those items would be entirely out of proportion to other costs in such a small burn. Second, work time shown is productive time recorded to the nearest five minutes; no rest time is included.

Costs of similar work might vary considerably from one stand condition to another. The high mopup cost after the re-burn was unavoidable. Necessity for this work has been explained—changes from predicted weather conditions can occur in the eastside pine type at almost any time. When we consider the time-cost table and the qualifications above, we conclude that broadcast prescribed burning for hazard reduction cannot be done for "the cost of a box of matches."

Experimental Replication

Except for a fall burn trial, we considered replications of these three burns under exactly similar or slightly modified prescriptions and conditions to be unnecessary. In each case we learned at least one important lesson which implied the fruitlessness of repetition: first burn—do not burn during warm dry conditions because of the danger of losing control; second burn—do not burn in unpruned or otherwise untreated pole stands because of the danger of damaging crown fires and creation of new fuel; third burn and re-burn—it is questionable whether the apparently fleeting reduction in fuel hazard obtained justifies the cost incurred during pre-burn preparation and burning.

Factors Affecting Feasibility of Burning

Weather

An area quite similar in appearance and treatment to the third burn area was prepared but never burned. Our goal was a fall burn for fuel hazard reduction in a pole stand. Plans were cancelled in 3 successive years because of unfavorable weather.

Inspection of Blacks Mountain weather records for a 19-year period, and records kept for the reported burns, shows that weather and fuel moisture conditions appropriate for prescribed broadcast burns exist for only a few hours on a few days each year—almost never would they exist all day for a few successive days. Rapid and wide daily fluctuations of air temperature and relative humidity are characteristic of the area in spring and fall. Weather conditions, then, would severely limit the period when areas could be broadcast burned safely in the eastside pine type. Weather forecasts needed for planning have been shown to lead into unexpected or sudden difficulties with fire control.

Stand Structure

For each burn, we tried to select an area of reasonable uniformity in stand structure. The object was to reduce the potential variables in fire behavior and the after-effects. The general stand structure of the eastside pine type, however, is a mosaic of patches of trees of rather uniform size or age classes. Most of these patches are small—from less than one-tenth of an acre to a few acres. Stand densities range from as many as 17,000 stems per acre in stagnated sapling stands to scattered small groups of trees and isolated stems near the sagebrush flats.

Eastside pine stands consisting of pole-size or smaller stems, with the possible exception of stagnated sapling stands, usually have at least some differentiation of crown classes. This structural characteristic provides in many places a ladder of relatively fine aerial fuel from the ground upward. This ladder can be broken by pruning or thinning,

Figure 7. — *A young immature stand of ponderosa pine. White stick is 6 feet long.*

or both, so that some elements of a stand would survive one or more broadcast burns hot enough to accomplish some fuel hazard reduction. However, labor to accomplish this result is bound to be relatively costly. Alternatively, this ladder of aerial fuel could be broken in untreated areas by low-intensity burns, but only at the expense of killing large numbers and entire groups of seedling- and sapling-size trees. Additional burns required to clean up the newly created fuels would undoubtedly cause increasing problems of stem distribution. We must protect cost-free growing stock because regeneration is expensive. In summary, the stated conditions of stand structure are now seen as formidable obstacles confronting anyone attempting to use broadcast burning in the eastside pine type.

Immature ponderosa pine (75–150 years old)—the next age class larger than poles—is probably the most youthful stand condition in which broadcast burning could be used efficiently for any management purpose *(fig. 7)*. In such stands, litter and other fuels could probably be reduced by fire without causing much mortality. Repeated burns, however, might create an unacceptable number of fire scars. The desirability of removing all litter from a stand, considering what is known about erosion and the effect of litter on soil moisture relationships, might in itself be debatable—particularly if the trees covered a slope.

Fuel Hazard Reduction

Data from the third burn area illustrate the difficulty of getting for more than a very brief period a significant net reduction of hazardous fuels in young stands. It might be argued that an additional burn, or burns, after all standing dead fuels had fallen would solve the problem. But the size, quantity, and jackstraw arrangement of these fallen fuels would probably require that any such subsequent burn be of very low intensity if the creation of even more dead fuels were to be avoided.

We have shown that low intensity fires actually burn less than half the area intended for treatment, and are inefficient in that sense. One can speculate on differences which might occur under the same burning conditions on a larger area where drip torch lines would be spaced farther apart than 5 to 10 feet, as was our practice. In the quantitative sense, however, such fires can reduce some fuels significantly, even if temporarily. Potential total benefits of scheduled periodic burns conducted primarily for the purpose of fuel hazard reduction are, of course, still open to question.

Thinning

These studies indicate that dense seedling and sapling groups—those most in need of thinning—essentially would be completely killed by broadcast burns, thus adding to a fuel hazard problem (and a regeneration cost). And about the same amount of fuel would be created by any mechanical thinning method. A mechanical method would, however, have the advantage that superior trees would be left at desired spacing. We cannot credit fire with the intelligence to do that for us.

We have shown indirectly that fire could be used to thin pole stands, but only by spending about $34 per acre to protect the stands from excessive mortality. In 1964, a thinning contract awarded on the east side of Lassen National Forest cost about the same—"leave" trees in pole and sapling stands were marked and thinning work accomplished (including special work on 50-foot wide fire lanes) for about $33 an acre.

General Implications

No significant amount of living timber stands in California has been intentionally broadcast-burned during recent times. Judicious use of fire in other parts of the United States has been an inexpensive means of reducing hazards and accomplishing certain degrees of thinning, but foresters in California have been reluctant to prescribe fire use for such purposes. Their reluctance might be a reaction to long-term observation of prevailing weather patterns, and of the behavior and results of fire in patchy stands. Such stands are not confined to the eastside pine type, but exist on much of California's commercial timber land.

In commercial timber stands, certain applications of prescribed burning to reduce ground or standing fuels, or both, seem entirely feasible: clearing organic material from clearcut areas, creating relatively wide fuel-breaks, or even hazard reduction in relatively large areas of certain "open" stand types. But our experience indicates that broadcast prescribed burning is not feasible in the eastside pine areas designated for high-level wood production, whether for fuel hazard reduction or thinning young stands.

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