Variations in the Monoterpene Composition of Ponderosa Pine Wood Oleoresin

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The Author

Richard H. Smith is studying the problems of resistance of pines to destructive forest insects. He joined the U. S. Department of Agriculture in 1947. Before coming to the Berkeley station in 1955, he served at the Forest Service's Southeastern Station, where he conducted studies of bark beetles and borers infesting southern forests, and at the Beltsville Forest Insect Laboratory, where he studied the biology and control of powder post beetles. A native of Ellenville, N. Y., he earned bachelor's (1942) and master's (1947) degrees in forest entomology at the New York State College of Forestry, and a doctorate (1961) in entomology at the University of California, Berkeley.

Pine wood oleoresin has long been suspected of playing an important, if not decisive, role in the resistance of pines to bark beetles. Resin (oleoresin) is considered a secondary plant substance and, therefore, does not re-enter the basic metabolic pathways, although some workers have expressed doubt about the secondary status. Resin is a complex mixture of molecules and, in essence, can be considered a supersaturation of rosin in turpentine. Rosin is a mixture of resin acids; turpentine a mixture of terpenes.

Mirov (1960) summarized the work on pine terpenes before 1959. Most of these studies have been of two types: (a) bulk sample analyses in which the resin from several trees was mixed before analysis; and (b) single tree analysis. These procedures either masked individual tree variation or failed to account for it. Practically all studies were based on resin collected from an open wound cut into the pine stem, steam distillation, and conventional chemical methods which at best could not detect constituents of small percentage. These methods were slow and required as much as a quart of resin.

The use of gas chromatography for terpene analysis was mentioned briefly by Mirov (1960). Bannister et al. (1960) applied this analytical procedure to the study of hybridism in *Pinus radiata* D. Don and *P. attenuata* Lemm. Their results showed some but not striking variation in terpene composition between individual trees of these two species. Williams and Bannister (1962) analyzed the wood terpenes of 22 species of pines grown in New Zealand. Analyses of 21 of the species were based on single tree samples. No reference was made to the original source of the tree. Sandermann (1962) found differences between 10 trees of *P. maritima* and 3 trees of *P. pinaster* in the percent of α-pinene and β-pinene. Smith (1964) found considerable differences in the quantitative terpene composition of 10 trees of *P. contorta* Dougl.

A brief résumé of the research efforts attempting to relate resin with the resistance of pines to bark beetles has been published recently (Smith 1961; Smith and Eaton 1963). Resin properties which have been investigated include quantity,[1] pressure (Vité and Wood 1961), and quality (Smith 1961). Research on quality showed that *Dendroctonus* bark beetles were differentially affected by resin vapors of different pine species. Recent investigation by the author has suggested that individual terpenes of pine resin differed in their effect on adult bark beetles.

The possible implication of terpenes in the resistance of pines to bark beetles and the lack of adequate data on the variation in terpene composition between ponderosa pines pointed to a need for study of this variation. This paper reports on a study seeking to determine variability in pine resin terpene composition of ponderosa pine which might be associated with (a) time and place of obtaining resin from a tree, (b) method of preparation and analysis of the sample, and (c) age, elevational, and local differences between trees.

Procedures

All samples of resin were collected with a closed-face microtap (Smith 1961); practically all taps were one-half inch in diameter, though a few were 2 inches. Samples usually were prepared for analysis within 2 to 3 days after collection, although a 1- to 2-month delay caused no change in the terpene constituents.

Two subsamples were prepared from each collection of resin, if enough resin was available. From 1 to 8 cc. of fresh resin were poured from the collection vial into a Hickman molecular still; 0.5 to 1.0 cc. was allowed to remain in the vial, and an ether or ethanol extract was obtained by adding these two solvents at the rate of from one to one-third the volume of resin. The molecular still was operated at 40° C. for 20 to 24 hours,

[1] Callaham, R. Z. Oleoresin production in the resistance of ponderosa pine to bark beetles. 1955. (Unpublished doctor's thesis on file at Univ. Calif., Berkeley.)

using ice to cool the condensing surface. The recovered distillate and the prepared extract were transferred to ½-dram screwcap vials and held at 5° C. Molecular distillation was not possible when a collection held less than 2 cc. of resin.

Samples were analyzed by gas-liquid chromatography.[2] Helium was the gas phase; the column was 8 feet by ¼ inch stainless steel. The liquid phase for practically all work was 10 percent or 20 percent β, β′ oxydipropionitrile (ODPN) (Klouwen 1962) on a solid support of 60/80 acid washed Chromosorb W. For qualitative comparisons, two other liquid phases were used: 20 percent didecylphthlate (DDP) (Bannister 1959) and 20 percent LAC-446 (Bernhard 1961). The data recorder, a Brown "Electronik" with disc integrator, had a sensitivity of 1 millivolt full span and a balancing speed of 1 second full span.

Operational conditions for the oxydipropionitrile columns were: temperatures of 120° to 130° C. on the injector, 55° to 60° C. on the column, 145° to 151° C. on the detector; filament current of 200 ma.; helium flow of 60 or 90 ml. per minute at the outlet port; sample volume of 0.2 μl to 4.0 μl.

Qualitative determinations were made by comparing relative retention times with existing values and with those obtained by the use of known compounds and known mixtures. These determinations were cross-checked on all three columns. Quantitative determinations were made by internal normalization of disc integrator values (fig. 1); that is, the number of integrator units for each peak was divided by the total units for the sample to give the percent of each terpene in the whole sample.

[2] Aerograph A-90-P with thermal conductivity detector. Mention of commercial products in this report does not constitute an endorsement of products by the U.S. Forest Service.

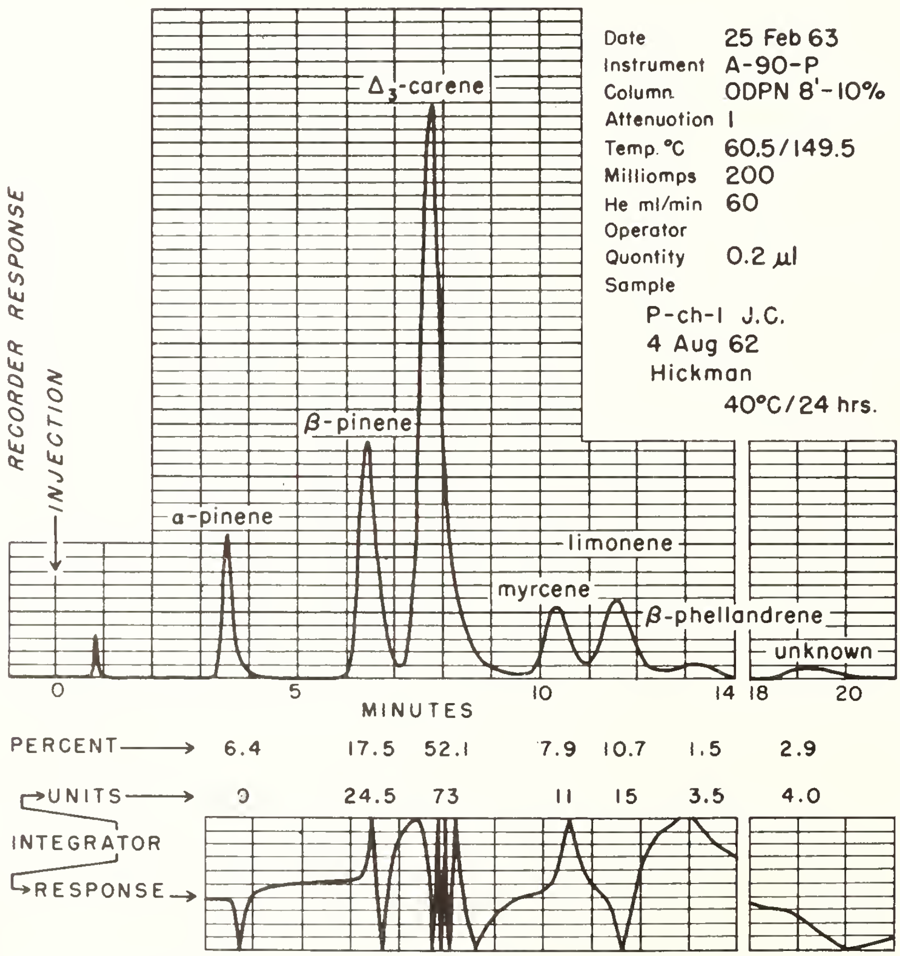

Figure 1.—Chromatogram of the monoterpenes in the resin of a ponderosa pine.

Results and Discussion

Column Comparisons

Columns were compared for qualitative determinations. Relative retention values for the LAC–446 and ODPN columns were obtained for ponderosa pine resin and for a synthetic mixture of terpenes whose individual retention times had been obtained beforehand (table 1). The coincidence of the unknown peaks with the known terpenes on two different columns is a sound basis for the qualitative determinations.

Quantitative comparisons of the three columns (table 2) showed very close agreement. This result essentially eliminated the possibility of reactions while the sample was passing through the column and provided a basis for assuming that the values obtained on any one column were nearly the real values.

Sample Preparation

Quantitative comparisons were made between the two types of sample preparations, ether extract and unaltered molecular distillate. Selected samples represented a wide range of terpene composition. Approximately the same values were obtained for both types of preparations (table 3). Both preparations should be made, though, because the ODPN column does not clearly separate ether and heptane, and a small impurity of ether coincides with part of the camphene peak. The ether preparation is fast and is recommended for studies in which many samples are to be processed quickly or where heptane and camphene are absent or are minor constituents. It is also the only method which can be used if the resin sample is less than 1 cc.

Distillation and Holding Time

The period of distillation and the length of time of holding the sample after distillation could cause variation in the analysis of terpene composition. A check of the period of distillation was made by processing about 7.5 cc. of freshly collected ponderosa pine resin in the molecular still. At successive intervals the distillate which had collected since the previous interval was analyzed; the percent terpene composition was determined for each period. The cumulative values (table 4) show that

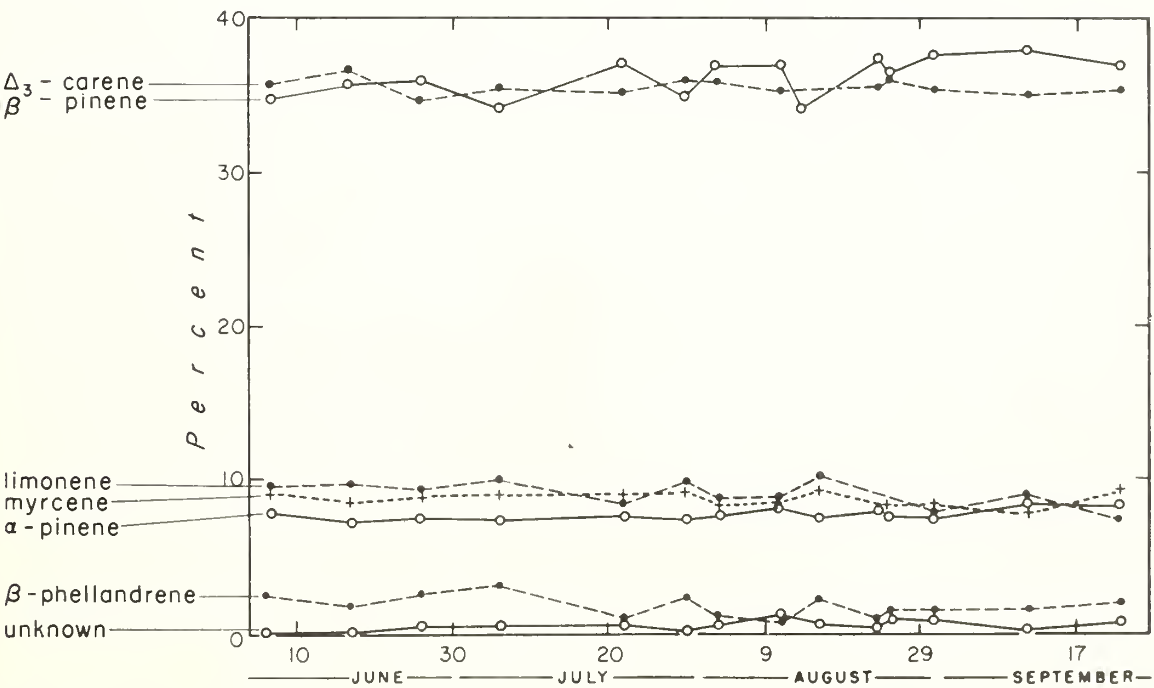

Figure 2.—Seasonal trend in the monoterpene composition of the resin of one ponderosa pine.

even the first few drops of distillate gave a reasonable representation of the actual composition. Practically no change occurred after 12 hours. Therefore, the 20- to 24-hour period removes all terpenes from small samples of ponderosa pine resins. These results also indicated that this resin was essentially azeotropic; that is, the constituents of the mixture of volatiles vaporized in proportion to their concentration in the mixture. Holding the samples had no effect on the results as shown by the analyses of these same samples 3 months later.

The effect of holding time of both distillate and extract was determined by analyzing samples representing a wide range in composition. The results (table 5) show no change in either preparation for 6 months, the maximum time tested.

Period of Resin Flow

The molecular distillates of the first and second 24-hour flow of resin from the wounds of five different trees were analyzed for terpene composition to substantiate the assumption that there was no change related to time of flow from a wound. The results (table 6) showed approximately the same composition for both periods.

Variation within a Tree

Tests were made to determine the magnitude of variation of terpene composition which could be related to the time and place of tapping a tree.

One tree was tapped at the four cardinal directions at 3 feet and at 60 feet above the ground. The samples were prepared with ethanol and were analyzed with the didecylphthlate column. The results (table 7) showed little difference between the four compass positions or between the two heights. Further work will be needed to determine the authenticity of a slight increase in β-pinene and slight decrease in limonene plus β-phellandrene when going from the top of the tree to the bottom. The slight changes could be due to sampling or analytical methods.

Five trees were tapped at 3 feet and at 15 feet

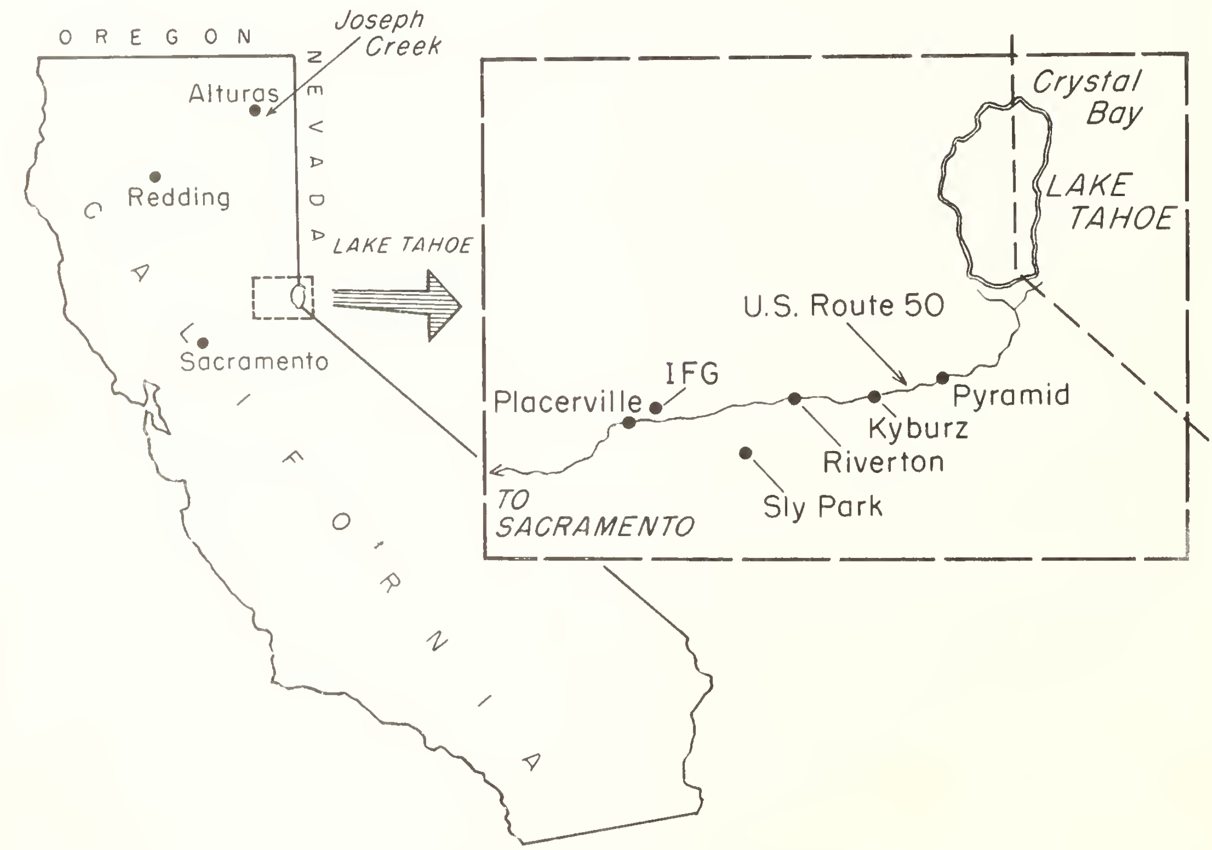

Figure 3.—Location of ponderosa pines used for gas chromatographic analyses of terpenes.

above the ground (table 8), and no changes could be associated with height; though myrcene percentage is consistently higher at 15 feet, the difference is still quite small.

Seven trees were tapped on the north and south sides (table 9). Again no changes in terpene composition could be associated with place of sampling the tree.

The effect of time of sampling a tree was determined by tapping: (a) one tree periodically during the growing season (fig. 2), (b) 11 trees both in the growing season and in the dormant season (table 10), and (c) one tree in four consecutive years (table 11). Each of these variables had little or no effect on terpene composition. The slight reduction in β-phellandrene during the dormant season was consistent for all trees, but it may be too small to be real and may be simply an attribute. of procedure. Additional sampling will be needed to see if there is a trend from year to year. Other ponderosa pines and other species of pines may not give the same results obtained by these limited samples.

Age, Elevation, and Local Variation

Seven locations were selected in the central Sierra Nevada and one location in the north Warner Mountains near Alturas, California (fig. 3) to give a range in age, elevation, and locality of ponderosa pine. The average terpene composition for each plot (table 12) showed no pattern which might be associated with age or elevation, although the plots differed widely. A larger sampling should be made to permit a sounder basis for any conclusion about age or elevation.

Variation between Trees

Resin was collected from 64 trees located in the eight plots (table 12). Table 13 summarizes the average analysis for each tree; figure 4 illustrates the frequency distribution and the average value for each terpene. The wide range in composition from tree to tree is readily apparent. Variations

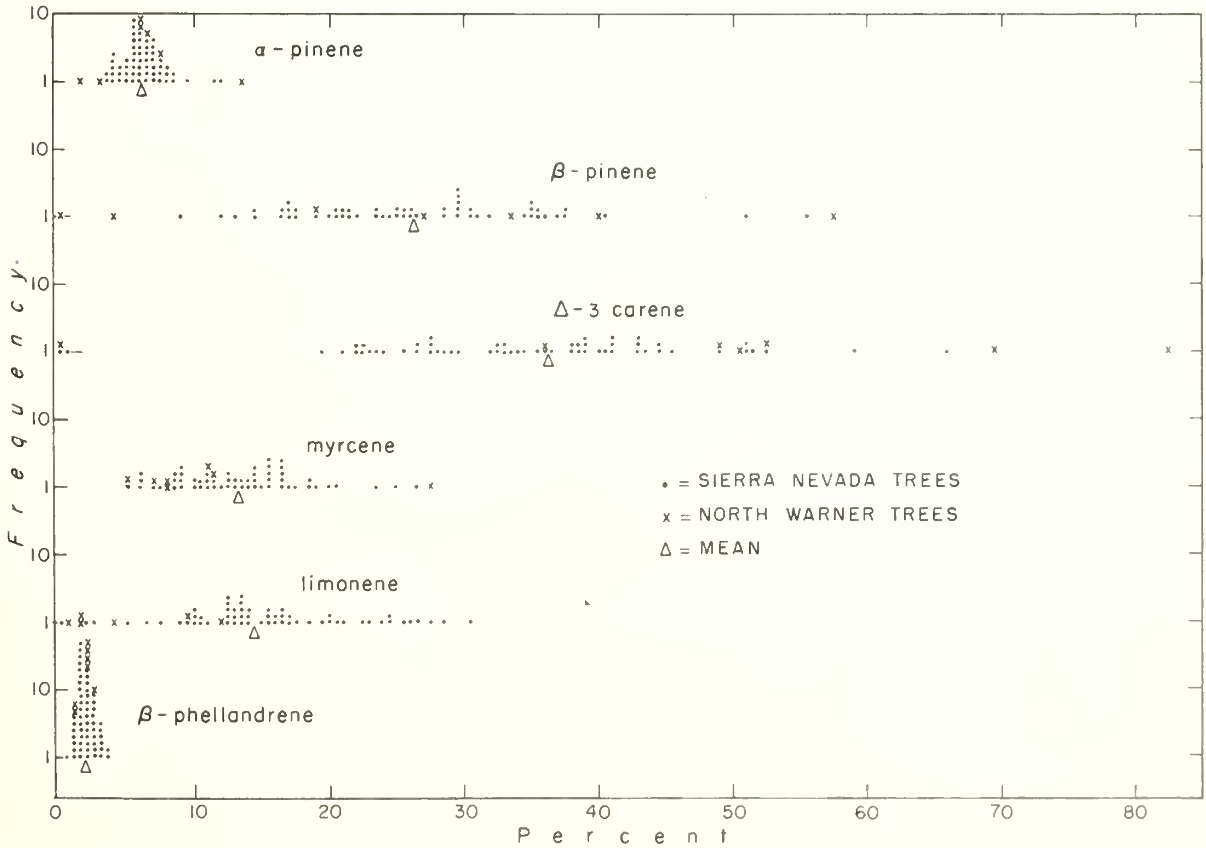

Figure 4.—Variation of individual terpenes in the total terpene of the resin of 64 ponderosa pines.

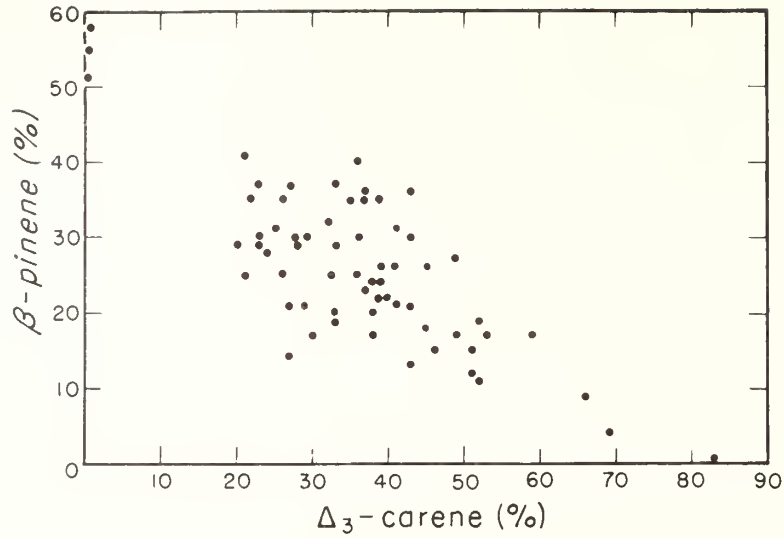

Figure 5.—Relationshop of Δ_3-carene and β-pinene in resin from 64 ponderosa pines.

between trees were much greater than those of plot averages. A far greater range in percent composition was obtained than reported by Mirov (1960) for bulk sample analysis for ponderosa pine resins representing the extensive range of this tree in western United States. Furthermore, Mirov (1960) called Δ_3-earene "the speeifie terpene of *Pinus ponderosa*," yet 3 trees out of 64 had amounts which could be elassified only as traee. A fairly strong inverse relationship existed between the amount of β-pinene and Δ_3-earene (fig. 5).

Obviously, the terpene composition of ponderosa pine resin is not uniform. An analysis of one tree or a small number of trees may mean very little in defining this characteristic. Further sampling and analysis should be made to more adequately determine the limits of terpene composition and to see if there are distinct types.

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APPENDIX

Table 1. Relative retention time[1] on two different columns for known compounds and for ponderosa pine resin vapor

Peak	Terpene	ODPN[2]		LAC-446[3]	
		Known	Ponderosa pine	Known	Ponderosa pine
1	Heptane	--	.29	--	.15
2	α-pinene	1.00	1.00	1.00	1.00
3	Camphene	1.54	1.51	1.43	--
4	β-pinene	1.89	1.88	1.83	1.81
5	Δ_3 carene	2.30	2.32	2.40	2.38
6	Myrcene	3.16	3.19	2.73	2.70
7	Limonene	3.51	3.54	3.45	3.40
8	β-phellan- drene	4.00	4.01	3.67	3.62
9	Unknown	--	5.91	--	5.89

[1]*Based on 1.00 for α-pinene.*
[2]*3.415 minutes to α-pinene at 55° C. and 60 ml./min.*
[3]*10.620 minutes to α-pinene at 60° C. and 60 ml./min.*

Table 2. Ponderosa pine resin monoterpene composition determined with different columns

Tree	Column	α-pinene	β-pinene	Δ_3 carene	Myrcene	Limonene	β-phellan-drene	Unknown[1]
		- - - - - -	Percent	- - - - - -				
1	LAC	6.5	31.4	46.8	8.1	7.1		--
	ODPN	5.4	25.9	51.2	7.0	6.3	2.0	2.2
2	LAC	5.6	13.8	43.5	14.0	23.1		--
	ODPN	4.4	12.9	43.7	13.1	22.3	3.6	(2/)
3	LAC	7.5	13.9	49.8	12.1	14.1		2.6
	ODPN	5.0	14.6	51.8	11.2	13.1	1.9	2.3
4	LAC	8.6	37.4	34.2	10.6	9.2		--
	ODPN	7.4	33.8	34.4	9.7	10.0	2.1	2.7
5	DDP	1.5	3.9	72.1	9.5	12.2		--
	ODPN	2.2	3.3	73.3	7.8	11.1	1.1	1.1
6	DDP	5.9	38.3	43.8	11.7	.4		--
	ODPN	7.6	40.0	37.4	11.3	1.4	2.3	2.3
7	DDP	5.4	18.2	55.4	9.5	11.0		--
	ODPN	6.4	17.5	52.1	7.9	10.7	2.5	2.7

[1]*Determinations of the unknown were not made for the DDP column.*
[2]*Trace.*

Table 3. Terpene composition of the resin of selected ponderosa pine prepared by ether extract (Ext.) and by molecular distillation (Dis.)

Tree number	Preparation	α-pinene	β-pinene	Δ_3 carene	Myrcene	Limonene	β-phellandrene	Unknown
		- - - - - -Percent- - - - - - - - -						
1	Dis.	5.9	21.0	37.6	19.6	13.2	1.2	1.4
	Ext.	5.4	19.8	38.6	17.3	14.6	1.9	2.4
2	Dis.	9.1	22.1	28.6	15.0	21.9	2.5	.7
	Ext.	8.0	20.6	29.1	13.4	25.1	1.7	2.0
3	Dis.	11.8	49.2	--	16.5	18.7	3.8	--
	Ext.	10.8	52.8	--	14.9	19.2	2.3	--
4	Dis.	6.9	28.9	19.2	16.9	25.2	1.6	1.2
	Ext.	6.3	29.5	20.1	14.4	26.2	2.2	1.2
5	Dis.	5.6	21.4	26.5	24.1	19.1	1.8	1.6
	Ext.	5.2	21.4	28.2	21.8	20.2	2.0	1.1
6	Dis.	3.8	13.8	26.5	25.5	25.5	3.0	1.9
	Ext.	4.2	14.5	27.7	23.3	27.3	1.4	1.6
7	Dis.	4.4	16.9	52.7	9.5	11.7	2.0	2.8
	Ext.	3.4	15.7	55.5	9.0	12.6	1.1	2.8
8	Dis.	8.0	9.0	66.5	8.2	4.5	.4	3.3
	Ext.	7.8	9.1	64.4	9.1	5.3	.7	3.7

Table 4. Terpene composition of molecular distillates of a sample of ponderosa pine resin at cumulative periods of time

FIRST ANALYSIS

Hour	Cumulative amount recovered	α-pinene	β-pinene	Δ_3 carene	Myrcene	Limonene	β-phellandrene	Unknown
	Ml.	- -	- -	- -	- - Percent- -	- -	- -	- -
1st	0.2	11.0	39.5	32.3	7.9	6.2	3.1	(1/)
2nd	.5	10.4	38.1	33.0	8.5	6.9	3.1	(1/)
3rd	.7	9.9	38.5	33.0	8.4	7.1	3.0	0.3
4th	.85	9.5	38.0	33.1	8.4	7.4	3.2	.4
5th	1.00	9.2	37.5	33.3	8.6	7.5	3.4	.6
9th	1.20	8.8	36.7	33.5	8.7	7.8	3.8	.8
13th	1.35	8.6	36.1	33.5	8.8	8.0	4.0	1.3
24th	1.45	8.4	35.8	33.6	8.8	8.1	4.2	1.2
ANALYSIS THREE MONTHS LATER								
1st	--	10.2	38.4	31.6	8.2	6.8	4.4	.4
2nd	--	9.2	36.6	31.6	8.8	8.2	5.1	.5
3rd	--	9.0	36.8	32.3	8.9	8.0	4.5	.5
4th	--	8.6	36.0	32.9	9.0	8.4	4.6	.4
5th	--	8.3	35.6	33.2	9.1	8.8	4.6	.5
9th	--	8.0	35.0	33.6	9.1	9.0	4.8	.5
13th	--	7.9	34.7	33.8	9.1	9.2	4.8	.5
24th	--	7.7	34.5	33.9	9.1	9.2	5.0	.5
Ether extract		7.0	31.4	35.0	10.2	11.1	3.1	2.1

[1] *Trace.*

Table 5. Analysis of two types of sample preparation of ponderosa pine terpenes at two times after preparation

Tree	Type of preparation	Time of analysis[1]	α-pinene	β-pinene	Δ_3 carene	Myrcene	Limonene	β-phellandrene	Unknown
			- - - - - - -	- - - - - - -	- - - - - - -	-Percent-	- - - - - - -	- - - - - - -	- - - - - - -
1	Distillate	(a)	5.3	14.4	50.5	11.2	12.3	2.1	4.2
		(b)	6.2	15.6	52.7	10.0	11.7	1.0	2.7
2	Distillate	(a)	7.8	35.5	35.2	8.6	9.4	1.6	2.0
		(b)	7.7	36.0	36.0	8.6	9.3	1.4	1.0
3	Distillate	(a)	8.0	41 4	20.7	11.9	15.3	1.9	.8
		(b)	8.2	42 4	21.1	10.6	15.3	1.6	.8
4	Distillate	(a)	12.2	52.0	(2)	17.2	16.8	1.8	.0
		(b)	12.3	52.0	(2)	16.5	17.1	2.1	.0
5	Distillate	(a)	5.6	21.4	26.5	24.1	19.1	1.8	1.6
		(b)	5.5	21.9	26.5	23.3	19.2	1.4	1.9
6	Distillate	(a)	3.8	13.8	26.5	25.5	25.5	3.0	1.9
		(b)	4.1	15.0	27.1	24.2	26.5	1.8	1.2
7	Extract	(a)	4.1	17.4	30.2	15.1	31.4	1.7	(2)
		(b)	3.4	16.7	30.7	14.8	31.8	1.5	1.1
8	Extract	(a)	6.1	27.6	27.3	12.2	21.2	4.1	1.5
		(b)	5.3	29.6	29.6	12.1	20.4	2.9	(2)
9	Extract	(a)	6.2	36.2	44.1	6.4	5.3	1.8	(2)
		(b)	6.8	36.8	43.4	5.5	4.8	.9	1.8
10	Extract	(a)	14.1	55.2	(2)	28.0	(2)	2.8	.0
		(b)	12.4	59.3	(2)	26.0	1.2	1.2	.0
11	Extract	(a)	8.4	38.1	34.3	12.5	2.9	2.9	.9
		(b)	7.1	39.2	36.5	11.6	2.0	2.0	1.6
12	Extract	(a)	3.3	5.4	64.2	9.2	12.9	2.5	1.7
		(b)	2.7	3.6	70.5	7.6	11.6	1.8	2.2

[1](a) *Immediately after preparation of sample.*
(b) *Four to six months after preparation.*

[2]*Trace.*

Table 6. Monoterpene composition of the first and second 24-hour flow of ponderosa pine resin

Tree number	24-hour period	α-pinene	β-pinene	Δ_3 carene	Myrcene	Limonene	β-phellan-drene	Unknown
		- - - - - - -		-Percent-	- - - - - - - - -			
1	1st	8.9	34.4	30.9	9.5	10.0	4.0	2.3
	2nd	8.2	34.9	35.8	8.9	8.3	1.9	2.1
2	1st	5.0	14.6	51.9	11.2	13.1	1.9	2.3
	2nd	5.4	13.8	52.2	10.8	12.9	2.7	2.3
3	1st	6.7	34.3	38.2	9.5	7.1	2.1	2.1
	2nd	7.2	31.8	37.0	10.5	8.0	3.1	2.5
4	1st	6.1	31.6	44.3	9.4	7.1	.5	1.0
	2nd	5.8	31.1	40.9	9.3	8.9	1.6	2.4
5	1st	8.0	41.0	20.4	11.5	16.4	1.5	1.2
	2nd	8.2	42.4	21.1	10.6	15.3	1.6	.8

Table 7. Monoterpene composition of a ponderosa pine resin at two heights on the trunk and at the cardinal directions around the tree

Compass position	α-pinene	β-pinene plus myrcene	Δ_3 carene	Limonene plus β-phellandrene
		60 FEET HEIGHT		
	- - - - -	-Percent-	- - - -	
N	7.1	45.9	38.4	8.6
E	7.4	45.3	39.9	7.5
S	7.4	46.7	39.9	6.0
W	8.2	45.8	38.4	7.6
X	7.5	45.9	39.2	7.4
		3 FEET HEIGHT		
N	5.7	49.3	40.2	4.8
E	7.0	49.1	39.6	4.3
S	7.3	47.6	40.1	4.9
W	6.9	47.3	39.7	6.9
X	6.7	48.3	39.7	5.2

Table 8. Monoterpene composition of the resin of ponderosa pines at two trunk heights

Tree number	Height	α-pinene	β-pinene	Δ_3 carene	Myrcene	Limonene	β-phellandrene	Unknown
	Feet	- - -	- - -	- - -	- -*Percent*-	- - -	- - -	- - -
3	15	5.7	35.2	52.9	3.1	0.4	0.9	1.8
	3	5.5	34.7	52.0	3.6	.7	.9	--
10	15	6.6	23.3	48.5	8.3	7.5	4.4	1.5
	3	5.0	29.1	48.3	6.8	6.3	1.3	3.1
14	15	1.2	--	86.3	11.8	--	(1/)	(1/)
	3	1.0	--	86.7	9.4	1.5	.5	1.0
56	15	7.8	40.8	34.0	12.1	1.9	1.9	1.5
	3	7.6	40.0	37.4	11.3	1.4	2.3	(1/)
Ch. 1	15	8.1	17.1	46.1	9.7	11.0	4.5	3.5
	3	6.4	17.5	52.1	7.9	10.7	2.5	2.9

[1]*Trace.*

Table 9. Monoterpene composition of ponderosa pine resin from the north (N) and south (S) side of the tree

Tree number	Side of tree	α-pinene	β-pinene	Δ_3 carene	Myrcene	Limonene	β-phellandrene	Unknown
		- - -	- - -	- - -	- -*Percent*-	- - -	- - -	- - -
1	N	5.5	25.9	38.9	13.0	14.3	1.4	1.0
	S	5.3	26.2	38.3	13.1	14.0	1.6	1.6
2	N	3.1	15.4	38.5	13.6	25.9	2.1	1.4
	S	4.0	17.8	37.4	14.5	22.3	1.2	2.8
3	N	5.8	35.2	25.4	14.4	16.2	1.8	1.2
	S	7.1	33.3	26.0	14.6	15.4	3.7	(1/)
4	N	6.1	27.6	27.3	12.2	21.2	4.1	1.5
	S	5.3	29.9	29.3	11.7	19.6	3.2	.9
5	N	8.0	25.9	23.5	12.0	27.9	2.8	(1/)
	S	7.4	29.8	24.7	10.7	26.4	1.0	(1/)
6	N	6.4	31.3	31.7	12.8	13.6	3.0	1.1
	S	5.0	29.8	33.1	13.6	14.0	3.7	.8
7	N	6.5	35.9	24.9	14.7	15.5	1.1	1.4
	S	7.8	36.9	22.9	14.9	12.0	4.7	.8

[1]*Trace.*

Table 10. Monoterpene composition of ponderosa pine resin obtained during the active (August) and inactive (March) growing seasons

Tree	Month	α-pinene	β-pinene	Δ_3 carene	Myrcene	Limonene	β-phellan-drene	Unknown
		- - - - - -	- - - -	- - Percent	- - - -	- - - -	- - - -	- - - -
1	August	7.8	35.3	34.7	9.1	9.5	1.7	1.9
	March	6.9	34.5	37.5	8.9	9.6	.9	1.7
2	August	5.8	14.9	50.8	11.0	12.7	2.0	2.8
	March	5.0	14.6	53.6	10.5	12.3	1.0	3.0
3	August	7.9	35.9	37.3	8.6	6.7	1.4	2.2
	March	8.2	35.1	38.2	8.1	7.3	1.3	1.8
4	August	6.6	30.7	35.9	16.0	6.0	2.5	1.6
	March	6.5	33.4	36.6	15.3	5.7	.6	1.9
5	August	7.9	41.0	21.2	11.1	16.2	1.7	.9
	March	7.3	40.9	20.1	11.5	18.1	.9	1.1
6	August	6.4	30.1	43.1	5.9	10.4	1.7	2.4
	March	7.3	32.6	40.0	5.1	12.6	1.3	1.1
7	August	7.9	34.9	38.9	5.2	10.1	1.4	1.6
	March	7.1	32.9	41.2	5.8	10.4	1.0	1.6
8	August	5.7	25.8	44.5	6.8	13.6	1.6	2.0
	March	5.8	27.9	42.6	6.6	14.0	1.3	1.8
9	August	7.7	8.9	65.9	8.5	5.0	.9	3.1
	March	7.1	9.4	62.7	9.7	6.5	1.2	3.4
10	August	7.2	35.3	37.4	9.2	7.5	1.6	1.8
	March	6.7	35.0	36.2	10.9	8.4	1.6	1.2
11	August	7.1	29.4	40.9	9.2	9.8	1.6	2.0
	March	6.3	33.3	38.9	10.3	8.6	1.1	1.5

Table 11. Monoterpene composition of one ponderosa pine in 4 years

Component	July 1960	July 1961	July 1962	March 1963
	- -	--Percent- -	- -	
α-pinene	8.4	7.3	7.4	7.0
β-pinene	39.1	35.8	33.8	33.6
Δ_3 carene	36.8	36.7	34.4	37.5
Myrcene	7.1	8.6	9.7	9.4
Limonene	7.3	9.9	10.0	9.9
β phellandrene	.7	1.7	2.1	1.0
Unknown	.6	(1)	2.7	1.6

[1]Trace.

Table 12. Terpene composition for average ponderosa pine resin in eight plots in the central Sierra Nevada and Warner Mountains, California

Plot, trees sampled (No.)	Elevation	Stand age	α-pinene	β-pinene	Δ 3-carene	Myrcene	Limonene	β-phellan-drene	Unknown
	Feet	*Years*	- -	- -	-	*Percent*	- -	- -	-
Institute of Forest Genetics - 11	2,700	25-50	7.1	29.4	40.9	9.2	9.8	1.6	2.0
Sly Park No. 1 -12	3,600	50-75	6.0	26.5	31.4	13.7	18.9	2.4	1.1
Sly Park No. 2[1] - 6	3,600	15-30	7.1	31.5	24.6	12.9	20.5	2.1	1.3
Riverton - 6	3,000	150-300	7.9	30.4	25.4	17.5	16.0	1.9	.9
Kyburz - 7	4,000	150-300	6.0	24.9	28.8	17.4	19.8	1.8	1.3
Pyramid - 3	5,000	150-300	4.4	18.2	46.8	14.1	13.0	1.7	1.8
Crystal Bay - 12	6,300	50-80	5.2	22.3	42.4	13.3	13.4	1.8	1.6
Joseph Creek - 7	4,700	50-80	6.2	25.9	48.6	11.1	4.7	1.8	1.7
Mean (weighted)	--	--	6.3	26.4	36.2	13.3	14.5	1.8	1.5

[1]50 yards from Sly Park No. 1.

Table 13. Average monoterpene composition for ponderosa pines and for plots

Tree number	α-pinene	β-pinene	Δ_3 carene	Myrcene	Limonene	β-phellan-drene	Unknown	Number of analyses
	- - -	- - -	- - -	- Percent -	- - -	- - -	- - -	
				INSTITUTE OF FOREST GENETICS				
1	7.8	35.3	34.7	9.1	9.5	1.7	1.9	9
2	5.8	14.9	50.8	11.0	12.7	2.0	2.8	8
3	7.1	29.4	40.9	9.2	9.8	1.6	2.0	3
4	6.6	30.7	35.9	16.0	6.7	2.5	1.6	5
5	7.9	41.0	21.2	11.1	16.2	1.7	.9	4
6	6.4	30.1	43.1	5.9	10.4	1.7	2.4	4
7	7.9	34.9	38.9	5.2	10.1	1.4	1.6	3
8	5.7	25.8	44.5	6.8	13.6	1.6	2.0	7
9	7.7	8.9	65.9	8.5	5.0	.9	3.1	3
11	7.2	35.3	37.4	9.2	7.5	1.6	1.8	6
12	6.5	30.9	40.4	9.9	8.9	1.5	1.9	5
X	7.1	29.4	40.9	9.2	9.8	1.6	2.0	--
				SLY PARK NO. 1				
1	5.3	26.3	38.5	12.8	14.0	1.6	1.5	5
2	3.8	17.2	37.9	13.6	24.1	1.5	1.9	4
3	6.2	34.9	26.5	14.0	15.0	2.6	.8	3
4	4.5	17.2	29.6	15.4	30.7	1.8	.8	3
5	5.7	29.4	28.7	11.9	20.3	3.1	.9	4
6	7.1	27.5	24.2	11.5	27.4	2.1	.2	4
7	6.9	24.3	38.8	16.4	11.0	1.3	1.3	2
8	6.2	31.9	31.9	12.9	13.1	3.0	1.0	3
9	7.5	37.3	23.4	14.7	13.4	3.0	.7	3
10	6.5	23.4	36.7	11.7	17.5	2.2	2.0	4
25-1	6.8	30.3	22.3	20.2	16.5	2.9	1.0	4
25-2	5.5	16.9	49.2	8.5	15.5	2.3	2.1	2
25-3	6.3	24.9	25.7	12.6	25.3	3.7	1.5	2
X	6.0	26.5	31.4	13.7	18.9	2.4	1.1	--
				SLY PARK NO. 2				
1	8.4	31.8	24.8	18.2	13.3	2.4	1.1	3
2	5.0	24.0	38.5	9.0	20.1	1.5	2.0	2
3	4.8	18.9	32.6	14.7	24.5	2.3	2.2	3
4	5.8	29.3	28.1	5.9	28.3	1.3	1.3	2
5	7.2	29.6	23.2	13.8	21.0	3.5	1.7	2
6	11.5	55.3	.4	15.5	15.5	1.8	--	2
X	7.1	31.5	24.6	12.9	20.5	2.1	1.3	--
				RIVERTON				
1	5.7	20.7	38.2	18.4	13.8	1.4	1.8	3
2	9.3	34.9	22.2	20.4	10.5	2.4	.3	2
3	8.7	21.4	28.8	14.4	23.2	2.4	1.1	3
4	11.9	51.2	(1/)	16.6	18.2	2.1	--	6
5	5.5	25.3	35.5	16.8	13.4	2.0	1.5	4
6	6.1	28.6	27.7	18.3	16.9	1.4	1.0	3
X	7.9	30.4	25.4	17.5	16.0	1.9	.9	--
				KYBURZ				
1	6.7	29.3	19.6	15.7	25.8	1.8	1.1	3
2	7.6	36.9	33.3	7.4	12.6	1.5	.7	3
3	5.6	21.4	27.3	23.3	19.5	1.5	1.4	4
4	4.0	14.4	27.3	24.9	26.5	1.8	1.1	5
5	6.3	25.7	21.9	19.1	24.3	1.7	1.0	3
6	6.2	21.8	38.9	14.8	13.2	2.5	2.6	3
7	5.4	24.8	33.1	16.5	17.1	1.6	1.5	3
X	6.0	24.9	28.8	17.4	19.8	1.8	1.3	--

See footnote at end of table.

Table 13. Average monoterpene composition for ponderosa pines and for plots, continued

Tree number	α-pinene	β-pinene	Δ3 carene	Myrcene	Limonene	β-phellandrene	Unknown	Number of analyses
	Percent							
PYRAMID								
1	4.0	16.5	52.6	10.3	12.3	1.9	2.4	5
4	5.2	20.5	43.2	14.3	14.2	1.3	1.3	6
5	4.2	17.6	44.7	17.6	12.4	1.8	1.7	3
X	4.4	18.2	46.8	14.1	13.0	1.7	1.8	--
CRYSTAL BAY								
1	4.4	12.8	43.6	12.5	22.6	2.8	1.3	5
1a	5.3	25.8	40.8	10.3	13.6	2.1	2.1	2
1b	4.0	20.8	41.2	10.8	19.9	1.3	2.0	2
1c	6.2	16.7	59.2	15.5	(1/)	.3	2.1	2
2	4.6	22.4	39.8	13.5	16.4	1.8	1.5	5
2a	6.1	28.5	33.1	12.5	16.1	2.4	1.3	2
2b	3.5	11.8	51.0	16.6	12.8	1.9	2.4	2
2c	3.4	14.5	45.5	16.7	15.5	1.7	2.7	2
3	7.4	35.9	43.0	6.0	5.3	1.5	.9	5
3a	6.9	37.7	26.6	10.1	16.6	1.5	.6	3
3b	5.0	20.0	32.7	26.4	12.4	2.9	.6	3
3c	5.4	21.2	51.7	8.6	9.9	1.2	2.0	4
X	5.2	22.3	42.4	13.3	13.4	1.8	1.6	--
JOSEPH CREEK								
3	5.8	33.3	50.6	4.6	1.3	1.8	2.6	3
10	5.8	27.1	49.0	7.2	6.5	2.3	2.1	4
14	1.5	.1	82.5	11.1	1.5	1.4	1.9	6
56	7.7	40.0	35.8	11.6	1.8	2.0	1.1	5
Ch-1	6.4	18.8	52.5	7.8	9.6	2.2	2.7	4
Ch-4	13.3	57.5	(1/)	27.5	.4	1.3	--	3
Ch-5	2.8	4.1	69.4	8.2	12.0	1.8	1.7	3
X	6.2	25.9	48.6	11.1	4.7	1.8	1.7	--
Grand X	6.3	26.4	36.2	13.3	14.5	1.8	1.5	--

[1] *Trace.*

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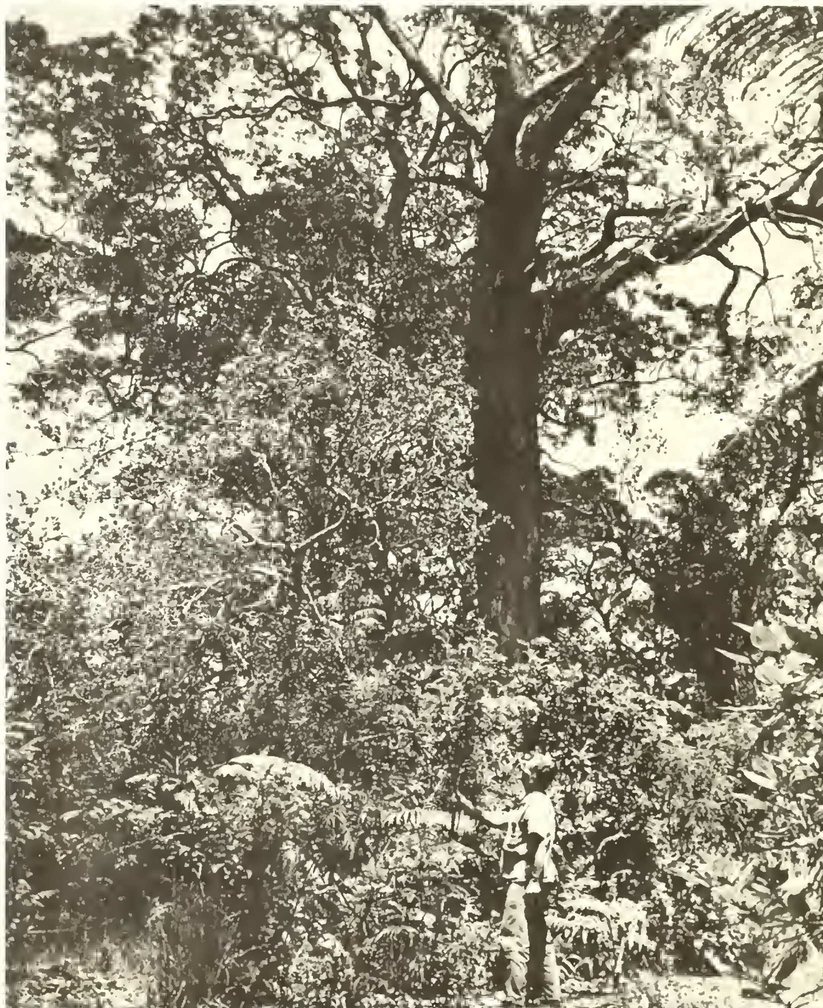
Silvical Characteristics of Koa
(*Acacia Koa* Gray)

Craig D. Whitesell



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

CONTENTS

U.S. Forest Service research in Hawaii
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and Natural Resources, State of Hawaii.

The Author

Craig D. Whitesell is conducting research on the silviculture of native forests and plantations in Hawaii, with headquarters in Hilo. A native of Pennsylvania, he served 3 years in the U.S. Army Air Force during World War II. He received his bachelor's degree from West Virginia University, and his master's degree from Duke University—both in forestry. He joined the Pacific Southwest Station staff in 1962, after graduate studies in forest genetics at North Carolina State University. He worked for Maryland's Department of Research and Education for 10 years, in silvicultural research, and cooperated with the U.S. Forest Service's Northeastern Forest Experiment Station on forest surveys and tree improvement studies in that State.

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Koa (*Acacia koa* Gray) is considered the most valuable common native timber species in Hawaii (*21, 38*).[1] From the time of the early Hawaiians, this tree has been prized for its exceptionally fine wood. Koa has curly grain, striking coloration, and takes a high polish (*9, 26*). It grows on each of the six main islands, but the only extensive forests remaining are on the island of Hawaii. It occurs in nearly pure stands, or in admixtures with ohia (*Metrosideros polymorpha* Guad.). Other tree species are of limited occurrence in these forests. A large evergreen hardwood tree endemic to the State, koa belongs to the thornless, phyllodinous group of the genus *Acacia*, subfamily Mimosaceae of the Leguminosae.

Koa forests must have been much more extensive in the past than they are today. Land clearing, poor cutting practices, and destruction by animals, insects (*33*), and fire (*18, 25*) have all taken a toll. Koa forest land in the State now totals about 50,000 acres, ohia-koa forests about 150,000 acres. Volume of koa sawtimber totals about 121 million board feet (*35*).

Habitat Conditions

Climatic

Koa grows in a widely diverse tropical climate. The northeasterly trade winds dominate, although seasonal storms also influence the islands (*6*). Mountains, especially massive Mauna Loa and Mauna Kea on Hawaii and Haleakala on Maui, strongly modify the marine effect.

Snow seldom falls at elevations below 8,500 feet (*6*). Below 10,000 feet snow seldom persists on the ground. Frost is not uncommon during the winter months on the upper slopes where koa grows.

"Kona" storms from the south or west during winter, and occasional tropical storms throughout the year often bring high winds and heavy rains to the islands. Rainfall varies greatly within short distances. Monthly amounts recorded over a period of years at weather stations in the koa belts show a phenomenal range. Most stations — even many of those where the annual normal is 100 inches or more — occasionally have dry periods when rainfall totals less than an inch a month. Conversely, some of the driest points — where the annual average is 20 to 30 inches — may have an amount approaching or surpassing this annual average in just a few days (*15*).

Koa grows best in the higher rainfall areas of from 75 to more than 200 inches annually. Cloud cover and fog commonly shroud the middle forest zone where koa is concentrated. Koa also occurs in semi-arid and moderately wet areas that receive from 25 to 75 inches of rain annually.

The annual temperature range is relatively small, as may be seen from data for the island of Hawaii (table 1).

Edaphic

Koa is found on volcanic soils of all degrees of development — from the oldest on Kauai to some of the relatively young "aa" rocky soils on the island of Hawaii. Insufficient work has been done to evaluate the tolerance of koa to different soil conditions. The tree grows on both well-drained (*27*) and poorly-drained soils, the latter including the Hydrol Humic Latosols. Most koa forests occur upon the Yellowish-Brown and Reddish-Brown Laterite soils described (*45*) as rain forest soils — occurring between 1,500 and 5,000 feet. Physically these soils are characterized by their permeability

[1]Italic numbers in parentheses refer to Literature Cited, p. 11.

to moisture and air, their granular structure, friability, high percentage of colloids, and high moisture equivalents. Chemically, they have a high content of organic matter, hydrous oxides of iron and aluminum, manganese and titanium. Low in silica, calcium, potassium, and sodium, they generally have a marked degree of phosphorus fixation, although this and other features are variable within the group. Soil reaction is distinctly acid in most areas. Mottling is an occasional feature. Soil texture ranges from a silty clay loam to a very fine sandy loam, and structure is variable. Koa is also found on Lithosols and shallow soils (humid), and on rough broken land.

Physiographic

The range of koa extends from longitude 154° to 160° west; its latitude ranges from 19° to 22° north. It grows at elevations from 600 (*39*) to 7,000 feet (*26*), on both flat lands and slopes. MacCaughey (*33*) listed koa as a component of the forests occupying gulch and ravine walls sloping 40° to 80°.

Biotic

Hillebrand (*21*) divided the flora of Hawaii into groups occupying different zones of elevation:

The lowland zone. — Open country, with isolated trees or clumps of trees. Koa rarely grows here.

The lower forest zone. — An upper limit between 1,000 and 2,000 feet. Tropical in character, woods are rather open. Koa occurs in scattered stands, in admixture with ohia.

The middle forest zone. — An upper limit of 5,000 to 6,000 feet. This zone lies within the region of clouds, and develops the greatest luxuriance in trees and jungle. Here koa reaches its greatest development in size and number.

The upper forest zone. — Extending as high as 8,000 or 9,000 feet. Koa reaches into this zone, but seldom above 7,000 feet.

Trees associated with koa (*18, 21, 22, 39*)[2] include:

- ahakea (*Bobea* spp. Gaud.)
- 'ala'a (*Sideroxylon sandwicensis* (Gray) Benth.)
- kalia (*Eleaocarpus bifidus* Hook & Arm.)
- kauila (*Alphitonia ponderosa* Hbd.)
- kolea (*Myrsine lessertiana* D.C.)
- kopiko (*Straussia* ssp. Gray)
- loulu palm (*Pritchardia* ssp. Seem. & H. Wendl.)
- mamani (*Sophora chrysophylla* Seem.)
- naio (*Myoporum sandwicense* (D.C.) Gray)
- 'ohe'ohe (*Tetraplasandra hawaiiensis* (Gray))
- ohia (*Metrosideros polymorpha* Gaud.)
- olapa (*Cheirodendron gaudichaudii* (D.C.) Seem.)
- olopua (*Osmanthus sandwicensis* (Gray) Knobl.)
- pilo (*Coprosma* spp. Forst.)
- sandalwood (*Santalum* spp. L.)

Botanists and foresters have listed more than 80 trees, shrubs, vines, herbs, ferns, club mosses, grasses, and sedges associated with koa.

Relatively few species of birds are now associated with koa. Their numbers have been reduced largely by land clearing and the introduction of mammals and plants that have helped destroy the specialized habitats required by endemic birds (*2, 14*). Several exotic birds, including the white-eye (*Zosterops palpibrosus japonicus* Temminck &

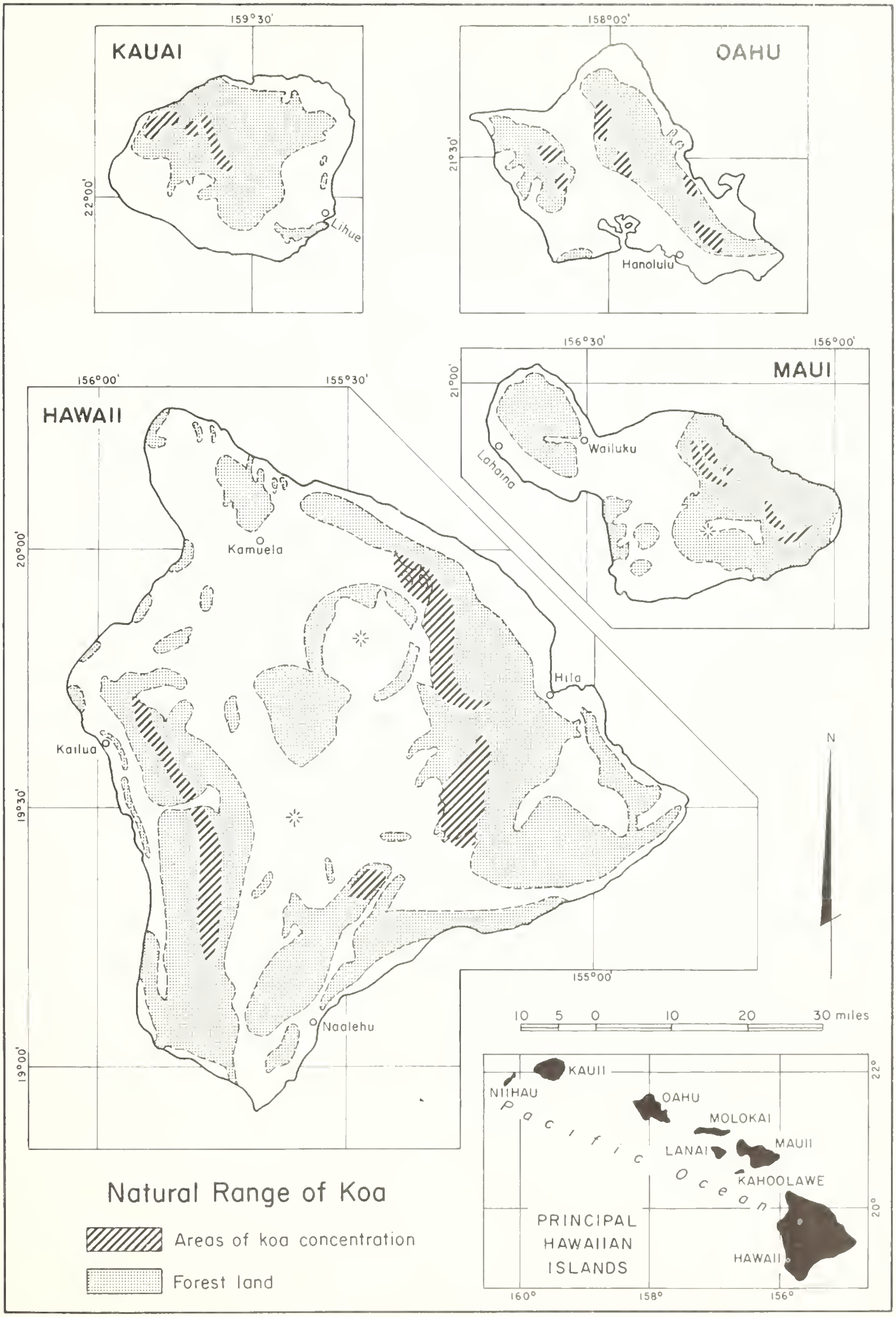
[2]Personal correspondence with M. F. Landgraf, Hawaii Forestry Division, Hilo, Hawaii, Dec. 6, 1963.

Table 1. Mean temperatures for six stations, island of Hawaii[1]

Station	Elevation above sea-level	Mean January temperature	Mean August temperature
	Feet	*°F.*	*°F.*
Hilo	40	71	76
Olaa	280	70	75
Mountain View	[2]1,530	65	70
Hawaii National Park	[2]3,971	58	64
Kulani Camp	[2]5,190	53	58
Mauna Loa Observatory	11,150	39	47

[1]*Source: Blumenstock (6).*

[2]*Elevations at which koa occurs.*



KAUAI
159°30'
22°00'
Lihue
OAHU
158°00'
21°30'
Honolulu
MAUI
156°30'
156°00'
21°00'
Wailuku
Lahaina
HAWAII
156°00'
155°30'
155°00'
20°00'
19°30'
19°00'
Kamuela
Hilo
Kailua
Naalehu
N
10 5 0 10 20 30 miles
KAUII
NIIHAU
OAHU
MOLOKAI
LANAI
MAUII
KAHOOLAWE
HAWAII
Pacific Ocean
PRINCIPAL HAWAIIAN ISLANDS
160°
158°
156°
22°
20°
Natural Range of Koa
Areas of koa concentration
Forest land

Flowers and phyllodes of koa.

Schlegel), have successfully competed with the native birds for food; others have introduced diseases and parasites (*2, 14*). Munro (*34*) mentioned several species of the Hawaiian honey-creeper family (Drepanididae) and the small Kauai thrush (*Phaeornis palmeri* Rothschild) as residents of the koa forests. These species feed on insect enemies of koa and are now believed to be uncommon, rare, or extinct (*2, 34*). The parrot-billed koa finch (*Pseudonestor zanthophrys* Rothschild), a bird confined to the higher koa forests on Mount Haleakala, Maui is a good example of the close association of a honey-creeper and koa forests. Henshaw, in 1902, observed:

> ". . . the bird appears never to wander far from the koa, and obtains the principal part of its food, the larvae of longicorn beetles (cerambycids) by tearing open the small terminal dead twigs of this tree in which the larvae burrow, secure from all bird enemies less formidably equipped. . . . The koa upon Maui has suffered much of late years from the ravages of the insect pests above alluded to, and thousands of mature trees have been killed. The life of *Pseudonestor* is so inseparably connected with the koa tree that the destruction of the latter will be almost certainly followed by the extinction of the former, and it is to be feared that this interesting and valuable bird, confined as it is to one island, has before it no very long term of existence" (*20*).

By 1950, Amadon (*2*) considered this bird "perhaps extinct."

Life History

Seeding Habits

Flowering and Fruiting

Other than Rock's (*40*), few observations on the flowering and fruiting periods of koa have been published. Trees at the lower elevations flower at different times than those at higher elevation. Flowers have been observed during February at 1,800 feet, and during June[3] and December at about 4,200 feet, but the number of flowering periods per year is not known. A 2-year-old specimen has been observed in fruit and flower (*3*). A pollinating insect found on koa flowers was an unidentified species of bee. The extent to which other insects, birds, and the wind affect pollination is being studied.

The inflorescence of koa is an axillary raceme of pale yellow heads composed of many flowers. Each flower has an indefinite number of free stamens and a single elongated style.

The fruit is a tardily dehiscent legume about 6 inches long and 1 to 1½ inches wide. It contains about 12 ovules. The seeds vary from dark brown to black. They mature at different times throughout the summer — depending upon the location.

Seed Production

Koa bears seeds often and abundantly. The actual quantities of seeds produced per tree, or per acre, however, is not known. No records of the frequency of exceptionally good or poor seed years are available. Mature trees probably produce the most seed, but the quantity of sound seed has not been estimated.

In three samples, the number of clean seeds per pound ranged from a low of 2,400 to a high of 7,400.

Many koa seeds are destroyed by the larvae of four different species of Tortricid moths (*42*). These seed moths may destroy as much as 99 percent of any given seed crop in the pods (*44*).

Seed Dissemination

Koa seed pods dehisce while on the tree, or fall to the ground unopened, where they either dehisce

[3]Field observations by G. B. Richmond, July 10, 1963. Data on file at Hilo, Hawaii, office of Pacific SW. Forest and Range Expt. Sta., U.S. Forest Serv.

or disintegrate. Judd (*26*) reported that "the horny seed often remains on the tree for a year after it ripens, and when lying on the ground is known to have retained, for a period of 25 years, its ability to germinate." Koa seeds are seldom dispersed very far beyond the crown. Occasionally, the wind may carry unopened pods some distance. Seeds from koa growing in gulches possibly are carried downstream to lower elevations, especially during torrential rains.

Vegetative Reproduction

An intensive study of koa reproduction was conducted by Baldwin and Fagerlund (*5*) on an area of the Volcano National Park having an annual rainfall of about 40 inches. Koa stands appeared to regenerate almost entirely by means of root suckers on this once heavily grazed site. These authors reported that "many vigorous suckers arise from the buried and exposed roots of a single tree. . . . In three cases, suckers were seen 50, 90 and 95 feet away from the base of isolated koa trees. Suckers develop into healthy trees three to six inches in diameter at breast height in five or six years [and were] estimated to be 12 feet in height."

Koa root sprouts have also been observed in rain forests. The extent to which koa will root sprout, in the absence of fire or grazing animals, has not been established. Stump sprouts have rarely been observed. Propagation of koa by grafting or cuttings has been reported in the literature. Evidence of natural layering has been observed.[4]

Seedling Development

Establishment

Under favorable conditions—that is, bare mineral soil and exposure to sunlight — koa seeds will germinate readily. Seedlings are commonly observed soon after land is cleared for pasture or roads, or after fires. Judd (*30*) reported that as many as 143,537 koa seedlings per acre were counted in the vicinity of old koa trees in burned-over areas. Possibly seeds escaping the flames are induced to germinate by the heat. Rarely do koa seedlings survive in the dense rain forests unless openings have been created, such as those in a commercial cutting operation. Kraebel (*31*) reported that "where cattle have been excluded for a number of years, koa groves are developing with surprising speed on exposed and barren ridges."

Although no specific germination tests have been reported, nurserymen indicate that obtaining "good" germination is no problem. The customary presowing treatment is to place the seeds in hot water, and let them soak.

Direct seeding of koa on prepared seed spots has been moderately successful (*7, 10*).

Judd (*23, 26, 28*) recommended koa for watershed planting on well-drained areas: "The one native tree which can be easily handled in nursery and planting operations, . . . suitable for the larger portion of areas in need of reforestation and particularly for the drier edges and slopes" (*24*). In Judd's time, the standard nursery practice was to start the seeds in wooden flats and to transplant seedlings to tin cans (*24*).

Other investigators, less enthusiastic about planting koa, do not recommend it (*10, 11*). Crosby and Hosaka (*11*) reported that "Results on older soil formations have been uniformly disappointing. Frequently the trees die out after 15 or 20 years." Plantations established on Maui during the late 1930's contain scattered large trees, but they are of exceptionally poor form and are being removed.[5]

Early Growth

Koa seedlings grow rapidly. Judd (*30*) determined that one month after a burn koa seedlings were an inch high; after three months they ranged from 4 to 11 inches tall, averaging about 5 inches. On a cleared area at 1,700 feet elevation, 1-year-old seedlings varied from 2 to 13 feet in height, and averaged 6 feet. In favorable localities seedlings will attain 30 feet in 5 years (*26*).

Sapling Stage to Maturity

Root Development

Little is known of the root development of koa. It grows on the deeper Hawaiian soils, but also reaches impressive size on the shallow aa lava flows. "The root system of the mature koa," according to Baldwin and Fagerlund (*5*), "is shallow and extensive, spreading out radially from the base of the tree up to 100 feet or more." Judd

[4]Field observations by R. M. Lanner, Aug. 4, 1963. Data on file at Hilo, Hawaii, office of Pacific SW. Forest and Range Expt. Sta., U.S. Forest Serv.

[5]Personal correspondence with K. H. Korte, Hawaii Forestry Division, Kahului, Maui August 23, 1963.

(*26*) agrees that "the tree has a shallow rooted system, a flat plane of roots spreading out in all directions just beneath the surface of the ground. For this reason the larger top-heavy trees are easily overturned by severe wind storms. . . ." In describing the root systems of lava-flow plants, MacCaughey (*32*) classified koa as one of the comparatively deep-rooted woody species..

Growth and Yield

We have no way of determining the maximum age reached by koa. The species does not appear to produce annual rings. Old relic forests still in existence were probably present at the time Captain James Cook discovered the Hawaiian Islands in 1778.

A permanent growth plot established in a 12-year-old plantation (10-foot by 10-foot spacing) had a survival of 85 percent, with 28 vigorous trees and 12 suppressed trees. The average diameter breast height of the 28 larger trees was 4.3 inches, and their average height was 25 feet. The tallest individual was 40 feet.[6]

The form of koa varies greatly. Most mature trees have large, open, scraggly crowns, and limby, fluted boles. In the rain forests on deep, rich soil, an occasional koa tree may reach 110 feet; but few possess clean, straight boles. On drier sites the form of koa is even poorer, and trees are often stunted and misshapen.

Precise yield figures are not available.

Reaction to Competition

Koa is rated as intolerant—both in the dry forests (*19*) and in the rain forest. Hall (*18*) rated the species "intolerant of shade at all ages, and will not germinate or grow without a large amount of light." Under favorable light and soil conditions koa can compete aggressively with other vegetation.

Hathaway (*19*) classified koa as a pioneer species on the grassy slopes of dry forest sites, whereas Forbes (*16*) considered it a climax species. Judd (*26*) considered koa the ultimate forest type, following the ohia forest on the ancient aa lava flows. Russ observed that "at maturity a grove [of koa] casts a shade in which its own seedlings have difficulty in growing, and unless they fill a vacancy in the parental ranks, they must seek the outer limits of the stand" (*41*). Available evidence indicates that koa is a sub-climax type.

[6]Pickford, G. D. (Unpublished data on file, Hawaii Forestry Division, Hilo, Hawaii, 1961.)

Condition and Quality

Missing from the koa and ohia-koa forests in many areas are the koa size classes that normally form the recently mature, vigorous stands. Rock (*39*), in 1913, graphically described the condition of large tracts of koa forest:

> Above Kealakekua, in South Kona, of the once beautiful koa forest 90 percent of the trees are now dead, and the remaining 10 percent in a dying condition. Their huge trunks and limbs cover the ground so thickly that it is difficult to ride through the forest, if such it can be called. . . . It is sad, however, to see these gigantic trees succumb to the ravages of cattle and insects.

The forest survey of 1959–1961 clearly indicates the present condition of much of the sawtimber-size koa (trees over 10.9 inches d.b.h.). Of the 103 trees classified according to merchantability based on form and defect, 36 percent were considered merchantable, 15 percent sound cull (with such defects as crook, excessive limbs, or poor form), and 49 percent rotton cull (excessive rot). The "average" tree was 35 inches d.b.h. (basis: 103 trees), 72 feet high (basis: 31 trees), and had a crown diameter of 58 feet (basis: 31 trees). Log grades were determined for logs in 103 koa trees. Less than two-fifths of all butt logs (first 16 feet) met the specifications for either factory lumber logs or tie and timber logs. More than three-fifths were considered cull logs. Only 35 percent of the 103 trees sampled had an upper log of 8 feet or more, and more than half of these logs were graded cull.[7]

Principal Enemies

Hawaiian forestry literature is full of references to the disastrous effects of cattle, sheep, and goats on koa and other native species (for example: *1*, *4*, *5*, *11*, *18*, *24*, *27*, *39*). Cattle, especially, are particularly fond of koa root sprouts, seedlings, pods, and leaves. They straddle and trample large saplings to devour the foliage.

[7]Hawaii forest survey, 1959–1961. (Unpublished data on file at Honolulu, Hawaii, office, Pacific SW. Forest and Range Expt. Sta., U.S. Forest Serv.) Log grade specifications were from U.S. Forest Serv. Forest Products Lab Rpt. 1737 (*46*).

A

B

A Decadent, dry forest koa stand in a rangeland lacking in koa reproduction. Area was heavily grazed for many years.

B Decadent old koa, surrounded by root sprout regeneration, on land once heavily grazed and now in a national park in Hawaii.

C Koa seedlings nine months after removal of overstory.

C

Hawaii Forestry Division records show that more than 250,000 pigs, goats, and sheep were destroyed from 1921–1946 in the forests on the island of Hawaii (*8*), where an active exclosure program was conducted. Such efforts did much to reduce the amount of browsing by these animals on koa forests.

Koa attracts other kinds of animals. Black-tailed deer (*Odocoileus hemionus* Richardson), recently introduced from California to the island of Kauai, eat koa reproduction. There is evidence that the tree rat (*Rattus rattus* L.), during a heavy population buildup, will girdle koa saplings 1 to 2 inches in diameter by stripping off bark as high up as 4 feet.[8]

More than 40 species of native insects are considered enemies of koa (*43*). Insect damage to koa is well documented (*12, 17, 36, 37, 42*). Swezey (*44*) has compiled an excellent checklist. This recognized authority believes "there are more endemic insect species attached to this koa complex (*Acacia koa* and related Hawaiian members) than to any other genus in the Hawaiian Islands." C. J. Davis, State entomologist for Hawaii has evaluated the most important of these insects:[9]

- The most destructive insects of koa are lepidopterous defoliators of the genus *Scotorythra.* Fortunately, they appear to be under good control biologically and seldom build up to damaging levels.
- The koa seed worm (*Cryptophlebia illepida* Butler) is very destructive to the seed and will be a factor to contend with if seed is harvested for reforestation purposes.
- At the higher elevations, koa terminals are sometimes heavily attacked by *Pantomorus godmani* Crotch, (Fullers rose weevil), but this appears to be highly seasonal and of no serious consequence.
- Koa rust (*Uromyces* sp.) persists on young trees at the higher elevations (5,000–7,000 ft.) and the [infected] malformed trunks [and] branches are attractive to [the moth] *Enarmonia walsinghami* (Butler).

Little information on diseases of koa is available. Dieback is common in the crowns of older trees. It was observed in more than half of the sawtimber-size koa measured during the 1959–1961 forest survey. The root rot *Armillaria mellea* (Fr.) Quel. is probably the cause of this disease.[10] Stands possibly weakened by old age, extended droughts, and grazing have succumbed to attack by this root rot. Other diseases of koa include sooty molds, such as *Meliola koae* Stevens, which cover the leaves and restrict growth. The rust *Uromyces koae* Arthur, an obligate parasite on young koa, causes bud proliferations which attract destructive insects. The Hawaiian mistletoe (*Korthalsella complanata* [v Tiegh.] Engl.) has been observed in some decadent koa stands.[11] It also deforms young koa.[12] More than half the large koa measured in the 1959–1961 forest survey were classified as unmerchantable because of excessive rot, including the heart rot *Ganoderma* sp.

Pole-size trees and the smaller sawtimber-size koa have relatively thin bark. Fires can damage the bark, or kill the tree.

Weed species are serious problems in certain areas. The banana poka (*Passiflora mollissima* (HBK) Bailey) smothers both koa reproduction and mature trees by laying a curtain of vines over them. The German-ivy (*Senecio makanioides* Otto)[12] is also difficult to control.

Special Features

The true leaf of koa consists of 12 to 15 paired, bipinnate leaflets. They are most commonly found on the younger plants, although one may find both the true leaves and phyllodes (dilated petioles) on the same seedling. The older trees usually bear only the laurel green, sickleshaped phyllodes, but sometimes true leaves also grow on lower branches.

The most important use of koa timber by Ha-

[8]Korte, K. H., Rodent damage in koa reproduction. 1963. (Unpublished report to State Forester, Hawaii Forestry Division, Kahului, Maui.)

[9]Davis, C. J., in personal correspondence with R. E. Nelson, Pacific SW. Forest and Range Expt. Sta., U.S. Forest Serv. Honolulu, Hawaii. Jan. 9, 1963.

[10]Personal correspondence with R. D. Raabe, University of Hawaii, Hilo, Dec. 4, 1963.

[11]Bega, R. V. Forest disease research. 1962. (Unpublished report on file at Pacific SW. Forest and Range Expt. Sta., U.S. Forest Serv., Berkeley, Calif.)

[12]Personal correspondence with R. E. Daehler, Hawaii Forestry Division, Honolulu, Hawaii. Oct. 10, 1963.

A

Ralph Daehler, Hawaii Forestry Division

B

A Curtain of banana poka vines *(Passiflora mollissima)* hangs over a koa tree.

B Koa seedlings, showing true leaves *(lower)* and phyllodes *(upper)*.

C Koa logs piled in a cleared koa rain forest area.

C

waiians was to build canoes. The largest of the giant war-canoes extended 70 feet; their hulls were made of single giant koa logs (*9*). Koa was also used for surf boards, some 18 feet or longer (*9*), for paddles; and for framing grass-houses (*13*). The bark provided dye for kapa, a light cloth made from the bark of wauke (*Broussonetia papyrifera* (L.) Vent.) (*13*).

Koa wood is now used primarily for furniture, cabinet work, and face veneers. It is widely used in woodcraft. Cabinet makers recognize a dozen or more types of koa wood, including curly or "fiddle back" koa, red koa, and yellow koa (*9*). One local use is for making ukuleles. At one time koa was sold on the world market as Hawaiian mahogany (*39*).

Large logs have a narrow, creamy white band of sapwood. The heartwood may vary through many rich shades of dark red, golden brown, or brown. The heartwood seasons well without serious degrade from warping, checking, splitting, or stain.[13]

Races and Related Species

The koa in any given location may not necessarily be native to that location.

Morphological differences in koa have been observed on several islands. Rock (*40*) named two varieties: *A. koa* var. *lanaiensis* (Hillebrand's *A. koa-β* var. and *A. koa* var. *hawaiiensis*, after the islands upon which they were found. It would not be surprising to find considerable ecotypic variations, from island to island. Studies of such variations are complicated by past plantings of koa from seed collected at various places. There are no known hybrids of koa.

On western Kauai—one of the oldest Hawaiian islands—a form of acacia differs from koa in sepals, petals, inflorescence (*40*), and seed shape (*26*). This species is *Acacia kauaiensis* Hillebr.

Another species closely related to koa is *Acacia koaia* Hillebr., a narrowly distributed, small, shrubby tree occupying dry sites on Molokai, Maui, and Hawaii. Koaia differs from koa in the shape of the pods and phyllodes (*40*).

Acacia heterophylla Willd. is endemic to Reunion Island and Mauritius Island, both about 450 miles east of Madagascar, in the Indian Ocean. It is so similar to koa that Gaudichaud identified them as the same species. Asa Gray identified the two as separate species entirely on the basis of distance and isolation (*40*).

Tasmanian blackwood (*Acacia melanoxylon* R. Br.), native to Australia and Tasmània, resembles koa. But it has straighter and shorter phyllodes, a narrower curved pod, and a more pointed crown (*40*). Another closely related species, *Acacia simplicifolia* (L. f. Druce), grows in Samoa and Fiji (*39*).

Koa is a tetraploid with $2n = 52$; all other phyllodinous acacias studied have the diploid chromosome complement (*3*). The chromosome complements of *A. kauaiensis*, *A. koaia*, *A. heterophylla*, and *A. laurifolia* have not been reported. Atchison (*3*) reasoned "that polyploidy in *A. koa* occurred after the initiation of phyllody. This is supported by its distribution as an endemic island extension of the Australian flora."

[13]Personal correspondence with R. G. Skolmen, Pacific SW. Forest and Range Expt. Sta., U.S. Forest Serv., Honolulu, Hawaii, Aug. 28, 1963.

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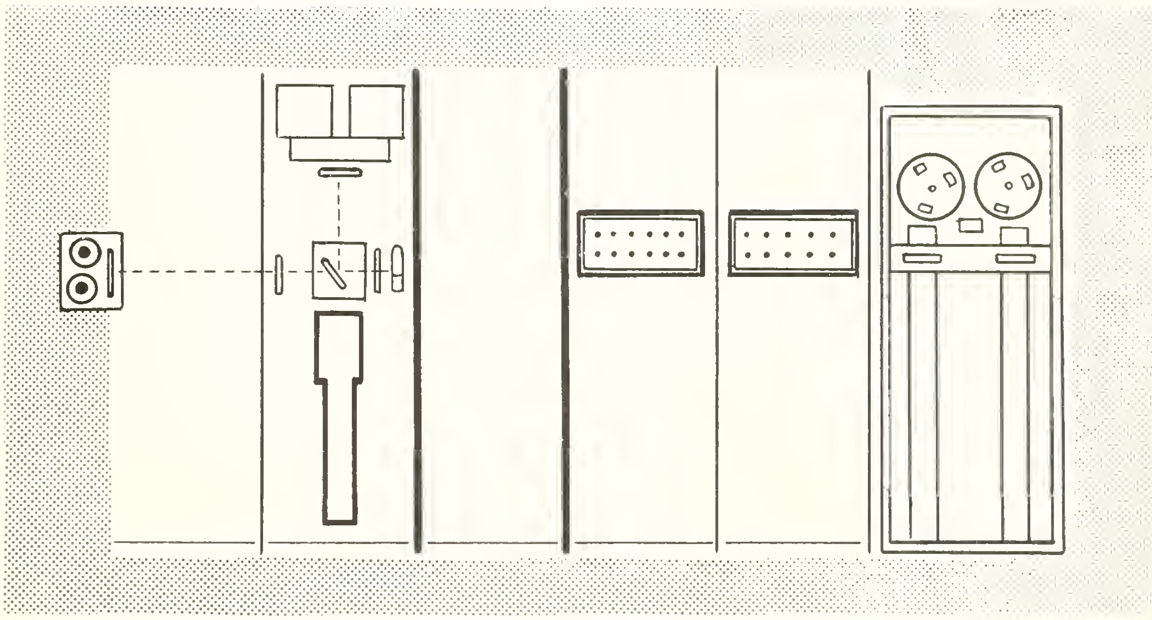

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Glossary

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 (record).

Cell: the map area assigned a code number (analogous to one dot in a dot grid); cell is a rectangle one-fifth (measured horizontally) by one-sixth inch, or one-thirtieth square inch.

Code: unsigned, nonzero, two-digit integer (i.e., a number between 01 and 99 inclusive).

Code system: a list of up to 98 code numbers 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.

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 conducting forest economics studies, with particular emphasis on multiple-use problems. A 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 and 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 U. S. Forest Service's Division of Forest Disease Research in Beltsville, Md.; Lake States Station in St. Paul, Minn., Division of Engineering in Alexandria, Va.; and Northeastern Station in Upper Darby, Pa.

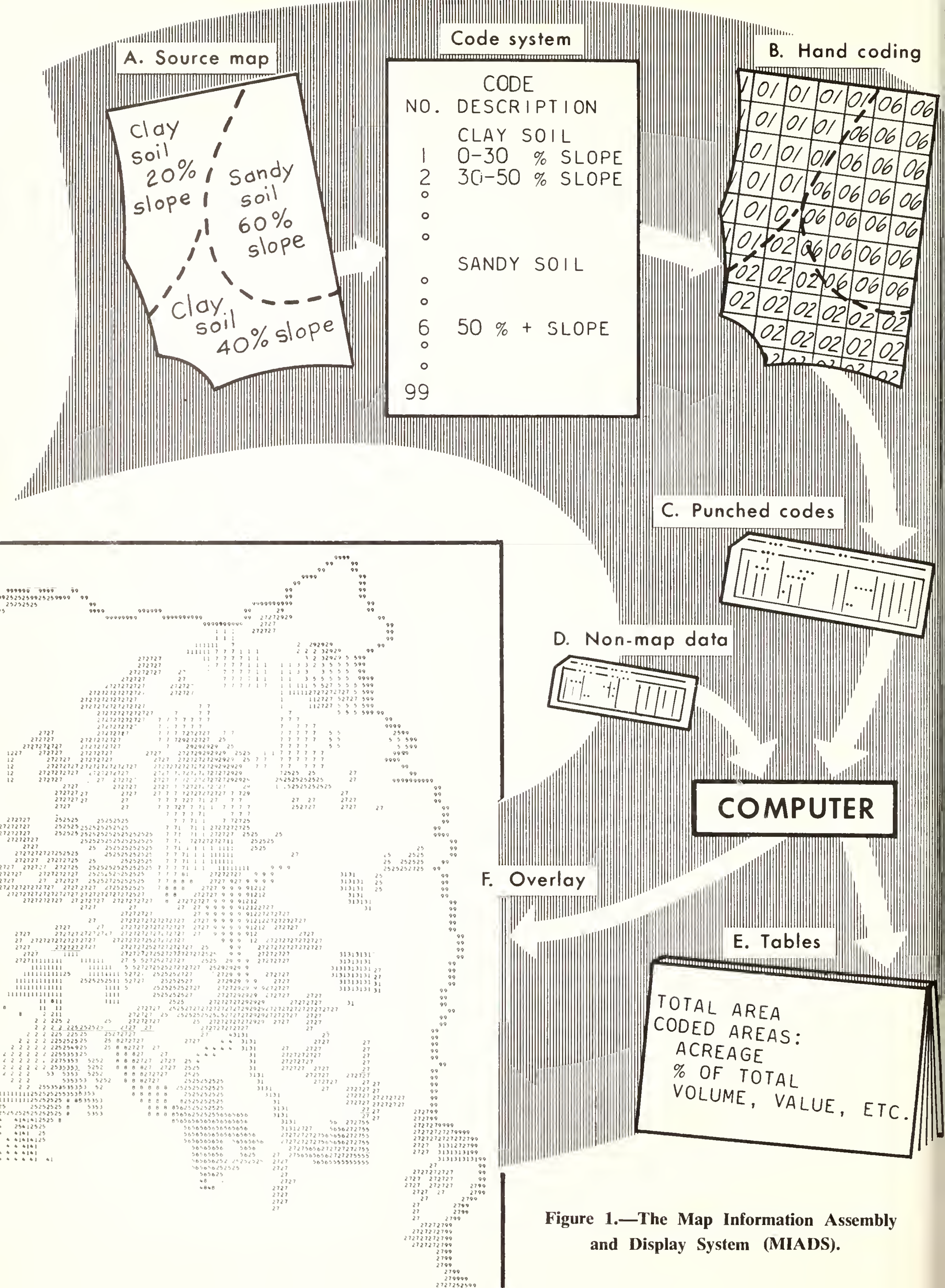

Figure 1.—The Map Information Assembly and Display System (MIADS).

Maps contain much of the information available to administrators responsible for managing large areas of land. To use information in making decisions, it must generally be assembled in a tabular form, which is more easily understood than maps themselves. To implement these decisions usually requires the preparation of overlays that show definite map locations. This can be an expensive process. Futhermore, vegetative cover, management objectives, or patterns of land can often change with the passage of time. Therefore, assembling and displaying map information is also a continuing process.

In a recent study we wanted to determine the possible impact of recreation development on timber production in a National Forest in California. Source data had to be assembled from timber and recreation management maps. It took us several man-months of work to assemble the initial data. We then had to do a great deal more work in order to simulate the impact of alternative levels of possible recreation development on timber yields.[1] This experience stimulated studies from which we have developed a computer-oriented system that can record, update, assemble, and display map information rapidly and efficiently.

How the System Works

The Map Information Assembly and Display System (MIADS)--as we call it--is a method for taking descriptive map and associated quantitative data and making them available for analysis and decision-making. It uses both handwork and a computer. The process starts with a *source map* (see also Glossary, p. i) that shows various land characteristics (fig. 1, A). Each different item of information wanted from the map is defined and given a 2-digit *code*. This limits each *code system* to 98 classifications (99 is the boundary code and is not tabulated). A rectangular grid is placed over the source map, and each grid *cell* is assigned a predetermined code number (B). The entire map is hand coded a *line* at a time; the wider the map, the more *strips*--columns of line--are required. Mapped codes are then transcribed to punch cards (C). The cards are then fed into a computer.

The assembled map data can be processed to calculate the acreage of an area represented by each code, and the proportion of an area in that code. The user, however, usually will want to combine with this map information certain supplementary *nonmap data* (D) which is also keypunched. For example, he may want to estimate the cost of converting from brush to grass, or to calculate the total volume of the sawtimber inventory. He supplies a brush-conversion cost or volume per acre for each relevant map code for computer multiplication by the corresponding code acreage. Given these "rates per acre," tabular output by the computer (E) for each *block*--group of lines--will contain information on acreages, proportions, and products (acreage times rates).

The computer at the same time produces a map card for each one that was entered, but with selected codes masked out. These output cards are put into an accounting machine. The resulting output consists of paper strips which, when fastened together, can become an overlay (F) of the same size and scale as the source map. Together the overlay and the tables show the location and extent of certain mapped conditions.

MIADS uses numbers--chiefly because map characteristics can easily be designated by numbers. But any legal character acceptable to computer input-output can be used to represent these characteristics. Numbers have several advantages: their position in an overlay shows where they are; and counting them tells how much area there is of each map characteristic.

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[1]Amidon, E. A., and Gould, E. M., Jr. The possible impact of recreation development on timber production in three California National Forests. U. S. Forest Serv. Pacific SW. Forest & Range Expt. Sta. Tech. Paper 68, 21 pp., illus. 1962.

Application of the System

Although several techniques to assemble map data are available, most of them do not take advantage of computers. The trend has been toward greater reliance on machines to prepare or interpret maps. Recent advances in photogrammetry, coupled with the rapid development of analogue and digital computers, show that progress is being made toward automation of both map preparation and map interpretation.[2] Tobler has discussed the possibilities for automation in cartography.[3] Berry compared sampling methods for extracting flood data from maps.[4] Wallis and Bowden have developed a method and computer program for obtaining area-elevation information for hydrologists.[5] But much more research is needed before the task of transforming conventional map information into a form suitable for automatic data processing can be fully automated.[6]

At present the system requires handwork to transcribe data for machine processing. Thereafter, computer methods are used to take care of (a) retrieving, updating, and combining descriptive map data for display in the form of overlays; and (b) summarizing map and supplementary quantitative data for presentation in tabular form.

We have applied the system to wildland problems that range from estimating the water-holding capacity of a watershed to simulating the management of a forested area over a period of time. MIADS, however, can be applied to all land-oriented problems--including those dealing with agricultural and urban land uses.

In developing and testing MIADS, we coded and processed information on about a million acres of land. We found that:

•The system works. This paper is not a proposal for future development, but reports on a working, operational management tool.

•The system is not expensive to use. In one application, involving considerable data preparation and processing, the cost was only fifteen-hundredths of a cent per acre.

•The system does not require the use of either expensive equipment or highly trained personnel to prepare map information for transcribing to punch cards. This first and most costly phase of the work can be done by personnel in field offices.

After data preparation, however, the job must be handled by persons trained to use key punch machines and someone familar with electronic computors. The necessary technical information on data processing and on the logic of the program for this phase of the system is given in the appendix.

Case Studies

Several different jobs were undertaken during development of this system to devise data compilating methods, test the computor programs, provide cost estimates of hand and machine work, and produce the desired information.

This paper describes three case studies to illustrate various types of conditions to which MIADS applies. The first example is a relatively simple, static case. The next two examples introduce the complexities of updating management information and retrieving selected data from a large amount of stored information.

Water-Holding Capacity of a Watershed

The resident watershed scientist for the 46,800-acre Big Creek Watershed Pilot Area,located within the Sierra National Forest in central California, needed an estimate of the water-holding capacity of the soil for his water accounting calculations. He could have obtained this information by dot-counting or planimetering the soil conditions

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[2]Bertram, Sidney. The automatic map compilation system. Photogrammetric Eng. 29(4):674-679. July 1963.

[3]Tobler, Waldo R. Automation and cartography. Geographical Rev. 44: 526-534. 1959.

[4]Berry, Brian J. L. Sampling, coding and storing flood plain data. U. S. Dept. Agr., Agr. Handb. 237, 27 pp., illus. 1962.

[5]Wallis, J. R., and Bowden, K. L. A rapid method for getting area-elevation information. U. S. Forest Serv. Pacific SW. Forest & Range Expt. Sta. Res. Note 208, 10 pp., illus. 1962.

[6]Langley, P. G. Can forest photo interpretation be automated? (Paper presented at annual meeting of Amer. Soc. Photogrammetry, Columbia River Sec., Portland, Ore., Dec. 5, 1961.)

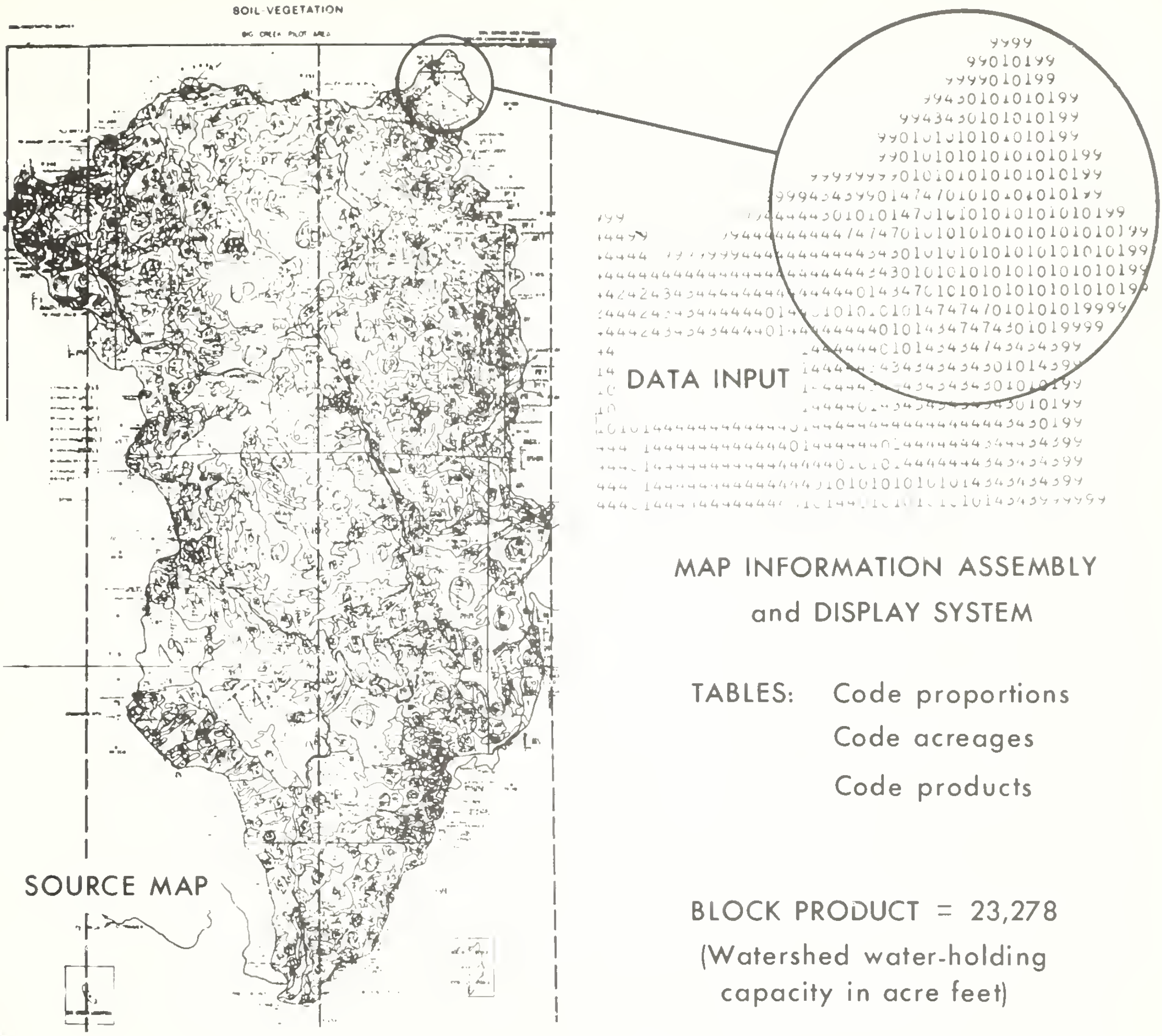


Figure 2.—Water-holding capacity of Big Creek watershed.

shown on a Soil-Vegetation Survey map of the area.[7] He did not need an overlay, and the key variables--soil types and depths--would change so slowly that updating mapped data was not a problem. In short, it was a straightforward data assembly task for the computer mapping program.

We established a code system before beginning hand coding. It allowed for 10 soil series groups, each containing 4 depth classes subdivided further into 2 slope classes. Three codes were added: for water, for unclassified soil (rock), and for the watershed boundary (code 99). Although the maximum number of codes in the system was 10 x 4 x 2 + 3 = 83, only 41 codes actually were used, primarily because not all depth classes occurred in each soil series classification. It took 3 man-days to hand code and verify the Big Creek Soil-Vegetation survey map, which had a scale of 2 inches per mile. Three strips, containing 390 lines were required to cover the watershed (fig. 2). Keypunching and keypunch-verifying took nearly another day.

The resident watershed scientist provided the supplementary data. Moisture-retention factors derived from laboratory analyses of soil profiles were already available for the watershed soils. A

[7]State Cooperative Soil-Vegetation Survey. Soil-Vegetation Surveys in California. 27 pp., illus., November 1958.

water-holding rate per acre was hand calculated for the average depth of each of the four possible depth classes in a soil series (table 1).

Further refinement of the rates to account for slope was not warranted.

Data processing took a half hour on an IBM 1620 computer. By contrast, the job of processing the same data on an IBM 7090 required only a half minute. The total water-holding capacity of the watershed soils was 23,278 acre feet.

Priorities for Type Conversion

This study taxed the capabilities of the mapping program much more than the first for four reasons. First, information was collected from several map

Table 1. Water-holding capacity and soil depths of Big Creek Pilot Area, Kings River North Working Circle, Sierra National Forest, by soil series

Item No.	Soil series: Number	Soil series: Name	Average soil depth	Water-holding capacity
			Inches	*Acre feet*
1	7319 & 851	Trabuco and Coarsegold	18	0.238
			30	.438
			42	.638
2	743 & 743V	Auberry and Auberry variant	30	.423
			42	.588
			54	.757
3	716 & 716V	Holland and Holland variant	30	.440
			42	.619
			54	.763
4	7121 & 7127	Corbett and Shaver	30	.321
			42	.477
			54	.633
5	7132	Stump Springs	42	.381
			54	.453
6	7117	Musick	42	.715
			54	.911
7	7129	Chawanakee	12	.118
			30	.296
8	854	Sacata	30	.414
			42	.552
			54	.720
9	749	Ahwahnee	30	.280
			42	.376
			54	.472
10	784	Tollhouse	12	.087

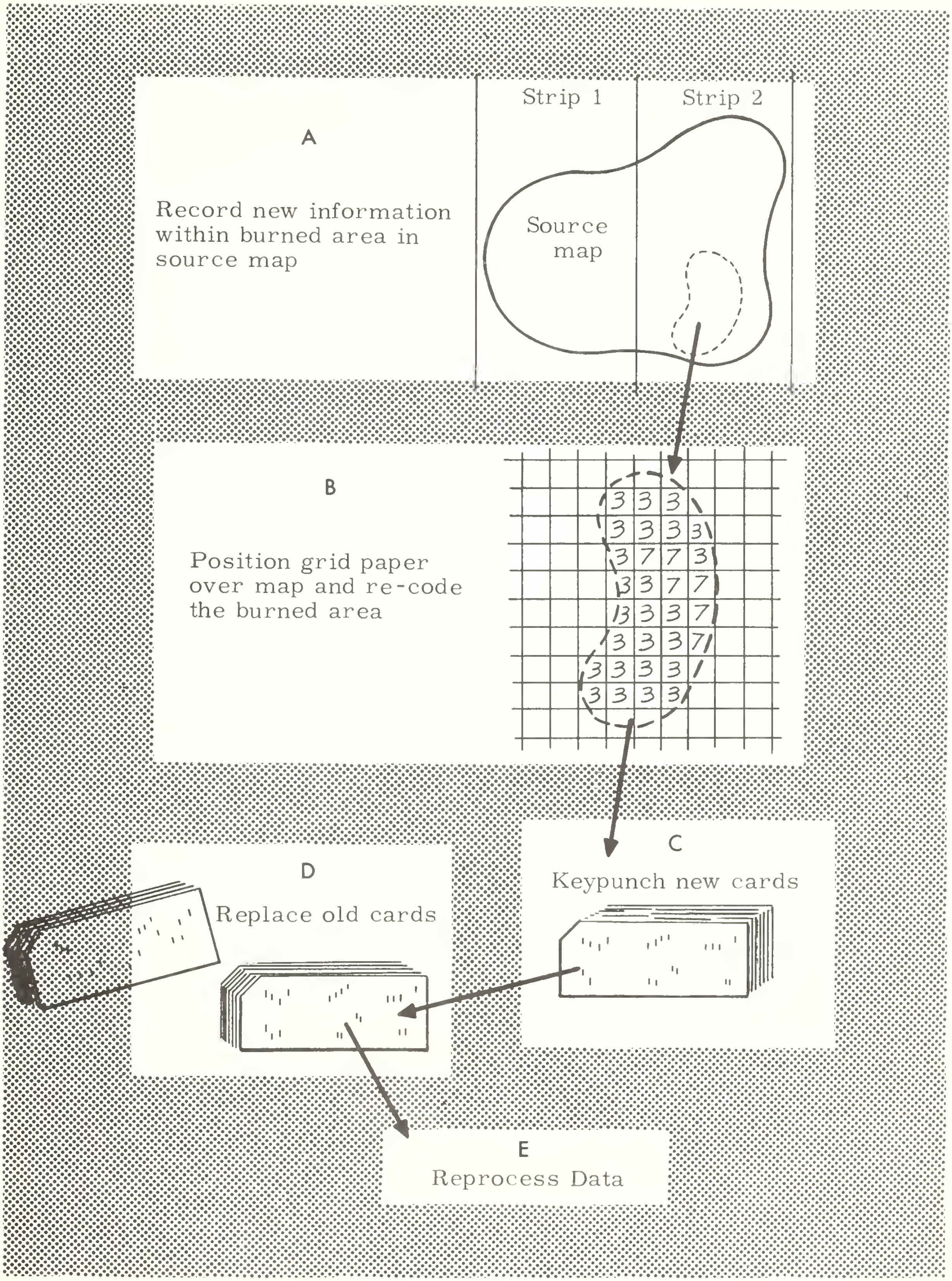


Figure 3.—Method for updating mapped information.

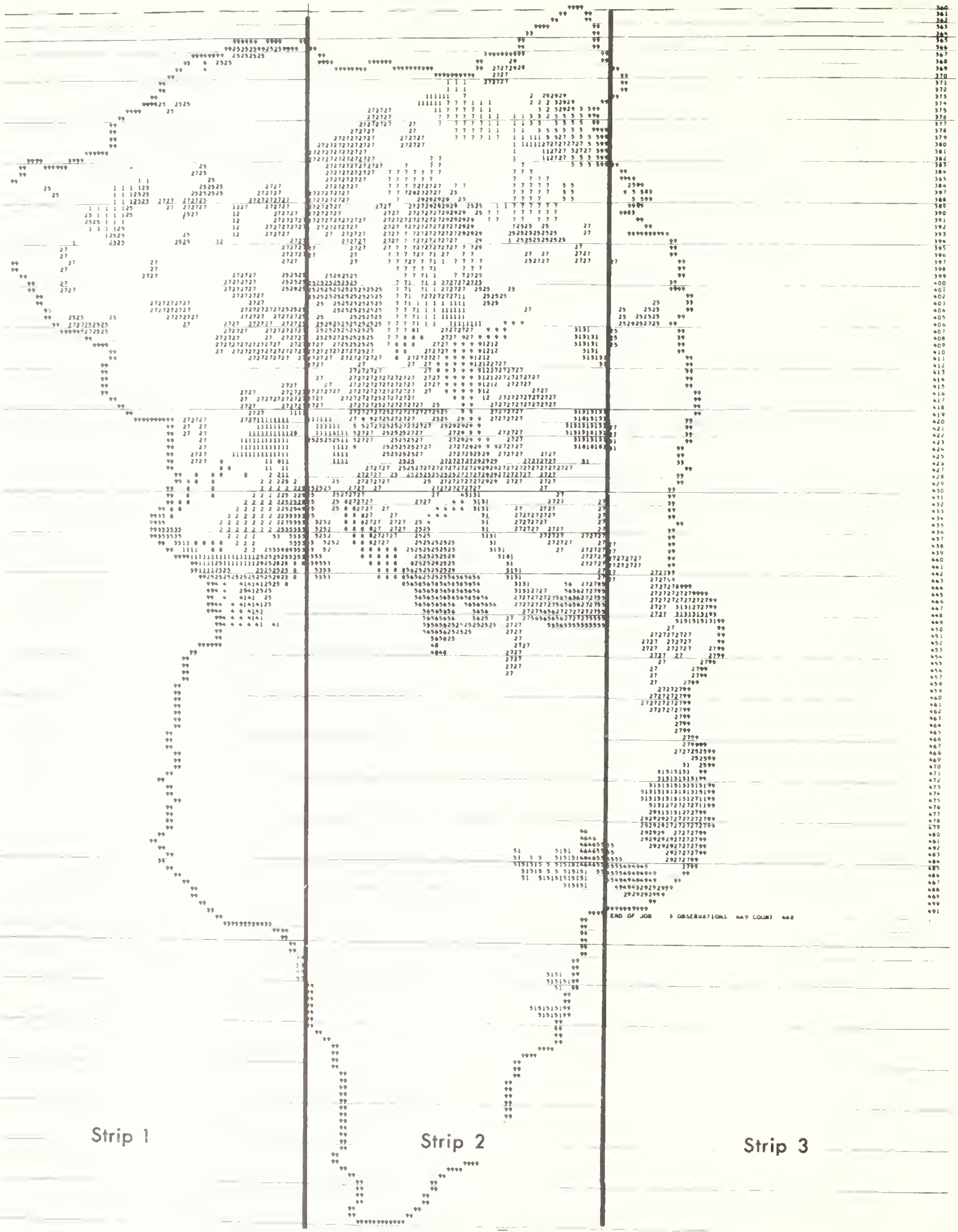


Figure 4.—Overlay showing timber priorities.

and non-map sources. Second, overlays were needed because the location and the amount of each condition were important. Third, fire had changed a portion of the ground cover and the data needed updating. Finally, several management functions were involved.

A schedule of priorities for converting existing vegetation types to more desirable types had been established for the Big Creek Pilot Area. There were 11 ranked treatments for timber, 6 for range, and 3 for wildlife. Ranking was determined by kind and density of existing vegetation, slope, and site quality, i.e., variables affecting treatment cost and productivity. Treatment categories, by public and private ownership, were combined during the hand coding stage into one map and into a 91-code system. Additional experience offset the increased coding complexity so that this study, like the first, required 3 days of hand coding and verifying.

After keypunching and processing, which took about one day or the same amount of time as in the first case, we found that a portion of the area had burned since the original map work was done. Part of the recent burn was already being converted into range and timberland. The burned area was delineated, several new codes added to the existing code system and the cards affected were pulled by hand and replaced by new data cards. If more extensive revision had been required, or if all the codes available had been used, the updated information would have been stored in a new code system until it was judged worthwhile to update the entire area by machine.

Treatment costs per acre for conversion to timber and range were obtained from foresters familiar with the area. A timber priorities overlay was a useful reference for this work (fig. 4).

Conversion at Big Creek Pilot Area has been confined to the highest priority classes on slopes less than 30 percent. Since site preparation generally requires complete removal of the existing vegetation, recent burns are scheduled for early treatment both to take advantage of the reduced cover and to prevent erosion. The cost estimates are only approximate because the lower priority classes have not actually been treated. Direct treatment costs--those for materials, equipment and labor, including supervision--at the site were $110 per acre for top priority brush conversion to range. The corresponding cost for conversion to timber ranged from $85 on recent burns to $125 on old brush fields.

The cost estimates and map data were processed simultaneously to give total treatment cost for each priority class. The results help determine the total budget required for a given amount of conversion work or, alternatively, help estimate the amount of work that can be accomplished for a given budget. For example, we found that about 1,100 acres, or 2.3 percent of the National Forest land in the watershed, was in the top priority class for conversion to timber. This was non- or poorly-stocked land with slopes less than 30 percent, timber site class 3 or better. The direct cost of tree planting this category would be about $112,000. In contrast, about 11,200 acres, or 23 percent of the National Forest land, were included in all priority classes, but this included land too steep to plant by present methods. All six priority classes for conversion to range, by brush removal and seeding, totaled 2,400 acres, or 5 percent of the National Forest land in the watershed. Only half this area, the top three priority classes, could be treated by known methods, at a direct cost of $143,000.

Timber and Soil Characteristics of a Large Area

This last study was the largest undertaking in two respects. First, the area covered was eight times larger than the cases just described and was coded twice. In effect, 760,000 acres were processed. Second, we needed a supplementary computer program that would take information from each of two code systems for subsequent processing and production of tables and overlays. We call this supplementary program the combinations program.

The Kings River North Working Circle on the Sierra National Forest contains about 380,000 acres of National Forest land. In 1961 it consisted of three timber management zones, now called primary, modified or deferred areas (fig. 5). Timber production is the main objective in the primary area. The modified area includes land surrounding lakes or beside streams and roads where watershed or recreation interests dominate. The deferred area consists largely of wilderness-type areas.

Two coding systems were established to collect detailed information only from the primary area. The first system of 97 codes contained data collected from a set of 22 Timber Stand-Vegetation

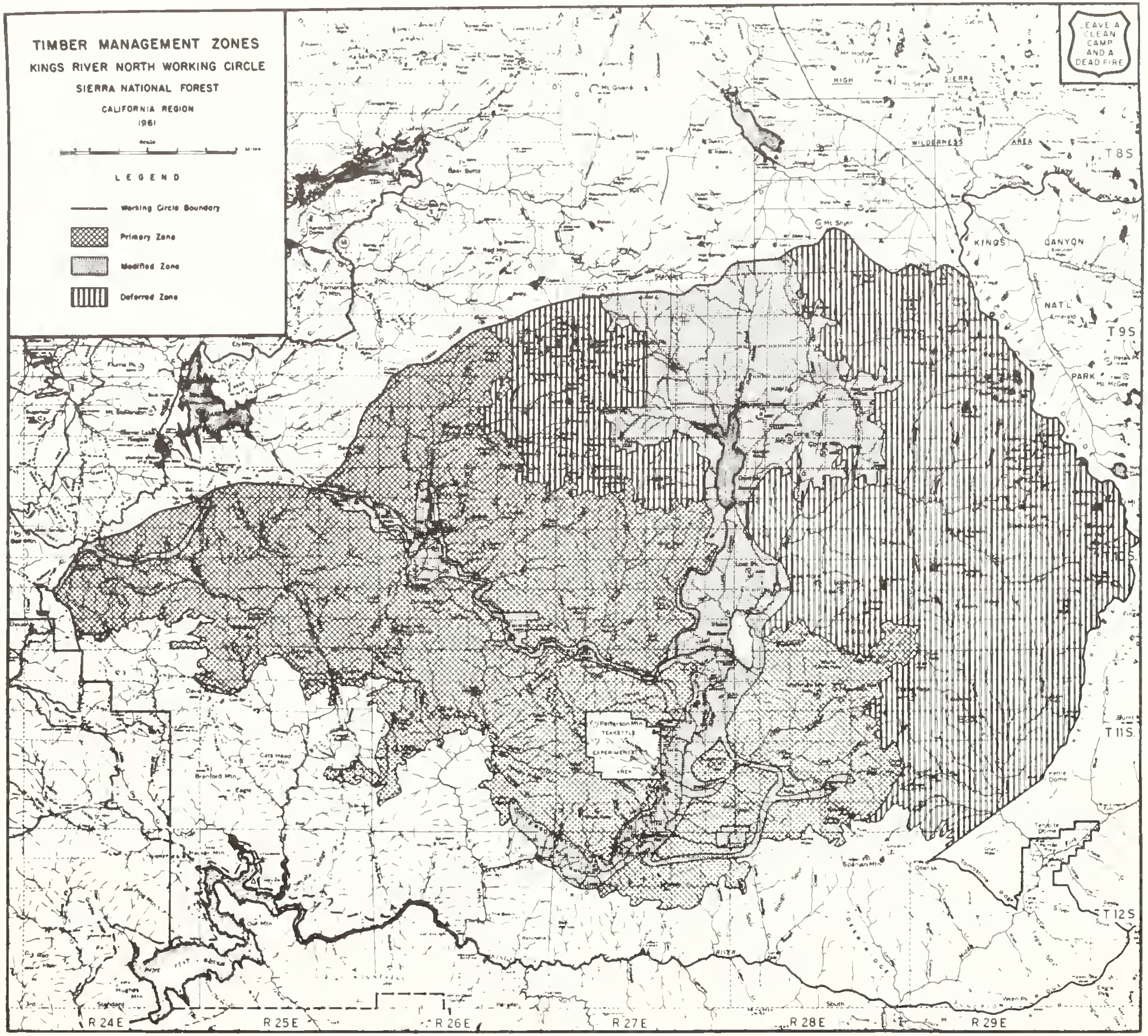


Figure 5.—Timber management areas of Kings River North Working Circle.

quadrangles at a scale of 2 inches per mile. Most of the codes represented timber stand age-density characteristics. The second, an 89-code system, drew on data derived from a corresponding set of Soil-Vegetation maps. These codes represented site quality, soil depth, and slope classifications. In each system, it took 5-6 man-weeks to hand code and verify and 7 man-days to key-punch the records. Both systems required 2,700 cards in 12 strips which, when joined together, formed a map about 4-½ by 6 feet long (fig. 6). For each system, producing block tables and one overlay under the control of the mapping program took 2-⅓ hours of IBM 1620 time.

The timber stand and soil vegetation tables by themselves presented useful inventory information. However, data were needed from both coding systems for such activities as tree planting or harvesting. For example, to find the most desirable timber cropland to plant within the primary zone, site quality, and soil depth data for slopes under 30 percent in one system needed to be combined with stand age-density classes from the second system (fig. 7). We also wanted information on the presence of bear clover (*Chamaebatia foliolosa*), also called mountain misery. This low plant competes strongly with tree seedlings for available moisture. To insure a high seedling survival rate, land must be terraced to scrape off bear clover roots before planting begins. The additional work due to bear clover can increase site preparation cost by about one-half.

From the two sets of working circle data, the computer combined high sites with low stand densities. High sites had no bear clover and were site class III or better. Low stand densities had less than 50 percent of sawlog stand, total-stand, and total woody vegetation density. To compare processing speed, the data were processed by two combination programs: first, a Fortran II, and then Fortran IV. The first run took 6-⅓ minutes, the second 3-⅓ minutes. The IBM 1620 was not used because each run would have required about 25 hours of machine time.

The combinations output was then processed by Fortran II and IV versions of the mapping program, requiring 3.8 and 2 minutes, respectively. Both printed tables and overlay cards were produced.

Mapping program output from earlier runs had shown that (a) 22,000 acres were free of bear clover and met the site and slope requirements for planting, and (b) 5,300 acres met the density criteria. The subsequent processing by the combinations and mapping programs showed that 1,850 acres met both sets of criteria. At a direct planting cost of $90 per acre, it would require $167,000 to plant these highly productive sites.

A great deal of planning and field work remains before specific planting activities can be scheduled. But the mapping and combinations programs have shown where to start and the size of the task.

Potential Uses of the System

Judging from these case studies, the system has greatest application where map characteristics, land treatment methods, and objectives change continually over time. The demand for wildland products is likely to increase in the future, and will require continual changes in land management inventories and plans.

Land managers are familiar with inventory maps, overlays, and tables and appreciate the effort required to keep their inventories current.

The uses to which the system is put will depend on the needs and imagination of the user. Many uses will be simply variations of inventory type work. Therefore, we consider two less obvious applications possible with the present system.

Assume that we must estimate the tax contribution to a county or other government unit. A map is available showing the distribution of assessment classes (i.e., use types) such as forest types, or other taxable lands. A second, administrative map shows taxation zones, and assessment rates are known. Once each map is hand coded independently, the contribution of each zone and the total estimated tax can be determined by the computer programs. The change in the total tax associated with incremental changes in the rate structure could also be determined easily.

Another use of the system is to simulate future forest conditions--20, 40, or 60 years away--which will result from decisions made both today and in the future. The present timber stands in the forest are classified by age and volume, and a timber rotation age is established. The combinations

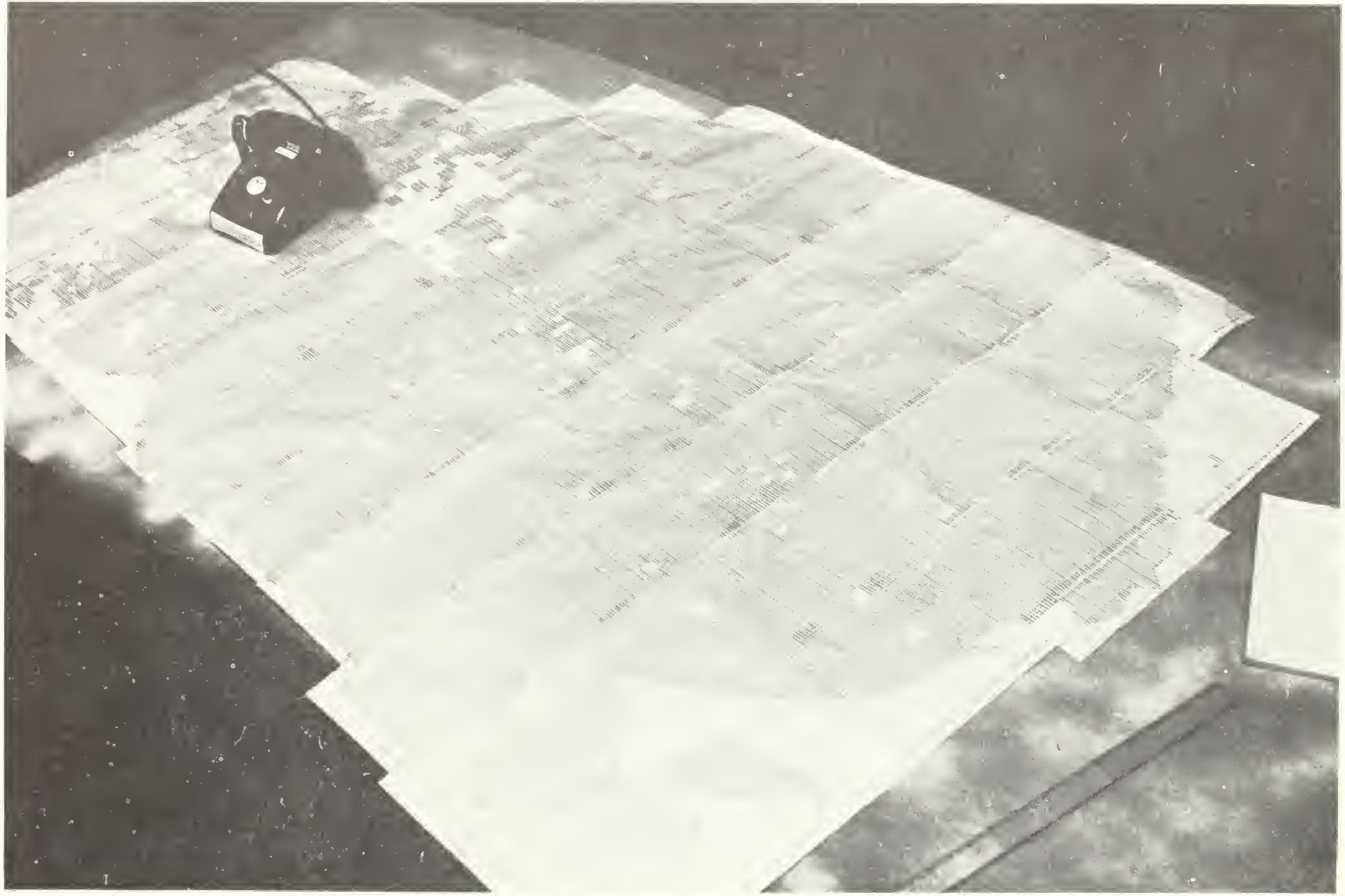


Figure 6.—The Kings River North Working Circle, coded into 2,700 lines, arranged in 12 strips.

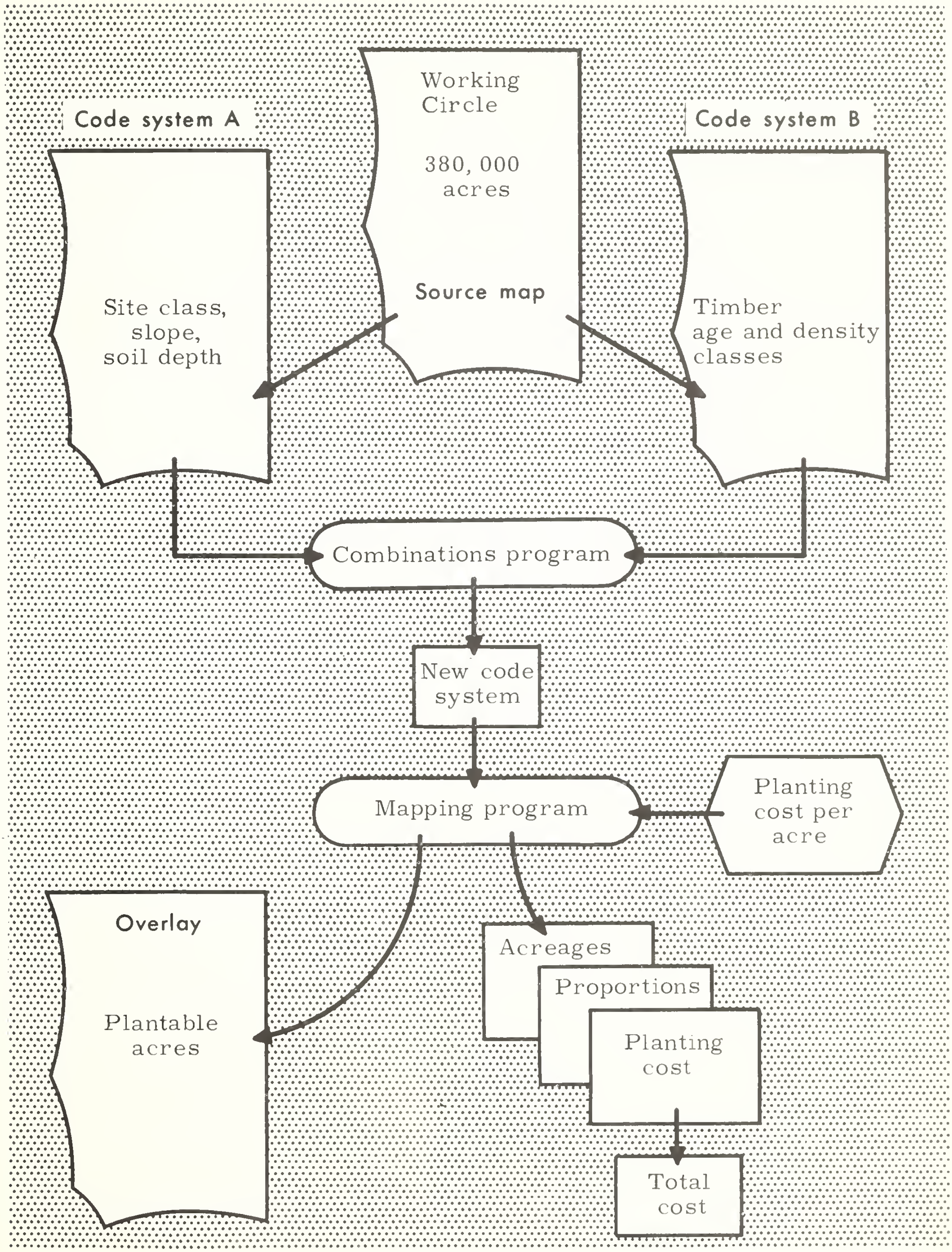
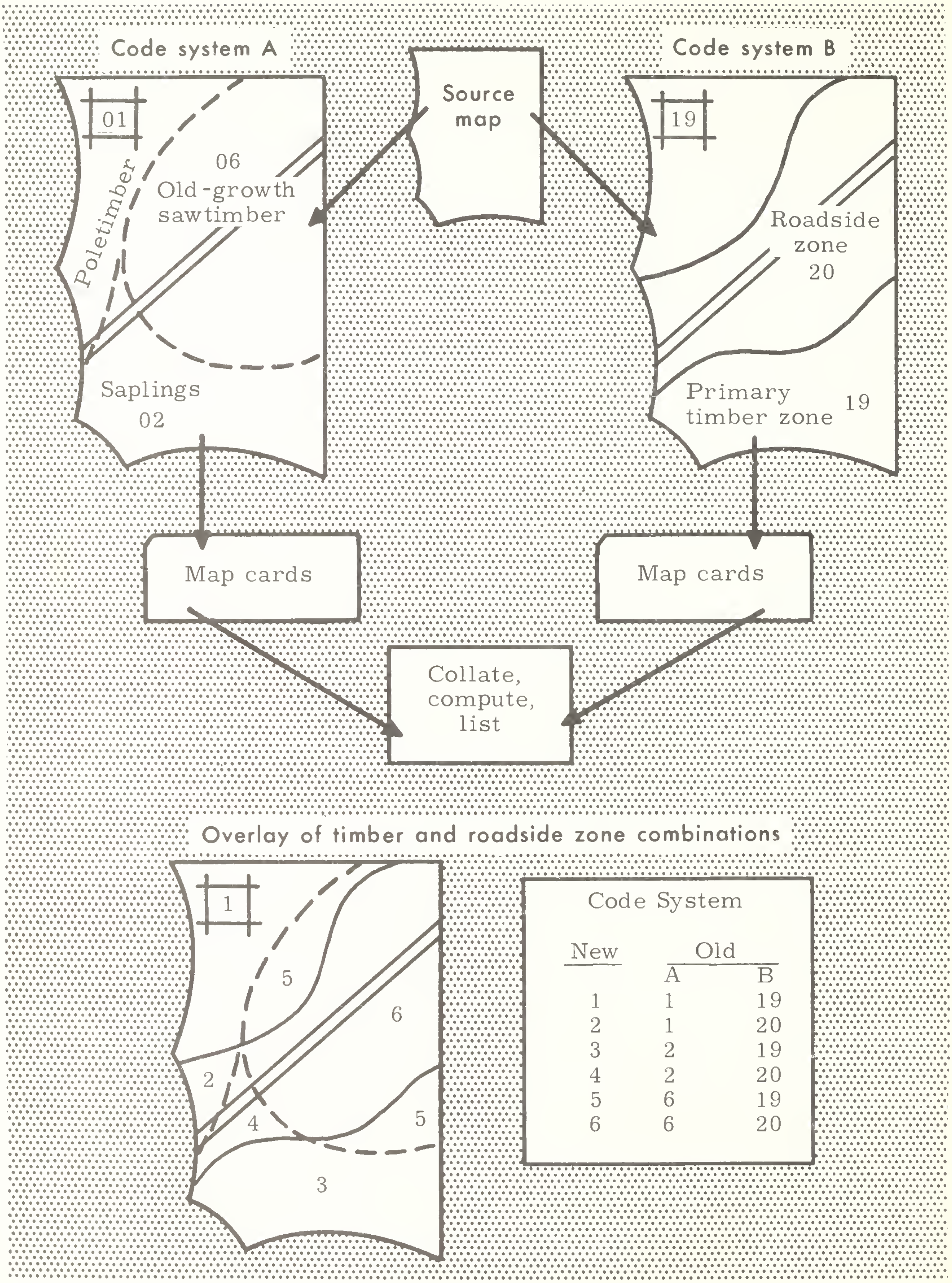


Figure 7.—Map data can be combined to determine plantable acres.



New	Old A	Old B
1	1	19
2	1	20
3	2	19
4	2	20
5	6	19
6	6	20

Figure 8.—Data from two source maps of a given area can be combined.

program is used to advance all stands by one age class and indicate those mature stands to be "cut" and "regenerated." The card output from this time increment becomes input to the mapping program. Then the age-volume data are used to compute growth and yield at the end of the end of the first time increment. The mapping program output in turn becomes input for the combinations program to start a second cycle. By repeated cycling, inventory tables and overlays can be produced for any number of future time periods. The impact of alternative rotation ages on future yields could be similarly predicted and displayed. This application should be useful in management planning and as a training aid for educational programs.

Special Characteristics of the System

Combinations Program

To make the mapping program of MIADS more versatile, we developed a supplementary computer program called the combinations program. The combinations program has two distinct functions: (a) changes (rearranges) codes within a code system, or (b) combines codes from 2, 3, or 4 systems simultaneously into one system of 99 codes or less. The first function allows a code system to be flexible. Codes inevitably must be rearranged because classification needs change over time, e.g., because of such agents as fire, or timber growth. The second function enables the user to combine selected information from several different maps of a given area into one code system. For example, one map might have timber classifications; the other land management zones.

The objective may be to produce a "new" map showing the distribution of timber stands within a roadside zone (fig. 8). The maps are hand coded independently, each with its own system of up to 99 codes. The grids are aligned so that coding begins from a common map reference point insuring that any given pair of cells will have the same coordinate position. Subsequent use of the combinations program should be anticipated in order to maintain this correspondence and avoid duplication of hand coding work. The two groups of map cards are merged and a computer searches the combinations. The desired combinations are assigned a new code in a single code system. As before, card output can be used to make a "new" map or, the map data can be processed by the mapping program to make an overlay showing particular conditions within the roadside zone and to produce simultaneously timber volume tabulations.

Computer Options and Output

A major objective throughout the development of the system was to produce computer programs adaptable to various machines. We wrote Fortran II programs specifically for the IBM 1620 computer and Fortran II and IV programs for the larger IBM 7090 computer. These programs can be adapted to other computers having Fortran compilers. For the programs developed, direct processing cost was always lower on the IBM 7090 than on the IBM 1620. The IBM 7090's greater expense per hour was more than offset by its higher computational speed. Land managers, particularly those located near smaller metropolitan areas, however, may have direct access to smaller installations so that the total cost for a particular job may be lower on the smaller machine. Since the programs were designed to be adaptable to quite different computers, additional features or increased speed may be gained by modifying the programs for specific installations.

Options

All options described below apply to both the IBM 1620 and the 7090 computer programs unless otherwise noted.

The land manager will often want data tabulated for each of a series of administrative or geographic units (block) as well as a grand total for all blocks. For example, in progressing from smaller to larger administrative units, he might want tables for each of five compartments in District "A" (with accumulated tables) followed by compartment tables in District "B" (with accumulated tables for A and B). He would be limited by computer memory storage to 20 individual blocks using the IBM 1620 or 99 for the IBM 7090.

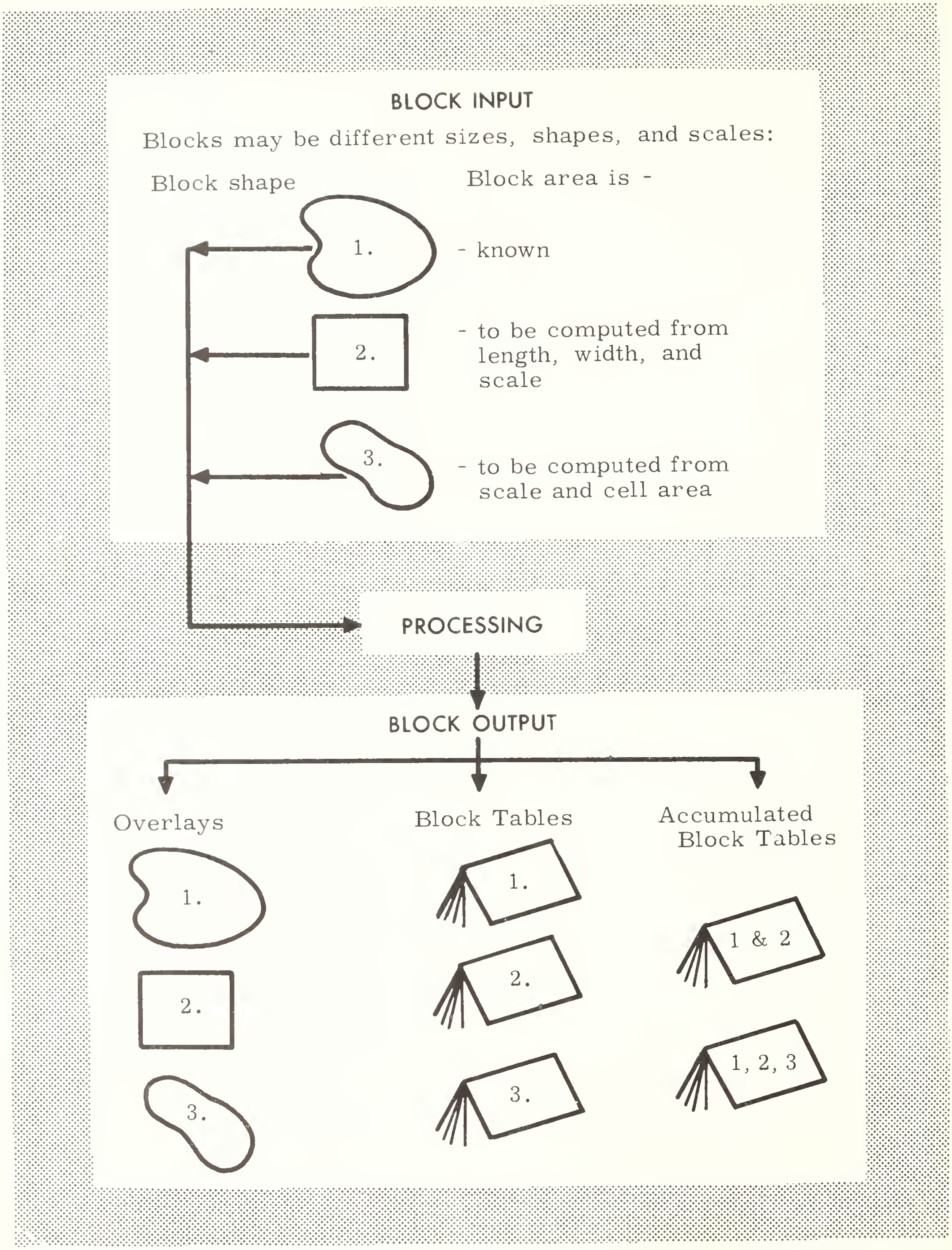


Figure 9.—Block input and output can be varied.

The area of each block can be supplied by the user or calculated from supplementary information. For a rectangular or trapezoidal area--such as an entire map quadrangle--block length, width and scale must be provided. Finally, the area of a block of any form can be calculated from its scale and the number of coded cells.

Figure 9 illustrates the preceding description. Three blocks, each with a different scale and whose areas are calculated by a different method, are processed in a single computer run. Three sets of individual block tables and two sets of accumulated block tables are produced. The user has the option of producing tables and/or map overlay cards.

Output

Overlays are of the same size and scale as the block input. Overlay scale cannot be varied within the computer. Blocks can be made the same scale externally by varying the spacing of the grid used while hand coding.

If rates per acre are provided, the user will get tables for each block or for accumulated block output. As mentioned before, the basic information contained in the tables are code acreages, proportions, and arithmetic products. The tables include cumulation of this information over codes which is similar to the accumulation of data over blocks discussed earlier. A complete list of the tables and miscellaneous items produced is shown below:

BLOCK TABLES

Block:
1. Code frequencies
2. Code proportions
3. Code acreages
4. Cumulative code proportions and acreages
5. Code products (acreages x rates)
6. Product proportions
7. Cumulative product proportions and acreages

BLOCK ITEMS

1. Block frequency total
2. Block acreage
3. Acreage represented by one grid cell
4. Total block product

ACCUMULATED BLOCK TABLES

Accumulated Block:
1. Code proportions
2. Code acreages
3. Cumulative code proportions and acreages
4. Code products
5. Products proportions
6. Cumulative products proportions and products

ACCUMULATED BLOCK ITEMS

1. Total block acreage
2. Total block product

Data Preparation

Hand Coding Map Data

Coding--translating map characteristics into numbers--by hand is the first and most expensive and time-consuming step of the entire process. At present there is no substitute for the human data interpreter.

Conceptually, there are many enumerative or stochastic methods of collecting the map data. An example of each method, respectively, is the planimeter and the dot-grid; both are commonly used in land management. The method used in this study seeks to reduce human work and errors as much as possible. Thus, the available machinery strongly influences the attributes of the system. For example, the systematic grid used and size and shape of grid cell (one-fifth by one-sixth of an inch) are dictated by the listing machine. Similarly, an accurate grid could be drawn on stable plastic, placed over a map, and codes recorded on a form --with some transposition errors. Instead, a less precise grid is printed as needed on a listing machine and the codes are recorded directly on the paper.

The user is not physically restricted to the techniques described in this section. For example, he could ignore the overlay option, devise any type of grid, collect data by any number of sampling schemes, and produce tables. However, only by following the recommended procedures will he be able to use all the system's options.

The computer programs will accept only map characteristics translated into 98 (or fewer) integer codes; code 99, reserved for boundaries is not counted. Letters have mnemonic value and with a redesigned program could be processed about as

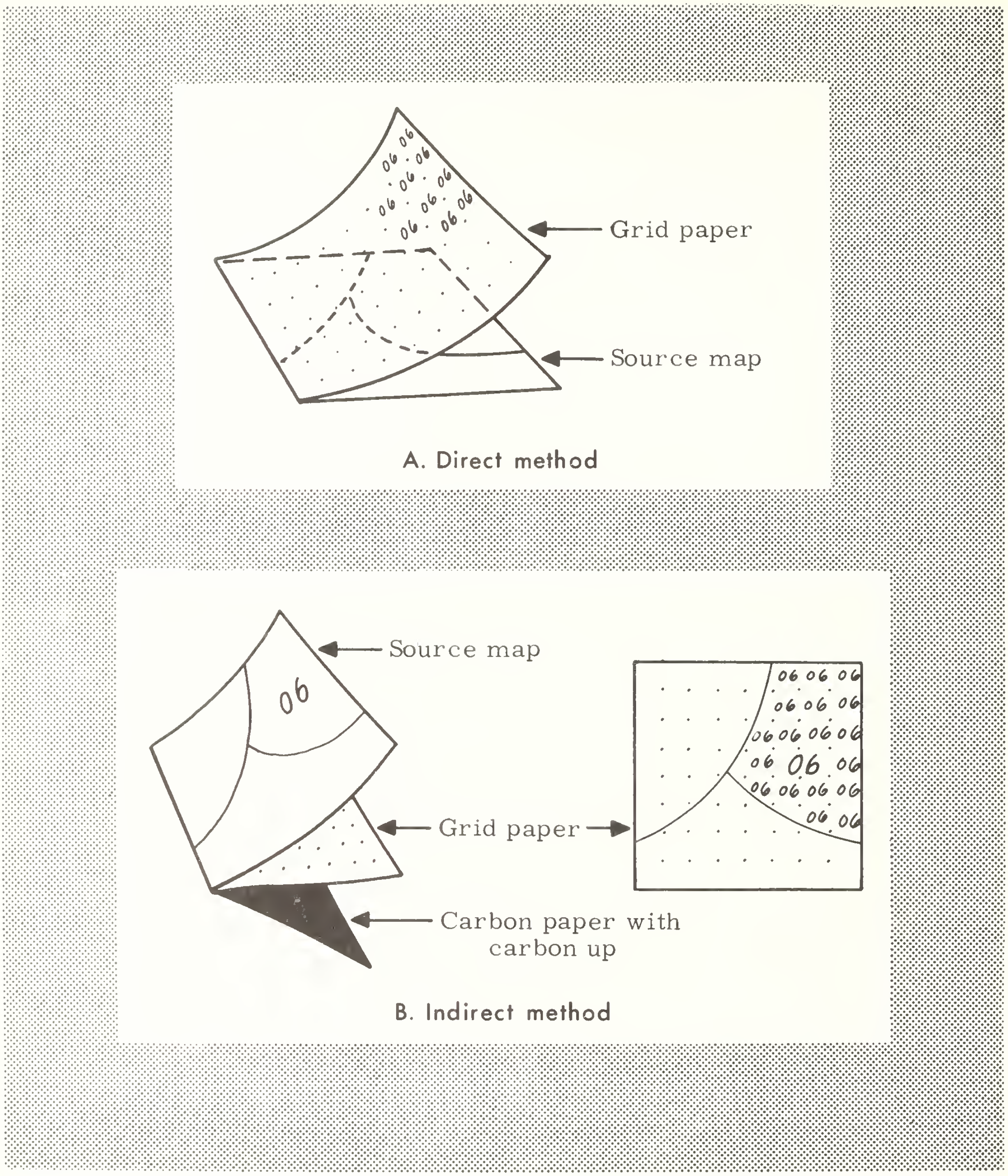


Figure 10.—Two hand coding methods can be used in the system.

fast as numbers. The addition of pairs of letters or numbers and letters (e.g., AZ, B9) would allow more than a thousand categories in a code system. Although a map may have thousands of distinct categories, generally 98 or fewer groups will yield sufficient information for making particular decisions. Development of a larger code system is planned, however, because more intensive information requirements are expected in the future.

Two Coding Methods

Basically, we used two hand coding techniques. Only a light table was required as special equipment for the first one. Neither technique had a clear-cut advantage in all cases. Before the data are ready for the computer, they must be coded, verified, key-punched, and keypunch verified. Keypunch work is the same for both methods.

The first, or *direct*, method is used if the original source map cannot be reproduced cheaply because it is color-coded or for some other reason. The opaque grid and map are fastened to a light table. If machine-produced grid paper or its equivalent is used, the code numbers can be written within each cell (fig. 10). A second person should verify the original hand coding to minimize errors, particularly those arising from a systematic misinterpretation of a map characteristic. After verification the grid paper is sent for keypunching and keypunch-verifying.

Since a person looks through the grid both for coding and for verifying, the coding rate will depend on the clarity of the mapped characteristics. The most difficult situation arises when colors have been added to the original map, e.g., blue shading on a blue-lined map. The coder's symbols may obscure map features and make the verifier's job more difficult. Finally, the more maps being coded simultaneously the more light table area needed. Our experience with problems of this type led to the development of an alternative method.

In the second,or *indirect* method, codes are recorded directly on a copy of the original map. Nearly all coding work during program development was done by this technique. Coding, especially code verifying, was easier because the operators looked directly at the map; the grid paper lay underneath (fig 4). The indirect method consists of four steps:

1. Fasten carbon paper with the carbon side up to any smooth, hard surface. Affix the grid paper to the carbon paper. Tape the map to be coded over the grid.
2. Delineate the boundary of each mapped condition with a hard pencil or ball point pen. Write the characteristic's code number once within the outlined area.
3. Verify the code number assigned to each condition and remove the grid paper. It will have a carbon impression on the reverse side.
4. Place the grid paper on a white surface so that the carbon impression is visible through the paper. If the impression is faint, a light table may be needed. Use a fine red ball point pen to write the same code number in each cell within a delineated area. This copy work could actually be done by a keypunch operator.

A variant of this method is to place the carbon paper on top of the grid. However, the impressions made by delineating and numbering the characteristics--and by accidental smudges--slow subsequent keypunching.

Those persons collecting data from sources other than paper maps should plan to develop their own techniques and equipment. Based on considerable experience with the indirect method, we found that about 13½ square inches of grid paper can be coded, verified, and numbered per hour. Given this rate, expense per acre will vary with map scale and labor cost. For a wage rate of $2 per hour and a map scale of 2 inches per mile, hand coding and verifying would cost one-tenth of a cent per acre. A hand coder must be familiar with maps and have methodical work habits. His coding speed will depend directly on his ability to remember each map symbol and its corresponding code number.

Appendix

This appendix describes the logic behind major program segments, gives more precise information for estimating cost, and includes detailed instructions for preparing and processing data. From this point on, an elementary knowledge of data processing would be quite helpful. Moreover, it is assumed that anyone using the system can get assistance from a computer programmer. Very likely the computer programs in this report will need minor modifications, even for other IBM 1620 and 7090 machines. Even with identical computers and peripheral equipment, job processing procedures may vary between installations. For this reason, and given the rapid changes in machines and in machine languages, a programmer will be needed for minor revisions of the programs.

A. *Map Input Data Preparation*

Map Card Format

Item	Field	Columns	
(1)	36 I2	1-72	Map codes (1-99)
(2)	I1	73	Block terminus indicator (1, 2, or blank)
(3)	I2	74, 75	Block number (7090:1-99), (1620:1-20) if any
(4)	I5	76-80	Identification number

Details of map card preparation:

(1) Map codes - unsigned, nonzero, two digit integers (i. e., 1-99) are processed. Blanks or zeroes are ignored.

(2) Block terminus indicator: an integer showing that the end of a block of mapping program input has been reached. The number 1 calls for tables based on the last block and for all tables up to and including that block. The number 2 calls for tabulations over the last block only. Blank (or zero) means that the end of the block has not been reached.

(3) Block number: the number of the block for which tabulations are to be made. Block integers must start with 1 and ascend sequentially (i. e., 1, 2, 3, ...). A block number must follow (on the same record) a terminus indicator.

(4) Identification number: may be blank, or an integer. Card sequence numbers are not checked, any sequence can be used.

(5) Map card output has the same format as input. A block terminus indicator or number on an input map card will be punched into the corresponding output card.

Hand Coding

Hand coding represents such a large portion of total cost that the two methods used were described in detail earlier in this report. Hand coding cost data were based on the smallest possible staff and fixed investment: two men and a light table. Even remote field stations with sporadic hand-coding needs can expect to attain the rate achieved in this study: 13 1/2 square inches per hour for coding, verifying, and numbering. Unfortunately, this rate is not likely to decrease drastically given a basic dependence on human map data interpretation. Within the procedure described, costs may be reduced by training a keypunch operator to interpret map characteristics, thereby reducing or eliminating hand numbering.

One additional detail--strip alignment--must be determined at the hand coding stage. Usually two or more strips are needed to cover the map area to be coded. Coding must start from a definite, if arbitrary, base point and line. For example, the corner and edge of a map quadrangle makes a convenient starting position. This reference can be recorded separately or incorporated into the coded data deck. Map corners can be indicated by intersecting rows and columns of code 99's. Also, as for the overlay shown earlier (fig. 6), code 99's can be used to delineate an outside boundary, because they are not counted. Finally, card identification numbers insure vertical alignment between strips. A note is made on a form that record No. 1, first strip, is opposite record 133, second strip, which in turn is opposite record 354, third strip. By using code 99's to indicate reference points or boundaries and recording matching strip record numbers, every grid cell will have an implicit coordinate position and overlay placement over the source map will be uniquely determined.

Record Keeping

The type of forms required will depend on the magnitude of the job undertaken and can be devised by the user as the need arises. We found two types of forms useful in this study for keeping track of about 30 maps during coding and verifying. The first form had definitions of the map characteristics coded along with the assigned code numbers. The second form provided a continual record of each stage of processing for each map. It also had a place to sketch the physical relationship of the strips with one another, along with reference points and matching record identification numbers.

Listing

Map overlay strips are printed by listing computer card output. Ordinary machine paper may be used but with some risk of misinterpreting the codes. Codes are printed continuously, e.g., 9373.., therefore it is not immediately obvious that a particular cell is 93, 37, or 73. Special paper with 5 vertical lines per inch would avoid ambiguity in distinguishing codes; i.e., show 93/37/73. However, experience has shown that interpretation without the lines is not difficult if only a few codes are printed on the overlay and boundary or reference code 99's are printed.

Listing can be done on an IBM 407, 408, or 409 accounting machine or its equivalent. A special control panel can be wired to prevent zeroes or negative signs from being printed so that the overlay will not be cluttered. Listing is continuous unless a skip card

(X-punch in Col. 80), placed between strips, is encountered. All 80 columns of the map output cards are listed with a type bar setting of 10 characters per line inch and 6 lines per inch. This is a common spacing. No other spacing can be used without changing the computer program.

Grid paper can be made by listing a special deck of cards. Each card has a period (12-8-3 punch) in every other column beginning with 1 and ending with 73. The remaining columns (76-80) are used for sequence numbers, from 1 up to whatever number is convenient.

Map input records should contain only code numbers; no other characters are permissible. Therefore, any single card column should have only one punch. Letters and other characters are recorded in card columns by multiple punches. Erroneous multiple punches can be detected by passing all input records through a reproducing punch (e.g., IBM 514) using a double punch detector board. Two single punch characters, a plus (+) sign (12 punch) and a minus (-) sign (11 punch), cannot be detected in this manner. List and scan the data input to spot and change these signs before computer processing.

Those persons familiar with data processing may wish to use computer programs for the data checking and card handling methods described.

All 7090 table output is printed. IBM 1620 output will contain map and table cards intermixed. The two types of cards are separated on a card sorter by sort-suppressing on Column 2. A general (80-80) control panel is used to list the table output.

B. Supplementary Data Preparation

Only the mapping program uses supplementary information. The user must decide how block acreage will be computed and provide the necessary data. The only other type of supplementary data--rates per acre--is optional. These rates are multiplied by the computer times the acreage of each code.

Calculating Block Acreage

Block acreage may be computed in one of four ways, depending on the form of the map data or the user's preferences. The criteria for selecting a method and the computational procedure used are:

Method of determining block area:	Select this method when block--	Computer calculations[1]
1. Given by user	Area is already known	None
2. Block length, width, reciprocal of representative fraction	Is a square, rectangle, or trapezoid	$A=(R^2/K)(L)(W)$

3. User provides reciprocal of representative fraction and program computes cell area with:	Has an irregular (or any) form	
a. Every cell coded, or		$A = (R^2/(K)(D))(N)$
b. Every other cell coded		$A = (R^2/(K)(D))(N)(2)$

[1] A = Block acreage
R = Reciprocal of representative fraction (e.g., 31680 for an R.F. of 1:31680)
K = (43560) (144)
L = Block length, inches
W = Block width, inches
D = Number of cells per square inch (30)
N = Block cell frequency

Rates per Acre

The rates, or weights, per acre may represent board-foot volumes, treatment cost, animal-unit months, or other units. Such diversity means that the magnitude of the rates may vary widely. In order to allow for this variation, rates are entered on control cards in E-format. Tables of arithmetic products, however, are in F-format (F10.0) because this form is easier to read. Those preparing input data have the responsibility of scaling the rates accordingly. If scaling is overlooked, or done incorrectly, overflow may occur. Fortunately, the IBM 1620 will punch the correct value of an entry in E-format whenever the F-format is exceeded. In this case, nothing is lost except some computer time. The larger computer does not have this feature so that as a partial substitute, block totals are printed in both formats. If these values are unequal, a gross scaling error has been made. Eight significant digits for each table entry probably will provide enough leeway, but if scaling proves bothersome a programmer can change table output to E-format. This change removes a chance for error at the price of additional clutter and misinterpretation of the exponential-type format by the ultimate user.

C. *Computer Programs*

Mapping Program

Computational procedure.--The mathematical bases for the tables and miscellaneous items calculated by the mapping program are shown below in algebraic notation. Note that "cumulation" is applied to within-block and "accumulation" to over-block summing of code items.

1. Code defined

c_{ijk} = ith number, jth code, kth block

$1 \leq c_{ijk} \leq 99$ $\quad$ $i = 1,n$

$j,k = 1,m$

$1 \leq m \leq 99$

2. Block code frequencies

$\sum_{i=1}^{n} c_{ijk}$ = the number of times the jth code occurs in the kth block

3. Block frequency total

$\sum_{i=1}^{n} \sum_{j=1}^{m} c_{ij}$ = the frequency of all codes in the kth block

4. Block proportions

$\sum_{i=1}^{n} c_{ij} / \sum_{i=1}^{n} \sum_{j=1}^{m} c_{ij} = p_{jk}$ = proportion jth code is of all codes in the kth block

5. Block code acreages

b_k = total acreage of kth block

$(p_{jk})(b_k) = a_{jk}$ = acres of jth code in kth block

6. Acreage represented by one grid cell

$$g = b_k / \sum_{i=1}^{n} \sum_{j=1}^{m} c_{ij}$$

7. Block cumulative code proportions and acreages

a. Proportions

$$S_k = p_{1k} + (p_{1k} + p_{2k}) + \ldots + (p_{1k} + p_{2k} + \ldots + p_{mk})$$

b. Acreages

$$s_k = a_{1k} + (a_{1k} + a_{2k}) + \ldots + (a_{1k} + a_{2k} + \ldots + a_{mk})$$

8. Block code products

r_j = rate per acre, jth code

$(a_{jk})(r_{jk}) = v_{jk}$ = product of jth code, kth block

$\sum_{j=1}^{m} v_{jk} = y_k$ = total block product

9. Block product proportions

$$\frac{v_{jk}}{y_k} = t_{jk}$$

10. Block cumulative product proportions and products

a. Proportions

$$W_k = t_{1k} + (t_{1k} + t_{2k}) + . . . + (t_{1k} + t_{2k} + . . . t_{mk})$$

b. Products

$$w = v_{1k} + (v_{1k} + v_{2k}) + . . . + (v_{1k} + v_{2k} + . . . + V_{mk})$$

11. Accumulated block code proportions

$\sum_{k=1}^{m} b_k = B$ = total accumulated acreage

$$\frac{\sum_{k=1}^{m} a_{jk}}{B} = P_j$$

12. Accumulated block code acreages

$(P_j)(B) = A_j$ = accumulated acreage, jth code

13. Accumulated block cumulative code proportions and acreages

a. Proportions

$$S' = P_1 + (P_1 + P_2) + . . . + (P_1 + P_2 + . . . + P_m)$$

b. Acreages

$$s' = A_1 + (A_1 + A_2) + . . . + (A_1 + A_2 + . . . + A_m)$$

14. Accumulated block code products

$A_j r_j = V_j$ accumulated product of jth code

$$\sum_{j=1}^{m} A_j r_j = Y = \text{total accumulated product}$$

15. Accumulated block product proportions

$$\frac{A_j r_j}{Y} = T_j$$

16. Accumulated block cumulative product proportions and products

a. Proportions

$$W' = T_1 + (T_1 + T_2) + \ldots + (T_1 + T_2 + \ldots + T_m)$$

b. Products

$$w' = V_1 + (V_1 + V_2) + \ldots + (V_1 + V_2 + \ldots + V_m)$$

Numerical example.--The arithmetic behind the mapping program tables is shown below in a simplified example. The objective of the hypothetical illustration is to show how all tables are calculated with minimum numerical detail. The raw data and hand calculations are followed by IBM 1620 output based on exactly the same information.

(a) Hypothetical data on which the tables are based

1. Coded map data

Cell code numbers

Block 1 1, 1, 1, 2, 2, 2, 2, 2, 3, 3 (First map input card)
Block 2 1, 1, 1, 1, 2, 2, 2, 3, 3, 3 (Second map input card)

2. Total block areas. This is the first option--the user supplies the acreage of each block. Since each block contains 10 coded cells and their total area differs, then so do their scales.

	Acreage
Block 1	100
Block 2	1000

3. Rates per acre for each code

Code	Rate/acre
1	.4
2	.5
3	.6

(b) The 14 tables. The method of calculating table entries is shown in footnotes.

1. Block code frequencies

	Frequency	
Code	Block 1	Block 2
1	[1] 3	4
2	5	3
3	2	3

[1] 1+1+1=3

2. Block code proportions

	Proportions	
Code	Block 1	Block 2
1	[1] .30	.40
2	.50	.30
3	.20	.30

[1] 3/10

3. Block code acreages

	Acreage	
Code	Block 1	Block 2
1	[1] 30	400
2	50	300
3	20	300

[1] (.30) (100)

4. Block cumulative code proportions and acreages

	Proportions		Acreages	
Code	Block 1	Block 2	Block 1	Block 2
1	.30	.40	30	400
2	[1] .80	.70	[2] 80	700
3	1.00	1.00	100	1000

[1] .30+.50

[2] 30+50

5. Block code products

	Products	
Code	Block 1	Block 2
1	[1] 12.0	160
2	25.0	150
3	12.0	180
	49.0	490

[1] (30) (.4)

6. Block product proportions

	Product proportions	
Code	Block 1	Block 2
1	[1] .245	.326
2	.510	.306
3	.245	.367

[1] 12.0/49.0

7. Block cumulative produce proportions

	Proportions	
Code	Block 1	Block 2
1	.245	.326
2	[1] .755	.632
3	1.000	.999

[1] .245+.510

8. Block cumulative products

Code	Products Block 1	Products Block 2
1	12.0	160
2	[1]37.0	310
3	49.0	490

[1] 12.0+25.0

9. Accumulated block code proportions

Code	Proportions
1	[1].391
2	.318
3	.291

[1] (30+400)/(100+1000)

10. Accumulated block code acreages

Code	Acreage
1	[1]430
2	350
3	320

[1] 30+400

11. Accumulated cumulative code proportions and acreages

Code	Proportion	Acreage
1	.391	430
2	[1].709	[2]780
3	1.000	1100

[1] .391+.318
[2] 430+350

12. Accumulated block code products

Code	Product
1	[1]172
2	175
3	192
	539

[1] (430) (.4)

13. Accumulated block product proportions

Code	Proportion
1	[1].319
2	.325
3	.356

[1] 172/539

14. Accumulated cumulative product proportions and products

Code	Proportions	Products
1	.319	172
2	[1].644	[2]347
3	1.000	539

[1] .319+.325
[2] 172+175

Input

```
   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
101010202020202020303                                                          2 1     1
101010102020202030303                                                          1 2     2
```

Output

```
JOB NUMBER     1 OF     1 JOBS

 JOB NUMBER     1 OF     1 JOBS
DERIVATION OF MAPPING PROGRAM TABLES. NUMERICAL EXAMPLES.  11/22/63
1 1 1 2 2 2 2 2 0 0 0 0 0 0 0                                                  2 1     1
                      BLOCK   1 CODE FREQUENCIES
 NO T BL IDENT
                              1         2         3         4         5         6
  1 2  1    1                3.        5.        2.        0.        0.        0.
 BLOCK   1 FREQUENCY TOTAL =                 10.
                      BLOCK   1 CODE PROPORTIONS
 NO T BL IDENT
                              1         2         3         4         5         6
  1 2  1    1          .3000000  .5000000  .2000000 0.0000000 0.0000000 0.0000000
                      BLOCK   1 CODE ACREAGES
 NO T BL IDENT
                              1         2         3         4         5         6
  1 2  1    1               30.       50.       20.        0.        0.        0.
 BLOCK   1 ACREAGE =                100.
 ONE CELL =      10.00000000 ACRES
             BLOCK   1 CUMULATIVE CODE PROPORTIONS AND ACREAGES
 PROPORTION    AREA PROPORTION    AREA  PROPORTION    AREA  PROPORTION     AREA
           1                   2                   3                   4
 .3000000      30.   .8000000      80. 1.0000000     100. 0.0000000        0.
                      BLOCK   1 CODE PRODUCTS
 NO T BL IDENT
                              1         2         3         4         5         6
  1 2  1    1               12.       25.       12.        0.        0.        0.
 BLOCK   1 PRODUCT =                 49.
                      BLOCK   1 PRODUCT PROPORTIONS
 NO T BL IDENT
                              1         2         3         4         5         6
  1 2  1    1          .2448979  .5102040  .2448979 0.0000000 0.0000000 0.0000000
             BLOCK   1 CUMULATIVE PRODUCT PROPORTIONS AND PRODUCTS
 PROPORTION PRODUCT PROPORTION PRODUCT  PROPORTION PRODUCT  PROPORTION PRODUCT
           1                   2                   3                   4
 .2448979     12.   .7551020       37.  .9999999       49. 0.0000000        0.
1 1 1 1 2 2 2 0 0 0 0 0 0 0                                                     1 2     2
                      BLOCK   2 CODE FREQUENCIES
 NO T BL IDENT
                              1         2         3         4         5         6
  1 1  2    2                4.        3.        3.        0.        0.        0.
 BLOCK   2 FREQUENCY TOTAL =                 10.
                      BLOCK   2 CODE PROPORTIONS
 NO T BL IDENT
                              1         2         3         4         5         6
```

Output (continued)

```
   1 1  2     2          .4000000  .3000000  .3000000 0.0000000 0.0000000 0.0000000
                         BLOCK  2 CODE ACREAGES
  NO T BL IDENT
                                1         2         3         4         5         6
   1 1  2     2             400.      300.      300.        0.        0.        0.
  BLOCK  2 ACREAGE =               1000.
  ONE CELL =    100.00000000 ACRES
            BLOCK  2 CUMULATIVE CODE PROPORTIONS AND ACREAGES
  PROPORTION   AREA PROPORTION    AREA  PROPORTION    AREA  PROPORTION    AREA
           1                 2                   3                   4
  .4000000       400.  .7000C00      700. 1.0000000      1000. 0.0000000        0.
                         BLOCK  2 CODE PRODUCTS
  NO T BL IDENT
                                1         2         3         4         5         6
   1 1  2     2             160.      150.      180.        0.        0.        0.
  BLOCK  2 PRODUCT =                490.
                         BLOCK  2 PRODUCT PROPORTIONS
  NO T BL IDENT
                                1         2         3         4         5         6
   1 1  2     2          .3265306  .3061224  .3673469 0.0000000 0.0000000 0.0000000
            BLOCK  2 CUMULATIVE PRODUCT PROPORTIONS AND PRODUCTS
  PROPORTION PRODUCT PROPORTION PRODUCT  PROPORTION PRODUCT  PROPORTION PRODUCT
           1                 2                   3                   4
  .3265306       160.  .6326530      310.  .9999999       490. 0.0000000        0.
                         ACCUMULATED CODE PROPORTIONS
  NO T BL IDENT
                                1         2         3         4         5         6
   1 1  2     2          .3909090  .3181818  .2909090 0.0000000 0.0000000 0.0000000
                         ACCUMULATED CODE ACREAGES
  NO T BL IDENT
                                1         2         3         4         5         6
   1 1  2     2             430.      350.      320.        0.        0.        0.
  ACCUMULATED ACREAGE =               1100.
            ACCUMULATED CUMULATIVE CODE PROPORTIONS AND ACREAGES
  PROPORTION   AREA PROPORTION    AREA  PROPORTION    AREA  PROPORTION    AREA
           1                 2                   3                   4
  .3909090       430.  .7090909      780.  .9999999      1100. 0.0000000        0.
                         ACCUMULATED CODE PRODUCTS
  NO T BL IDENT
                                1         2         3         4         5         6
   1 1  2     2             172.      175.      192.        0.        0.        0.
  ACCUMULATED PRODUCT =               539.
            ACCUMULATED BLOCK PRODUCT PROPORTIONS
  NO T BL IDENT
                                1         2         3         4         5         6
   1 1  2     2          .3191094  .3246753  .3562152 0.0000000 0.0000000 0.0000000
            ACCUMULATED CUMULATIVE PRODUCT PROPORTIONS AND PRODUCTS
  PROPORTION PRODUCT PROPORTION PRODUCT  PROPORTION PRODUCT  PROPORTION PRODUCT
           1                 2                   3                   4
  .3191094       172.  .6437847      347.  .9999999       539. 0.0000000        0.
 END OF JOB NUMBER     1 OF     1 JOBS
 CONTROL CARD COUNT =      2, COMPUTER CARD COUNT =      2
 IDENTIFICATION NUMBER OF LAST(NO.    2) CARD PROCESSED IS      2

  END OF JOB NUMBER     1 OF     1 JOBS
  CONTROL CARD COUNT =      2, COMPUTER CARD COUNT =      2
  IDENTIFICATION NUMBER OF LAST(NO.    2) CARD PROCESSED IS      2
```

Control card preparation. --The instructions below for preparing mapping program control cards are for the IBM 1620 and IBM 7090 computers except as noted.

(a) Control card number and format

Control Card Format				
Type	Number of cards	Field	Columns	Description
A	1	I5	1-5	Header card - number of separate jobs
B	1		2-80	Title
C 1.	1	I5	1-5	Job number
2.		I5	6-10	Number of data cards
3.		I5	11-15	Largest code number used
4.		I5	16-20	Number of code numbers removed
5.		I5	21-25	Number of blocks
6.		I5	26-30	Number of rates per acre
7.		I2	31, 32	Select type of output
D	1-3	36 I2	1-72	Codes removed from card output
E 1.	1-99	I2	1, 2	Basis for computing block area
2.		F10.0	3-12	Block area as given by user
3.		F10.0	13-22	Map reciprocal of representative fraction
4.		F6.2	23-28	Map length in inches
5.		F6.2	29-34	Map width in inches
F	1-13	8E10.0	1-80	Rate per acre for each code

(b) Details for preparing and using each type of control card

1. Type A. A single card, used only once, showing the number of separate jobs.

2. Types B to F. These precede the data cards of each separate job.

3. Type B. Title. One card containing any legal characters. Leave Column 1 blank. If a title is not wanted use a blank card.

4. Type C. Note: Each of the six items below must at least equal one regardless of options selected.

(1) Job number: The number of the last job must equal the number of jobs shown by the Type A control card.

(2) Number of data cards: The number of map cards.

(3) Largest code number used: The largest code number occurring in the map cards. If unknown, put 99.

(4) Number of code numbers removed: The number of codes (1-99) to be removed (changed to zero) from map card output.

(5) Number of blocks: A number between 1 and 20 (IBM 1620) or between 1 and 99 (IBM 7090).

(6) Number of rates per acre: A number equaling the largest code number to which a rate per acre is applied. For example, if one rate per acre is to be multiplied by code 88 acreage, put 88, not 1.

(7) Select type of output.

a. Zero (blank) - Card output, i. e., map overlay cards only.

b. One - printed table output only

c. Two - both printed tables and card output

Note: There is no option as to which printed tables are produced.

5. Type D. Codes removed from card output. Codes may be in any order, i. e., 01, 99, 14, etc. If no codes are to be removed, insert one blank card.

6. Type E. Basis for computing block area. There are four ways to compute block area. For each block there is one card indicating which method is used, and the necessary information for that particular way. If no area is desired, insert a blank card for each block.

(1) Basis for computing block area

a. One - Block area given by user.

b. Two - Block area computed from map "scale" (reciprocal of representative fraction), length and width.

c. Three - Block area is computed from map "scale," given that every grid cell is coded.

d. Four - As above, given that every other (horizontally) grid cell is coded.

(2) Block area given by user. The area in acres, being already known, is supplied by the user.

(3) Map reciprocal of representative fraction. A number necessary under options 2, 3, or 4. If, for example, the map "scale" is 1/62, 500, put 62500.

(4) Map length in inches. Needed for the second option only. Measurement is to nearest hundredth inch, e. g., exactly 10 inches would be 10. 00 inches.

(5) Map width in inches. As above.

7. Type F. Rate per acre for each code. Rates must be sequentially ordered in 1 - 99 successive fields corresponding to the code numbers used. Some rates may be zero. For example, assume that only codes 8 and 33 are to be multiplied by rates "A" and "B". The first card would be blank in the first 7 fields (70 columns) with rate "A" punched in the last, eighth field (Cols. 71-80). The following three cards, representing codes 9 - 16, 17 - 24, and 25 - 32, respectively, would be blank. The first field (Cols. 1 - 10) of the fourth (and last) would be punched with rate "B."

If the rate per acre option is not used, insert one blank card.

Processing cost. --IBM 1620 and 7090 computer processing times are not precisely comparable. For the IBM 1620 used, which had a 60K memory and automatic floating point hardware, data processing includes card input and output. For the larger computer used, the IBM 7090 at the Computer Center, University of California, Berkeley, off-line input and output time is not included in total processing time.

Time estimates are presented for specific operations on the IBM 1620. For the faster IBM 7090, much grosser time estimates suffice.

Mapping program processing time estimates:

IBM 1620:

1. Load squeezed object deck	2 min.
2. Type control cards	2-7 min.
3. Process map cards	
a. With overlay cards punched	18-25 min.
b. Without overlay cards (tables only)	30-40 min.
4. Compute each table	1/2 min.

IBM 7090:

Fortran II - Process map cards with overlay and table output	1-1/2 min/M cards
Fortran IV - as above	3/4 min/M cards

Combinations Program

Code changing and combining method. --Code changing applies to one code system. Code combining refers to 2, 3, or 4 code systems processed in a single computer run.

Assume a code system contains 3 codes: 1, 7, and 9. The user wants, say, to sequence his code system and simultaneously remove a code from an overlay. He writes 1, 7, and 9 in the first three fields of a control card. In the corresponding three fields of another control card he writes 1, b (nothing), and 2. The computer will leave code 1 alone, change 7 to zero and 9 to 2.

Combining codes is somewhat more complex. Suppose the user wants one combination, 0308 (03 in the first and 08 in the second code system) to become 04 in the new system. He writes 03 in the fourth field of one control card and 08 in the fourth field of a second control card. Now, however, he must decide what code number all excluded (unwanted) combinations will have. If he assigns zero, excluded combinations will be set equal to zero and subsequent processing of the new code system by the mapping program will ignore zeroes. If he chooses a nonzero code for excluded combinations, they will be counted subsequently. Therefore, his choice of zero or a positive integer affects the acreage base used on subsequent mapping program calculations.

Detailed instructions follow for handling both included and excluded combinations from two to four code systems simultaneously. The instructions apply to both computers.

Control card preparation. --

(a) Control card number and format

Control Card Format				
Type	Number of cards	Field	Columns	Description
A	1	I5	1-5	Header card - number of separate jobs
B	1	--	2-80	Title
C 1.	1	I5	1-5	Job number
2.		I5	6-10	Number of data cards
3.		I2	11, 12	Number of code systems
4.		I2	13, 14	Number of codes to be changed or combined
D 1.	1-3	40 I2	1-80	Map codes to be changed
2.	1-3	40 I2	1-80	Map codes after they are changed
E 1.	1	I2	1, 2	Code number of an excluded combination
2.	1-5	20F4.0	1-80	Combinations selected from 2 code systems
3.	1-8	13F6.0, 2X	1-80	Combinations selected from 3 code systems
4.	1-10	10F8.0	1-80	Combinations selected from 4 code systems

(b) Details for preparing and using each type of control card.

1. Type A: a single card, used only once, showing the number of separate jobs.
2. Type B to E: these precede the data cards of each separate job.
3. Type B: one card containing any legal characters. Leave Column 1 blank. If a title is not wanted, insert a blank card.
4. Type C:
   (1) Job number: the number of the last job must equal the number of jobs shown by the Type A control card.
   (2) Number of data cards: for one code system, this is the number of map data cards. When combining codes, state only the number of data cards in one system, not the total number for all systems.
   (3) Number of code systems: a number between 1 and 4, inclusive.
   (4) Number of codes to be changed or combined: a number between 1 and 99, inclusive.
5. Type D: used only when changing codes within one system.
   (1) Map codes to be changed, and
   (2) Map codes after they are changed.

   Special instructions:

   a. A code whose numeric value is not changed, but which is wanted in the output, must be changed to itself (e.g., 98 to 98) or it will be changed to zero.

b. As a result of "a.," above, a nonzero code can be changed to zero by omission. The converse is not true; a zero value cannot be changed to a nonzero code.

c. A code to be changed, say in the fifth position of (1) above, will be changed to the value in the fifth position of (2) above; that is, code values before and after changing must have corresponding array positions.

6. Type E: used only when combining codes from 2 to 4 code systems.

Number of systems combined	Control card type used
2	E. 1.
	E. 2.
3	E. 1.
	E. 3.
4	E. 1.
	E. 4.

(1) Code number of an excluded combination. As indicated above, this card is required when combining 2, 3, or 4 code systems. Previous control cards have shown which code combinations are wanted; this card tells what to do with an unwanted (excluded) combination. An excluded combination may be changed to zero or a number between 1 and 99, inclusive. A zero value will not be counted later by the mapping program, a positive value will be tabulated. If a nonzero value is selected, say 7, then the corresponding position (seventh) in types E. 2., E. 3., or E. 4. must be blank. The blank prevents ambiguity; it avoids two combinations (1 included and all excluded) being assigned the same code number--7 in this case.

(2) Combinations selected from 2 code systems. Selected (included) combinations of 2 code numbers. As explained above, one position may be blank. The position (index) of an included combination is its output code number. For example, the first two fields might be the desired combinations: 99998972. The combination 9999 would be punched 01 and 8972 punched 02.

(3) As for (2), but for 3 code systems.

(4) As for (2), but for 4 code systems.

(c) Data input arrangement

1. Map card format
The format is exactly the same as for the mapping program and was described earlier.

2. Map card input
(1) One code system. The data cards are simply placed behind the control cards, in any order.
(2) Two to four code systems. Each card in a system must have an identification number identical to, and in the same position as, the corresponding card in the other system(s). The map cards can be match-merged and

placed behind the control cards if the identification numbers within each system are in ascending order. If the sequence of identification numbers vary within a system, compare the numbers on a reproducer and then merge the cards.

In merging two or more code systems, one must decide the system sequence. The sequence is determined once the selected combinations control cards (E2, 3, or 4) are made. For example, in combining two systems, the first desired combination might be 02 from system 1 and 33 from system 2. The first field of control card E. 2. would be punched 0233. When merging the two decks of cards, the first card must be from system 1, the second from system 2, and not vice-versa.

Processing cost. --IBM 1620 and 7090 computer processing times are not precisely comparable for the reasons mentioned earlier.

IBM 1620:

1. Load squeezed object deck	1 1/2 min.
2. Type control cards	2-7 min.
3. Process map cards	
a. Changing map codes	
(1) Blank cards	26/min.
(2) Full cards	23/min.
b. Combining two code systems	
(1) Blank cards	9/min.
(2) Full cards	1/min.

IBM 1620:

Fortran II - Combinations from 2 code systems	2 1/3 min. /M cards
Fortran IV - As above	1 1/4 min. /M cards

Additional Information Available

Those interested in using the system may obtain the following forms and additional information by writing to the Director, Pacific Southwest Forest and Range Experiment Station, P. O. Box 245, Berkeley, California 94701:

1. Data collection forms used
2. Reproducing punch control panel wiring diagram
3. Sample grid paper
4. Computer program listings (specify which of the below lists are needed):
   a. Mapping program
      (1) Fortran II, IBM 1620
      (2) Fortran II or IV, IBM 7090[8]

   b. Code changing and combining program
      (1) Fortran II, IBM 1620
      (2) Fortran II or IV, IBM 7090[8]

[8] Source deck can be compiled for either Fortran II or IV program.

GPO 969-749

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Interception Processes During Snowstorms

David H. Miller

U. S. FOREST SERVICE RESEARCH PAPER PSW-18

Pacific Southwest
Forest and Range Experiment Station
Berkeley, California

1964

Forest Service - U. S. Department of Agriculture

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 interception of snowfall by vegetation—the first step in a complex chain of events that affect the accumulation and melting of snow.

This paper is the first of several reporting the 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

Acknowledgments

I wish to acknowledge the help of Professor S. Ogihara with interpretation of the study by the Meguro Forest Experiment Station, and of Clark E. Holscher, Kenneth R. Knoerr, Arnold Court, Henry W. Anderson, Nellie Beetham Stark, A. J. West, Lloyd Gay, B. C. Goodell, Marvin D. Hoover, and others who took the time to review and criticize earlier stages of this study.

The Author

DAVID H. MILLER has been studying problems in snow hydrology and meteorology for more than 20 years—in operational work of the U. S. Army Corps of Engineers (1941-1943), and in research with the Engineers' snow studies (1946-1953) and with the U. S. Forest Service (1959-1964). 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.

The vegetation of a drainage basin alters the way in which precipitation is delivered to the receiving surfaces of the basin's soil mantle. Plants that intercept precipitation change the amount, timing, and areal distribution of the water input to the basin as a hydrologic system; yet interception has been studied mostly as a by-product after all the effects of vegetation upon runoff or soil moisture are lumped. The Kerr Report (U. S. Senate 1960) speaks of the need to establish "the importance of interception in the water balance," and Hoover (1962) poses several questions about interception of snowfall in particular, which, despite its great importance to land management, cannot be answered from present knowledge. A search for answers to these questions can be considered a logical starting point for an examination of the role of forest vegetation in the hydrologic systems of snow-covered drainage basins, looking upon interception as the series of events that precede those other geophysical processes affecting the winter snow mantle on the ground and its dissolution in spring.

Such an examination of available evidence on snowfall interception suggests that the term encompasses a group of some 15 to 20 physical processes that can be distinguished and separated in field measurements and laboratory experiments. Four of these processes are discussed in this paper: delivery of snow to a forested slope, throughfall of particles to the forest floor, impaction and adhesion of particles to foliage and branches, and cohesion of particles into snow loads. Processes that have to do with disposition of the intercepted snow will be described in later papers.

Delivery

Many studies of the effects of exposure on the accuracy of precipitation measurement emphasize the disruption of the air flow by the gages and by obstacles near them, but the effect of roughness of the upper surface of forest canopy on falling particles has seldom been studied. There is little knowledge of the delivery of snow to the canopy surface, though it is plain that it must vary greatly from place to place, and add to the problems of sampling the snow that penetrates to the forest floor or adheres to the canopy.

Kuz'min (1963) discusses velocities of snow particles falling in the open and summarizes some observations on speeds and angles obtained from photographic observations. The average angle from the horizontal is 4 degrees, confirming the visual impression one receives of the nearly horizontal movement of snowflakes. He also discusses a motion analogous to Brownian motion of molecules, when snowflakes fall in calm air, which also enters the problem of delivery of snow to forest.

Delivery of snowflakes from the airstream to forest has been measured a few times by precipitation cans at crown level (Davis 1939, for example), but results have not been analyzed with regard to turbulent motion of the air or roughness of the forest surface. The siting of precipitation gages is difficult, and sampling snowfall at crown level may require many gages. Where snow falls in wet storms of low wind speed, annual catch at crown level approximates that in cans in small openings (Rowe and Hendrix 1951), but the relation in single snowstorms, especially if the snow is dry and winds are high, is not known. As is well known, some doubt attaches to the interpretation of measurements in forest openings, again for reasons of complex turbulent motion.

The speed of falling snowflakes, less than a meter per second and an eighth or tenth that of rain drops, produces a basic difference in impingement on vegetation. The low speed causes the flakes in a moving air stream to approach the ground or trees at low angle, and hence to hit the sides of tree crowns nearly directly, as Harrington (1893) notes. When trees are in a forest, the low angle of approach of snowflakes has the effect of increasing the surface of an incompletely closed forest canopy.

Horton (1919) points out that the number and sizes of openings in such a forest are reduced, so that to the approaching snowflake the forest is a continuous, though irregular, surface. Delfs (1955) also discusses increased storage of snow by forest from this cause. The effect is like the absorption of low-angle solar radiation by a forest that, viewed in a vertical aerial photograph, has low density. Perhaps for this reason, crown coverage if regarded only as a two-dimensional plane, has turned out to be a poor predictor of snowfall interception when measurements in many stands of forest are compared.

Analyses of data published by Kittredge (1953) suggest to me that selective logging influences interception less by changing crown cover than by removing dominant trees that project above the canopy—and perhaps by making forest edges more porous. Both conditions act directly upon snow delivered at low angles.

When snowflakes enter the zone of lower wind speed just above the crowns, their angle of approach becomes more vertical, but their paths also come under the influence of eddies produced by the rough upper crown surface and by openings. These eddies bring snowflakes into contact with the foliage, so that at no time, except in dead calm, is throughfall governed merely by the openings in a two-dimensional plane seen by a man below it looking at the sky. While crown closure is often the only reported variable describing forest, and has to be used in lieu of quantitative data on foliage area, branch-wood volume, and structure, it is not an accurate predictor of throughfall.

The boundary airstream through which precipitation particles pass before reaching the ground is always in turbulent motion, of particular severity when it flows over rough surface. Increased turbulence brings more precipitation particles down into the crowns, a process that has been studied for fog droplets (Hori 1953). Costin, Gay, Wimbush, and Kerr (1961) refer to the effect of the turbulence produced by the tree canopy and by small openings upon snow deposition, and its decrease as the size of openings grows larger. Turbulent eddies induced by topography also affect the delivery of snowflakes and may account for the extreme snow loads sometimes reported on trees of lee slopes.

Deposition of Snow from the Air Stream

Deposition of snow out of a flow of snow and air impinging on the porous layer of the forest canopy can probably be determined from formulas established by such students of snow drifting as Dyunin (1961, 1963) and Komarov (1963). Komarov, for example, concludes that deposition "depends on the difference between at least the cube of the initial and final velocities" so that a small decrease in wind speed results in large deposition of snow. Wind measurements in the air stream above and at the crown level would make possible the application of these relationships, which should be particularly useful in mosaic landscapes of tree groups and interspersed openings.

Some idea of deposition of snow from an air stream can be gained by studying Japanese measurements of snow load on models and on a tree (Japan 1952). The snow load on models was measured with reference to that received on a flat, elevated board, and I have computed loads at zero and 1 meter per second wind speed for comparison. Compared to the deposit of snow at zero wind, that at 1 m/sec. is as follows:

1. On flat, exposed board (Japan 1952, p. 126) — (Load 650 g. at zero wind, 420 g. at 1 m/sec.)
   35 percent decrease;
2. In stack of shelves of same size, 15 cm. apart (equation 8, p. 124) —
   (excluding top shelf) 140 percent increase;
3. In pyramidal stack of shelves, 15 cm. apart (equation 14, p. 131) —
   55 percent increase;
4. On solid pyramid (equation 9, p. 127) —
   40 percent decrease;
5. On crown of cryptomeria tree (fig. 8, p. 145) —
   maximum deposits (from enveloping line)
   30 percent decrease;
   mean deposits (from mean line)
   25 percent decrease.

The decrease of snow on the tree at a wind speed of 1 m/sec. is like that on the solid pyramid, where all snow accumulates on the outer surface. The snow load on a solid hexagonal pyramid of base 585 sq. cm. and height 25 cm., in percent of accumulation on the flat board, was equal to 91 − 36v, in which v is wind speed in m/sec.; on a steeper pyramid the wind coefficient is about the same. Stacks of boards separated by various spaces and supported above the ground to simulate a tree crown displayed an increase in relative accumulation as wind speed increased to 1.2 m/sec.; moderate air movement transports snow into the interior of the stacks. The increase is largest on boards separated the most. Hexagonal pyramids showed similar results, the wind coefficient being modified by vertical spacing of shelves. Snow loads in these experiments ranged to about 15 mm. mass on a flat exposed board and 25 mm. in the vertical stack, on the basis of its horizontal projected area.

When the snow load on a cryptomeria tree, as a percentage of snowfall reaching the ground, is plotted against wind speed in the range 0.5 to 2.5 m/sec. (Japan 1952; fig. 8, p. 145), a line that envelopes 34 of the 37 storms indicates that at wind speeds above 2 m/sec. interception is usually, but not always, small. At speeds around 1 m/sec., it varies from 40 to 130 percent of snowfall. Photographs of the tree under loads of 10 and 40 kg. show how snow loads force the crown into a pyramidal shape. More rigid branches would open access to the interior of the crown, and an increase in wind, up to some critical value, would deposit more snow, as it does in the stack of shelves. I estimate from published graphs (Japan 1952; pp. 142, 143) that storage of snow at temperatures higher than -3°C. may have reached 15 mm. water equivalent.

That transport of snow into the interior of crowns and extension inward of the wetted or supporting surface may have increased storage in Kittredge's (1953) study is suggested by Court's (1957) finding that near Donner Summit in the Sierra Nevada in California less than 2 percent of the precipitation in three winter months (which totaled 33 inches) occurred during calm. On the other hand, extremely high winds are not common during snowfall in many forested areas. Deposition on trees in high winds becomes a function of adhesion, greatest not in snow but in supercooled rain. Many studies discuss the formation of rime, which represents a situation in which the forest augments the amount of atmospheric water received by the earth's surface, but their results have little direct value for determining delivery of snow to a forested slope.

Klintsov (1958) describes gales of wet snow in Sakhalin, in which heavy snow accumulated on the windward and upper halves of crowns of conifers about 7 m. tall, to nearly 100 kg. Near the freezing point, snow may be mixed with undercooled droplets of liquid water and form rime on solid objects. Heikinheimo (1920) describes storms of northern Finland in which rime and snow are plastered on trees by strong winds. Although the admixture of liquid droplets is not large, since he reports that density of the deposit averages 0.15 and seldom exceeds 0.3, it helps the snow adhere to the trees in layers 30 cm. thick. This admixture is common enough to have a Finnish word—*tykky*. At high wind speed, the angle of approach of the snow is nearly horizontal, and the deposits have a sharp lower limit, about 300 meters above sea level, that is visible on mountain sides from great distances. This limit is also noted by Hustich (1940), who measured accretion on sticks of 7 cm. diameter; those mounted on birch trees at elevations of 360 meters and 470 meters (treeline) accumulated six to seven times as much snow and rime as those at 300 meters. Deposits on bare poles were as thick as 13 cm.

Grunow (1955) points out that water in the solid state intercepted from a horizontal airstream makes up 15 percent of the total received by the forest floor in the interior of the stand, and 45 percent at the edge; corresponding figures for liquid horizontal precipitation are 20 and 57 percent. Although less snow is screened out of the air or deposited by turbulence on vegetation than liquid water, the amounts are significant and indicate the role of high wind speeds; in Salamin's (1959) words, "trees 'sift' snow out of the moving air." The relative heights of the level of condensation and the level of freezing often are such that in cloudy weather the zone of heavy fog drip is near ridges. However, in snow storms, the snow is often dry near the crests and wet at lower elevations (Baumgartner 1957), where the wind is weaker and horizontal interception is minor (Baumgartner 1958).

Ratzel (1889) reports excess interception of snow by trees on edges of forest or valley, or on exposed slopes, to the point of frequent snow break. Eidmann (1954) shows that spruce intercepts more on slopes, perhaps because crowns are more densely closed. Costin and Wimbush (1961) weighed the deposits of rime and ice formed on eucalyptus foliage in sub-freezing weather, finding rates greater than 25 mm. per day, considerably greater than in warmer air, when little condensation of vapor occurs to add to the intercepted load of raindrops.

Research Approaches

Understanding delivery of precipitation requires looking at the forest cover from above, as a mantle on the earth's surface. This comes more naturally to biologists used to microscopes than to the man on the ground. Harrington (1893) takes this point of view, and Horton (1919) visualizes the scene as a snowflake descending toward the forest top. Micrometeorologists also generally have this point of view toward a grass cover underlying a turbulent air stream.

As micrometeorological research produces expressions of turbulent exchange, shear stress or drag, level of displacement, and other boundary-layer concepts, these expressions should be immediately seized on to elucidate the complex deposition of snow particles from a turbulent air stream onto and into a rough porous layer over which the stream flows, into which it penetrates, and which it deforms.

Micrometeorological work over forest cover faces a problem of reproducibility. The upper surface of the crown canopy, even in a simple forest type of unbroken closure, has not been described adequately. Without means of quantifying the boundary surface, students of turbulence will be reluctant to choose trial-and-error field measurement over more concrete problems confronting them elsewhere. Mosaic forests of tree groups and interspersed openings present an experimental situation of greater complexity, which perhaps can be studied by profile measurements of wind speed and fluctuation, not to 10 meters above the canopy, but to the next larger order of magnitude, through a boundary layer some hundreds of meters deep. Studies of storms on a synoptic scale are also needed, to determine eddy turbulence in the deposition of snowflakes.

The vibration of trees in wind, and their changes of shape and relative position as gusts pass over, are perhaps too complex to formulate other than as a recurrent quasi-elastic perturbation in roughness of the boundary and a recurrent fluctuation in drag. The coupling of perturbations in wind flow and boundary roughness that might come into phase with each other where wind fetch is long enough is a problem to which current work on the interaction between wind and waves can perhaps be applied.

Penetration of moving air into crowns may be measurable by micrometeorological instruments. It is indirectly made visible in terms of transport of snowflakes into crown interiors, and this should be measurable, as these paths are now studied photographically in the open (Kuz'min 1963). Determination of the wind speed at which transport and deposition is largest has begun with models, and should continue on trees with rigid branches in wind tunnels. Work can then be extended to trees that deform or close up under wind stress.

Wind-tunnel studies must simulate snowflakes of proper size, density, roughness, shape, falling speed, and wetness. It is doubtful that ice shavings fill this need. Materials lighter than ice have been used in some reduced-scale studies (Gerdel and Strom 1960) and may be useful in studies of forest action. Eventually, full-scale wind-tunnel studies should be done, at first with tree branches, and then including such phenomena as bending and deforming of trees. Deposition of snow in calm air onto branches and trees of various shapes would be studied first, then deposition from a moving air stream. The concentration of snowflakes in the air stream can probably be sampled by the drift meters used in Antarctic studies. Hydraulic model experiments on bed load and suspended load in streams may furnish parallels to the delivery of snow to a forest; their analogies to snow drifting have been noted by Kuz'min (1963) and others.

Many studies in controlled environments may be needed before going to field installations, except perhaps that driftmeter measurements could start in a few places.

Our estimates of the amount of snow delivered to the upper surface of a forest—whether based on measurements in cans in small glades or in large open areas, or in sites subjectively appearing sheltered but not too much so---must be recognized as no more than estimates that we have no way to check. Traditional means of measuring precipitation in the canopy zone have unknown accuracy, and exploration might begin by positioning precipitation cans, drift meters, and anemometers in the humps and hollows of a forest top, to help identify sampling problems.

The old question, whether precipitation is greater on forest than on open land, was in doubt when Harrington in 1893 suggested it was necessary to measure precipitation over a forest. By 1913 Pearson indicated that the question was dead. It was not to revive until the 1950's. While active in the latter 1800's, it occasioned great interest in forest problems generally, and indirectly benefited interception research. If the question again becomes scientifically attractive, it may bring interest in determining rate of delivery of snow to forest.

'True' Throughfall

Defining as "true" throughfall the snow that penetrates forest canopy without alighting for any length of time on branches or foliage, as mentioned by Colman (1953), we find a problem analogous to that of solar radiation penetrating directly to the forest floor. However, sunflecks can usually be measured separately, while directly penetrating snowflakes are not easily distinguished from those falling from snow masses on branches, except in dead calm. Laboratory and wind-tunnel experiments should give the amount of true throughfall and its relation to snow delivered to the forest top. At times when no snow is blowing through the trunk space or falling from overloaded branches, true throughfall can be measured accurately. If foliage is very open, some precipitation particles are bound to fall through, no matter how light the intensity (Costin and Wimbush 1961; Ney 1894). If stands are dense, such as those described by Fenton (1959), with a "nearly impermeable" meshwork of branches, true throughfall in a wet snowstorm is very small.

In laboratory and field, short-exposure photographs may prove useful in determining the density of snow per unit volume of air above and beneath the canopy. Some method of measuring attenuation of radiation over a fixed course, as is used in determining concentrations of vapor or carbon dioxide, might also be employeed. Another approach is indicated by studies on oil sprays released above forest (Maksymiuk 1963), in which the true throughfall of particulates is measured by oil-sensitive cards on the ground.

Impaction and Adhesion of Snow on Foliage

Recent aerodynamic research on impaction of airborne particulates on solid objects of different sizes has relevance to collection of snowflakes by foliage and branches of forest,[1] but the necessary bridging work has not yet been done. Present discussion of this process can only be empirical, by summarizing what is known of the effects of characteristics of (a) the impacted particles—the snowflakes, as related to temperature-dependent wetness; (b) the relative motion of particles and obstacles—wind speed through the forest crowns; and (c) the obstacles.

Temperature Effects

Adhesion of snow to foliage presumably increases as temperature rises toward the freezing point. The Japanese study reports snow loads to be small at low temperatures, moderate to large at temperatures just below freezing; the trend can be expressed as an increase in interception of approximately 30 percent of snowfall for each Celsius degree of warming. Much of this increase can be ascribed to increased adhesion, which has been shown in laboratory studies (Kuriowa 1962) and field experiments (Minsk 1961) to be temperature-dependent, perhaps because of the role of a thin liquid-water film.

In frontal weather, snow falling through quiet air near the earth's surface approaches the ground vertically; references to wet snow "clinging" to trees are common (Chittenden 1909; Delfs 1958; Kittredge 1948; Tikhomirov 1934). Baldwin's (1957) comment that high-density snow is more intercepted than low-density presumably refers to wet snow. Rosenfeld (1944) speaks of wet snow overbalancing the crowns so that trees lean, and intercept more snow until they break; trees on sheltered lee slopes intercept the most snow, and are most subject to damage; he says that in the catastrophic break of 1888 in Silesia, when wind was from the northwest, trees on north and west slopes sustained a third of the damage, while trees on south and east slopes, in wind shadow or calm, sustained two-thirds. Hirata and Hotta (1951) describe heavy damage on steep lee slopes and on the concave slopes between spurs.

[1]Personal correspondence with G. M. Corcos, University of California, 1961.

Wind Effects

Wind-transported particles impact upon obstacles because they come out of the air stream where its acceleration is largest, which occurs at sharp changes in direction. Minsk (1961) reports that winds of 8 to 10 knots increased the frequency of adhesion of snow to mesh panels, though the amount of snow accumulating was less than at lower speeds.

Dry snow in strong winds is generally intercepted less than wet snow. (We are not discussing drifting snow here.) Five storms in which a cryptomeria tree (Japan 1952) intercepted snow amounting to less than 20 percent of that on the ground were cold—temperature lower than -3°C.—and presumably the snow was dry; wind speed was moderate in two storms and low in three. Wellington (1950), discussing snow interception in a cold region (Sault Ste. Marie, Ontario), says that the small retention of dry snow in deciduous trees is caused by greater vibration rather than lack of impaction. Rusanov (1938) notes that snow storms have stronger winds in the deserts of central Asia than in the bordering semi-arid regions, and intercepted snow does not build up on desert plants enough to break them.

Jaenicke and Foerster (1915) compared snowstorm deposits on a large open "park" in Arizona with those in an adjacent area of intermingled tree groups and small openings where wind speed during storms was less than half that in the park. The reported net difference in snow reaching the ground in four winters was small and variable. Their description of snow being deposited like silt settling out of a stream of water suggests horizontal transport of snow, such that catching of falling snow by crowns of tree groups would not necessarily be evident on the ground immediately beneath. From their figures of wind speed in storms of two winters, I could detect no relation to differences in the deposit in park and forest.

Wind that transports snow into the interior of tree crowns influences the shape in which it accumulates there. Salamin (1959) says that in fir the snow lies loosely, but in pine crowns it forms cushions or balls, a difference that may reflect relative penetration of the crowns by snow-bearing and snow-packing winds. His photographs suggest that snow masses may be classified by shape. Micro-structure of the wind field within forest canopy presumably differs from species to species.

The difference in storage of snow and rain is much commented on, but seldom measured. The equations of Rowe and Hendrix (1951) for interception in snowstorms and rainstorms of comparable size indicate greater storage of rain (3 mm.) than of snow (2 mm.). But while the authors say that the smaller value for snow indicates that less water is "retained in wetting the vegetation than when precipitation occurred as rain," they also state that differences between the equations are not of significance. (Their measurements include few if any storms of cold, dry snow, so that "wetting" means adherence of snow.) Costin and Wimbush (1961) report much greater interception at temperatures below freezing—one to two liters water equivalent per pound of foliage an hour, rather than a quarter of a liter. An approximate value of crown wetting coefficient was determined in *Pinus silvestris* as 1 millimeter for rain; 0.7 millimeter for snow (Krečmer and Fojt 1960).

Okhliabinin (1911) reports 22 percent interception on rainy days in the cold season of the year, 16 percent on snowy days. Differences in interception of rain and snow, however, depend on adhesion of water or snow to foliage. Without better information on surface roughness, it is hard to make a decision between the two conflicting ideas, or even to formulate a hypothesis that would account for the observations.

Vegetation warmer than freezing melts the first snow to touch it, but if cold snow continues to fall the meltwater refreezes into a firm bond, according to Heikinheimo (1920). The opposite situation—when trees are cold and snow warm and wet, perhaps more common—leads to adhesion of great quantities of snow; Tikhomirov (1934) regards weather favoring this sequence of events as the most important factor in formation of heavy deposits of crown snow. Sometimes snow falling after glaze adds to tree loading (Bennett 1959, p. 154).

Characteristics of the Obstacles

Roughness of surfaces of leaves, twigs, branches, and tree trunks affects adhesion of snow; for example, Salamin (1959) points out that snow forms in bands on deciduous trees if bark is smooth, in heaps if it is rough. Horton (1919) refers to roughness as a factor in the wetting caused by rain and hence in interception storage; and it would play a similar role in wetting by meltwater. In discussing stemflow, Delfs (1955) notes that the wetting value is less on smooth surfaces.

Flexibility of foliage determines its value for support of adhering snow. Time-lapse photography shows that white pine needles accumulate snow only at the base of the fascicles before the needles are bent into a platform (Lull and Rushmore 1961). Balsam fir, with many stiff branchlets and with needles persisting along the branches, was the best collector of snow; hemlock, of the four species studied, was the poorest since its needles are "feathery and flexible." Maule (1934) comments on the difference between stiff needles of Norway spruce,which intercepted the most snow, and the long, soft needles of red and white pine, which intercepted the least. The brushlike arrangement of needles on a variety of spruce is important in holding snow (Delfs 1955). Alpine-ash eucalyptus *(Eucalyptus delegatensis)* intercepts little snow because foliage is open and twigs flexible (Gay 1958), whereas snowgum eucalyptus *(E. pauciflora)* has heavy leaves and stiff twigs and petioles which mat down, as snow piles on them, into a platform that can bear a heavy load. This load has been estimated as great as 100 cu. ft. of snow per tree, or 25 mm. of water on an areal basis (Costin, *et al.* 1961).

Surface area or volume of foliage plays a role in interception but its exact importance in not well defined. Insect-killed lodgepole pine and Engelmann spruce that had lost needles and finer branches intercepted less snow than live trees (Love 1955), but remaining branches still intercepted some snowfall.

Kittredge (1948) reports leaf area of pines at 5,000 ft. elevation in the same part of the Sierra Nevada as his snow research; 28-year-old ponderosa pines had 4.2 sq. cm. of leaf surface (both sides) for each sq. cm. of crown projectional area. If the leaf-surface ratio of the stand is estimated as 3, and interception storage of snow over the stand as 1 mm. (or 0.1 cu. cm./sq.cm. of ground surface), then 0.1 cu. cm. of water is held on 3 sq. cm. of leaf surface, of which half would be upper surfaces; the water equivalent on the average upper surface of needles is 0.6 mm. Strong adhesion of rime particles intercepted at an air temperature below freezing results in a loading of approximately 2 mm., as calculated from data of Costin and Wimbush (1961). For comparison with liquid-water films, it may be noted that Grah and Wilson (1944), in a sprinkling experiment on a small Monterey pine, found approximately 0.1 mm. of liquid water remaining, after shaking, per unit area of upper surfaces of needles.

Foliage weight, from Kittredge (1948), may be taken as of the order of 0.1 g/sq. cm. of ground surface. Weight of a 2 mm. snow load is 0.2 g/sq. cm., but some of it is borne by the branches directly. A load ratio of 2:1 is much smaller than ratios reported in severe ice storms, which have reached 10:1 or 20:1 (Bennett 1959), but mainly on the bare branches of deciduous trees. It is comparable to the ratio of 3:1 from the data by Costin and Wimbush (1961) on rime interception.

Winter bareness of hardwoods may deceptively lead one to the assumption that they intercept no snow, when this is not true. Wellington (1950) says that they hold less only because they vibrate more in the wind than conifers, not because surface area is less. He points out that deciduous trees that are overtopped and out of the wind hold on branches and forks snow as deep as the snow on conifers (20 cm.). The role of foliage is difficult to separate from that of branches, but the difference may not be as important as it seems. Wood (1937) feels that rainfall was about equally intercepted summer and winter in an oak-pine forest, and that loss of oak foliage in winter made little difference. Bühler (1884, 1886, 1892) reports appreciable interception by beech and larch; Burger(1933) by beech. On the other hand, zero or negative interception by hardwoods sheltered from wind, in comparison to snowfall in open fields, is reported by many investigators (Eitingen 1938; Garstka 1944; Kienholz 1940; Maule 1934; Ratzel 1889).

Snowfall while leaves remain on a hardwood stand, while rare, throws additional light on the effect of foliage volume on interception. Roth (1941) reports that an early snowfall at Fernow Experimental Forest in 1935 damaged 27 percent of a stand of poplars by breakage that led to stem decay. *Climatological Data* does not show a large snowstorm at any station near this West Virginia forest; I conclude that this storm probably did not bring more than 6 or 8 inches of snow, or more than an inch water equivalent. The heavy damage which Roth (1941) ascribes to the fact that leaves were still on the poplars presumably represents heavy interception. Australian investigators could help clarify this effect by more measurements of interception by eucalyptus.

Differences between beech and spruce interception are reported in most of the Central European studies of forest weather since Fankhauser (1882), but it is not always clear how much of the change measured in throughfall between summer and winter is caused by change in foliage and how much by the change in phase of precipitation.

Horton (1919) speaks of water storage with moist snow on trunks and branches of deciduous trees as being larger than with rain. Salamin (1959) illustrates accumulation of snow in deciduous trees in a variety of forms: cushions and balls on branches and on dry leaves remaining on the trees, and "walls" along tops of horizontal branches. Generally such snow is more compacted than the loose snow in conifer crowns.

Flexibility of branches affects snow load. Baldwin (1957) shows that when heavily loaded, the branches of fir, spruce, and hemlock droop and let the snow slide off, while the stiffer branches of pine continue to hold it. The flexibility of pine needles may be countered, in large storms, by stiffness of pine branches. Klintsov (1958) ascribes the difference in snow load, 8 mm. on a pine and 6 mm. on a spruce, to rigidity of the pine and flexibility of the spruce; however, the spruce was 10 percent smaller than the pine in d. b. h., height, and crown area.

A comparison of accumulation of dry and wet sawdust on a cryptomeria branch and on a slat model (Japan 1952) showed that beyond a certain load the branch accumulated no more, while accumulation continued on the model. This difference can be interpreted as due to the bending of the branch. Reports of less snow being caught in large storms (Horton 1919; Kienholz 1940; Morey 1942) suggest the vulnerability of large masses to being blown off, or sliding off, if they force branches to bend.

The effect of branch width is indicated in the Japanese model study (Japan 1952, p. 118), in which snow depth was about six times the board width taken to a fractional exponent of 0.7 to 0.9; that is, $D = 6W^{0.7}$.

Bühler's (1886) statement that critical damage in a snowstorm near Zürich was reached at 26 mm. in hardwoods, and at 46 mm. in needle-leaf trees, may reflect the more vulnerable branching habit of hardwoods. Hardwoods are shown much more vulnerable to damage by ice loading (Bennett 1959, p. 159) than conifers with their resilient branches, small upper crowns, and mechanically strong branching habit. Gay[2] notes that the erect habit of branching of alpine-ash eucalyptus does not favor interception on the limbs. Delfs (1955) compared interception in spruce varieties with different crown shapes; it was least in Kammfichte (comb-spruce) and greatest in Burstenfichte (brush-spruce) that had side branches that rise sharply upward. A photographic report (Anon. 1953) shows natural selection among races of spruce, particularly the contrasting Kammfichte and Plattenfichte (flat spruce). The Plattenfichte has spreading horizontal branches and is more vulnerable to snow break, but is strong in ice and rime loading.

Wide separation of branch whorls in Scotch pine is described by Bühler (1886) as reducing the surface storage for snow, in spite of its long needles. Models of separated stacked boards (Japan 1952, page 124) show greater relative catch per board when they are separated, but the separations were not large, and this result may reflect transport of snow into the interior of the stack. At a given wind speed, there is probably an optimum separation of whorls for interception.

Bühler (1886) was the first to note that snow lies in the interior and lower parts of crowns of bare trees, whereas it lies on the upper whorls and ends of branches of evergreens, which are thus more subject to top break. Many later authors note this tendency for the load to be exterior; this pattern also occurs with glaze loads, which total less in conifers than in hardwoods because they coat the outside of the crowns (Bennett 1959, p. 163).

Ratio of branchwood to stem size is important. Rosenfeld (1944) says that spruce stands damaged worst in a severe storm in 1916 were in an age class in which dense stocking produced slender, high-crowned trees; and Pfeffer (1955) analyzes the mechanics of break in terms of concentration of snow load in a crown at the end of a long lever arm. Even brittle-wooded trees survive heavy loads if they have coarse branching (Bennett 1959, p. 169).

Location of snow load in the crowns is especially important if crowns are unsymmetrical, and many foresters report the hazard of unsymmetrical development. Snowthrow, defined as the bending or uprooting of trees, is ascribed by Spaeth (1941) to unsymmetrical snow loads in crowns; snowbreak he ascribes to top damage from wind action on frozen wet snow. Leaning trees intercept more

[2]Gay, L. W. The influence of vegetation upon the accumulation and persistence of snow in the Australian Alps. 1958. (Unpublished thesis on file at Australia Forestry School, Canberra.)

snow and the unbalanced trees bend and take on more load until they break (Rosenfeld 1944). Unsymmetrical crowns on trees growing on mountain slopes may make them more vulnerable. Eidmann (1954) and Delfs (1955) report higher interception by trees on slopes, apparently due to a larger catching surface. The increase in spruce is half again as much on 31- to 40-degree slopes as on 11- to 20-degree slopes; the change in beech is less marked. The sides of crowns of individual trees on steep slopes are more exposed to snow falling at a low angle than those on flat sites.

Trappe and Harris (1958) report that young, thin-stemmed lodgepole pine in Oregon are often damaged by snowbreak: "...once a small patch of snowbreak starts, it grows larger every year. Trees along the edge of the patch, having lost support, bend into the opening under snow weight." Residual trees left on a clear-cut area were similary subject to damage (Trappe 1959). Curtis (1936) makes a similar statement about plantations in Massachusetts, in which trees bordering openings develop one-sided crowns that make them vulnerable to snow-bending.

Crown depth, volume, and density, more undefined characteristics than crown coverage or closure, recognize the three-dimensional nature of forest canopy. These characteristics can be used as indexes to interception of precipitation or radiation (Miller 1959), which bear certain analogies to each other. If flakes are wet and stick to foliage, there is an analogy to solar radiation absorbed each time it touches a leaf surface, if allowance is made for the effect of gravity on snowflakes. If flakes do not easily adhere to foliage on contact, they penetrate deeply about twice as much snow as solar radiation penetrates a forest of the same stem density (Miller 1955, fig. 7).

Morey (1942) compares crown depth and closure, and concludes that a stand with more trees per acre and thinner canopy intercepts less snow than one with fewer trees and deeper canopy.

Research Approaches

Catching of the first snow by foliage and branchwood represents adhesion between the rough surface of a dry snowflake, or the wet surface of a warm sticky one, and the rough or smooth foliage surface. Friction coefficients and roughness generally have not been measured. Those of the snowflake seem to be temperature-dependent, and also bear the marks of the flake's history of growth, evaporation, and melting as it fell, and of its abrasion against other flakes. The angle of leaf surface at which friction is equal to the gravity component parallel to the slope has gone unmeasured, either initially or as it changes under snow loading. Under load, evergreens with flexible branches become more like solid objects, and snow is held by adhesion on pendant outer surfaces as well as supported on top of branch whorls. In some evergreens, branches are rigid and needles flexible, and adhesion of snow is important if a load is to accumulate. The variety of kinds of snow damage to trees—top break, throw, crushing—suggest the variety of load distributions. Snow damage differs from ice damage, suggesting differences in adhesion as well as weight.

The freezing of a wet flake to cold foliage has been observed during storms, when the problem of interception passes over into that of accumulation of glaze and rime. Refreezing of snow to foliage when weather suddenly gets colder is frequently reported, but only qualitatively.

The methodology of investigating the adhesion of snow to foliage has been non-instrumental, and also sporadic. Analogy between adhesion of snow and rain can be misleading, although in wet snow the concept of wetting coefficient is useful.

Adhesion of snow has been determined in laboratory work, mostly with old snow on plastic or metal surfaces. New snow on foliage should be measured by the same methods. Friction coefficients of several kinds of snow and foliage should be measured by standard methods at different temperatures, to develop experimental relationships. In wind tunnels it would then be possible to test adhesion of snow deposited under various wind impacts on modelled or real foliage.

The freezing of wet snow to cold foliage could be simulated in cold chambers. The heat balances of refreezing situations could be reconstructed, and the strength of the bonds measured.

Extension of laboratory work to the field requires consideration of the slopes of needle surfaces, which might be quantitatively described by methods developed to obtain slope distributions of ocean waves. This information would make it possible to distinguish adhesion of snow to the pendant outer branches of a fir tree from the supporting action of a branch directly beneath the load.

Analogies to adhesion of snow may be found in wetting of foliage by rain, and in adhesion of rime or glaze icing. Current investigations in these areas should be examined for methods and results, as soon as enough laboratory work on snow has been done to give a basis for comparisons.

Cohesion of Snow

After the first layer of snow particles has adhered to the foliage, further accumulation is a function of cohesion among particles. Cohesion may represent the toothed interlocking of young dendritic flakes or the sintering that later develops with translocation of vapor or liquid water to form new solid bonds, in response to temperature gradients or wind pumping.

In light winds, vertical piling up of snow requires enough cohesive strength to counter the force of gravity at the angle of repose, and experiments with snow accumulations on boards indicate a steep angle. Dry snow particles cohere by friction, as Kuz'min (1963) notes, especially, according to Wellington (1950), if they are of the crystal, plate, or graupel forms rather than powder. Wellington (1950) and Pruitt (1958) report considerable depths of snow piled up in crowns or Arctic forests, and Pruitt's comments suggest that although crown snow between storms may seldom be deeper than 3 to 5 cm., during storms the depths of low-density snow on spruce in sheltered valleys must be much greater, to produce the snowbreak reported.

Maximum depths of fresh snow upon cut branches supported in similar positions above the ground was measured by Lull and Rushmore (1961) as between 10 and 12 cm. on balsam fir, red spruce, and hemlock, and 16 cm. on white pine. Goodell (1959) reports weights of snow caught by a severed tree (a 4.5-m. Engelmann spruce) after one storm that brought 19 cm. of dry cold snow with a water equivalent of about 10 mm., as 16 kg., which adhered so tenaciously "that violent shaking to simulate a strong wind dislodged but one-third of the initial accumulation." Assuming a crown projectional area of 3 sq. m., the load is equivalent to 5 mm. water. I have weighed snow beaten off a young lodgepole pine at the Central Sierra Snow Laboratory as equivalent to 6 mm. water.

Atmospheric Conditions

Shidei (1954) says that "the snow crown of the tree grows large and heavy at night, when the air temperature falls to about 0°C. and the air is calm, with no radiation," and points out that the depth of snow crowns depends on the width of the supporting objects. Each leaf and branch catches a small amount of snow, but the closing of adjacent snow caps increases the base width and allows the depth to become much greater, so that as "the snowfall continues, the crowns of trees become covered with one large and deep snow crown at last." In another Japanese study, the depths of snow crowns on boards in various arrangements were recorded in 47 storms (Japan 1952) when wind speeds were relatively light, averaging 0.6 m/sec. in all the storms. The influence of temperature on cohesion of snow can be examined from the Japanese model and tree experiments. Depth of snow on boards 1, 2, and 4 cm. wide, relative to that on a 16-cm. board, was greater at higher temperatures: at -1°C. it was double that at -3°C. Similarly the catch of wet sawdust, to simulate warm snow, by a tree branch and a board model was twice that of dry sawdust (Japan 1952, p. 151).

Weights of snow on a cryptomeria tree, in percentage of snowfall in the open, at air temperatures ranging from -5°C. to +1°C., were always small at low temperatures, but moderate or heavy at high temperatures. The envelope of points on a graph of air temperature against snow load as a percentage of snowfall is expressed by: $Y = 156.8 + 27.5x$, in which Y is snow load in percentage of snowfall, and x is air temperature, which was below freezing. No storms plot above this enveloping line, and most seem to follow a trend of similar slope expressed as: $Y = 130 + 30x$. While cohesion in some types of snow grows even at low temperatures, it generally increases most rapidly at temperatures approaching the freezing point. The opposing actions of different metamorphic processes, one destroying the mechanical linking of irregular flakes, the other increasing the sintering or bonding by vapor translocation, are oppositely temperature-dependent, but the latter seems dominant.

Continuous weighing of a snow-laden tree provides case histories of interception in individual storms. In one, for example (Japan 1952, p. 143, fig. 6), when air temperature remained between -3°C. and -4°C. during the whole period, the snow load closely followed the curve of accumulated storm precipitation. In another storm, in which the air temperature, initially slightly above freezing, fell to -1°C., snow load accumulated rapidly and uniformly. In proportion to snowfall on the ground, it outweighed loads in other storms, reaching 22 kg. in 10 hours. The rate of increase of load, 1 mm. water equivalent per hour, was a large fraction of the rate of snowfall. Most of this increase occurred at night.

Snowfall at night added more to the load on the tree than that by day, as is indicated by a plotting of weights during seven storms on a common time scale (Japan 1952, p. 142, fig. 4). The most rapid accumulation of crown snow occurred after 2000, with peak loads being reached near sunrise. From these graphs, I calculate the average load at 1800 to be 2 kg., and by 2-hour intervals thereafter to be 5, 7, 11 (midnight), 12, 14, 14, 14, 10, 6 (noon), 3, and 1 kg. (1600). The most rapid accumulation was between 2200 and midnight.

Wind accelerates metamorphosis of snow that is suspended in small masses in the airstream, and may cause cohesion to increase, although this effect is difficult to separate from its effect in transporting snow into the crowns and plastering it onto the foliage by impact. Current laboratory and field research on the metamorphosis of snow on the ground, as being done by the U. S. Army Cold Regions Research and Engineering Laboratory, is developing much knowledge about such thermal and mechanical phenomena as bonding of grains, viscous flow, permeability to air, density, and grain-size distribution, that bear on the problem of cohesion and accumulation of snow in large masses and thick coatings on foliage. Reresults of this research may be directly transferrable to future studies of intercepted snow, or, at least transferrable after experiments are made in wind tunnels or other controlled environments on snow masses of various ages and histories of exposure.

The accumulations of snow measured by Klintsov (1958) after warm gales in Sakhalin were mostly on the windward sides of the small conifers (spruce and pine 7 m. tall), and totaled 6 and 8 mm. water equivalent, respectively, over the crown projectional area. The peak load was greater, since he reports that some snow had slid off before he could knock off the load and weigh it. These values indicate the amount of snow that can be plastered onto a tree under conditions of wind and good cohesion.

Rime droplets mixed with snow particles increase cohesion, since the freezing of the supercooled droplets cements the snow load together more rapidly than cohesive forces develop among solid particles. On the fjelds of north Finland, these coatings reach great thicknesses, reported by Heikinheimo (1920) in terms from which I calculate a load of as much as 30 mm. water equivalent.

Contradictory reports of heavy interception on windward slopes and on lee wind-shadow slopes suggest that adhesion and cohesion may be large in either high or light winds, presumably depending on wetness and temperature. If snow is sticky, high winds plaster it over a large intercepting surface on the crowns, especially in an open forest or one on a windward slope. If snow does not adhere strongly to the foliage but has appreciable cohesion, light winds and lee slopes allow deposition to reach a great thickness on a small intercepting area.

In general, adhesion and cohesion depend on temperature, with maximum effect just below zero degrees. Layering of the atmosphere, so that cold snow falls into warmer air or wet snow into colder air, produces different kinds of adhesion. Wind beyond some critical speed that depends on snow cohesion extends the intercepting and storing surfaces of tree crowns. The critical wind speed at which deposition is largest depends on meteorological factors other than air movement, and joint action is evident in snowstorms with high winds. If the snow has considerable adhesive strength, as when it is mixed with supercooled droplets of liquid water, or has acquired water films aloft that are supercooled in colder air near the ground, interception loads are increased by stronger winds.

Some of the interrelationships between the effects of temperature and movement of the air may be summarized in the following statements:

1. In calm, the relation of snow load to temperature is asymmetrically curvilinear, with a maximum at or just above the freezing point.

2. In cold storms, the relation of snow load to wind speed is curvilinear, with a flat maximum at 1 to 2 meters per second. Load decreases rapidly at higher wind speeds.

3. In storms with temperatures just below the freezing point, snow load increases with wind speed up to a fairly high value, particularly on trees that close their crowns under wind pressure or load.

An unscaled pattern developed from these three statements (fig. 1) shows maximum load occuring at low wind speeds and temperatures near freezing, in a distribution that with increasing wind speed slopes toward lower temperature. Away from this zone of maximum load, the gradient is most steep upward with increase in temperature above freezing, and diagonally downward toward cold, windy weather. This pattern represents only the two macroatmospheric parameters of air movement and temperature. It takes no account of micrometeorologic factors within the tree crowns, which are evidenced in the shaping of snow masses illustrated by Salamin (1959), nor of radiative energy exchange. Nor does it consider such biological factors as crown geometry, which affects micrometeorologic forces, or vibration of branches and deformation of trees in the wind.

Crown Conditions

Biological factors that may affect cohesion of snow particles and the snow loads in tree crowns should be mentioned, though few numerical data on their effects are available. Some trees hold snow on sprays of foliage, others on their branches, but the long rivalry between beech and spruce in Central European forestry yielded few data on the question whether foliage or branchwood is more important in intercepting snow. Since the difference between leafless beech and evergreen spruce is confounded with the difference between summer rain and winter snow, careful observations of snow catch over many winters are insufficient to permit us to determine the relative roles of foliage and branches. Every statement in the literature that deciduous trees intercept no snow can be matched by a statement that they intercept considerable amounts.

Flexible leaves hold less snow than rigid ones, but this condition may be confounded with branch flexibility. A pine that has soft needles on stubby branches may hold as much snow as a fir that has stiff needles on drooping branches. Without data on the mechanical properties of each member of the load-bearing structure, we cannot evaluate the relative roles of leaves and branches in interception studies by Buhler (1884) as an implausible idea that less snow is intercepted in big storms, when overloaded branches shed their loads, than in small storms.

Age of trees, which looks like a useful parameter because it is a number, was brought into interception, and cannot prove or disprove the provement on the oversimplified dichotomy forest-versus-open. However, its relevance to interception hinges upon an association with crown coverage that is not consistent. It does not seem to be a good predictor of interception unless combined with such physical dimensions as stem numbers or basal area.

"Species" is a catchall that lumps the roughness, area, and pattern and flexibility of foliage with the size, strength, and structure of branchwood, giving a single term impervious to analytical attack. Differences that are measured between throughfall of snow in stands of different species cannot be definitely ascribed to any single characteristic, because species usually differ with respect to several characteristics rather than one only. Moreover, differences between species are not always found; some pure stands of different species differ less from one another in throughfall than they do from mixed stands made up of the same species. Buhler (1886) identified closure, foliage, and branchwood as factors, but these characteristics have not yet been measured adequately for the analysis of snow loading.

Studies of the ecology of marginal areas, like the Arctic or alpine forest, suggest that interception of snow is an agent of natural selection that favors one tree form, species, or forest pattern over others. On the equatorial margin of the zone of frequent snowfalls, Griffith (1945) reports heavy damage in the New Forest estate at Dehra Dun in India to exotic 20-year old trees that had never experienced snow, from a storm with 24-hour precipitation of 0.98-inch water equivalent. Local species were hardly affected. While these ideas suggest that certain mechanisms of interception may be active, the interactions among the mechanisms make it difficult to ascribe a definite role in interception to any one biological characteristic.

Breaking or other damage of trees by snow loads is commonly reported, but often the atmospheric data are too few to permit one to estimate how large the loads were and what their relation was to storm precipitation, wind, and temperature. Spaeth (1941) describes snow break, snow throw, and snow crushing, which differ in origin as a result of different sequences of weather after a snow load is established. Stoeckeler[3] says that "the problem of resistance to breakage and uprooting of various tree species is of transcendent importance in practical forest management. It is complex. Involved are type and strength of central stem, rooting habits, crown depth, branch angle, branch length, number of branches per whorl, needle type and quantity. The snow-or-glaze retention capacity is certainly correlated to some extent with crown geometry."

It appears that some of the properties of trees relevant to snowfall interception can be expressed in geometrical terms (roughness, exposed area of branchwood, slope of branches), and others in mechanical terms (flexibility of needles, rigidity and breaking strength of branches). However, data on these properties are few, and interpretation of snowbreak information to give information about interception is correspondingly difficult. Moreover, break often affects groups of trees, and interpretation requires data on stand density and mutual support among trees.

A snowstorm in Michigan with about 30 mm. water equivalent caused extensive damage, mostly by stem breakage but also by stem bending and uprooting, among 24-year-old recently thinned jack pine plantations (Godman and Olmstead 1962). Unthinned stands were little damaged.

Roe and Stoeckeler (1950), studying effects of a storm in 1947, found least damage in 10-year-old jack pine stands thinned 5 years before, heavy damage in unthinned stands, and worst damage in stands thinned the preceding year and having over-large, misshapen crowns. Reference to *Climatological Data* suggests that this result was brought about by snowfall of less than an inch of water equivalent, and presumably less snow load. Damage was not evenly distributed but produced patches as large as a quarter acre: "Mortality resulting from snow damage, because of its haphazard nature, cannot be relied upon to correct serious overstocking...On the contrary, it leads to an undesirable stand of patch-wise character" (Roe and Stoeckeler 1950).

A similar mosaic of tree-groups and openings is caused by snowbreak of spruce around edges of small openings in interior Alaska (Pruitt 1958), the openings enlarging to the size at which snow loads are restrained by entry of wind and sun. Fenton (1959) also reports hundreds of 6- to 15-year-old pine saplings going down in patches of a quarter-acre size.

Results of a snowfall of 35 to 45 cm. depth on tended and untended stands in a municipal forest in Switzerland (Grünig 1963) provide a comparison of some 19 species in four age classes, from which Grünig draws silvicultural recommendations, such as the avoidance of vertical edges in the stands. It appears that the thermodynamic role of forest in a snow-covered landscape might in some situations be difficult to reconcile with its survival in snowstorms.

Some species are able to withstand heavy snowloads, perhaps having been improved by selection. Eisen (1892) describes the elimination from snow country of evergreens that do not have sloping branches and upright stems and hence pyramidal form, and Butters (1932) ascribes the spire shape of spruce and fir of the Selkirk Mountains to heavy snowfall, which tends to make the branches short and pendant.

The development of a race of spruce (Kammfichte) in lower mountainous regions of Germany (Anon. 1953) is described as natural selection in an area of heavy wet snow. On higher slopes, presumably within storm clouds, where rime and icing are common, the native race (Plattenfichte) has sturdy horizontal branches less likely to be torn out by a load that in this climate does not as easily slide off as does wet snow. Hess (1933) describes differences in resistance to damage among races of pines.

Rusanov (1938) says that snow loads on tamarix of central Asia are large enough to reduce the trees to bush form, and cites a saksaul *(Haloxylon)* of 5 m. height broken to less than a meter. Iashina (1960) says that damage in particularly snowy winters is a major factor in forest ecology. This role of snow load in marginal sites may be confounded with the effects of deep spring snow cover on reproduction, but Heikinheimo

[3]Personal correspondence with J. H. Stoeckler, Lake States Forest Experiment Station, U. S. Forest Service, St. Paul, Minn., 1963.

(1920) says that in the zone most subject to damage from accumulation of snow and rime, near the Arctic tree line, 60 percent of the forest is pure spruce or spruce mixed with birch, pine being relatively uncommon; the more frequent the damage from snow loading, the higher the percentage of spruce-birch.

One may wonder whether paleontological distributions have been influenced by snow interception; the rapid northwest movement of spruce after the Pleistocene glaciation may be related to its behavior under snow loads. Much snowbreak damage in the wet mountains of Germany followed replacement of deciduous trees by spruce, often in overstocked monoculture, often by races less resistant to snow loads than to ice.

It should not be hard to determine the mechanical strength of stems and branches under snow loading, and to devise models for testing the loads that can be borne by trees and stands of different ages, species, densities, and crown sizes. The experiences cited suggest that less than an inch of water equivalent may be critical in some circumstances. This figure provides a crude approximation to limiting interception amounts but must vary widely in different sites and climates.

Recent Research on Snow Interception

Two recent papers on snow interception in Japan confirm and amplify some of the conclusions tentatively stated in this report. The long-awaited sequel to the preliminary study on weight of intercepted snow (Japan 1952), from which many basic data were drawn for this report, has recently been published (Watanabe and Ôzeki 1964) and was brought to my attention by G. C. Wilken, Geography Department, University of California, Berkeley. It reported weighing experiments in six winters. In three of the winters extensive measurements were made of snow load (kg.), depth of load (kg./m.^{2}), taking into account the decrease in crown projectional area under load and corresponding to mm. water equivalent, wind speed, air temperature, and dimensions of the crowns—area and depth, and the number, angle, and length of branches. Several trees, supported on scales, stood in a row in the open, exposed to falling snow that generally was warm (temperatures seldom lower than -2°C.) and of moderate density (0.10 on the average, not lower in any storm than 0.06) and in storms of moderate size (median water equivalent of precipitation about 20 mm.) The amounts of snow intercepted were, perhaps, larger than would be observed in a forest stand or in less favorable atmospheric conditions.

Trials compared two varieties of *Cryptomeria japonica* D. Don that have become differentiated in the Toyama Prefecture and the snowier Niigata Prefecture, an area exposed to frequent snowfalls in polar air streaming across the warm Sea of Japan. The trials also included trees of five ages, and trees subjected to silvicultural treatment in which crowns were shortened or thinned of intermediate branches. Weights of snow loads were associated with these biological and silvicultural differences but, more important, Watanabe and Ôzeki reported dimensions of the tree crowns that were directly and physically related to snow load. For example, the medians of maximum loads per unit crown area in 12 storms were 8, 10, 10.5, 9.5, and 10 mm. in crowns of the *kumasugi* variety of *Cryptomeria* of ages 10, 24, 32, 43, and 57 years, respectively; the largest load was held by the 32-year-old tree at culmination of growth. Moreover, measurements of total length of branches made possible a more direct association. These lengths were 52, 56, 86, 48, and 54 meters, respectively (all crowns had the same depth, 4.8 m.), and can replace age as a parameter in snowfall interception to form a more relevant relation.

Similarly, the two varieties of *Cryptomeria* differed in their mechanical properties in ways that could not only be seen but also quantitatively expressed as crown deformation under load. *Bokasugi*, the variety from the less snowy region, Toyama Prefecture, carried its branches, unloaded, at an angle of 53° from the vertical; when loaded, they bent only slightly, to 77° at 7 mm. load and 96° at at 14 mm. This difference increased the crown projectional area and hence the total weight of snow supported. In 90 measurements the median load on *bokasugi*, 8 mm.

over the crown area, averaged 3 mm. larger than the median load on *kumasugi,* the variety native to snowy Niigata Prefecture. *Kumasugi* branches, unloaded, formed an angle of 76° from the vertical. When loaded by more than 3 mm. of snow water, they bent below the horizontal; at a load of 11 mm., their angle was 110° to 120°. The crown projectional area was decreased by as much as a third.

Snow load on these two varieties of *Cryptomaria japonica* measured as the maxima in each of 11 storms one winter, were much larger on the stiff, spreading branches of the *bokasugi* (median = 16 mm.) than on the drooping branches of the *kumasugi* (median = 10 mm.); measurements other than when the maxima were reached displayed differences of 3 to 4 mm., and much of this can be ascribed to differences in branch angle.

Four silvicultural treatments of crowns of 30-year-old *kumasugi* trees were applied to investigate means of reducing snowbreak damage. Crowns were shortened by pruning their lower banches, or were thinned out by removing branches all through them. Both treatments were carried out so as to reduce crown depth (4.8 m. in the control tree) or number of branches (100 in the control tree, totalling 84 m. in length), by one third and by one half. The treatments also reduced crown projectional area (5.7 sq. m. in the control tree) by removing the longer branches, and therefore reduced crown volume. The total weight of intercepted snow on individual crowns, expressed as the median of peak values in 11 storms, was reduced from 55 kg. on the control tree to 20 kg. on the 1/3-shortened crown and 14 kg. on the 1/2-shortened crown, to 35 kg. on the 1/3-thinned-out crown and 25 kg. on the 1/2-thinned-out crown. Snow load was reduced proportionately to the decreased volume of the shortened crowns (my estimates), but was reduced still more in the crowns that had been thinned out. This reduction suggested that the absence of branches within the crown curtailed the opportunity to hold snow. Watanabe and Ozeki also found that the weight of intercepted snow was reduced in proportion to the decreased branch length in the thinned-out crowns, but more than proportionately in the shortened crowns. Branches of the shortened crowns, which were perhaps smaller in diameter because they were in the upper part of the crowns, supported thinner deposits of snow than did the average branch in the control tree.

Hydrologically significant is the effect of treatment on the mean water equivalent of intercepted snow over the projected area of the crowns. On the control tree, the water equivalent of the intercepted snow, as the median of peak values in 11 storms, was 10 mm. This value was reduced about 30 percent by shortening the crowns, and about 20 percent by thinning branches out of them; the medians of peak water equivalents of snow in the treated crowns varied between 6 and 8 mm.

A silvicultural study of snow damage (Sugiyama and Saeki 1963) in the Hokuriku District in a storm of 100-mm. precipitation showed little damage at elevations above 300 m. (where temperature would have been lower than -3°C.) and little on windward slopes. Damage in conifer plantations was severe on lee slopes, and in the analogous situation of openings in forest. Windward edges of forest, like windward slopes, incurred little damage. Damage to different species depended on "the crown form and its inner constitution"—characteristics that, so stated, do not have much practical value. But if crown characteristics are identified and measured, as Watanabe and Ôzeki did in recording crown depth and area, branch length and angle, and weights of intercepted snow, then chracteristics of tree crowns can be directly related to the processes of interception.

Promising Leads for Studies

From diverse sources we can glean some information on delivery of snow to forests, its impaction on foliage, and adhesion and cohesion during snowstorms—the processes that form snow loads of hydrologic and silvicultural significance. This information shows many gaps in our knowledge of these processes. The techniques needed to bridge these gaps in knowledge can, however, be drawn from many disciplines.

Research is required on the environmental framework in which these physical processes take place. The forest part of the environment is in need of systematic description, so that numerical expression of its attributes can be used by the laboratory experimenter to build a model that realistically simulates natural phenomena. These expressions would include such measurements as biomass in cubic centimeters or grams per square centimeters of crown projectional area, surface area of foliage, crown depth and volume, and branchwood networks of various diameters. They are more necessary in a geophysical problem than the conventional indexes of closure, or stocking, developed for other purposes and deficient in physical interpretation. Branch pattern and crown structure are attributes that need expression; methods of characterizing dendritic stream patterns in erosional terrain may, perhaps, be useful.

Mechanical strength and flexibility of foliage, twigs, and branches should be determinable by standard analysis. Besides aiding interpretation of snow loading data, such information will be useful in studying vibration or deformation of crowns under wind stress. Reduction in crown size by compression under wind pressure should be measured. Some attributes usually associated with species may be subject to measurement under standard conditions in a wind tunnel, and to standard mechanical tests of strength in compression, bending, and torsion.

The crown space of a forest or tree group can be regarded as a porous medium through which air, radiation, vapor, and snow particles flow. By analogy to general experiments with flow in porous media, such a system of pores can be characterized by certain coefficients of dispersion. Interstices and other openings, natural or cultural, among tree stands form a complex mosaic landscape, whose structures and edges influence the distribution of the moving airstream and its contained particles. Interception processes studied in crowns of single trees and tree groups can be extended to whole drainage basins if there is some means of quantifying this forest-and-openings mosaic. Research in quantitative ecology and geography may also provide techniques in which the concept of edge as a distinctive situation is taken into account.

The atmospheric part of the environmental framework in which interception processes occur is characterized by complex turbulent motion. Eddies of many sizes transport snow particles and determine their rate of delivery, motion, and impaction on the forest elements.

Research on aerosol diffusion should be applicable to research on suspended snow particles. Large-scale air movement sets in operation a complex pattern of micrometorological flows within the crown space, and it will be necessary to see how well current turbulence theory applies to this situation. Exploratory work with many small sensors in and above crowns of forest of reproducible dimensions should be carried out to define fundamental aerodynamic characteristics of the wind field that affect delivery and impaction of snow particles. The heterogenity of the crown zone requires intensive spatial sampling of the field of motion, but means are now at hand for mass sampling and analyzing of data. Photographic observations, as reported by Kuz'min (1963), may be helpful in exploratory phases of the work.

Relatively short runs in controlled environments may be sufficient to outline major aerodynamic factors in the interception processes, and a few selected periods in the field, under typical synoptic conditions, may be sufficient for analysis. The more that can be done in controlled environments, the shorter need be the outdoor experiment. Adhesion and cohesion of snow particles to foliage and previously deposited snow should not be difficult to determine in the laboratory, to delimit the relative significance of such factors as air temperature, wind speed, and snowflake type.

Controlled conditions will permit comparison of foliage roughness and flexibility, and branch flexibility and strength in providing a base for adhering snow and supporting snow loads. Extreme snow loads can be applied in the laboratory, to determine breaking points and load distribution.

Field measurements of weight of trees bearing snow loads should follow the example of the thorough Japanese research, though with an improved site and more measurements of environmental conditions and of such characteristics of the snowload as area of adherence, thickness, and location. Exterior and interior locations can be compared; pendent branches versus horizontal support; load in the upper crown versus that in the lower branches; density and wetness of the snow itself.

The field sample can be expanded by shaking or melting snow off a number of trees onto plastic films for weighing, at the time of maximum load during a storm. This technique does not give the progression of load size during a storm in response to meteorologic conditions that is obtainable by continuous weighing, but it would extend information on biological factors. Some field work as a kind of unstructured exploration of the problem and a means of geting crude data can be done while laboratory and other controlled-environment experiments are going on, as a means of assuring the eventual transferability of laboratory data to field sites.

The transfer of the principal investigation from the laboratory to the tree *in situ* depends on adequate information on micrometeorological conditions in both laboratory and open. Such information will also make possible the effective application of current research findings from aerodynamics and from other areas of micrometeorology to the interception problem.

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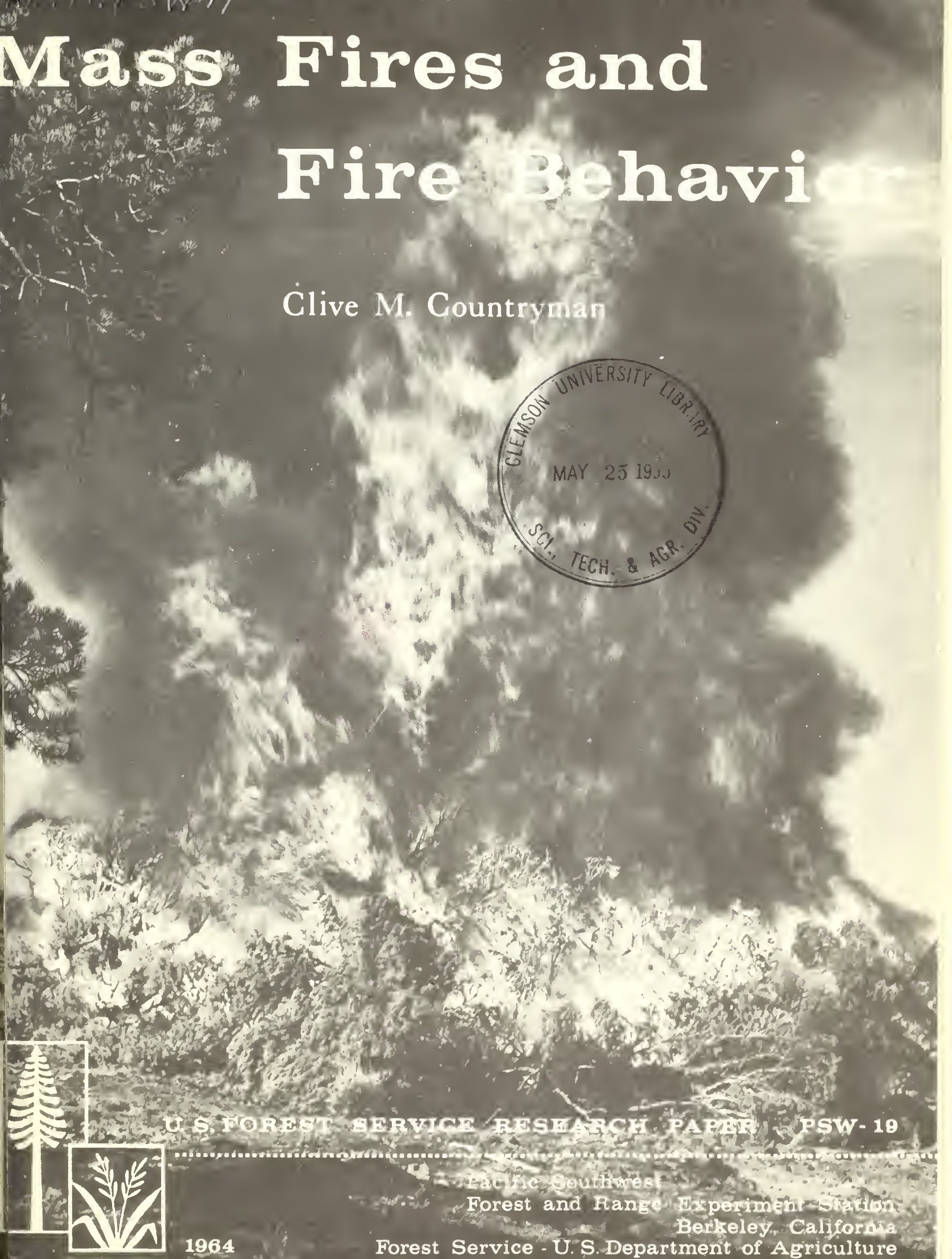

Mass Fires and Fire Behavior

Clive M. Countryman

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Forest and Range Experiment Station
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Foreword

Subtask 2521E, "Interaction of Mass Fire and Its Environment," sponsored by the Office of Civil Defense, Office of the Secretary of the Army, has been designed to help alleviate the lack of quantitative information on the characteristics and behavior of mass fire. The broad objectives of the project, as stated in the contract (OCD-OS-62-173, OCD-PS-64-3), are to:

1. Investigate and seek to establish the relationship of fire spread, fire intensity, and other fire behavior characteristics of mass fire in relation to air mass, fuel, and topography and to determine the effect of the fire system itself on the environment surrounding it under various synoptic conditions.

2. Investigate the rate of energy output of fires under various environmental conditions and also the output of noxious gases that might have a bearing on military and civilian action and safety.

Both field and laboratory work are needed to meet these objectives. Because of the need for quantitative information characterizing large and intense fires, present work has been largely confined to the development of instrumentation and the preparation and burning of field test fires. Size of test fires are being scaled upwards as instrumentation and ability to measure such fires are perfected.

This first interim report reviews knowledge of fire behavior and factors affecting it, describes the test fires that are being conducted, and presents results and observations from the initial phase, April 1962 through June 1964.

This report has been reviewed in the Office of Civil Defense and approved for publication. It should be noted that because of the exploratory nature of the fire tests reported herein, this report does not purport to describe a mass fire resulting from a nuclear weapon attack. The results are suggestive of possible future outputs of this work which could be applicable for operational planning purposes. Approval does not signify that the contents necessarily reflect the views and policies of the Office of Civil Defense.

Qualified requestors may obtain copies of this report from
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Contents

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Tahoe National Forest

The Author

CLIVE M. COUNTRYMAN has had more than 20 years' experience in forest fire research. He joined the U. S. Forest Service in 1939, and is now headquartered at the Pacific Southwest Station's forest fire laboratory, Riverside, Calif., where he is responsible for studies on fire behavior and fire environment. He received his bachelor of science degree in forestry from the University of Washington (1939).

The control of large fires is a problem of continuing concern to the Forest Service, other public agencies, and private owners of forest and rangeland. A few large fires each year account for all but a small share of the Nation's forest fire losses. In time of war, this problem can be of vital concern to civil defense. Modern weapons make it possible to ignite mass fires in both rural and urban areas. To improve their ability to combat such catastrophes, the fire services need much more quantitative knowledge of the characteristics and behavior of large fires.

Developing this knowledge is the aim of the studies reported here. They were designed primarily to gather information useful in civil defense problems, but much of the data will be applicable in predicting the behavior of wildfires that take a heavy toll in peace time.

Losses Due to Fire

In World War II, fires resulting from high explosive and incendiary raids often produced physical damages and casualties greater than those caused by the explosions themselves. Bond (1)[1] states that "the destruction was seldom less than two-thirds fire damage and in many cities, notably those of Japan, the damage was practically one hundred percent fire damage." The loss of life from such fires was enormous. Three raids on Dresden, Germany, on February 13, 1945 resulted in fires that caused an estimated 130, 000 deaths. The much publicized fire storm raid on Hamburg, Germany, caused an estimated 40, 000 deaths. Loss of life was also heavy in the 65 cities in Japan that were wholly or partially destroyed by fire.

Disastrous city fires are by no means confined to military action. The National Fire Protection Association (33) lists 133 major conflagrations in American cities during the period between 1900 and 1950. They include such well-known fires as the San Francisco fire in 1906 which destroyed 28, 000 buildings and caused $350, 000, 000 damage, and the Texas City fire in 1947 which caused $67, 000, 000 in damage. Other countries also have suffered disastrous peacetime fire losses. In 1923 an earthquake in Japan started fires in Tokyo that covered nearly 7 square miles (3).

The development of nuclear weapons has greatly increased the potential for destruction by fire. Atomic bombs dropped on Hiroshima and Nagasaki caused fires that burned out more than 6 square miles in the two cities (1). The area subject to immediate ignition and subsequent burn-out from multimegation nuclear weapons has been estimated to be between 450 and 1, 200 square miles, depending on weapon yield and height of burst (32). Under certain conditions ultimate spread from one nuclear explosion has been estimated to be as great as 10, 000 square miles (29).

Not so well known, but rivaling many city fires in damage and casualties, are wildland fires. Many of these are described by Holbrook (27). For example, at about the same time of the great Chicago fire in 1871, a wildland fire in Wisconsin burned 2, 000 square miles and killed 1, 152 persons, more than four times as many as were killed in the Chicago fire.

The huge areas over which ignitions and burn-out can occur with multimegaton weapons makes it virtually certain that wildland areas as well as cities would be involved in fire in many regions. The hazard to life and property in these regions has been greatly increased by recent population changes. In many places suburban developments are encroaching into formerly uninhabited wildlands. These developments do not replace the wildland fuel complex, but merely supplement it

[1]Numbers in parentheses refer to Literature Cited, p. 51.

Figure 1.--Dwellings and other structures in urban areas supplement wildland fuels.

Figure 2.--Part of destruction by the Bel Air fire, Los Angeles County, November 6, 1961.

(fig. 1). Fires starting in either structures or wildland fuels can spread from one to the other. The Bel Air fire in Los Angeles on November 6, 1961, which burned 6,090 acres and destroyed 505 buildings, started in wildlands and spread to residential areas where further fire spread was in both structures and wildland fuels (fig. 2). On July 10, 1961, the Harlow fire in the foothills of the Sierra Nevada in California burned 19,000 acres in 2 hours, and destroyed the towns of Awahnee and Nippinawasee. On March 16, 1964, three fires within the city limits of Los Angeles, Pasadena, Burbank, and Glendale burned 11,000 acres, destroyed 20 houses, severely damaged 10 more and seriously threatened hundreds of others. One of these fires started from a burning house and spread to wildland fuels; the other two started in wildland fuels from high tension lines arcing in the wind. Although the problems of a wildland residential fuel complex are perhaps most acute in California, similar problems exist in many other areas.

In the spring of 1962, fires in New Jersey burned 186,000 acres, caused the death of seven persons, and destroyed 500 homes and other buildings. A single fire burned 60,000 acres in one day.

Increasing recreational use has created additional hazards. During a 46,000-acre fire in an intensively used recreation area on the Tahoe National Forest, recreationists were--as one of the firefighters put it--"running out of the brush like rabbits." For a time people evacuating the area clogged the roads and hampered movement of fire-control equipment and crews. No loss of life occurred; the fire started as a single spot and spread as a moving front, giving time (sometimes barely sufficient) for people to escape. But escape for many would not have been possible if the fire had started by multiple ignition over the area.

Mass fire from whatever cause, in cities, wildlands, or in combinations of both poses a major threat to civilian populations, property, and natural resources.

Fire and Civil Defense

In event of nuclear or incendiary attack, fire poses three broad problems in the protection and welfare of civilian population:

Protection of personnel. --Provision of shelters or other measures and devices to protect people from fire raises these questions: How will fire affect air supply and quality? How much heat will be produced and for how long? How much area will the fire burn? How quickly will mass fire develop? And how quickly will fire spread to other areas?

Fire control. --To limit fire damage and danger to the population, effective countermeasures are needed to suppress the fire, or at least limit its spread. To take any kind of effective counteraction on a going fire, it is essential to know what the probable behavior will be as the fuels, weather, and topography change during the control effort.

Pre-fire planning. --Pre-fire planning, or pre-attack planning, is concerned with measures taken to minimize possible ignitions and to limit spread of those ignitions that do occur. Here again we need to know what the fire characteristics are likely to be if practical and effective countermeasures are to be devised.

Knowledge of fire behavior is of paramount importance in all three types of problems. We must be able to predict in quantitative terms fire characteristics and fire behavior for the wide variety of environmental conditions and situations that may be encountered.

Status of Fire Behavior Knowledge

What is known about the behavior of free-burning fires? Although we are a long way from a complete understanding of fire behavior and still farther away from being able to write precise mathematical equations of it, there does exist a large store of practical and scientific information concerning fire behavior and fire characteristics. This knowledge has been derived from years of research and operational practice in controlling and using fire.

Research by the National Fire Protection Association and experience of city fire departments have developed considerable knowledge concerning structural and urban fires. Similarly, wildland management agencies have acquired a large store of knowledge concerning fire behavior through research, years of fire suppression activities, and use of fire in wildland management. Fire is now a commonplace tool in wildland management. It is frequently and effectively used in silvicultural practice, in rangeland improvement, and in fuel hazard reduction. Such use of fire is not haphazard--the kind of fire needed to do a given job is obtained through manipulation of fuel and carefully prescribing the firing pattern and conditions of weather and fuel moisture required for each fire. Thus in approaching the solution of fire problems in civilian defense, we approach a field that is not completely new and unknown.

Much of the practical knowledge of fire and fire behavior is concerned with relatively small fires and those of low intensity. Most wildfires are suppressed when small. Control forces are efficient, and the combination of fuel, weather, and topography needed to produce large and intensive fires occur infrequently. Similarly, urban fires involving more than one structure are relatively rare. In applied use of fire, too, burning conditions are selected so as not to produce a fire that cannot be readily controlled.

Research on mass fire has been hampered by the necessity of confining studies to small-scale fires in the open or in the laboratory (fig. 3). Such studies are essential for understanding of fire phenomena. They permit careful control and measurement of experimental conditions, and allow accurate analysis of some basic fire relationships. There is considerable question, however, as to the validity of extrapolating from small fires to the large, intense fires which are of particular concern in civilian defense.

Some characteristics of large fires have not been observed on small fires, either because they do not occur in small fires or because they are too minute to be detected. It seems likely that a different set of controls of fire behavior may take over after a fire reaches a certain size or intensity. Scaling laws that will permit extrapolation of results of small fire studies to large fires have not been developed. In fact, it is not known if such laws can be developed for some aspects of fire behavior. It is an imposing problem to scale to laboratory size only the aerodynamic factors of the range and variety found in the environment affecting a large fire.

The difficulty of extrapolating from small to large fires is further complicated by the fact that behavior of fire is a pattern phenomenon--the behavior at one point is often dependent on the behavior at another point. The behavior of one part of a fire may change even if burning conditions at that point do not vary when the characteristics of the fire at some other point changes. Since fire behavior and characteristics are controlled by the environment in which it is burning, it is necessary to measure both the fire pattern and the environmental pattern controlling it.

Even though large urban fires occur occasionally and large wildfires more frequently, there is little quantitative information concerning them. This is understandable since the time and place that fires will occur is unknown, and the capability of making valid measurements on such fires has been virtually non-existent. Consequently, descriptions of fire behavior on large fires have been largely qualitative. Some attempts have been made to make post-fire analyses and to set up hypotheses for the observed fire behavior. Such analyses have usually been severely handicapped by fragmentary data on environmental conditions and by the uncertainty of eye-witness accounts. In recent years attempts have been made to obtain better information on both large fire behavior and the environmental conditions under which it burned (8, 10).

In general then, one must conclude that although there exists a considerable body of knowledge about the characteristics of small fires and of fires burning under "normal" conditions, there is a dearth of quantitative information concerning large and intensive fires.

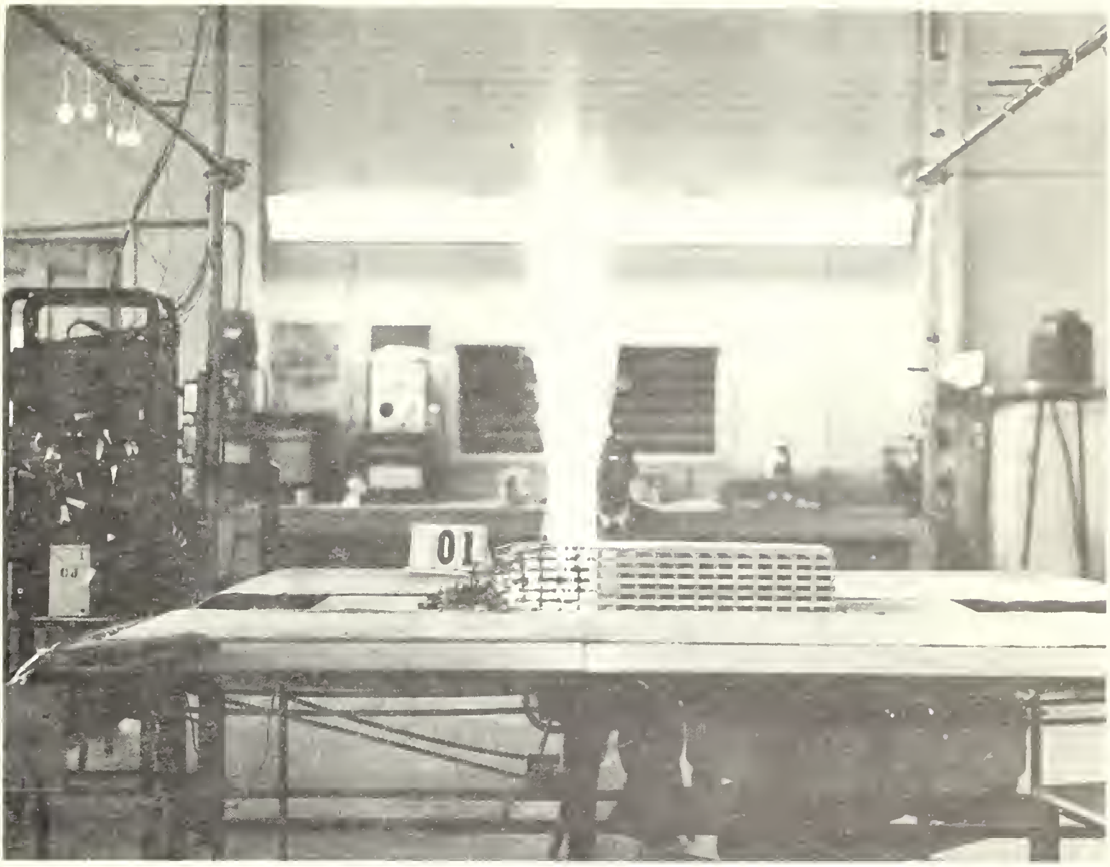


Figure 3.--A laboratory crib fire.

Classification of Mass Fires

Just where on the scale of fire behavior a fire becomes a "mass" fire has never been specifically defined. The term, however, has generally been applied to those fires exhibiting the more violent fire behavior. Fires large in area are not necessarily mass fires. When rates of energy released per unit of area or fire front are low, violent fire characteristics are usually absent, and the behavior of a small sector of the fire is little different than if that sector was burning alone. On the other hand, very small fires burning with a high rate of energy release also may not exhibit violent fire characteristics. The term "mass fire," then, carries the connotation of both large size and high rates of energy release.

Two broad classes of mass fire are generally recognized. These are:

Fire storms. --Fire storms represent the most violent type of mass fire. They occur when there are many ignitions over a wide area that quickly coalesce into a single fire, burning intensely over a large area. Convective activity in these fires is very great, and tall convective columns develop (fig. 4). Fire-induced winds become very strong, and large whirlwinds, or fire whirls, are common. There is usually little outward spread of fire in a fire storm. The lack of spread is probable due to the strong indrafts and also because fire storms appear to develop most readily under light wind conditions.

Conflagrations. --These are hot burning fires with definite and moving "heads" or "fronts" (fig. 5). The depth of the intensely burning area is usually relatively

Figure 4.--Tall convection columns are a characteristic of fire storms. This column was estimated to extend to 35,000 feet.

Figure 5.--Conflagrations develop numerous moving fronts or heads.

narrow. Tall convection columns may or may not develop. Whirlwinds and fire whirls often appear in conflagration type fires, but their size, violence, and duration is much less than those associated with fire storms. Conflagrations are strongly affected by wind and topography and, because they can move rapidly, they can burn out vast areas.

As with the separation of "ordinary" fire from mass fire, there is no clear cut line of demarcation between fire storms and conflagrations. Under certain conditions, particularly with the widespread ignition to be expected from nuclear explosions, both types of mass fire can develop at the same time. An ordinary fire may also develop in intensity and activity to a conflagration or fire storm and back again as conditions vary. Such fire behavior is common in wildland fires where spatial variations in fuels and topography are great and the life of the fire if often long enough to burn through major changes in weather conditions.

Fire Environment

"Fire environment" is the complex of air mass, fuel, and topographic factors that affects the inception, growth, and behavior of fire. Fire environment is not fixed, but varies in both space and time. The extent of the environment affecting a fire also changes with the size and characteristics of the fire itself. For a very small fire the environment of concern is limited to a few feet both horizontally and vertically. In a large fire the environmental envelope may cover many miles horizontally and extend thousands of feet vertically.

The factors of fire environment are closely interrelated--that is, changes in one group of factors can cause changes in others. Thus topography can affect local weather through differential heating and cooling of slopes of different aspects. Fuel (vegetative cover) can modify these changes. Weather in turn may modify such factors as fuel moisture and amount or kind of fuel.

Open and Closed Environments

Two broad classes of fire environment can be delineated: closed environment and open environment. In urban conditions the fire environment inside a building is nearly independent of the outside conditions. Fuel arrangement and fuel characteristics are dictated by the construction of the building and its furnishings or equipment. Climate and the moisture content of hygroscopic fuels is controlled by the heating and cooling systems. Wind movement as experienced in the open air is non-existent. There are no topographic effects. This is "closed" or confined environment.

In the city as a whole the environment is not confined. Current weather can vary with the synoptic weather patterns. Fuel temperatures can vary with the aspect and from day to night. Wind movement is almost always present. Topographic effects are prevalent. This is "open" environment.

Fire burning inside a building is controlled by the environment within the building. It is little affected by the outside environment. As long as the fire is within the building (fig. 6), there can be no spread to adjacent fuel elements--the fire is confined. Once the fire breaks out of the interior of the building, it is no longer burning in a closed environment. Outside conditions can affect the behavior, and the fire can spread to other fuel and grow in size and intensity (fig. 7).

Although not as clearly defined as with urban conditions, closed and open environments also exist in wildland fuels. A fire burning under a dense timber stand (fig. 8) is burning in an environment quite different than that above or outside the stand. Fuel moisture is frequently much higher and wind movement is greatly slowed within the stand (12). If the fire builds in intensity and breaks out through the crowns of the trees and becomes a crown fire (fig. 9), it then is burning in an

Figure 6.--Fire burning in a closed environment.

Figure 7.--Fire burning in an open environment.

Figure 8.--Fire burning in a wildland closed environment.

Figure 9.--Fire burning in wildland open environment.

open environment and comes under a different set of controls. Fire behavior and characteristics can change radically.

In wildland fuels fires may burn from a closed environment to an open environment and back again a number of times during its life. Such a series of changes is unlikely in urban fires.

Wildland fires that can be classified in the mass fire category are affected strongly by the open environment in which they burn. Knowledge of the fire environment pattern in the area involved often permits the behavior of the fire and the extent of spread to be predetermined (13, 14). In the Forest Service the position of "fire behavior officer" has been established in the fire-control organization to advise on relations between fire behavior and fire environment (9).

Because much of the fuel in urban areas is in a closed environment, the relation between open environment and mass fire behavior is not as strong as with wildland fires. Open fire environment does have considerable effect on mass fire in urban areas, however, and may be the deciding factor in whether a fire storm or conflagration may develop.

Components of Fire Environment

The major components of fire environment are fuels, topography, and air mass. The study of mass fire in relation to its environment, then, is concerned with fire characteristics and behavior as affected by these three variables.

Fuels

The characteristics of burnable fuels are of major importance in the inception, spread, and behavior of mass fires. Fuel characteristics may be grouped into either fuel particle characteristics of fuel bed characteristics.

FUEL PARTICLE CHARACTERISTICS

Fuel particles are the individual units that make up the fuel bed. They may vary greatly in size. In wildland fuels, the particles may be leaves, twigs, or stems of plants--or even stumps and logs. Fuel particle characteristics known or suspected of being important in ignition and fire behavior are:

Particle geometry.--Particle geometry refers to the shape (flat, irregular, round, angular) and size (thickness, diameter, length) of the fuel particles. Fons (21) found distinctive differences in ignition time and burning rates with variations in fuel particle geometry and used surface-to-volume ratio to quantify the variation in fuel particles.

Surface.--Other factors being equal, fuel particles with rough or fissured surfaces ignite more easily than those with smooth, even surfaces.

Moisture content.--The moisture content of fuel has long been recognized as having major influence on ignition and behavior of fires (25). All wildland fire danger rating systems use moisture content of fuel as one of the major variables (17). Numerous studies have been made of moisture content variations in dead wildland fuels. The moisture content of living wildland fuels has also been the subject of extensive research.

Chemical composition.--Little is known concerning the effect of chemical composition on combustion and fire behavior.. Although chemical differences are known to exist (35), there is surprisingly little difference in the total heat value of common forest fuels. Chemical differences may be reflected in burning rate, however. Observation of wildland fires has indicated that some fuel species burn more readily than others. Kilzer and Broido (30) have found that burning rate may be related to ash content of the fuel.

Specific gravity.--Fons, et al. (22) found a significant relationship between specific gravity of wood and rate of spread in crib fires.

Thermal absorbtivity.--The thermal absorbtivity of wildland fuels has been found to vary widely (6). In situations where radiation is important in the inception and spread of fire, this characteristics will be significant.

FUEL BED CHARACTERISTICS

Fuel beds are seldom homogeneous, but consist of a variety of fuel particles. It is the association of these fuel particles, each with individual characteristics, that determines to a major extent the fire behavior. Attributes of fuel beds considered of importance are:

Continuity.--"Continuity" is used to describe the gross distribution of fuel in the horizontal. Fuels may be spread more or less continuously over an area, may occur only in patches with bare areas in between, or may surround bare or nonflammable areas.

Arrangement.--Fuel arrangement refers to the vertical and horizontal distribution of fuel particles of various characteristics. For example, small or "fine" fuel particles may be uniformly distributed vertically throughout the fuel bed or may occur only at the ground level. Similarly, all fuel particles may be close together (compact) or may be widely spaced. Fuels may be concentrated in certain areas with relatively little between these spots.

Amount.--Amount of fuel is the total (dry) weight of fuel per unit of area. This characteristic of fuel beds is probably most easily measured. It must be considered in conjunction with fuel particle and other fuel bed characteristics, however, to be useful in prognosis of fire behavior. For example, an area covered with a few widely-spaced large logs may have the same total fuel weight as an area covered more uniformly with small fuel particles loosely arranged. Behavior of fire in these two areas would be vastly different.

FUELS AND FIRE BEHAVIOR

Observations of wildfires, prescribed burns, and test fires have indicated marked differences in fire behavior apparently associated with variations in fuel bed characteristics. There have been some attempts to quantify these variations in terms of rate of spread or combustion rate in laboratory scale fires and small field tests. Such investigations have not provided enough information, however, to have much practical application.

Studies have also been conducted on wildland fuels to obtain quantitative data on fuel bed characteristics. Most extensive of these was a study conducted on certain chaparral fuels in southern California during Operations Firestop (20). In that study, mil-acre plots of fuel were dissected to obtain amounts and distribution of fuel particles within the fuel bed. Results from typical plots in three different fuel "types" are shown in tables 1 to 3. This illustrates the great variation in characteristics of wildland fuels that are grossly similar in appearance.

In very small fires it is probable that the burning characteristics of individual fuel particles, their arrangement, and continuity are of paramount importance in the growth and spread of fire. Thus with a fire burning in a ground layer of pine needles, the rate of burning of each needle and its distance from the next unburned needle will determine whether the fire will continue to spread. As a fire becomes larger, both horizontally and vertically, the burning characteristics of the more gross elements of the fuel bed will control fire behavior and spread. In a crown fire in a timber stand, for example, it is the burning characteristics of the individual tree and the spacing of trees that determine whether the fire will continue to crown, the fire's intensity, and its rate of spread. The scale of the fire thus is a major factor in determining the fuel bed characteristics of importance in fire behavior.

A close parallel may be drawn between urban and wildland fuels. In urban fires, the characteristics of the individual fuel particles, their arrangement, continuity, and amount in an individual structure will determine the characteristics of a fire in the structure. In a mass urban fire, however, the individual buildings in effect become the fuel particles and the complex of structures the fuel bed, just as in a crown fire in timber, the individual tree becomes the fuel particle and the timber stand the fuel bed. In the urban fire, the arrangement and height of buildings of different types (fuel arrangement), their size and number (fuel amount), and the presence or absence of fuel-less spaces (fuel continuity) will determine fire behavior.

Table 1.--Composition of light chaparral fuel type

Item	Dry weight (tons per acre)	Percent of class weight
Total fuel:		
Living	2.19	17.6
Dead	4.10	33.0
Duff and litter	6.13	49.4
Total	12.42	--
Predominant species:		
California sage (*Artemisia californica*)	0.59	9.4
White sage (*Salvia apiana*)	4.45	70.7
Deerweed (*Lotus scoparius*)	1.25	19.9
Height (feet):		
Over 6	.00	.0
4 - 6	.02	.3
2 - 4	4.47	7.5
0 - 2	5.80	92.2
Size class:		
Flowers	.00	.0
Leaves	.76	12.1
Twigs to 1/4 in.	2.43	38.5
Stems 1/4 - 1/2 in.	1.45	23.1
Stems 1/2 - 1 in.	.98	15.6
Stems 1 - 2 in.	.76	10.7
Stems 2 in. or over	.00	.0

Table 2.--Composition of medium chaparral fuel type

Item	Dry weight (tons per acre)	Percent of class weight
Total fuel:		
Living	9.76	46.1
Dead	5.32	25.2
Duff	6.06	28.7
Total	21.14	--
Predominant species:		
Chamise (*Adenostoma fasciculatum*)	11.02	73.0
Buckbrush (*Ceanothus cuneatus*)	3.02	20.0
Sumac (*Rhus laurina*)	1.05	7.0
Height (feet):		
Over 6	.92	6.1
4 - 6	2.90	19.2
2 - 4	5.09	33.7
0 - 2	6.19	41.0
Size class:		
Leaves	1.20	8.0
Twigs to 1/4 in.	3.80	25.2
Stems 1/4 - 1/2 in.	2.78	18.4
Stems 1/2 - 1 in.	5.51	36.4
Stems 1 - 2 in.	1.81	12.0
Stems over 2 in.	.00	.0

A

B

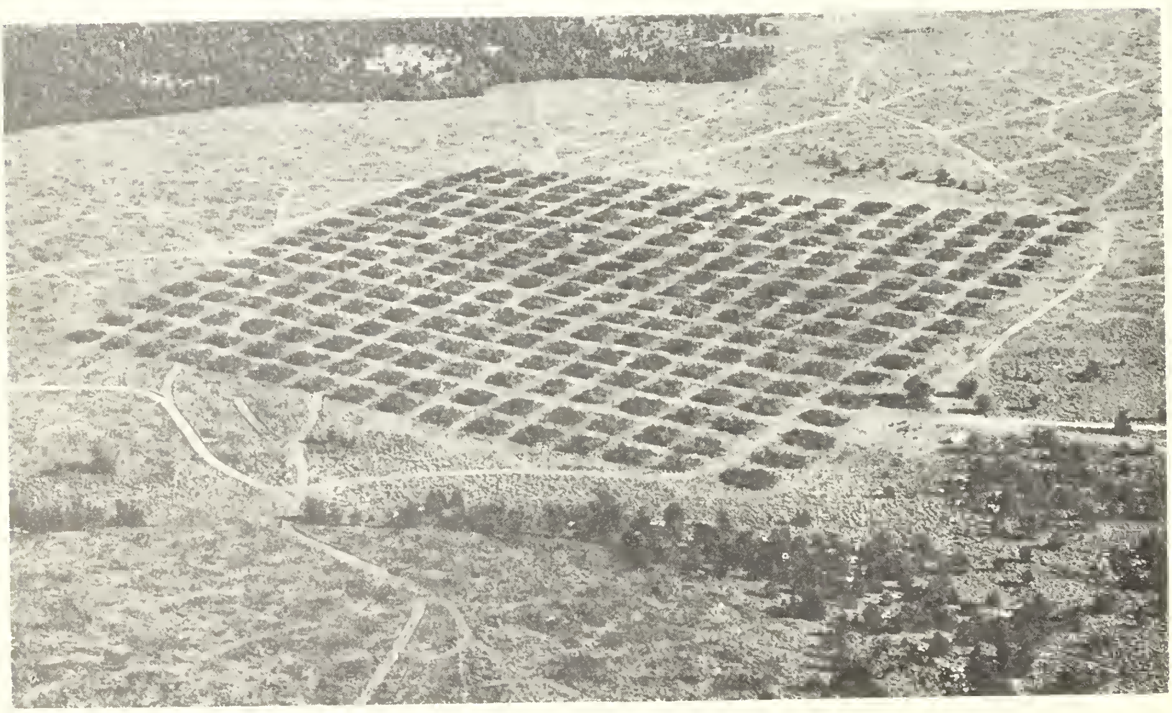


Figure 10.--Residential fuel type; A, new subdivision, B, simulated with wildland fuels in piles 50 feet on a side and spaced 25 feet apart.

Table 3.--Composition of heavy chaparral fuel

Item	Dry weight (tons per acre)	Percent of class weight
Total fuel:		
Living	28.62	72.6
Dead	2.56	6.5
Duff	8.25	20.9
Total	39.43	--
Predominant species:		
Scrub oak (*Quercus dumosa*)	22.80	73.1
Buckbrush (*Ceanothus cuneatus*)	8.38	26.9
Height (feet):		
Over 6	7.96	25.5
4 - 6	8.46	27.1
2 - 4	11.42	36.7
0 - 2	3.35	10.7
Size class:		
Leaves	2.64	8.5
Twigs to 1/4 in.	4.04	13.0
Stems 1/4 - 1/2 in.	4.08	13.1
Stems 1/2 - 1 in.	4.45	14.3
Stems 1 - 2 in.	11.36	36.3
Stems over 2 in.	4.61	14.8

The major differences between mass fire in urban and wildland fuels results from the differences in fuel bed characteristics. By arranging wildland fuel in a pile with the same general burning characteristics as a building, a burning building can be simulated. A number of such piles of fuel arranged as buildings in a city can be expected to produce the same kind of fire as would occur in a city (fig. 10). Since it is impossible to burn more than one or two buildings at a time for tests in urban areas, simulation with wildland fuels was the approach used in this investigation.

Topography

Topography has both a direct and an indirect effect on fire behavior. Fires spread more rapidly upslope than on level ground because fuels upslope from the fire are exposed to greater heating from radiation and convection and because of upslope winds are generated by the fire of natural heating. Rate of spread of wildland fires has been estimated to approximately double for each 15 degree increase in slope (38). It is not known if this relationship holds for urban fire, but acceleration of fires uphill in urban fires has also been noted (34, 39).

Fire spread downslope is generally slower than on level terrain because of lessened radiative and convective heating of fuels on the downslope side and opposing convective winds. An exception occurs when fire is spread downslope by rolling debris.

In broken topography with short slopes, fire spread is slower and behavior more erratic than with long, unbroken slopes. Orientation of the topography with respect to windflow is also important in fire spread and behavior.

In general, for short time periods fire spread in hilly or mountainous areas can be much greater than on level or rolling terrain; over longer time periods, spread on the less steep terrain may be greater (11). This difference is attributed to a greater number of breaks and barriers to fire spread in mountainous country. Slow spread downslope is probably also a contributing factor.

Topography affects fire behavior indirectly through its effects on local weather and microclimate (19, 26). The aspect of a slope affects the amount of local heating (23) and thus affects fuel moisture of dead and living fuels. The variation of heating on slopes of different aspects may also be reflected in the kind and amount of vegetation. Differential heating in mountainous areas has a major effect on local wind patterns and hence on fire behavior (13, 14, 16). Channeling of wind flow by topography is also an important indirect effect of topography on fire behavior.

Air Mass

The air mass overlying fuels and topography is perhaps the most variable of the components of fire environment. Near the surface the air mass is affected by the topography and interacts with the fuel. The air mass affects, and may be affected by any fire system that exists. Air mass characteristics now recognized as important in fire behavior are: wind, humidity, precipitation, temperature, and air stability.

WIND

Wind has long been recognized as a major element in fire behavior. Reports of city conflagrations frequently mention strong winds as a major problem (33). Wind also plays a major role in spreading wildland fires. Besides supplying oxygen to the fire and driving the flames forward into unburned fuels, wind can transport burning firebrands far ahead of the main fire. The structure of the wind field above a fire may also have a marked effect on fire characteristics. Byram (5) has associated wind speed profiles with fire behavior and has developed an equation relating strength of the wind field and energy release of a fire to the development of convection columns.

Wind can also have an indirect effect on fire behavior through its effect on fuel moisture (28). When exposed fuels are wet, wind will often promote drying, when more nearly dry, further drying can be slowed by the cooling effect of wind.

HUMIDITY

The effect of humidity on fire appears to be largely an indirect one. The moisture content of hygroscopic fuels is very closely associated with relative humidity. In finely divided fuels, the moisture content follows the relative humidity very closely. Relative humidity alone has sometimes been used as a parameter of fire hazard and a guide for stopping or curtailing operations in timberlands.

Test Procedures

One of the chief aims of the first tests in the study was to identify and describe, both quantitatively and qualitatively, various fire behavior and fire characteristics and the conditions under which they occurred. This store of information will provide the necessary data to (a) develop cause and effect relationships where data are sufficient, (b) check the validity of hypotheses postulated by theoretical or mathematical development, (c) develop hypothesis of fire behavior based on full scale data, and (d) design more sophisticated field or laboratory tests where needed to provide additional information.

Ideally, with this experimental approach it would be desirable to be able to vary fuel and fuel arrangement and the instrumentation to take full advantage of knowledge gained in one test in the next. Practically, however, this is not possible. Much time is required to prepare test plots and to allow the fuels to dry before burning. Weather conditions are variable; to burn under the desired conditions, the test plot must be ready beforehand. Consequently, it was decided to prepare several tests in each of four general fuel types and to vary the instrumentation and conditions under which each test was burned as seemed desirable or was possible.

Plots

One set of tests, called series 428, was in plots up to 92,000 square feet in area and loaded with fuels almost entirely less than 2 inches in diameter (fig. 11). Fuel consisted of typical central Sierra shrubs, chiefly ceanothus, scrub oak, and manzanita species crushed in place by a bulldozer. Additional fuel was brought into the plots to fill in light spots and provide uniform fuel loading. Fuel depth averaged about 24 inches. The test area (Sugarloaf, Sierra National Forest) had steep terrain. The plots were rectangular, the length being two to three times the width. They were laid out with the long axis generally at right angles to the slope.

Heavy-Fuel Plots

Timber killed by wildfire was used to build plots in the 380 and 330 series (Donner Ridge and Forest Hill test areas). The wildfire had burned most of the fine material in the timber stand, leaving only the tree trunks and the large limbs.

On six plots, the timber was bunched in tree lengths by a bulldozer. The piles varied in size from 7,200 to 49,750 square feet (fig. 12). Depth of fuel averaged about 60 inches on all plots except the largest (380-6-63), in which the fuel depth averaged about 96 inches. Fuel loading varied from 19 to 25 pounds per square foot in the smaller piles. The large plot contained 40 pounds of fuel per square foot.

On one additional plot in this area, 102,000 pounds of brush were brought into the plot and spread among the standing trees to provide fine fuels. The trees were then felled in place (fig. 13). This plot was about 170,000 square feet in area with a fuel loading of 3.5 pounds per square foot.

All plots in the 380 series have been burned.

The 330 series was planned as two multiple-fire plots--one of 218,000 square feet, the other of 653,000 square feet. Each plot was to have piles of fuel covering 2,500 square feet and spaced 25 feet apart. Construction of these plots proved to be excessively expensive because of the large stumps in the area, and work was discontinued after one plot of 96,250 square feet including 20 piles was completed. This plot has not yet been burned.

Mixed-Fuel Plots

Living pinyon pine and juniper trees provided the fuel for tests in the 760 and 460 series. Entire trees were uprooted by a bulldozer and grouped into piles by a log loader to minimize loss of fine material. Each pile covers about 2,500 square feet and contains about 40,000 pounds (dry weight) of fuel. This is about the same amount of combustible fuel as in a single-story residence and garage, and covers about the same area. In all, 15 single-pile plots and 15 multiple-pile plots were constructed in these two series.

The multiple-pile plots were designed to simulate urban conditions. They range in size from 218,000 to 2,200,000 square feet, (1 to 10 city blocks). Within the plots the piles of fuel were spaced 25 feet apart in one series and 115 feet apart in another (fig. 14). This spacing gave 9 simulated houses in the smallest wide-spaced plots and 36 houses in the close-spaced plots of the same size. In the largest plots the relative numbers were 81 and 420.

In all the multiple-pile plots but one, the fuel piles were arranged so that the "streets" were straight in both directions. In one plot alternate rows were offset so as to simulate blocked streets. This plot covers 653,000 square feet and contains 104 simulated houses.

Figure 11.--Fuel was spread uniformly over the area in the fine-fuel plots. Largest fuel in the foreground is about 2½ inches in diameter.

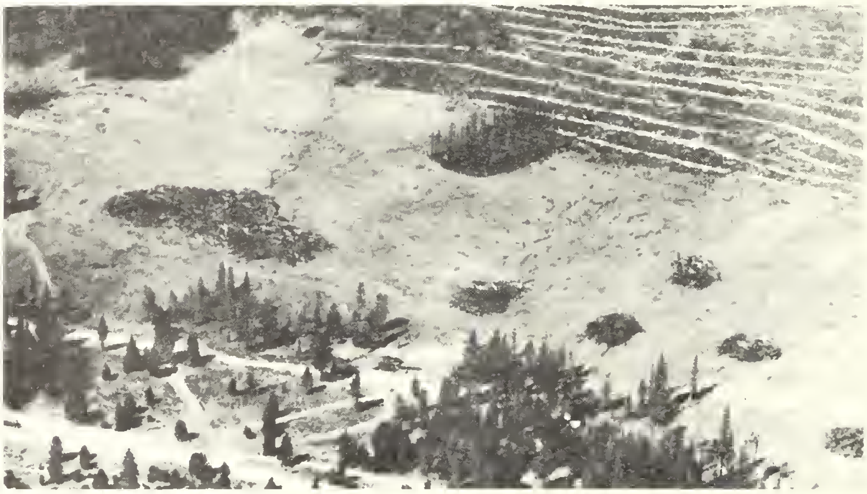


Figure 12.--Heavy fuel plots (380 series); largest pile about 370 feet long and 150 feet wide.

Figure 13.--Test plot 380-1-62. Felled fir and pine trees averaged about 8 inches in diameter.

Figure 14.--Multiple-pile plot of mixed fuels; A, close-spaced plot (piles 25 ft. apart) covering 218,000 square feet; B, wide-spaced plot (piles 115 ft. apart) covering 2,200,000 square feet.

Six single-pile plots and two multiple-pile plots have been burned in the mixed-fuel series.

Urban Fuel Plot

Only one test was prepared in this series (642). It consisted of a two-story wooden frame house covering 1,300 square feet (fig. 6). The exterior of the house was painted redwood siding; the inside, lath and plaster. Floors were wood, and the roofing consisted of wooden shingles covered with asphalt roofing paper.

Table 4.--Fuel size distribution, fine-fuel plot 428-1-63[1/]

Fuel	Percent
Litter	2.0
Leaves	7.9
Twigs:	
Less than ½ in. in dia.	32.4
½ - 1 in. dia.	22.5
More than 1 in. in dia.	35.2
Total	100.0

[1/] Pounds per square foot: 1.45 preburn; 0.01 postburn.

Table 5.--Fuel[1/] size distribution in heavy-fuel test fires

Diameter (inches)	Percent
Less than 4	1.78
4 - 6	3.21
6 - 8	6.96
8 - 10	12.10
10 - 12	10.50
12 - 14	15.66
14 - 16	15.23
16 - 18	11.31
18 - 20	10.22
20 - 22	6.76
22 - 24	1.70
More than 24	4.57
Total	100.00

[1/] Trunks only.

Fuels

The differences in the fuels used to build the test plots required a different analysis for each fuel type to determine fuel amounts and fuel particle size distribution. In the fine fuels, several mil-acre plots were established in the test areas. The fuel on half of these plots was collected before the areas were burned, separated into size classes, weighed, and the dry weights determined. The fuel remaining on the other half of the mil-acre plots was collected after the area had been burned. results of this analysis for one plot are given in table 4.

Obtaining fuel weights and size distrubution for the heavy-fuel plots had to be done indirectly since the fuel piles had already been built in land-clearing operations before the project was started. Fortunately about 1 acre of the fire-killed timber adjacent to the test area had not yet been cleared. The diameter (table 5) and length of the trees in this area were measured. These trees were then piled in the same manner as the test piles and the dimensions of the pile determined. Knowing the dimensions of the test piles, we could then estimate the amount of fuel in each pile. (The amount of small limbs was not determined since these made up a very small proportion of the total weight, and much of this material was lost in building the test piles.)

More elaborate sampling procedures were used in the mixed-fuel plots--partly because little was known about the type of fuel used and partly because these plots were to make up the more important tests. The dimensions of a number of randomly sampled pinyon pines were measured, and then these trees were cut and weighed. The moisture content of different parts of the tree was determined, and the dry weight of the entire tree calculated. This weight was then correlated with different tree dimensions. Good correlations were obtained between dry weight of the tree and stem diameter, average tree crown diameter, and maximum crown diameter. Because of the ease of measurement, the correlation with maximum crown diameter (fig. 15) was used to estimate amounts of fuel. Analysis of juniper trees showed that the same curve could also be used to determine the total weight of trees of this species. The wide-spreading growth habit of juniper compensated for its larger trunks and limbs.

Total heat value of the wildland fuels, obtained by calorimetric analysis varied little by species (table 6), and the values were in the same order of magnitude as those found by other workers for various kinds of wood. The possibility that partially burned material may have lost some of its heat value was also investigated. Sound wood samples taken from just beneath the charcoal layer on partly burned pine, and fir logs did not have significantly less heat value than samples taken from unburned material. Distribution of fuel particle sizes was obtained for pinyon pine (table 7).

Ignitions

All test fires conducted in the project thus far were stationary fires. That is, all of the area to be burned was ignited and there was no fire spread as a moving front. This type of fire was used to give the maximum area possible burning at high intensity for each plot so as to set up a fire storm potential.

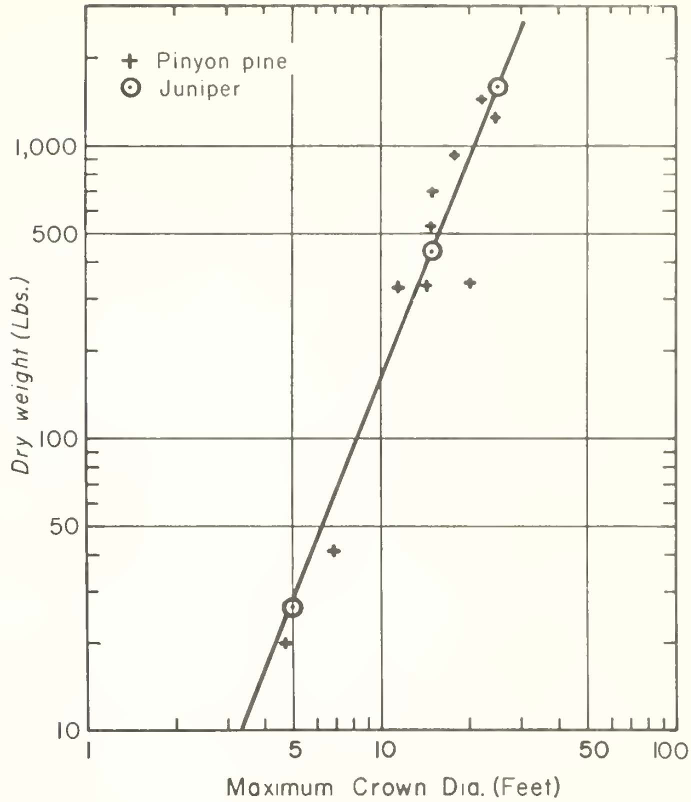
Table 6.--Heat value of fuels used in fire tests

Material	Heat Value
	BTU/lb. (dry wt.)
Tanoak wood	9,750
Tanoak bark	12,432
Douglas-fir	8,848
Madrone wood	8,419
Manzanita wood	8,676
Manzanita leaves	9,208
Ponderosa pine wood	9,386
Ponderosa pine needles	9,776
Ponderosa pine bark	9,603
Pinyon pine wood	8,762
Pinyon pine needles	9,480
Pinyon pine roots	8,300

Table 7.--Fuel particle size distribution, Pinyon pine trees, 6 inches diameter breast high, 9 ft. 5 in. tall

Size class (inches)	Weight (pounds)	Percent of total
Upper tree:		
Needles	32.50	33.0
Less than $\frac{1}{4}$	13.00	13.2
$\frac{1}{4}$ - $\frac{1}{2}$	5.00	5.1
$\frac{1}{2}$ - 1	7.00	7.1
1 - 2	5.50	5.6
2 - 4	11.00	11.2
4 - 6	16.00	16.3
Total	90.00	91.6
Roots:		
Less than $\frac{1}{4}$	0.25	0.3
$\frac{1}{4}$ - $\frac{1}{2}$	1.00	1.0
$\frac{1}{2}$ - 1	2.00	2.0
1 - 2	1.00	1.0
2 - 6	4.00	4.1
Total	8.25	8.4
Entire tree	98.25	100.0

Figure 15.--Weight of pinyon pine and juniper in relation to maximum crown diameter.



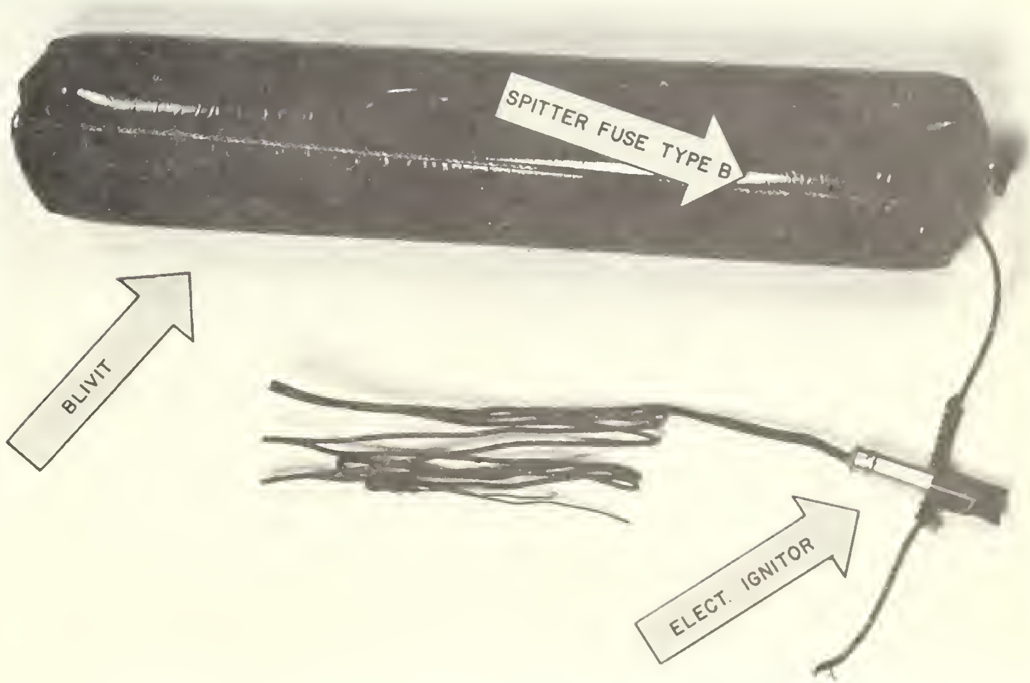


Figure 16.--Jellied diesel oil ignitor.

Jellied diesel oil in pliable plastic tubes (fig. 16) was used as ignition material in all but the fine-fuel plots. Each "ignitor" contained a half-pound of the jellied oil. Ten ignitors were used in each of the simulated houses in the mixed fuel plots giving an ignition density of one ignition to 250 square feet. In the heavy fuel plots, the number of ignitors varied according to the size of the pile with ignition densities always greater than 1 to 500 square feet. All of the ignitors were fired simultaneously in these plots by using spitter fuse wrapped around the tubes of jellied oil and igniting the fuses with electrical squibs.

The fine-fuel plots were fired with fused sections of fusees wrapped in one-third of a rubber automobile tube. The ignitors were also fired with electrical squibs. This method of firing was abandoned when the jellied diesel oil ignitors became available.

Test Results

Air Flow

Often mentioned in reports of urban conflagrations are the high wind speeds that occur in the vicinity of the fire. In wildland fires too, such winds have been mentioned frequently in narrative fire reports. Often these winds have been assumed to be indrafts flowing into the base of the fire replacing air and gases heated and rising in the fire convection column.

That such air flow is always into the fire base or fire area is by no means certain. Instances of wind blowing out of the fire at speeds considerably higher than the ambient wind have been documented (11, 15, 37). This phenomenon has been observed by the author on several large wildfires and it has been reported by others. There is also some evidence (36) that major air entrainment into the convection column may take place at considerable distance above the ground level. Qualitative observations on prescribed burns and some wildfires have indicated only light indrafts into the base of the fire.

As part of the instrumentation on the test fires, wind vanes and sensitive anemometers were installed at two levels (7 ft. and 20 ft.) on all sides of the fire. These installations were made about 100 feet from the fire edge so as to provide a reasonable chance that the equipment would survive the fire. Wind speed and directions were recorded at 1-minute intervals. Closer to the fire air movement was traced with colored smoke and no-lift ballons.

In the heavy-fuel plots (380 series), ambient wind speeds during the different burns ranged from 5 to 12 m.p.h. At 100 feet from the fire, no change in the wind speed or direction that could be attributed to the fire was observed at either the 7- or 20-foot level, despite the hot burning fire (fig. 17) that lasted for several hours. Smoke released close to the fire also showed little air movement into the fire on the windward and flanks; some smoke 3 to 5 feet from the edge drifted into the fire. No-lift balloons followed the same path as the smoke, not entering into the fire unless very close to the edge.

On the lee side of the fires, the air was observed to be very turbulent. Here, colored smoke was often drawn rapidly into the fire. Except for the one fire burned under the strongest wind conditions, this turbulent area did not extend more than 25 or 30 feet from the fire.

It is apparent from the behavior of the colored smoke and balloons that the fire served as a block to the ambient wind, and the flow around the fire was much the same as the flow of moving fluid around a solid object. Eddies and turbulence formed in the lee or "wake" of the fire (fig. 17, inset).

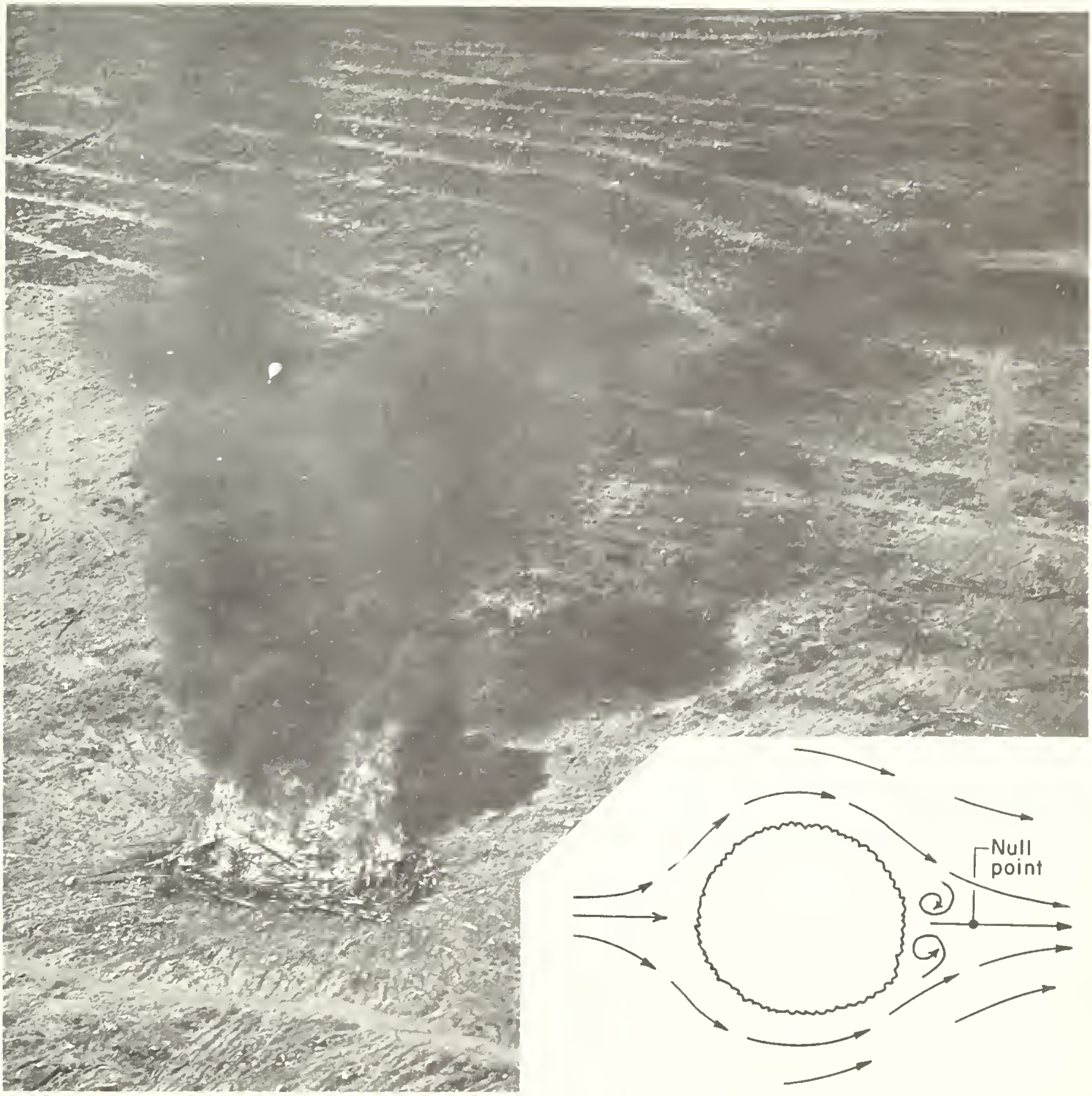


Figure 17.--Test fire 380-2-64 in heavy fuel plot near peak intensity. Flames are 50 feet high. No significant inflow of air was evident at ground level. (Inset: schematic of airflow around a stationary fire.)

During one of the heavy-fuel fires, an opportunity arose to observe the air flow in the turbulent area in considerable detail. A small spot fire started in a decayed log apparently just about at the point of no air flow (null point) on the lee side of the fire. This spot fire produced a steady stream of smoke that revealed the air flow pattern diagramed in figure 17 very clearly. At times the smoke moved directly into the fire and at other times directly away from the fire area. Whenever one of the wake eddies broke loose and moved downstream, the smoke from the spot followed the eddy and showed its circular motion.

The convection column cf test fire 380-3-63, which was burned under strong wind conditions, stayed close to the ground for a considerable distance downstream from the fire. Lateral movement of air into the fire could not be detected on the windward and flank sides. As might be expected, however, turbulence and eddy formation was much more pronounced in the wake of this fire. No-lift balloons moving past the fire appeared to accelerate in speed on the downstream side. This apparent increase in wind speed on the lee side could not be confirmed, however, since the anemometer station was not in line with the convection column.

Dust devils and whirlwinds frequently appear beneath a strongly tilted convection column on wildfires. This phenomenon was also observed on test 380-3-63. Dust devils formed frequently under the convection column at distances up to 400 feet from the fire. One no-lift balloon floated a few feet above ground downstream for nearly 600 feet before suddenly rising vertically into the convection column. Since outdrafts from fires have usually been observed under conditions where the convection column was strongly tilted, it appears likely the increase in wind speed is caused by transfer of momentum downward to the ground by turbulence between the convection column and the ground. Transfer of momentum in this manner may also account in part for the violent fire behavior Byram (4) has associated with wind profiles having a "jet point" near the ground surface.

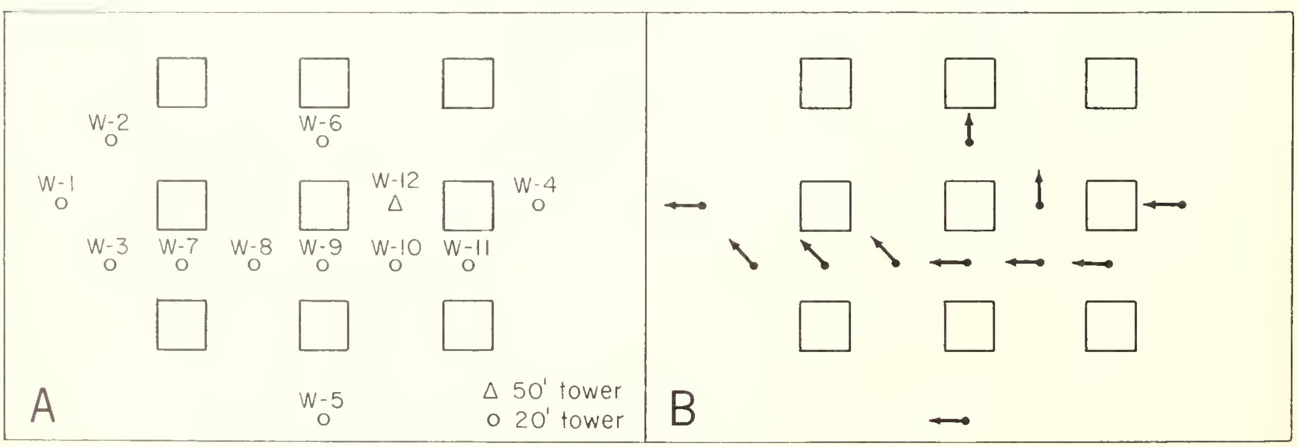
In test fire 760-1-64, anemometer stations were placed between the separate piles (fig. 18) as well as outside the fire area. Station W-12 was a 50-foot tower with anemometers and wind vanes at 2-1/2, 5, 10, 22-1/2, and 50 feet. The other stations had vanes and anemometers at 7 and 20 feet.

Wind flow patterns have been plotted at the 20-foot level for the most intense portion of the fire. Before ignition, wind direction near the ground was across the plot from right to left, approximately parallel to the "streets" as indicated by the outside stations W-1, W-4, and W-5 (fig. 18, B). Within the plot, the fuel piles apparently affected the wind direction to some extent.

The fire began to have a noticeable effect on the flow pattern very soon after ignition (fig. 19). Three minutes after ignition a definite indraft had developed into the fire from all sides. Opposing air currents were well developed around the center pile and on the downstream side of the fire within 6 minutes after the fire, and fire whirl activity was also observed about this time. Nine minutes after ignition air movement was still generally into the fire from all sides, but turbulence on the downstream side made the wind direction very erratic in this area. By 12 minutes after ignition, air flow on the windward side more closely approached the pre-fire condition, but the turbulence and whirl action was still present on the downstream side; 23 minutes after ignition, the indraft was no longer apparent.

Wind direction at the 50-foot tower (station W-12) did not fluctuate greatly during the fire. The direction, however, was not the same at all levels (fig. 20).

Figure 18.--Location of air flow measuring stations, A, and pre-ignition air flow pattern, B, in test fire 760-1-63.



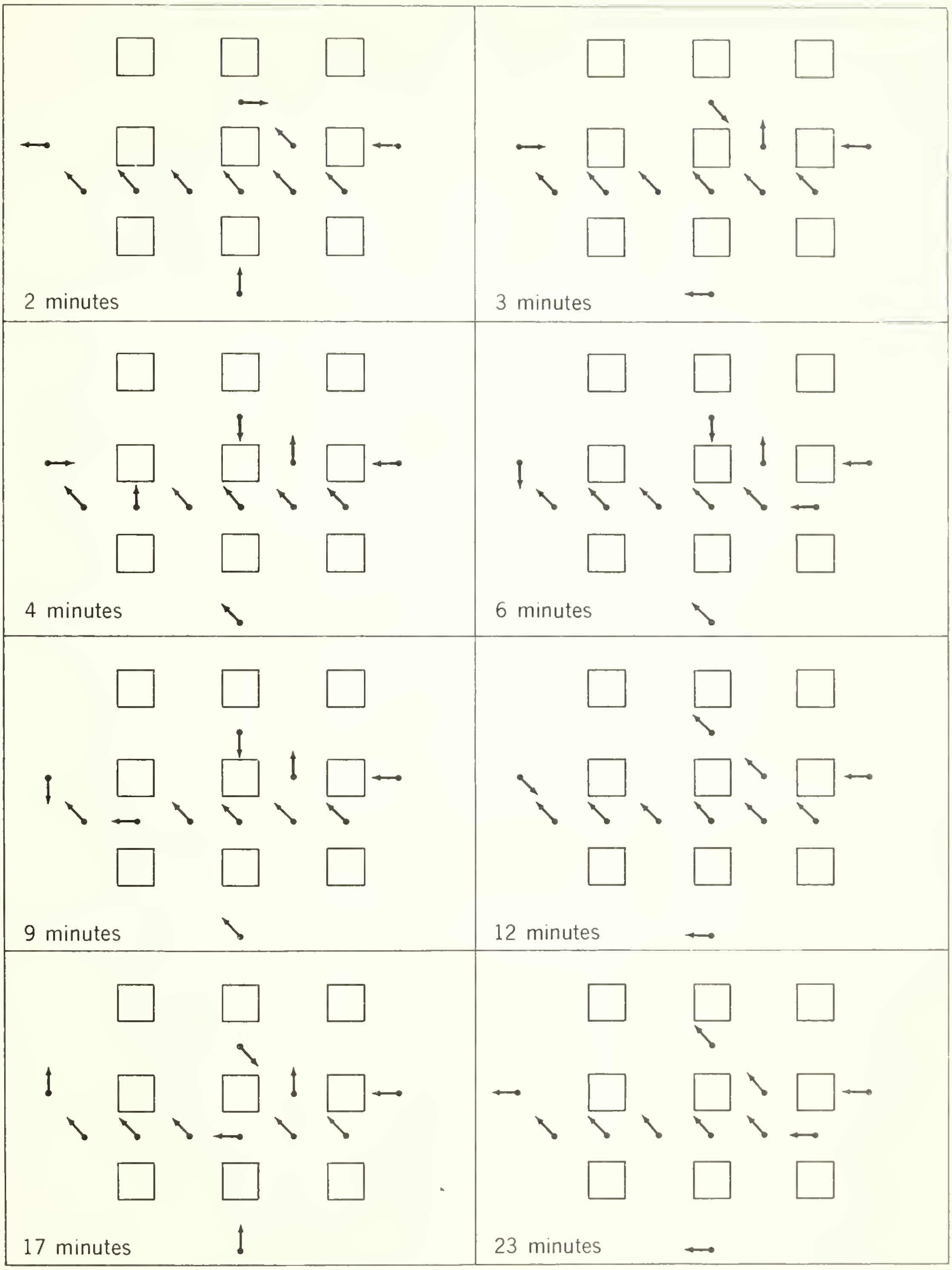


Figure 19.--Air flow pattern, test fire 760-1-63, at specified intervals, after ignition.

Wind speeds at all levels within the fire area showed a marked increase, but the pattern was not the same at different stations (fig. 21). Greatest increase in speed was at the 50-foot level, where a peak speed of 42 miles per hour was reached--more than 5 times the pre-ignition speed. Wind speed increased markedly at other levels, but the lower the level, the less the increase (fig. 22). The exact position of the tower with respect to the convection column at different times has not yet been determined, so that it is not certain whether this change in wind speed is an effect of the vertical currents on the horizontal-type anemometers or an effect of inflow into the convection column. In either case, it represents greatly increased air movement at higher levels as compared with the surface flow.

Fire Whirlwinds

Firefighters frequently report that whirlwinds develop in and adjacent to the intensely burning fires. Apparently originating at the ground surface, these "fire whirls"--as they are often called--are similar in appearance and behavior to the dust devils common to strongly heated bare land surfaces. Fire whirls vary greatly in size, strength, and duration. Whirls one-quarter mile in diameter and extending several thousand feet into the air have been reported from wildland fires. Speeds attained by the gases in these whirls have not been accurately determined but must be great: limbs may be twisted from trees and shrubs uprooted, even in moderate sized whirls. A large whirlwind that developed in the Polo fire near Santa Barbara, California, in 1964 moved out of the fire area and demolished a house and severely damaged several others (fig. 23). This whirl uprooted large trees and stripped limbs from others. A piece of quarter-inch plywood was driven 3 inches into an oak tree in the path of the whirl.

Fire whirls have also been reported in urban conflagrations. In the Tokyo fire after the 1923 earthquake, fire whirls were reported in several eyewitness accounts (3). One very large whirl in this disaster was apparently the cause of many casualties and of extensive fire spread.

Tornado-like winds have also been reported in both wildland and urban fires. These winds seem to differ from the fire-whirls in origin; that is, they appear to originate well above the ground surface and then extend to the ground where their behavior is the same as for fire whirls.

Besides the destruction caused by wind, fire whirls and tornadoes contribute greatly to fire spread because they pick up large firebrands and scatter them over a wide area. Many wildfires seemingly controlled have been lost when a fire whirl scattered burning debris across the cleared fire lines. Accounts of some urban fires indicate that fire whirls may transport noxious gases and deplete oxygen supplies.

Although the causes of fire whirls and tornadoes and the mechanism of their development is far from being completely known, research and observation have provided some clues. Byram (7) and Broido (2) have used a special device to create a fire whirl on a miniature scale. The device imparts a circular motion to the air flowing into a fire burning a small quantity of hydrocarbons. Greatly increased rates of burning and flame heights were observed in these experiments. Observers on wildland fires and prescribed burns report that whirls develop most frequently on the lee side of a ridge. It has been postulated that the whirls may result from lower pressure caused by the air flow across the ridge (24). Fire whirls have been observed to develop when fire burned over an area where an air flow eddy created by topography was known to exist (13). Fire whirls have also been observed to occur more frequently on wildfires when the air mass was unstable to a considerable depth. The Hamburg fire storm during World War II occurred during light wind and unstable air conditions (18).

Conditions conducive to fire whirl development, then, appear to be unstable air, a large heat source, circular motion in the ambient air, and fire on the lee side of a ridge. Test fire 428-1-63 was set up to meet as many of these conditions

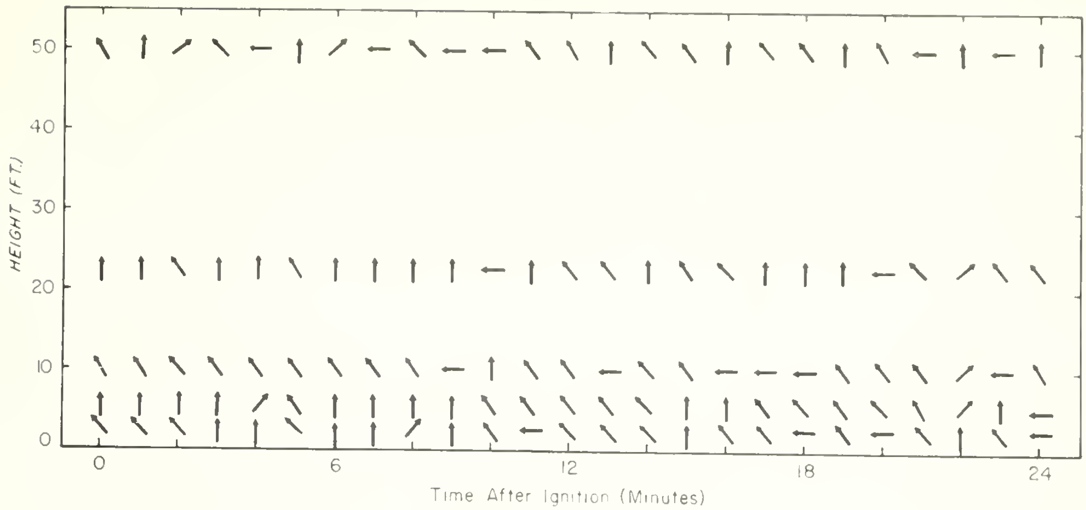


Figure 20.--Air flow direction at 50 ft. tower (station W-12, fig. 20 A), test fire 760-1-63.

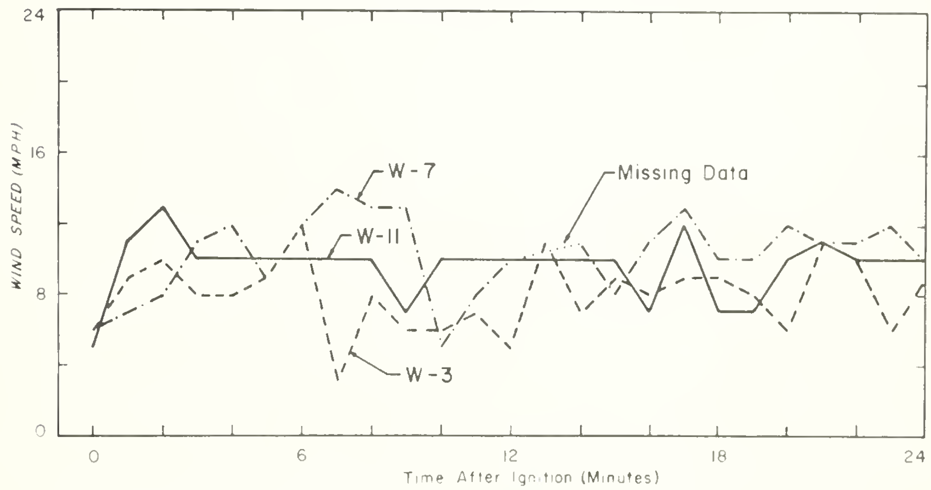


Figure 21.--Wind speed in ''streets'' (stations W-3, W-7, W-11, fig. 20 A), test fire 760-1-63.

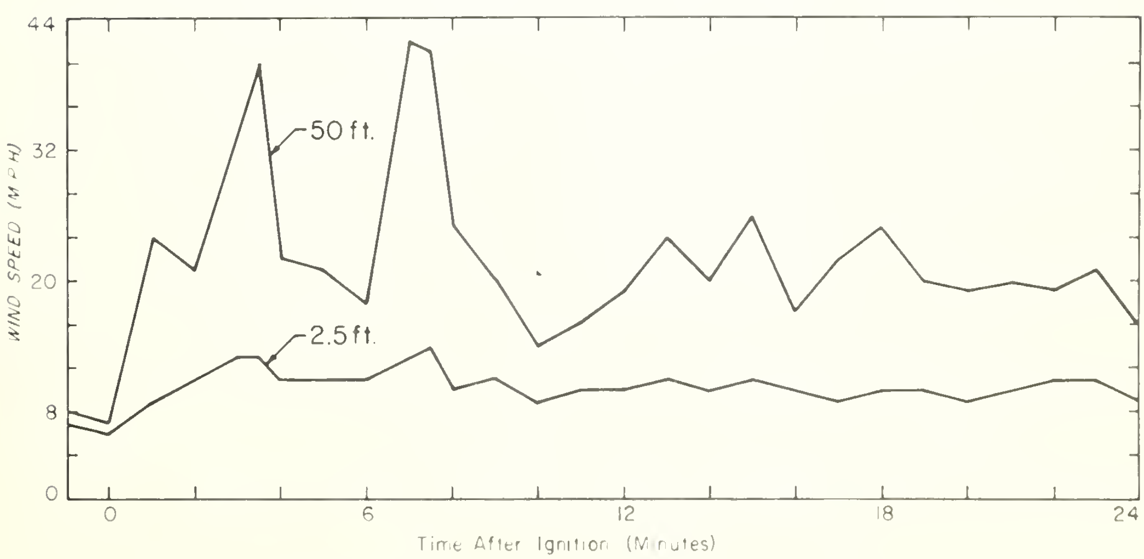


Figure 22.--Wind speed at two levels, station W-12 (fig. 20 A), test fire 760-1-63.

Figure 23.--House destroyed, and trees stripped and broken, by fire.

as possible. The plot of 72,000 square feet was located on the lee slope of a canyon. The plot was loaded uniformly with fine fuel at the rate of 1.45 pounds per square foot. The plot was fired in the late afternoon during unstable air conditions and with a wind of 8 to 10 m.p.h. across the ridge top.

Multiple ignitions were used to fire the plot, with a delay in firing the lower half to create upslope thermal winds (fig. 24). As expected, the fire built up in intensity very rapidly, and fire whirl activity commenced as soon as the ignition fires began to merge (fig. 24, B). The whirls increased in frequency and size as the fire developed (fig. 24 , C). The largest whirls, however, developed after the fuel was practically all consumed (fig. 24, D). The height of these whirls could not be determined precisely since their tops were in the smoke layer above the fire. As happens so frequently in wild fires, the whirls scattered so many firebrands in the adjacent plot that the suppression crew could not control them all and this plot burned also. Fire whirls were somewhat less numerous in the adjacent plot although strong and active whirls did develop. The difference in activity appeared likely to be due to the irregular ignition pattern caused by the spotting and a slower fire build up. Parts of the plot had burned out before the entire plot was ignited.

The strong whirl activity in test 428-1-63 destroyed much of the instrumentation--particularly temperature sensors--so that quantitative information in some areas was rather sketchy. A good photographic record of the fire is available, however, to confirm notes of observers on the scene.

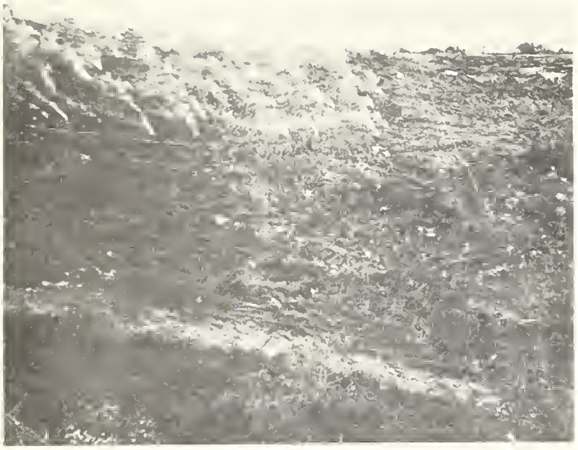
In the early and peak flaming periods of the fire the whirls consisted mostly of flame. Whirling activity was generally less than 30 feet in height with the flame usually less than half this height. Close-hand observation of development of these whirls showed that flames in a hot burning area would suddenly start moving in opposite directions. Flames that had been leaning up the slope would lean downslope while adjacent flames would continue to hold their upslope direction. A whirling motion would then begin, first over a relatively wide area. Once the whirling action started, the whirl was quickly compressed into a small area, and the speed of the circular motion increased greatly. Inflow into the whirl appeared to be solely from a layer close to the ground. A whirl 3 to 4 feet in diameter could be seen to affect flame direction at the ground level for at least 50 feet (fig. 24, C). The whirls tended to stop as suddenly as they formed. The speed of the whirl would decrease and the circular flow spread over a wide area and then stop entirely. Except near the ground surface, air flow into the whirl was not apparent; that is, no air entrainment into the whirl appeared to occur except at the bottom. In the later stages of the fire whirls heavily loaded with dust, ashes, and smoke extended more than 200 feet into the air.

The development and behavior of the fire whirls in this test closely parallels that postulated for vorticity. It is likely that theoretical and mathematical treatment of vortices can be applied successfully to fire whirls. This treatment will be attempted as quantitative data are collected.

Fire whirls were observed to develop in all test fires burned thus far, although not as numerously as in test 428-1-63 described above. Test 380-1-62 was also burned on a lee side of a ridge. This fire of about 170,000 square feet did not burn very intensely, and active whirl action was not observed until some time after peak intensity. In this fire, the height of each successive whirl tended to increase until the fire activity had decreased greatly (table 8).

Test fire 380-6-63 was burned on nearly level terrain and under relatively stable conditions. Although a very intense fire developed because of the size (49,750 sq. ft.) and heavy fuel loading (40 lbs./sq. ft.), comparatively little whirl activity developed. In one area outside the plot, long twisted whirls were observed to develop repeatedly and move into the fire (fig. 25) instead of out of the fire as in the case of other fire tests. It was observed that air flow in this area tended

A



B

C

D

Figure 24.--Test fire 428-1-63. A, Top half of plot was fired first to create upslope winds; B, fire whirl activity began as ignition fires began to merge; C, fire whirls increased in intensity and size as the fire developed; D, largest fire whirls developed after fuel was nearly all consumed.

Figure 25.--Whirling dust cloud just outside of fire at right marks place where fire whirls developed repeatedly in test 380-6-63. Picture taken after major flaming had subsided.

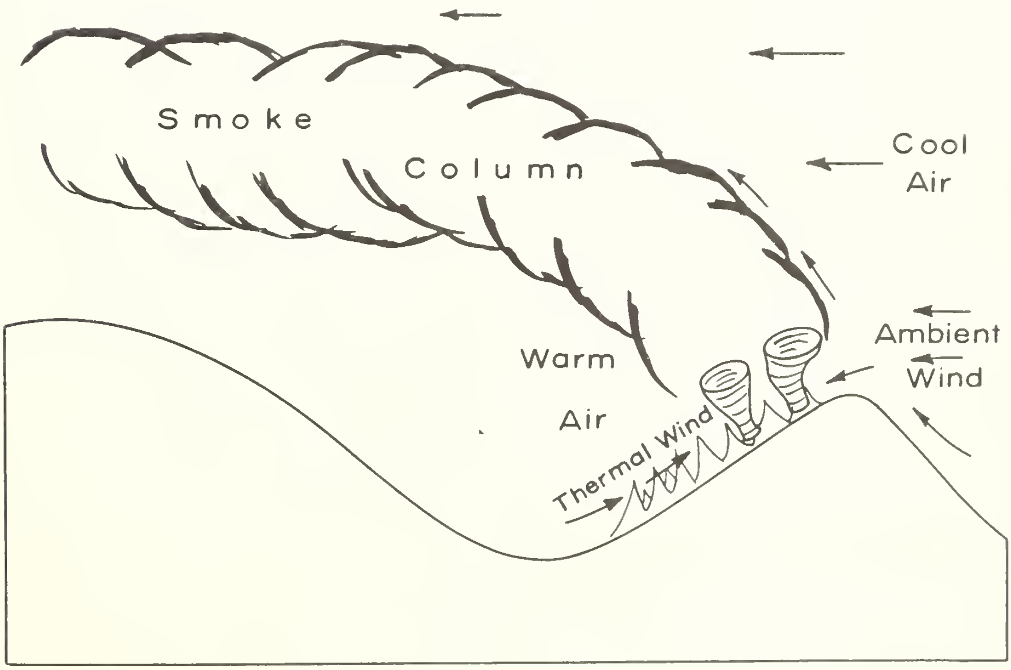


Figure 26.--Development of fire whirls on lee slopes.

Table 8.--Fire whirl heights, test fire 380-1-62

Time after ignition	Height (feet)	Description
9 min. 30 sec.	27	Flame
24 min. 15 sec.	134	Dust and smoke
28 min. 10 sec.	238	Flame, dust, and smoke
33 min. 30 sec.	310	Flame and smoke
35 min. 0 sec.	663	Flame, dust, and smoke
- - -	- -	(Moved out of fire)
46 min. 0 sec.	621	Flame and smoke
55 min. 30 sec.	477	Dust and ashes
79 min. 0 sec.	528	Dust and ashes

to move in opposite directions owing to the ambient wind, the configuration of the test plot, and indraft into the fire. In tests 760-1-63 and 760-2-64, major whirl activity tended to occur where air currents were opposed.

The frequency with which opposing air currents appear as a factor in the development of fire whirls indicates that this type of air flow is one of the requirements for fire whirl development and possibly for the development of fire storms. Such air flow may occur under natural conditions in situations where eddies tend to develop. Or the effect of the fire on air flow may induce such a flow pattern. When this pattern is present, heat from a fire apparently triggers the development of vortices. Air stability also appears to be of major importance in whirl development. When the air is unstable, upward movement of air is enhanced; consequently, fire whirls require a less intense heat source to start, or to become stronger with a given heat source than in stable air.

The prevalence of fire whirls on lee slopes is likely due to both fire-induced air flow patterns and air instability. When fire is burning over a sizeable area on the lee slope of a canyon somewhat sheltered from the ambient wind, the fire creates upslope thermal winds. These winds can be expected to meet the downslope ambient wind on the upper part of the slope. This is the area in which whirls have been observed to develop most frequently and was the case in test fire 428-1-63. The air within the canyon is heated by the fire; cool air flows over the ridge, an unstable condition is created which also favors the development of fire whirls (fig. 26).

Opposing air currents and air instability probably are not the only controlling factors of development of fire whirls. It is also not known with any degree of certainty how much fire area and rate of heat production are needed to produce such whirls with a given lapse rate in the atmosphere. Nevertheless, the knowledge that fire whirls are likely to occur where there are opposing air currents or eddies, and that they are more likely as instability increases, can help predict fire behavior in both wildland and urban fires. Knowledge of local air flow patterns should permit the fire control officer or fire behavior specialist to pinpoint areas where fire whirls are most likely to occur for a given fuel type and loading. Delineation of these danger spots could be done before any fire occurred and steps taken to limit the danger or to plan for control action and personnel safety.

Convection Columns

The convection column, which may tower 25,000 or 30,000 feet or more into the atmosphere, is probably the outstanding characteristic of a large fire. Perhaps because of the frequent occurrence of massive convection columns over large fires and their striking appearance, fire convection columns have received considerable attention and have been the subject of a number of theoretical analyses.

Usually such analyses have been based on the resemblance of a convection column to thermal plumes and jets. Actually there is little quantitative information available about the characteristics of a large convection column over a free-burning fire. Problems in obtaining measurements are extremely difficult and have not been adequately solved.

Although towering convection columns have sometimes been postulated as essential to the development of large and intense fires, there is little evidence that this is true. Under strong wind conditions, intense rapidly spreading fires often occur without a strong convection column. Rates of spread and areas burned in such fires often exceed those in similar fuels when active convection columns do develop. In fact, observation of wildland fires indicates that the development of a strong convection column may reduce rate of spread where long-distance spotting is not a factor. In some types of prescribed burning, such as logging debris disposal, ignition of the area in such a way as to produce a strong central column is often attempted. The indrafts produced when convective activity is strong help prevent fire spread beyond the desired boundaries.

A tall convection column may be a symptom of high rate of combustion and not necessarily the cause. The intensity with which a fire burns is often greater when convective activity is strong, and it is under these conditions that most erratic and unusual fire behavior occurs. It is likely that the strong fire convective activity results from favorable environmental conditions--low surface wind speed, unstable air mass, and plentiful dry fuels. Once an active convective column does develop, it may contribute greatly to fire spread under certain conditions by carrying firebrands far ahead of the main fire. It is also possible that through turbulence the momentum of the higher levels of air is transferred to the ground under certain circumstances.

From a distance, a convection column looks like a single rising stream of gases and smoke. On an active large fire the column appears to rise from the entire burning area as a continuous mass. Viewed close to the fire, however, it loses its continuity and is seen to be made up of a number of smaller convection columns developing over relatively small "hot spots" of active fire (fig. 27). These individual columns merge some distance above the fire area to form the single column appearance characteristic of the distant view.

Even on small test fires, the tendency for the fire to break up into small convection columns was evident. After the initial "flash over," which lasts for only a few minutes, fires as small as 2,500 square feet developed hot spots and separate convection columns with relatively clear air between (fig. 28). In some cases the separate columns developed immediately.

In the larger fires the hot spots were more numerous (fig. 29). The hot spots did not remain in one place but would form, burn actively a short time, die down, and then reappear later. Occasionally two or more of these active areas would merge for a short time. Over the burning mass of fuel, then, the more intensely flaming areas were continually shifting from place to place.

On test fire 380-6-63, low-lift balloons were released so that they would drift into the convection column. Usually these balloons reached the edge of the fire area and rose along the edge of the column to the rolling turbulence about 250 feet above the ground. Here they were drawn into the column, made an outward and downward loop, and be drawn back into the column again, occasionally appearing again in another roll higher above the ground.

On two occasions the balloons drifted directly over the center of the fire at a height of about 75 feet instead of rising along the edge of the column. These balloons did not rise immediately, but moved up and down several times before reaching the level of the rolling turbulence. Here they suddenly shot upward at high speed and disappeared in the smoke.

Figure 27.--Three separate convection columns are apparent in this wildland fire. Tallest trees on horizon are about 20 feet high.

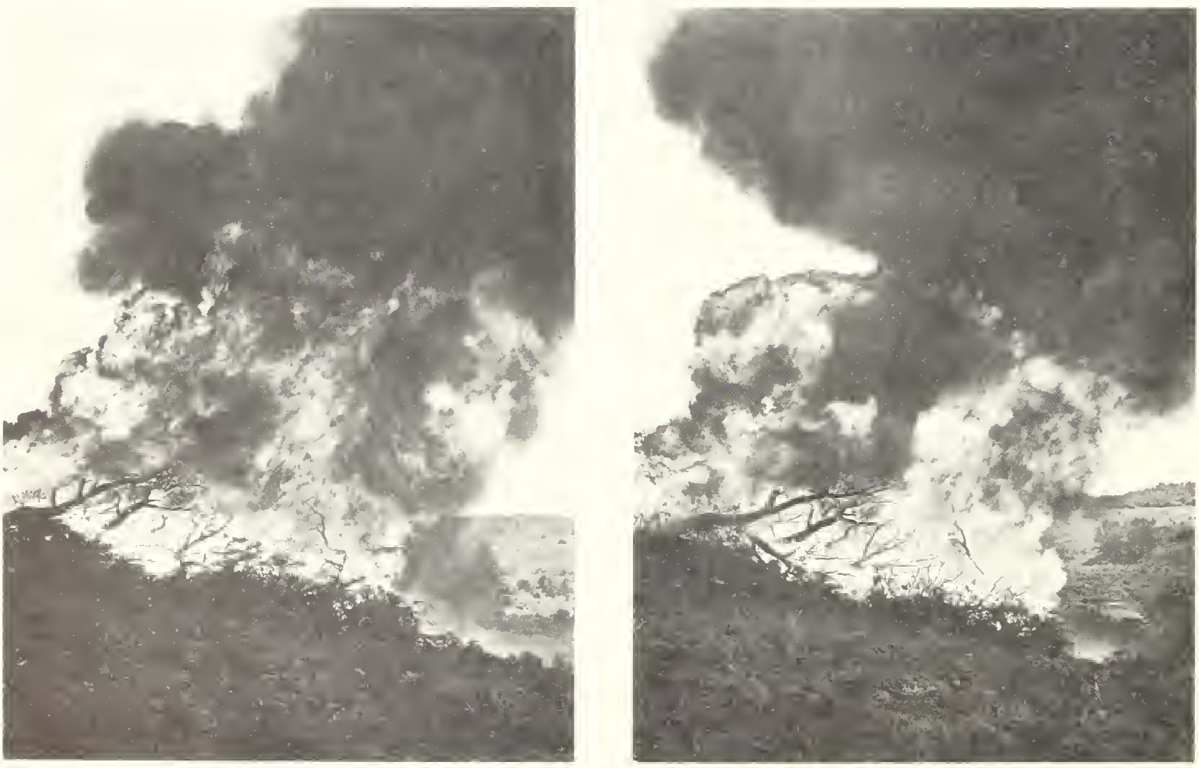


Figure 28.--Flame column beginning to break up into two separate columns, left; and separate columns fully developed, right. (Fire 760-1-63.)

Figure 29.--Hot spots and separate convection columns were numerous on larger fire areas. Flame heights in right foreground are about 55 feet. (Fire 380-6-63.)

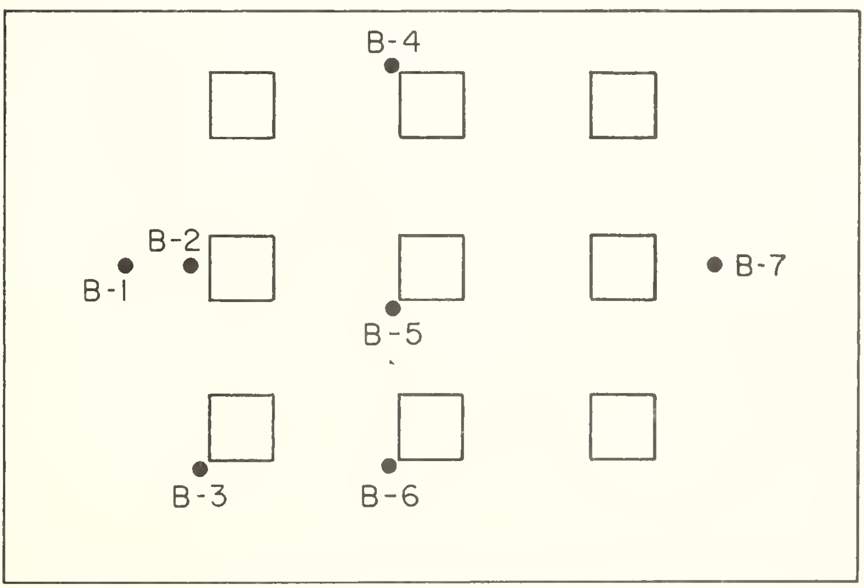


Figure 30.--Location of pressure sensors, test fire 760-1-63.

The behavior of these balloons and the tendency for hot spots to develop in the fire area strongly suggest that within a layer over the fire area both updrafts and downdrafts exist, and that the fire may obtain air for combustion from above as well as from the periphery of the fire area. Updrafts probably develop around the hot spots with downdrafts between. Thus the air for combustion does not necessarily enter the combustion zone at the level of the fuel bed, but may well be entering from a relatively deep area surrounding the fire. This mechanism of air supply would permit fire to burn simultaneously over a very large area--with combustion not limited by oxygen deficiency, and strong indrafts not necessary to supply air.

Pressures

The rapid vertical motion of heated gases and smoke in the convection column of a fire, and the movement of air into the combustion zone, has frequently led to the assumption that the pressure inside a fire is lower than the ambient pressure outside. To determine the magnitude of this pressure differential, a sensitive pressure device was buried underground in the fuel bed with the inlet tube about 18 inches above the ground surface. Surprisingly, a positive instead of a negative pressure was found in this area of the fire for the three fires in which such a measurement was made. This positive pressure persisted through a large part of the duration of the fire. Instrumentation difficulties make the magnitude of the pressure differences somewhat uncertain, but it appeared likely that the increase in pressure might be greater than 0. 5 inches of mercury.

The air flow pattern around the heavy-fuel fires suggested that a low pressure area might exist in the wake of the fire. A pressure sensor was buried about 20 feet outside the fire in test 360-6-63 in the area just upstream from where it was estimated that wake eddies would form. A negative pressure developed in this area as the fire approached its peak flaming period and apparently persisted for a considerable time. Again difficulties with the instrumentation made the exact magnitude and duration of the pressure difference uncertain. It appeared possible, however, that the negative pressure may have exceeded 1 inch of mercury for a time.

Pressure sensors were placed adjacent to and between piles of fuel in test 760-1-64 (fig. 30). All but one of these sensors (B-7, on the upwind side) showed substantial pressure drops. The sensors in the interior of the plot showed rapid fluctuations during the peak flaming period, varying quickly from negative to positive pressure and back again. These fluctuations may have been caused by fire whirls.

This pressure distribution, if substantiated, would be of major importance in the design and operation of ventilation systems in shelters which might be beneath burning buildings or debris or adjacent to fires. The positive pressure occurs within the fire where the maximum concentrations of carbon monoxide are found. This pressure could thus force lethal gases into a shelter located below. In a moving fire where a low pressure area may exist ahead of the fire, it is possible that an open ventilation system would permit air in the shelter to be partially evacuated, thus creating a greater pressure differential when the fire reached the shelter. These tentative findings suggest that during the time a fire is in the area of a shelter the ventilation system should be closed to prevent intrusion of combustion products into the shelter area.

Radiation

Obtaining the experimental data needed to establish an energy-rate balance on the test fire systems has been a basic goal. These data are necessary inputs toward quantifying fire ignition and spread problems. Radiation measurements, using flat plate or directional radiometers or both, were made on all of the test fires. One of the major purposes of making these measurements was to provide part of the necessary data to compute a heat balance for the individual fires. This analysis has not yet been attempted. The radiation data also served to show the relative rate of fire build-up for fuels of different types.

In the heavy-fuel plots, peak radiation occurred 10 to 18 minutes after ignition (fig. 31). The drop in radiation intensity in test 380-4-63 at 10 minutes after

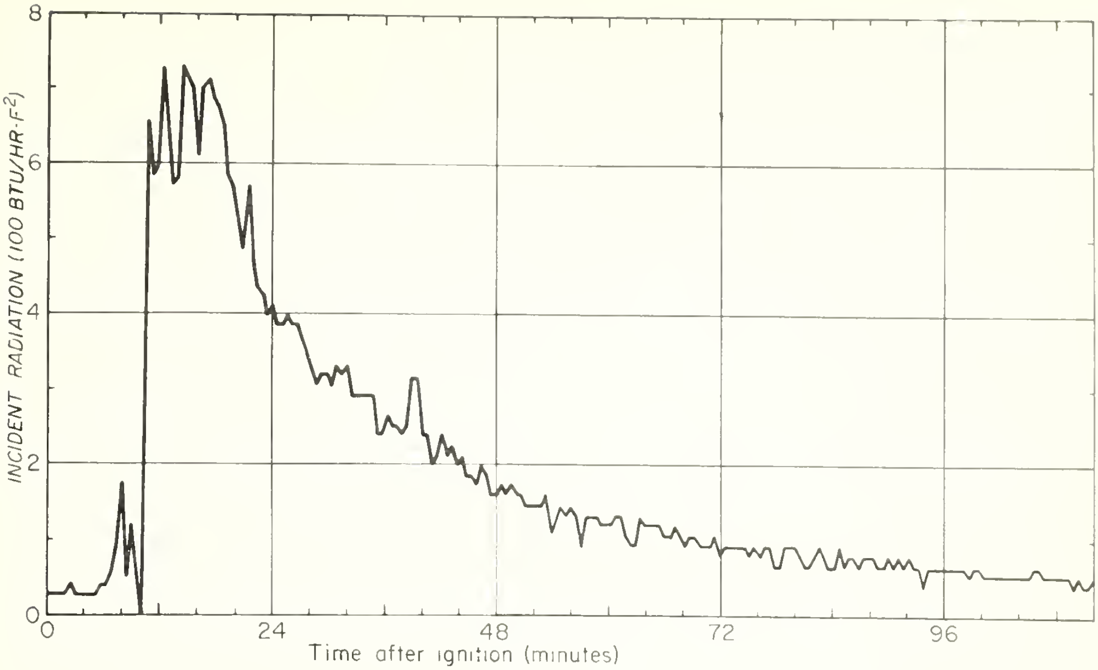


Figure 31.--Incident radiation on flat plate radiometer 100 feet from fire edge. (Test fire 380-4-63.)

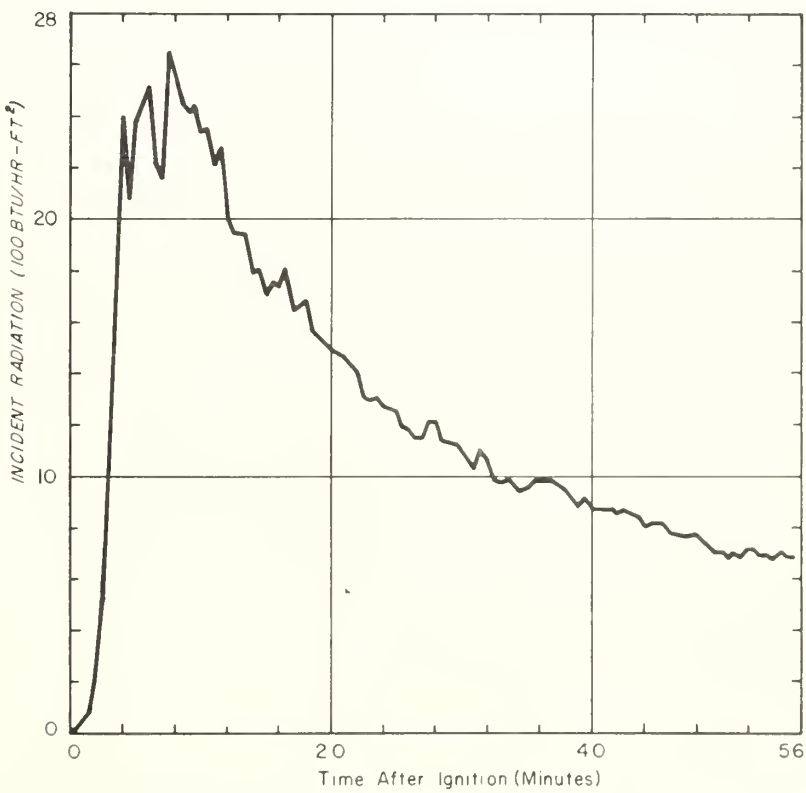


Figure 32.--Incident radiation on flat plate radiometer 90 feet from center of observed pile. (Test fire 760-1-64.)

ignition was probably caused by smoke momentarily obscuring the radiometer. In the mixed-fuel plots peak radiation was usually reached 4 to 8 minutes after ignition (fig. 32), but in one case occurred 2 minutes after ignition. Peak radiation on the flat plate radiometers occurred during the peak flaming period.

On all of the fire tests, it was observed that ignition by radiation of fuels on the ground outside the fire area was limited to a very short distance from the fire edge (fig. 33). On the windward side and flanks, this distance was limited to 3 to 5 feet; on the downwind side, to less than 15 feet. Even in the narrow zone around the fire, it was not certain how much ignition was caused by radiation alone and how much by small firebrands falling on heated fuels.

Radiation heating of small fuel particles was measured with dowels containing thermocouples. Hardwood dowels 4 inches long and 1/4 inch in diameter were drilled longitudinally to within 1-1/2 inches of the end; a thermocouple inserted in the hole was held in tight contact with the dowel by means of a wooden plug. These dowels were then exposed in an upright position about 24 inches above the ground at various distances from the fire edge.

On test fire 380-6-63, the maximum temperature of the dowel exposed 6 feet from the fire edge was only 295° F, despite flames that reached 50 to 60 feet in height and a hot fire that persisted for several hours. The temperature-time curve (fig. 34) of these dowels was similar to the radiation intensity curve measured with a flat plate radiometer. In the initial stages of the fire, the dowels close to the fuel pile were shielded from radiation and temperature of dowels farther away rose more rapidly (fig. 35). When the fire had enveloped the entire pile and the peak flaming period had passed, the logarithm of the dowel temperature varied linearly with the logarithm of the distance from the fire (fig. 36).

It is possible that fuels of a different size or configuration could be more strongly heated by radiation. In a fire moving through continuous fuels, however, it appears unlikely that radiation from flames above the fuel bed is a very important factor in fire spread because of the slow rate of heating. McCarter and Broido (31) found this to be true in crib fires. When fuel ahead of the fire was shielded from flame radiation, the rate of fire spread in the crib remained virtually unchanged. Observations of wildfires also have indicated that radiation becomes important in fire spread only under special situations, such as in very narrow, steep-sided canyons. Flame contact with unburned fuels and firebrands falling ahead of the fire appear likely to be the main mechanism by which fire spread, particularly where wind is a factor.

Temperature

To provide information on the magnitude and pattern of temperature in the fires, thermocouples were placed at various points in and above the fuel bed. Shifting fuels, fire whirls, and high fire intensity frequently destroyed or damaged the thermocouple supports or lead wires before the fires burned out. Methods of supporting and exposing the thermocouples were modified continuously to improve the durability of the temperature sensing system. Thermocouples sheathed in inconel or stainless steel and supported on insulated steel pipes were found to work most satisfactorily, and this system was used in the later tests.

Heavy Fuels

In the heavy-fuel tests, it was necessary to clear an area 5 or 6 feet in diameter around the pipe supports. Thermocouples on these supports were thus not in direct contact with the burning fuel, although they were frequently engulfed in flame. Thermocouples were also strung between pipe supports directly over the fuel bed.

Flame temperatures in these fires appeared to be considerably higher than the 1,400° to 1,600° F. reported for laboratory fires. Valid temperatures of 2,300° F. or greater were recorded on nearly all fires. Temperatures in fire whirls were probably considerably greater as indicated by the bright orange flame in the whirls as compared with the darker red of the surrounding flames.

Figure 33.--Snow drift on edge of mixed-fuel plot was not melted appreciably by radiation. Note unburned vegetation close to fire edge.

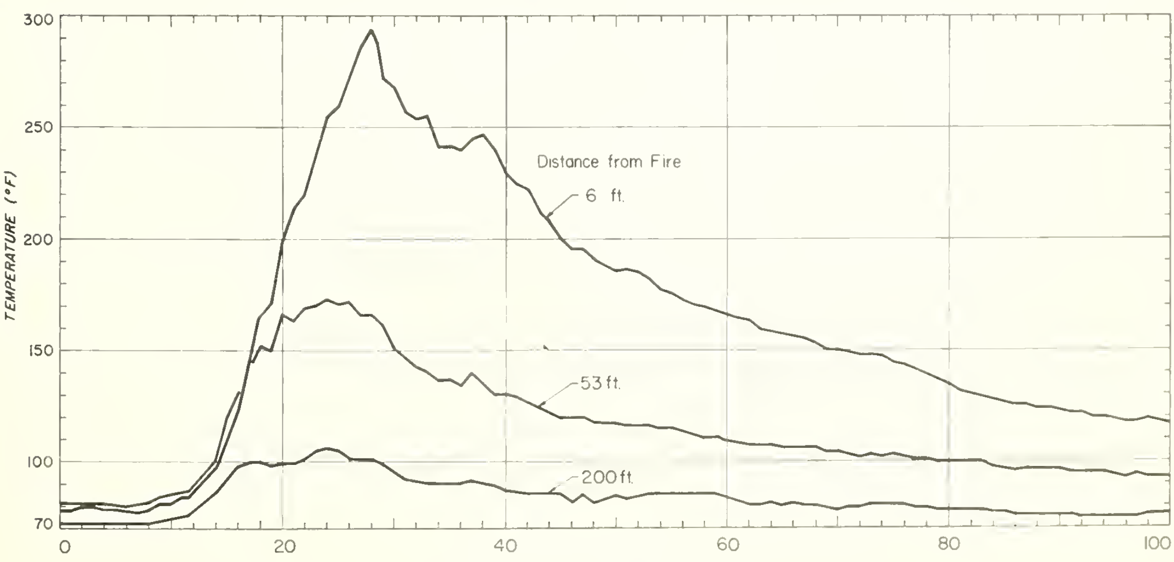


Figure 34.--Time-temperature history of fuel particles outside test fire 380-6-63.

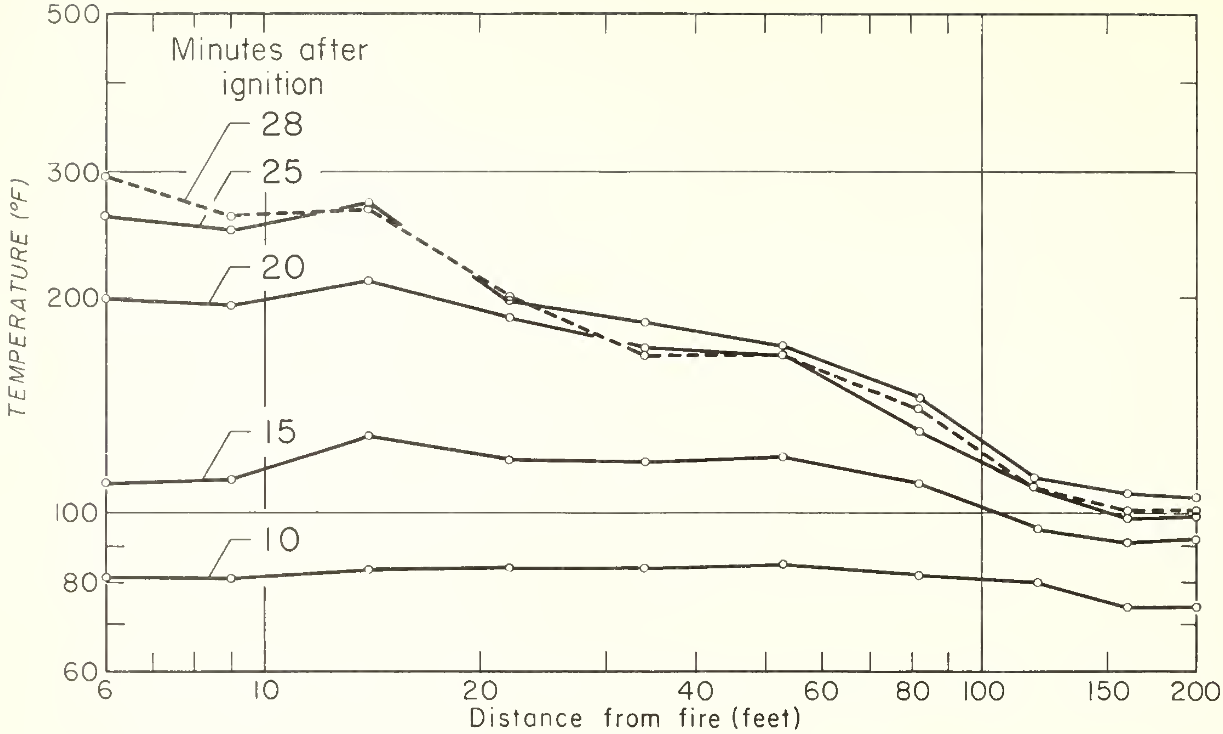


Figure 35.--Temperature of fuel particles outside test fire 380-6-63 during early stages of the fire.

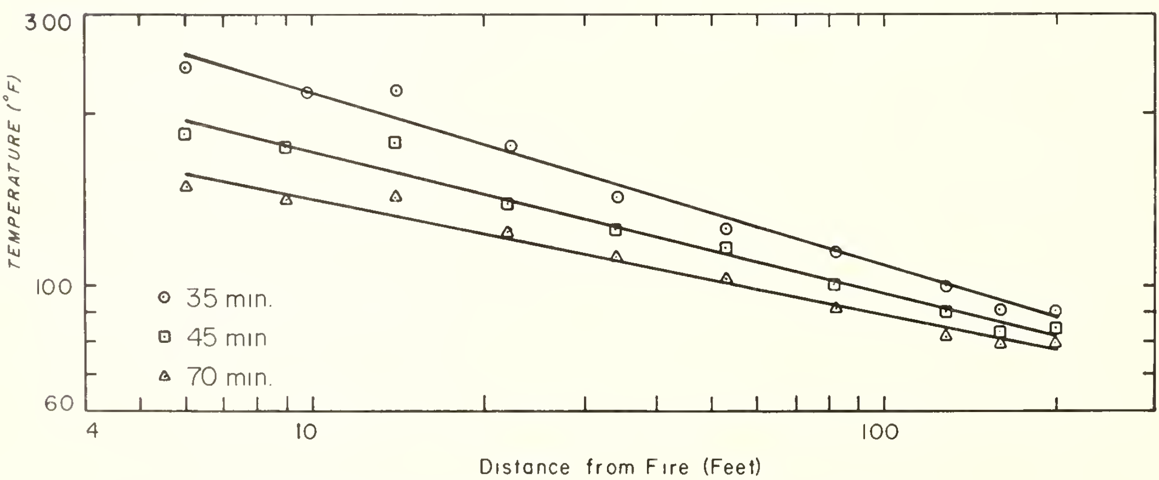


Figure 36.--Temperature of fuel particles outside test fire 380-6-63 during middle stages of the fire.

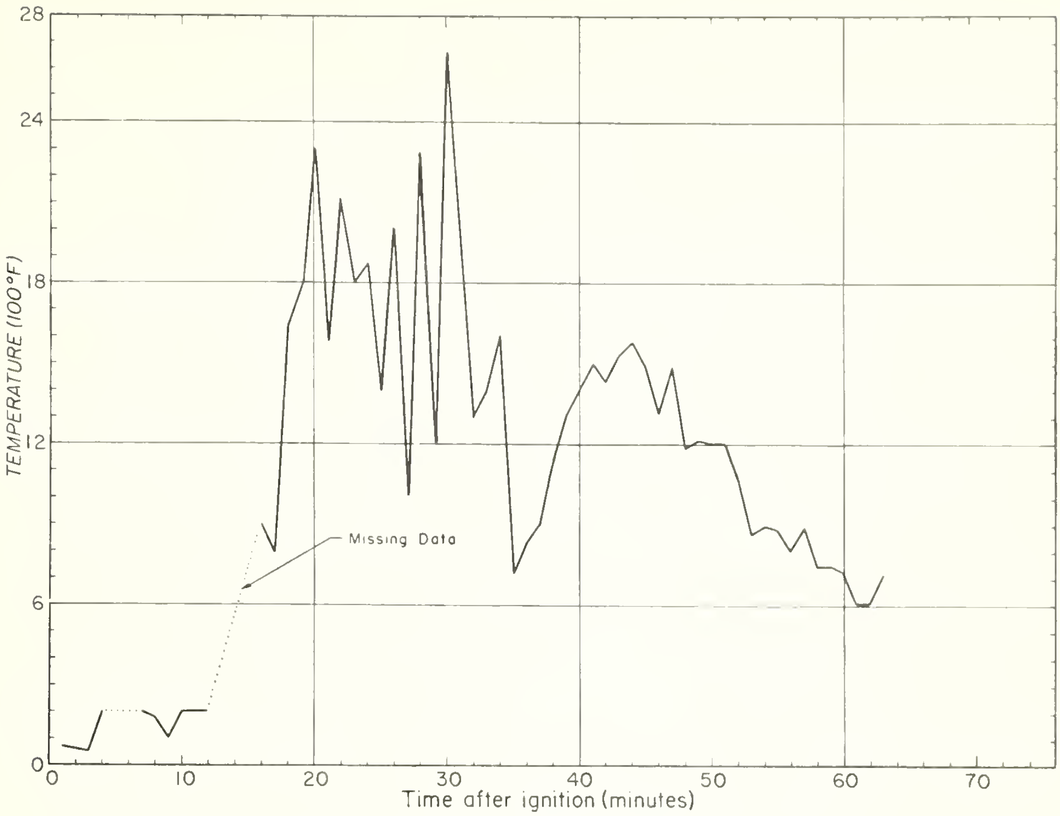


Figure 37.--Temperature at 15 feet above the fuel bed, test fire 380-4-63.

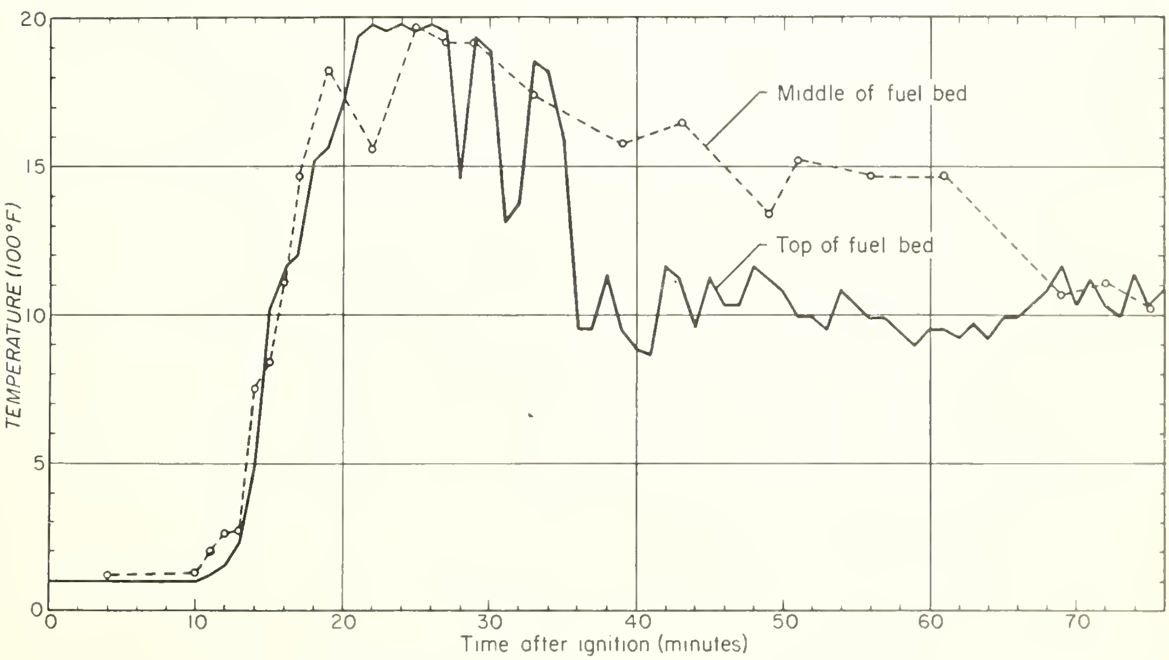


Figure 38.--Temperature at top and middle of fuel bed, test fire 380-4-63.

The temperature pattern of the thermocouples above the fuel bed was marked by very rapid fluctuations of considerable magnitude (fig. 37). This was caused by flame "flicker." Burning gases would shoot up rapidly and die away or shift position so that the temperature sensor was seldom more than momentarily in the flame. Only for a brief time during the maximum flaming period early in the fire history did a solid mass of flame appear above the fuel. For most of the active fire the combustion zone was a mass of constantly moving, shifting flames. "Hot spots" would develop, burn briefly, and die away only to reappear somewhere else.

Close to the top of the fuel bed and within the fuel bed, temperature fluctuations were not as rapid as above the fuel bed (fig. 38). The lower peak temperature measured in this area in test 380-4-63 is probably due to the cleared area around the sensor support. The indicated temperatures thus more nearly represent gas temperatures than flame temperature.

Mixed Fuels

The effect of wind on the temperature pattern was apparent in some of the individual fires in multiple-fire test 760-1-64. Thermocouples were strung in a line approximately 3 feet above the fuel bed and spaced so that one thermocouple was over the center of the pile, another about 9 feet in from the edge of the pile on the windward side, and a third the same distance from the edge of the pile on the downstream side.

In all three positions the temperature rose very rapidly soon after ignition (fig. 39). For the first 8 to 10 minutes, or during the violent flaming period, the temperature remained high at all three points. After this initial period the wind began to tilt the convection column. The temperature on the windward side then

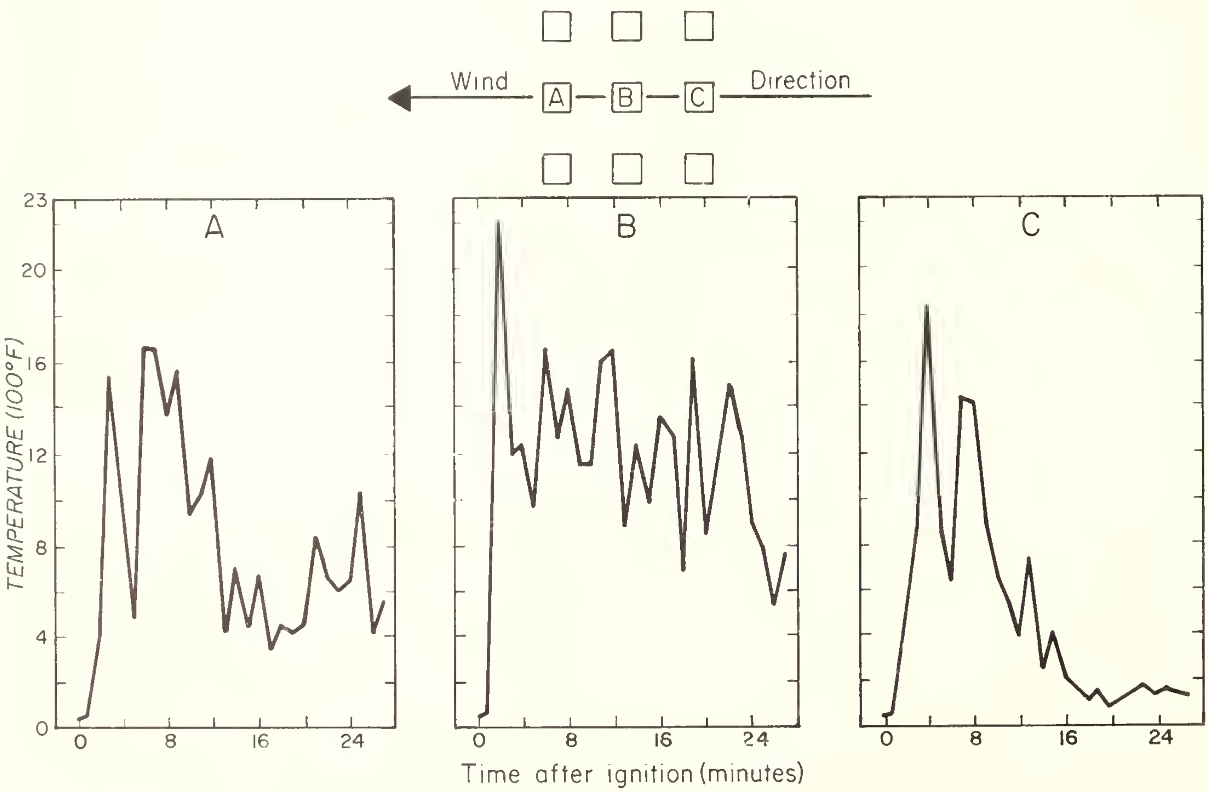


Figure 39.--Temperature 3 feet above test fire 760-1-64, at windward, middle, and lee locations.

dropped rapidly and after 16 minutes never rose more than 120° F. above the ambient air temperature. Above the center of the pile the temperature remained high; the temperature on the lee side, although lower than the center, was considerably higher than at the windward position.

Urban Fuels

In the house fire (test 642-1H-64) thermocouples were placed in a number of locations in all of the rooms. Ignitors were placed on the roof and outside walls, and in the rooms on the north side of the house. The ignitors on the roof and walls failed to start fires, but the house was ignited by the inside ignitors and by a fire that started in trash at the rear or east side. The fire at the rear built up most rapidly so in general the fire spread from the rear toward the front of the house. Thermocouples in the center of the first and second story rooms in the southwest corner of the house showed similar and typical patterns (figs. 40, 41). Temperatures rose slowly as the fire moved toward the rooms. When the rooms "flashed over" and became filled with flames, the temperature rose abruptly to more than 2,300° F. The walls of the rooms burned through quickly and, as the house began to collapse and outside air was able to enter, the temperature dropped quickly. The temperature rose again after the house had collapsed completely and the remaining fuel began to burn more intensely. The position of the thermocouple with respect to the fuel bed was not known during this latter period.

Convection Column

Temperature measurements in the convection column at greater heights than was possible with the steel pile towers were sought by suspending modified radiosondes from tethered weather balloons. Because of the extreme turbulence in the convection column, the balloons survived only a short time. The turbulence also made it difficult to keep the sensor in the convection column. Fragmentary temperature records, however, indicated that temperatures in the convection column 100 to 125 feet above the fire were surprisingly low. In test 760-1-64 at 16 minutes after ignition, the temperature at 125 feet was 98° F., indicating a great deal of air entrainment and heat loss in a very short distance.

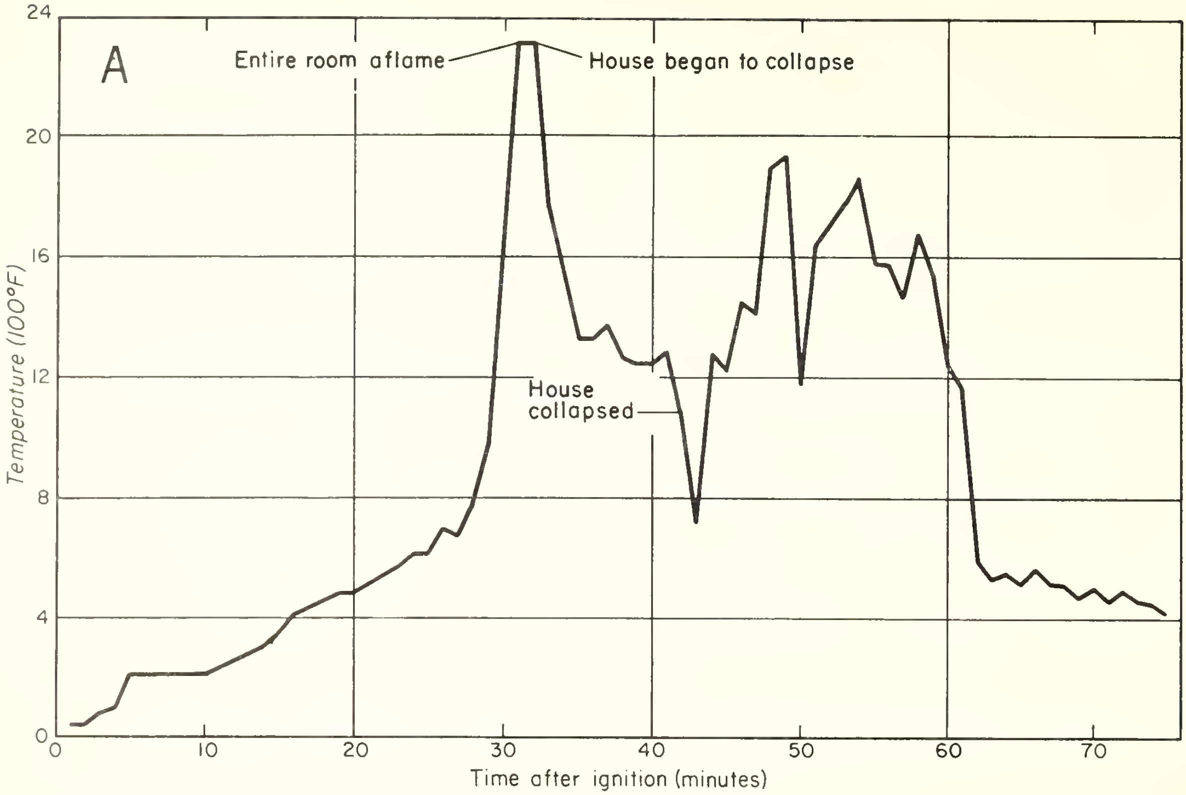
"Street" Temperatures

In test 760-1-64, an aspirated temperature sensor was placed between two of the piles at a height of 4.5 feet. Air temperature increased at this point soon after ignition, reaching a peak of 65° F. (24° F. above ambient) in 60 to 90 seconds (fig. 42). The temperature then dropped slowly and by 6 minutes after ignition was only 4 or 5 degrees above the ambient air. Although the air temperature was not high, the heat radiated from the burning piles made it impossible for unprotected personnel to walk in the streets between the piles during the first 12 to 15 minutes after ignition while flaming was at a maximum. After this initial period, it was possible to walk between the piles without undue discomfort, although the piles of fuel were still burning actively.

Noxious Gases

Reports of some fire raids in World War II noted that many people that died in shelters were apparently untouched by fire. In areas subject to high temperatures, the position of the bodies and mien of some victims indicated that death was probably not caused by fire. It has been postulated that deaths under these circumstances may have been caused by carbon monoxide poisoning or lack of oxygen or both. Medical examination of the bodies lent some evidence to this theory. Therefore, we decided to check this theory in some fires. In many of the completed test fires, continuous samples of gases were taken near the center of the fire, either within the fuel pile or 20 feet above the ground level. Intermittent samples were also drawn from other areas within or adjacent to the fire. These samples were analyzed for carbon monoxide, carbon dioxide, and oxygen.

Peak concentrations of carbon monoxide and carbon dioxide were found to occur during the intense flaming period when samples were taken near the ground



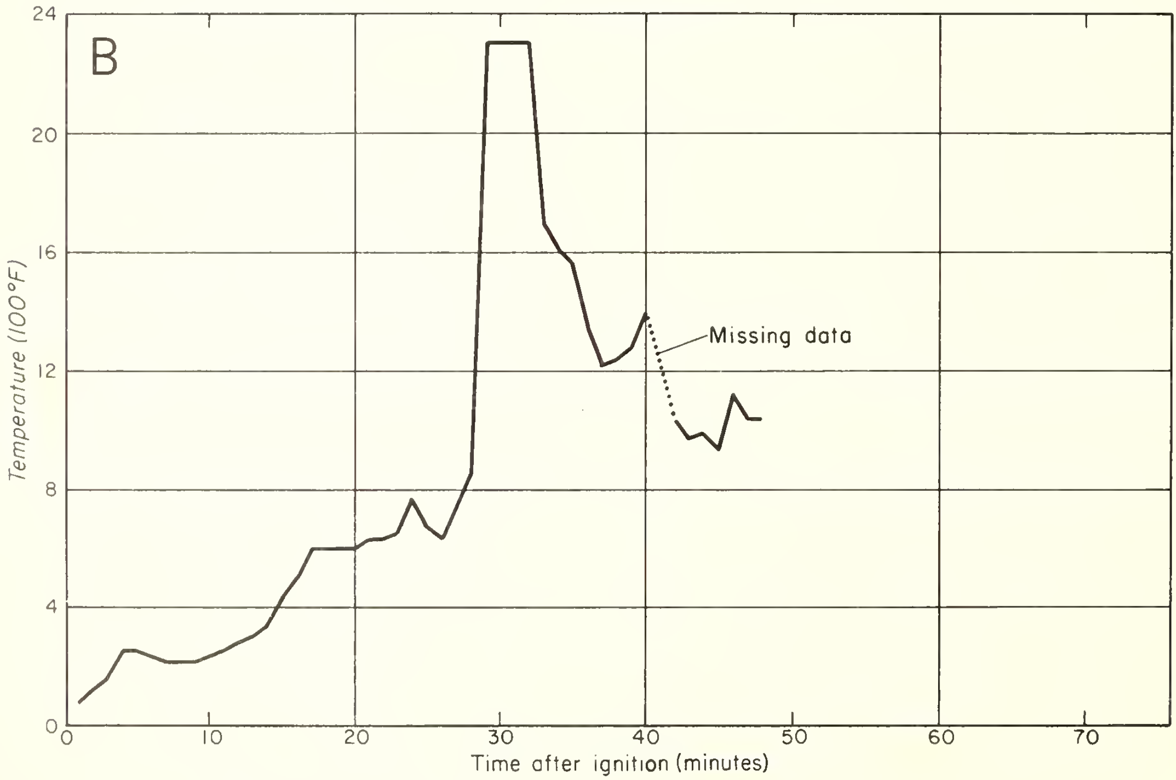


Figure 40.--Temperature pattern, test fire 642-1H-64; A, in center of first story sw. corner room; B, in center of second story sw. corner room.

Figure 41.--House fire (test 642-1H-64). A, North side showing ignitors (dark spots) on walls and roof. B, E, South side, at specified intervals after ignition.

A

B - 28 minutes

C - 36 minutes

D - 42 minutes

E - 65 minutes

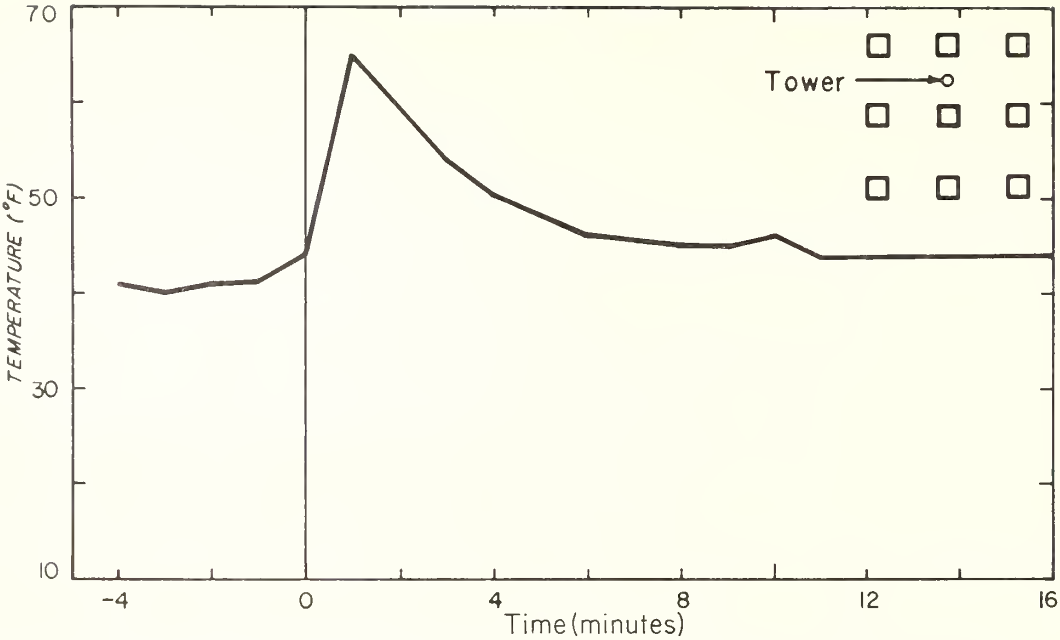


Figure 42.--Temperature at 4.5 feet in ''street,'' test fire 760-1-64.

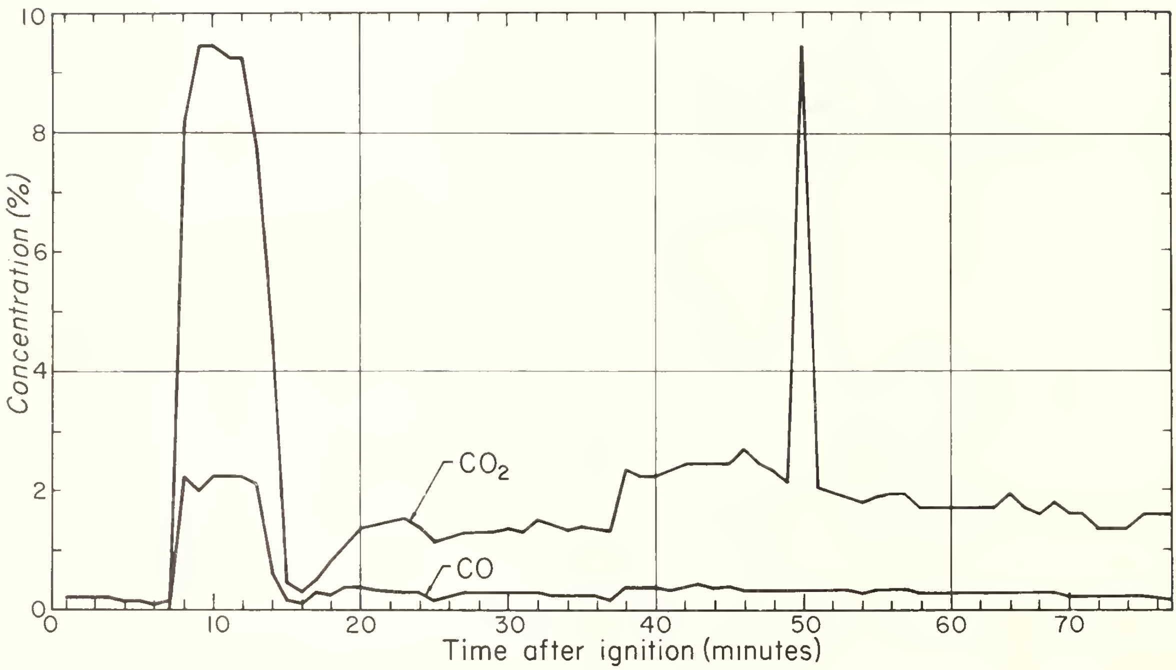


Figure 43.--Concentration of carbon monoxide and carbon dioxide 12 inches above ground, test fire 380-2-63.

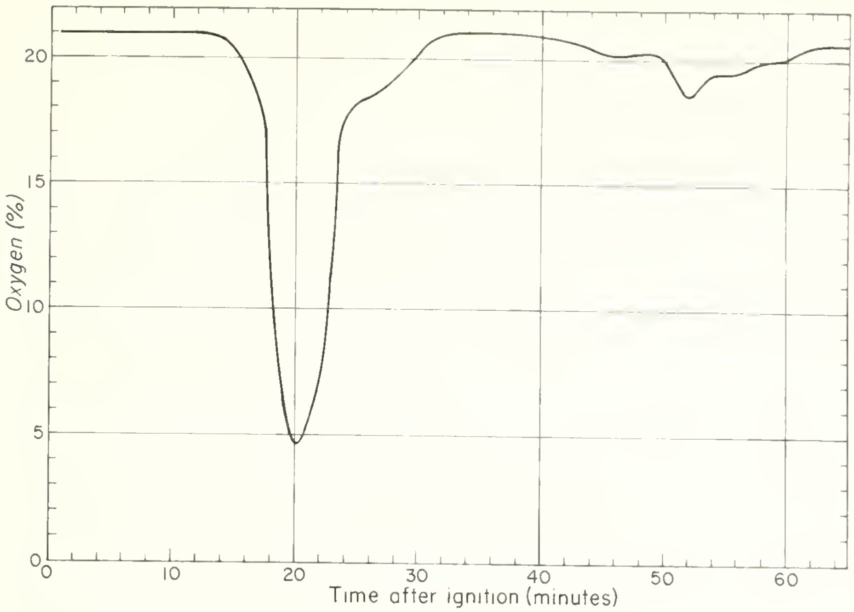


Figure 44.--Concentration of oxygen 12 inches above ground, test fire 380-3-63.

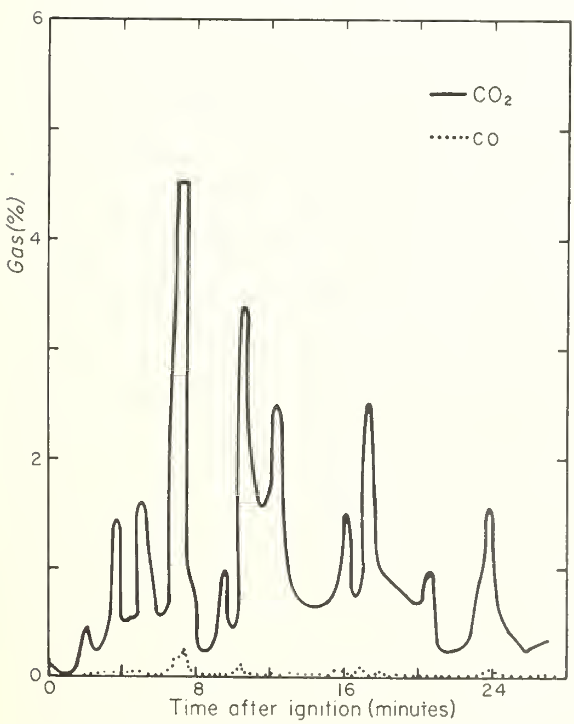


Figure 45.--Concentration of carbon monoxide and carbon dioxide 20 feet above ground, test fire 760-1-64.

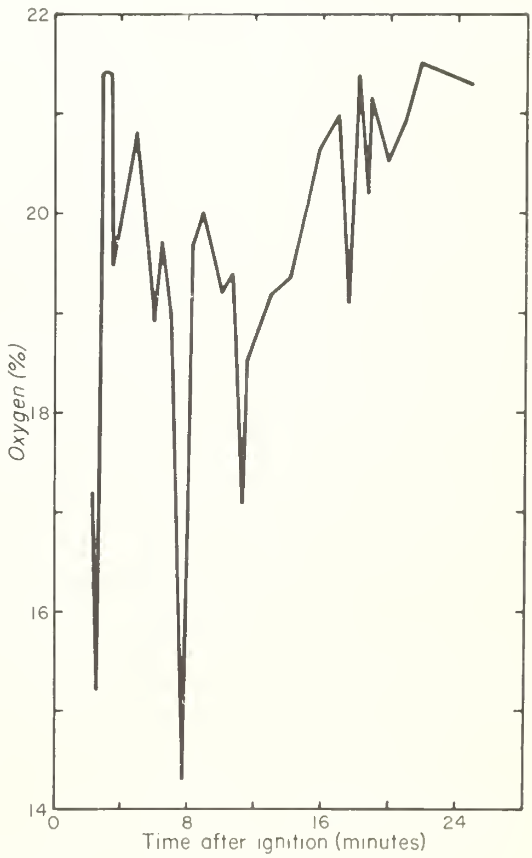


Figure 46.--Concentration of oxygen 20 feet above ground, test fire 760-1-64.

within the fuel pile (fig. 43). The high concentrations lasted for a relatively short time, but moderate concentration of carbon monoxide varied from fire to fire--in some cases exceeding 5 percent. Oxygen depletion was also very evident in the test fires (fig. 44). The greatest depletion also occurred during the maximum flaming period of the fire.

In test 760-1-63, the sampling tube was placed in the center fuel pile 20 feet above the ground. At this level carbon monoxide concentrations were relatively low, and carbon dioxide concentrations were also considerably less than at the 12-inch level of previous fires (fig. 45). Some oxygen depletion was still evident at this level (fig. 46).

The high concentrations of carbon monoxide in all probability is the result of incomplete combustion in the active part of the fire. Preliminary tests have indicated much lower concentration near the edge of the fire, and no significant concentrations of this gas were found in the "streets" of test fire 760-1-64. Whether lethal concentrations of gas or oxygen deficiency can be transported into nonburning areas in larger fires with closer spacing is yet to be determined.

Summary and Conclusions

The relatively small-scale field tests conducted on Project 2521E were largely exploratory in nature, and preliminary to larger multiple-fire tests planned in the later series. Fifteen multiple-fire plots have been prepared, the largest covering about 10 city blocks and containing 420 simulated houses. A gradual stepping up of the size of test fires was decided on. This approach was used because of the dearth of quantitative information about large fire behavior; even those factors to be measured, and the phenomena that might be significant were not known with any degree of certainty. No precedent existed for determining the kinds and amount of instrumentation needed and measuring systems that would succeed in large-scale tests. Large test fires are expensive to prepare and conduct. Essentially they are "one shot" affairs. Once ignited there is little opportunity for changing their course or modifying instrumentation to record any unforeseen event. The smaller fires burned so far were essential to provide at least a general knowledge of what to expect in larger tests and to develop instrumentation and techniques to gain maximum information from the larger tests.

The completed tests cannot be considered mass fires in the strict context of the term because of their relatively small size. Yet they have provided invaluable information about fire and provided good indications of what may occur in larger scale fires. Some of the data obtained also strongly suggests that conditions may exist in field-scale fires that are not evident in small-scale or laboratory fires. The results also indicate some areas where theoretical analysis can aid greatly in the prediction of probably fire behavior.

Some of the more important results and conclusions from the completed tests are:

1. <u>Wildland fuels can be used to simulate many urban conditions</u>.--Individual fires in the piled wildland fuels behaved in much the same manner as building fires conducted in this study and in other studies by the Pacific Southwest Station. The use of wildland fuels to simulate urban fires permits experimental fires of a size and intensity not practical under urban conditions.

2. <u>Field scale fires can be replicated</u>.--Tests conducted thus far have indicated that under like air mass conditions and with similar fuel types and arrangements the fire characteristics will also be reasonably similar. Fire behavior phenomena observed on one fire can thus be verified in replicate tests.

3. <u>Eddy circulations are important in the development of fire whirlwinds and possibly of fire storms.</u>--Observations of the fire tests showed that fire whirlwinds tended to develop in areas where opposing air currents or eddies occur. Such air flow may result from natural causes or from air currents induced by the

fire. Fire-induced whirlwinds appear more likely to develop under unstable rather than stable air mass conditions. Since it is possible that fire storms are large-scale vortices or groups of vortices, these factors are also likely to be important in the development of firestorms.

Locating areas where natural or fire-induced eddy circulations are probable should be feasible with present knowledge. Such information would be valuable for prefire planning of control and safety action. Modification of conditions so as to lessen the hazard would also be possible. Accuracy of such predictions can be greatly improved with more information on the interrelationships of rate of heat production, air stability, direction and strength of opposing air currents, and the development of vortices in fires.

4. Maximum air entrainment into the fire area may occur well above the base of the fire. --Air flow into the base of the single-fire test was negligible. On the one multiple-fire test (760-1-64), indrafts were more noticeable but still of low speed. In this test wind speed was considerably increased in the streets between the fires and this increase was greater with increasing height above the ground surface.

5. Fires may block ambient air flow. --Ambient air flow around a hot fire is similar to the flow of a moving fluid around a solid object with turbulence and eddies developing in the wake. There are some indications that with a tilted convection column there is transfer of momentum toward the ground from the convection column.

6. Radiation may be of minor importance in fire spread for many fires. --Very little effect of radiation on spread of fire was found in any of the test fires completed. This verifies observations on wildland fires and some laboratory tests. Where wind is a factor, fire spread is more likely because of flame contact with unburned fuel and firebrands falling ahead of the fire.

7. Behavior differences between small and large fires may be due in part to temperature. --Flame temperatures and consequently combustion zone temperatures were found to be considerably higher in the test fires than those found in small experimental fires. Flame temperatures in the test fires exceeded 2,500° F. and may be greater than 3,000° F. In a small fire, the air for combustion is drawn from the relatively cool ambient air which acts to cool the flame. In a large fire much of the air for combustion is drawn from above the fire and from air passing through the combustion zone from the sides. Air reaching the interior flames is superheated, often reaching 1,000° F. or more, and hence provides relatively little cooling. These higher temperatures can be expected to create more violent fire activity.

8. Fires burned as multiple jets after the initial "flash-over." --After the initial flaming period, fires tended to break up into a number of "hot spots" each with a separate convection column. Gas movement in a zone of considerable depth above a fire was highly turbulent, with both upward and downward currents. Above this turbulent zone the convection columns merged and the more organized flow of thermal convection was apparent.

During the initial flaming period, the fires had some aspects of a single-orifice diffusion flame. This quickly changed into a multiple-orifice "burner" with numerous and shifting areas of active flaming. Height of flames in a fire is therefore controlled principally by laws governing multiple jet orifices.

9. Temperatures within the convection column were relatively low. --The temperature within the "organized" flow of the convection column of a fire is apparently very much lower than in the turbulent combustion zone. This change in temperature may be rather abrupt. The ambient lapse rate (air stability) may thus have a much greater effect on the convection activity than supposed and may account in part for the observed strong effect of air mass instability on large fire behavior.

10. Positive pressures may occur in the combustion zone and negative pressures may occur outside. --Observations in the test fires have indicated that an increase in pressure may occur within the combustion zone and negative pressures may develop in the lee or wake of the fire.

11. Lethal concentrations of noxious gases occurred within and adjacent to fire. --High concentrations of carbon monoxide and deficiency of oxygen were

detected in the combustion zone of fires, with lower concentrations at the edge. The peak concentration of lethal gases and minimum oxygen concentration occur at about the same time, hence may have a more serious effect than their individual effects in a normal atmosphere. The presence of the lethal gases combined with the possible pressure pattern suggests that shelters beneath a fire or adjacent to it should be sealed during peak fire intensity at least. Significant concentrations were not found in the "streets" of the test fire area.

12. Heat intolerable to unprotected persons can be reached very quickly in a fire area. --The rate of build-up of a fire in a fuel bed ignited simultaneously on the exterior and interior is extremely rapid. Heat conditions intolerable for human survival can be reached within 2 to 3 minutes inside a building or in streets as wide as 115 feet between burning buildings.

13. Instrumentation is a major problem in large-scale fire tests. --The size of the tests, the nature of the phenomena involved, and the large number and variety of measurements needed make the instrumentation of larger-scale test fires a major problem. Conventional laboratory techniques are generally not practical. The problem is not insoluble, however, and solutions are being obtained in this and other projects.

14. Larger fires are needed. --Tests thus far completed have been indicative of the kind and magnitude of fire behavior phenomena observed in large and intense fires. Some leads have been obtained as to why extrapolation of data from small fires does not adequately predict observed behavior of large fires. Larger fires are needed to further explore and substantiate these indications and to determine the effect of fire size on the observed phenomena. Fires larger than those already prepared will probably be required.

15. Effects of fire pattern and ignition pattern need study. --Prescribed burning and observations of wildfire have indicated that both ignition pattern and fire pattern have a marked effect on fire behavior. These effects need to be quantified in controlled tests. Fine fuels, such as crushed brush, should provide media excellent for such tests. Preparation of tests in this fuel type is relatively low in cost, and the fuel is in plentiful supply.

16. Behavior of long-burning fires needs exploration. --There are some indications that long-burning fires, such as might occur in large buildings of heavy or relatively slow burning construction, may develop different fire behavior characteristics than more rapidly burning fuels. Tests are needed to explore this possibility. Because of the high cost of preparing such tests, they should not be attempted until more quantitative information on large fire behavior is available.

17. Intensive investigation of fire vortices would be invaluable. --Fire test 482-1-63 showed that strong vortices can be intentionally developed in experimental fires with the right combinations of weather, fire intensity, and topography. The role that each of these factors play in the development of vortices is not known except in a very general way. Additional information on fire vortices is expected from the currently planned tests. Because of the importance of this phenomenon in fire damage and control, a series of tests designed specifically to investigate large-scale vortices would be desirable to speed acquisition of data that would lead to the understanding and prediction of fire storms. It would also be desirable to attempt to map situations with a high potential for fire vortices in wildland and urban fires.

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Insect-caused Deterioration of Windthrown Timber in Northern California, 1963-1964

Boyd E. Wickman

U. S. FOREST SERVICE RESEARCH PAPER PSW- 20

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

1965

CONTENTS

The Author

Boyd E. Wickman is a research entomologist working on the problem of timber losses due to insect attacks. He joined the Forest Service's experiment station in Berkeley in 1955. A native of Orinda, Calif., he received his B. S. degree in entomology from the University of California, Berkeley, in 1958.

Acknowledgments

I wish to thank the Fruit Growers Supply Company, the Lassen Volcanic National Park, and the Lassen National Forest for providing study sites and trees; the Lorenz Lumber Company for providing infested logs for study; and James A. Litsinger and Benjamin H. Startt for assisting with the field phases of this investigation.

A windstorm of hurricane force struck the Pacific Northwest on October 12, 1962, and caused timber damage of catastrophic proportions. In northern California, the violent storm blew down nearly a billion board feet of coniferous timber. In some areas, especially along the Cascade Range's western slope, the blowdown centered in concentrated patches; in other areas, its effects were dispersed.

Immediately after the storm a survey of damage in northern California was carried out. It showed that 1½ million acres were affected in varying degrees.[1] Losses as of April 1963 were estimated at 600 million board feet; later estimates increased these losses to nearly 1 billion board feet. The blowdown, by species, in northern California was estimated as follows:

Species	*Percent*
Red fir (*Abies magnifica*) and white fir (*A. concolor*)	46
Ponderosa pine (*Pinus ponderosa*) and Jeffrey pine (*P. Jeffreyi*)	28
Douglas-fir (*Pseudotsuga menziesii*)	14
Sugar pine (*P. lambertiana*)	9
Others	3

The highest losses were concentrated on areas partially logged 1 to 5 years before the windstorm.

The two primary problems involving insects after such catastrophes are: (a) the degrade of downed timber resulting from the feeding of bark beetles and wood borers; and (b) the threat to standing timber by beetles attracted to or emerging from the downed timber. The extent of the heavy damage following the 1962 storm presented an excellent opportunity to study the problem of degrade and to collect data on the problem of beetle attraction. Therefore, study plots were established in the spring of 1963 and checked through the fall of 1964.

The objectives of the study were to learn more about (a) what species of insects attack windthrown timber, (b) how soon they infest the trees, (c) how long the trees remain attractive to wood-boring insects, (d) how much damage the insects do, (e) how long the trees are salvageable, and (f) the life history of wood-borers. This report describes the results of this work.

Study Sites

This work was centered at the Pacific Southwest Station's forest insect laboratory at Hat Creek in Shasta County. Study sites were within a 20-mile radius of the laboratory (fig. 1).

Four study plots (fig. 2, table 1) were placed within representative stand types as follows: (a) virgin mixed conifer —Plot 1; (b) cutover mixed conifer—Plot 2; (c) virgin ponderosa-Jeffrey pine —Plot 3; (d) virgin red fir-western white pine—Plot 4. Two other plots in virgin Douglas-fir and ponderosa pine were salvage logged at the beginning of the study and then abandoned. A seventh plot in virgin lodgepole pine was maintained in 1963, but dropped in 1964.

Area and damage estimates for the stands where plots were set up ranged from 2,000 acres with 300,000 board feet to 6,000 acres with several million board feet. Estimates were made primarily from aerial mapping, supplemented by ground checks.

Plot size ranged from 5 to 20 acres, according to windfall density. The direction of the windfall was generally north or northwest. On each plot about 10 trees were selected to represent a range of tree species, size, exposure, and type of damage. Damage classes included: windthrown trees with roots in ground, windthrown trees with roots broken off or exposed, and trees windbroken and standing.

[1] California Forest Pest Control Action Council. Northern California Blowdown Committee report April 1, 1963. (Unpublished report on file at Calif. Div. Forestry, Sacramento, Calif.)

Sampling Methods

The first phase of the study, during the summer of 1963, was primarily concerned with learning distribution patterns and abundance of the insects alighting on and presumably attacking downed trees. Visiting insects were trapped by 10- by 10-inch cardboard squares coated with "Tree Stickem Special"[2] (fig. 3). The traps were tacked to the downed tree trunks at the base, midcrown, and top, and wherever possible on four quadrants around the trunk—top, bottom, and both sides (generally east and west)—at each level. Usually traps were fastened to at least five trees per plot. A total of 162 traps was used.

Plots were visited weekly and the insects removed from the traps and preserved. We assumed that wood-boring insects caught in the traps made their attacks there. Observations on insect attacks and live insect collections were also made each week. Information on insect collection was recorded on forms suitable for automatic data processing.

The second phase of the study, during the summer of 1964, dealt with the amount of damage the insects could do after 1 year of activity, their changes in numbers, and changes in the susceptibility of the timber to attack. Small wood samples from some of the study trees were periodically chopped or sawn out to determine progress of damage. Samples from cold-decked logs, salvaged from windthrown trees and stored at a local mill, were also dissected.

In late October of 1963 and 1964, one or two 12-inch sample bolts were cut at midbole from several trees per plot and dissected to check insect

[2] Mention of trade names and commercial enterprises or products is solely for necessary information. No endorsement by the U.S. Department of Agriculture is implied.

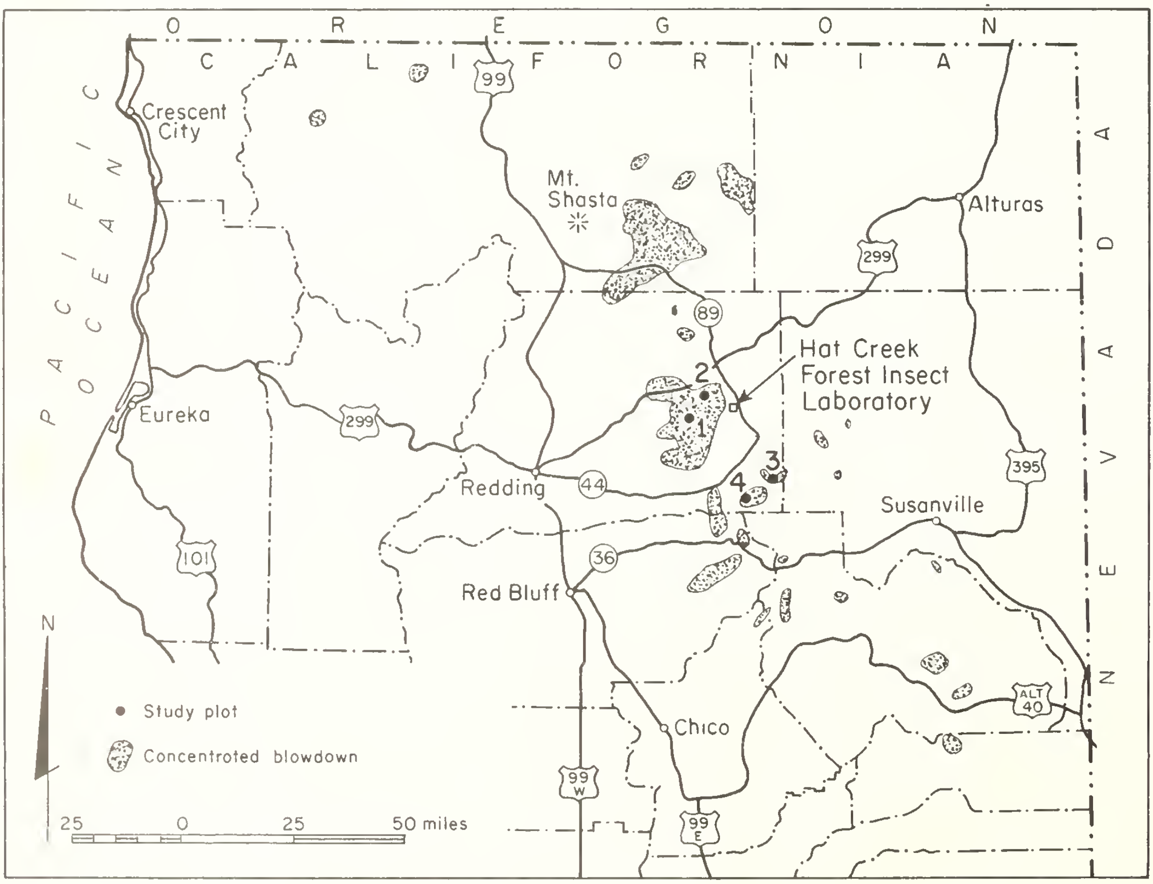


Figure 1.—Areas of concentrated blowdown in northern California, October 1962. Numbers indicate study plot locations.

Figure 2. — Kinds of sites used for studying insect-caused deterioration of windthrown trees. Top: *Plot 1, virgin mixed conifer stand, mostly white fir; hardwoods provided heavy shade.* Middle: *Plot 2, cutover mixed conifer, mostly white fir poles; this type of stand suffered heavy wind damage.* Bottom: *Plot 3, virgin ponderosa and Jeffrey pine; scattered large trees on open site.*

Table 1.--*Windfall study plots, Hat Creek area, summer 1963*

Plot No.	Location[1]	Date est.	Stand type[2]	Age class	Cut or virgin	Elevation	Exposure	Slope	Trees	D.b.h. ranges	Status[3]
						Feet		*Percent*	*Number*	*Inches*	
1	Snow Mt. (LNF)	June 18, 1963	MC	Mature saw-timber	Virgin	5,000	North	0	10	10-34	Used
2	Tamarack Rd. (FGS)	June 18, 1963	MC	Poles	Cut	4,000	North-east	2	14	10-24	Used
3	Butte Lake (LVNP)	June 25, 1963	PP JP WF	Mature	Virgin	6,000	East	0-20	16	12-54	8 trees logged Aug. 7, 1963. 8 used
4	Summit Lake (LVNP)	June 19, 1963	RF WWP	Mature	Virgin	7,100	East	10	10	17-25	Used
	Burney Flat (FGS)	June 16, 1963	PP	Mature saw-timber	Virgin	3,300	East	0-45	8	22-38	Cut June 21, 1963
	Hatchet Mt.	May 21, 1963	DF	Mature	Virgin	4,500	West	5	5	14-40	Cut May 30, 1963
	Bunchgrass Valley (LNF)	June 19, 1963	LP	Mature	Virgin	5,300	West	0	10	12-24	Dropped Oct. 31, 1963

[1]FGS = Fruit Growers Supply Co.; LNF = Lassen National Forest; LVNP = Lassen Volcanic National Park.

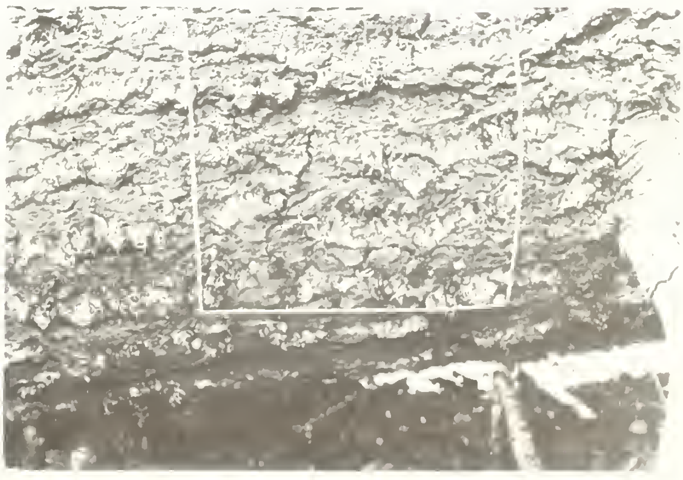
[2]PP = ponderosa pine; MC = ponderosa and sugar pines, white fir, Douglas-fir, and incense-cedar; DF = Douglas-fir; RF = red fir; WWP = western white pine; LP = lodgepole pine.

[3]Shows whether plot was salvage-logged or an active study site through the entire study.

Figure 3.—A 10- by 10-inch cardboard coated with "Tree Stickem Special" was tacked to windthrown timber to trap attacking insects.

Figure 4.—A 2- by 4-foot wire screen cage with zipper was stapled and caulked onto a windthrown tree to capture emerging insects. Sticky trap appears in foreground.

Figure 5.—String delineated a 10- by 10-inch emergence hole sample unit. White tacks mark the insect emergence holes.



development and wood deterioration. Three wood samples per selected bolt were also oven-dried to obtain moisture contents of a few downed trees which had some roots still in the ground. A few bolts were placed in rearing cages in case insect emergence occurred before plots could be revisited the next spring.

In 1964, wire screens, 2 by 2 feet and 2 by 4 feet, with long zippers, were stapled and caulked to study trees near the sticky trap to catch emerging insects that had completed their development (fig. 4). To check the reliability of the trapping technique, we also counted emergence holes at weekly intervals on 10- by 10-inch sample areas next to

Table 2.--*Insects causing deterioration of windthrown conifers in California, 1963-1964*

Family name		Number of species	Most important species
Common	Scientific		
Ambrosia beetles	Platypodidae Scolytidae	1 2	*Platypus wilsoni* Swaine *Trypodendron* sp. and *Gnathotrichus* sp.
Bark beetles	Scolytidae	6	*Dendroctonus* spp. and *Ips* spp.
Flatheaded borers	Buprestidae	11	*Melanophila* spp.
Horntail wasps	Siricidae	7	*Sirex* spp. and *Xeris* spp.
Melandryids	Melandryidae	1	*Serropalpus* sp.
Roundheaded borers	Cerambycidae	18	*Semanotus litigiosus* (Casey) and *Monochamus oregonensis* LeConte
Total		46	

Table 3.--*Destructive insects collected on windthrown trees, 1963 season*

A. Wood borers
- Coleoptera
  - Buprestidae: *Buprestis, Chalcophora, Chrysobothris, Melanophila, Dicerca, Acmaeodera*
  - Cerambycidae: *Monochamus, Acanthocinus, Asemum, Semanotus, Atimia, Callidium, Xylotrechus, Phymatodes, Leptura, Neoclytus, Stenocorus, Anaplodera, Spondylis, Poliaenus*
  - Melandryidae: *Serropalpus*
  - Scolytidae: *Trypodendron, Gnathotricus*
  - Platypodidae: *Platypus*
- Hymenoptera
  - Siricidae: *Sirex, Xeris, Urocerus*
  - Formicidae: *Campanotus*
- Isoptera
  - Hodotermitidae: *Zootermopsis*

B. Bark beetles
- Coleoptera
  - Scolytidae: *Ips, Dendroctonus, Scolytus, Pseudohylesinus, Pityopthorus, Pityogenes*

C. Wood borer parasites
- Hymenoptera
  - Ibalidae: *Ibalia ensiger* Nort.
  - Stephanidae: *Schlettererius cinctipes* (Cress.)
  - Ichneumonidae: *Megarhyssa nortoni* (Cress.), *Xorides* sp. or *Neoxorides* sp.
  - Braconidae: *Celoides brunneri*

the previous year's traps (fig. 5). Sticky traps were again maintained on some of the downed trees at higher elevations; these trees still had moist phloem and appeared to have remained susceptible to insect attack.

I identified many of the wood-boring insects, and sent unknown species to experts at the U.S. National Museum for identification.

Recording thermographs or maximum-minimum thermometers were set up under the shade of windthrown trees on each plot to check the possible correlation of insect captures or attacks with temperature. Weekly during the summers of 1963 and 1964, charts were replaced or maximum-minimum temperatures were recorded. Temperature records were concluded in late October 1964.

Results

Insects Responsible for Degrade

At least 46 different species of insects causing tree degrade were caught, reared, or trapped during the study (table 2). Flatheaded borers, especially *Melanophila*, were the most numerous wood borers; *Ips* and *Dendroctonus* were the commonest bark beetles. Table 3 lists wood borers and bark beetles, by genera, and wood borer parasites, by species.

Many insect species other than those causing degrade were also collected on sticky traps. Many of these, including some coleopterous families and parasites, were not identified and of unknown significance, but apparently were not involved in deterioration. An annotated list of insects will be prepared at a later date.

Adult Activity and Air Temperature

Bark beetle and wood borer attacks were not as heavy as expected. One reason may be an unusually cool summer in 1963, when weekly temperatures averaged about 5° F. below those of the last 10 summers.

Weekly averages from maximum-minimum temperatures at the U.S. Weather Bureau station in Burney were plotted with the number of flatheaded borers, ambrosia beetles, roundheaded borers, and horntail wasps collected from all plots in 1963 and 1964 (fig. 6). The figures from the Burney station were used as average because it is the nearest U.S. Weather Bureau station. The temperature trends there actually agreed quite closely with those recorded for the other plots. The data scale for roundheaded borers and horntail wasps was enlarged because of their fewer numbers.

The individual data for each plot showed a general decline in all insect numbers in 1964, except for a slight increase in roundheaded borers and ambrosia beetles in Plot 2—the true fir plot.[3]

The number of bark beetles collected in 1963 on all plots except No. 3, where flatheaded borers surpassed all insects, paralleled and slightly exceeded wood borer collections. Most of the bark beetles had emerged by early summer 1964. Two peak flight periods occurred—one in early July and the other in late August to early September of 1963.

Parasite collections closely paralleled those of bark beetles and were usually most numerous in the late August collections of 1963. Plot 2 had exceptionally large braconid flights in late August and early September 1963. Plot 4 had the smallest parasite collections in 1963. Few parasites were collected from any of the plots in 1964.

Analysis of Collections, by Trap Position

Flatheaded borer and ambrosia beetle collections made on the sticky-foot traps in 1963 were compared with emergence hole counts made in 1964. Not enough other insect groups were collected for analysis. Flatheaded borers and ambrosia beetles tended to attack certain portions of the trees. The number of attacks of flatheaded borers along the hole was: base > midbole > top. For ambrosia beetles the number of attacks was: base > top = midbole. The number of flatheaded borers around the bole was: top > west > east > bottom; for ambrosia beetles: west = east > top > bottom. Actually so few insects were collected on bottom (underneath) sticky-foot traps and so little emergence was noted that this area can

[3] Detailed graphs of insect collections and weekly temperatures for each plot are on file at the Pacific SW. Forest & Range Expt. Sta., U.S. Forest Serv. Berkeley, California.

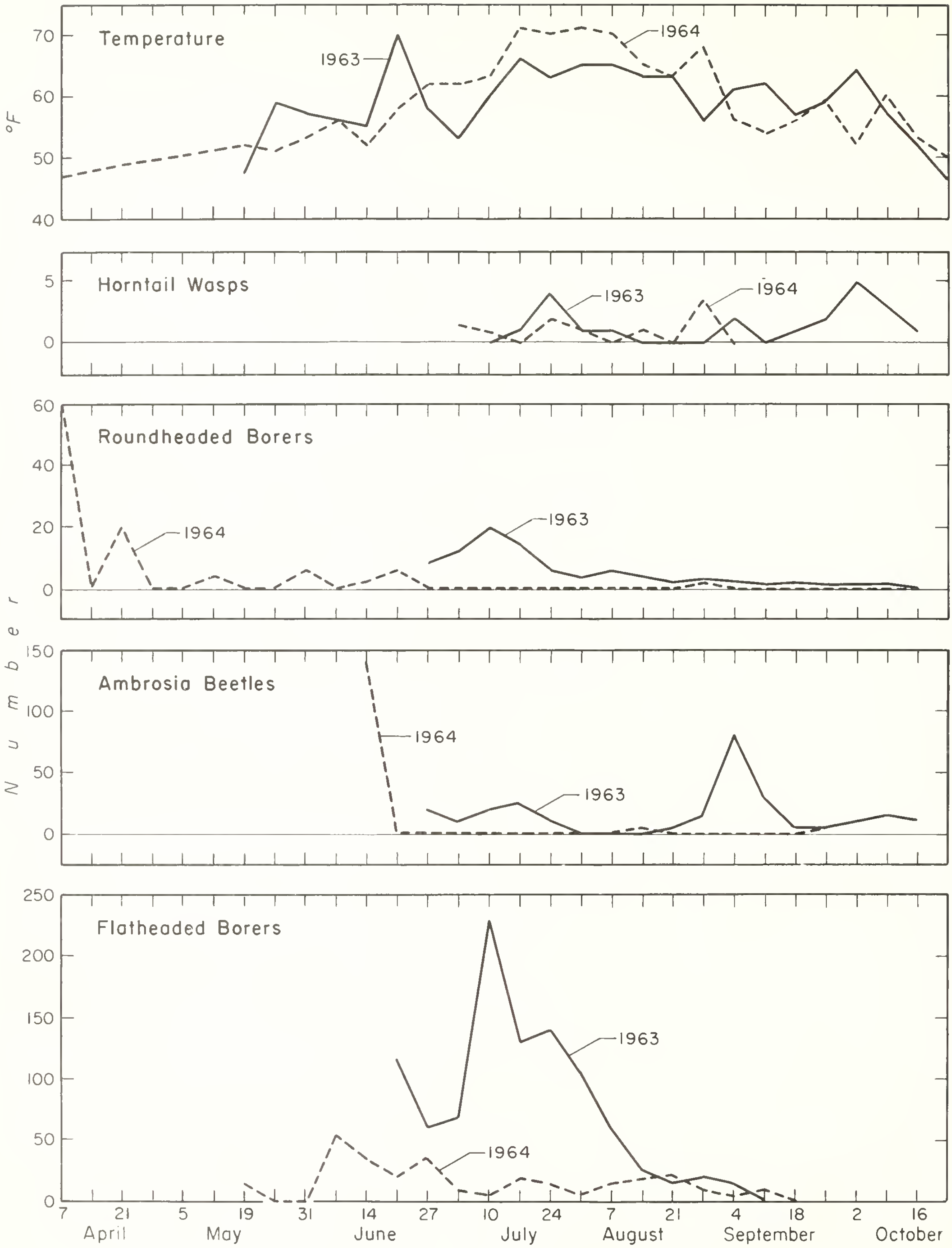


Figure 6.—Weekly collections of flatheaded borer, ambrosia beetle, roundheaded borer, and horntail wasp from plots compared with average weekly temperatures from Burney Weather Station, seasons 1963 and 1964.

almost be ignored as an attack site for these two groups of insects.

Table 4 summarizes the average number of collections made per trap, by sampling position, in 1963, and emergence hole counts made on comparable adjacent areas in 1964 for Plots 1, 2, 3, and 4.[4] The traps reflect relative numbers and not necessarily actual attacks; however, brood production for these insects did appear to be lower than normal.

Observations on Deterioration

The information given in this section is largely subjective, based on the author's impressions gained by tree dissections and many observations. The scarcity of insects permitted only a few measurements.

Four generalizations can be made about deterioration of the windthrow studied. Deterioration is defined here as the point where degrade due to insects made the tree unmerchantable to the lumberman.

- Smaller trees suffered more degrade than larger trees.
- Degrade was more severe below 5,000 feet elevation (table 5).
- Exposed trees were attacked sooner than shaded trees.
- Differences in degrade of windthrown trees with roots in the ground as against trees with roots broken off were not apparent.

[4] Tables giving totals for traps and emergence hole counts for individual plots are on file at Pacific SW. Forest & Range Expt. Sta., U.S. Forest Serv., Berkeley, California.

Table 4.--*Average number of insects per trap, 1963, and emergence holes, 1964, by sampling position; all plots (based on 10- by 10-inch sample)*

Sampling position and year	Top	Bottom	East	West	Average
FLATHEADED BORERS					
	Number				
Base:					
1963	7.3	0.6	5.8	10.6	7.0
1964	3.8	0	.9	.7	1.6
Midbole:					
1963	3.8	0	2.2	3.4	3.0
1964	3.0	0	.6	.7	1.5
Top:					
1963	2.0	--	0	0	1.6
1964	1.3	--	0	0	1.1
Average 1963	5.0	.5	4.1	7.2	
Average 1964	3.0	0	.7	.7	
AMBROSIA BEETLES					
Base:					
1963	5.2	0.7	6.6	5.9	5.3
1964	.3	.4	.2	0	.2
Midbole:					
1963	.9	0	1.5	2.2	1.4
1964	.4	0	.8	2.2	1.0
Top:					
1963	.6	--	5.5	0	1.2
1964	2.1	--	0	0	1.7
Average 1963	2.8	.6	4.5	4.2	
Average 1964	.7	.3	.5	1.0	

Table 5.--*Windthrow deterioration, by species, in the Hat Creek area, 1963 and 1964*

Host	Elevation (feet)	Principal insects	Development as of-- October 15, 1963	Development as of-- October 15, 1964	Class of deterioration[1] October 15, 1963	Class of deterioration October 15, 1964
Ponderosa pine	4,000	*Ips*	Emerged	--	Unsalvageable	--
	6,000	*Melanophila*	Young larvae	Emerged	Salvageable	Partially salvageable
Jeffrey pine	6,000	*Melanophila* & *Buprestis*	Young larvae	Emerged	Salvageable	Partially salvageable
		Sirex	Young larvae	Mature larvae	Salvageable	Partially salvageable
		Ips & *D.v.*[2]	Emerged & larvae	Emerged	Partially salvageable	Unsalvageable
Lodgepole	5,000	*Ips*	Young adults & emerged	Emerged	Partially salvageable	Unsalvageable
	7,000	*Trypodendron* & *Ips*	Emerged	--	Salvageable	Unsalvageable
Sugar pine	4,000	*Ips*	Emerged	--	Partially salvageable	Unsalvageable
	5,000	*D.m.*[2]	Larvae	Emerged	Partially salvageable	Partially salvageable
Western white pine	7,000	*Ips*	Emerged	--	Salvageable	Partially salvageable
Incense-cedar	4,000	*Semanotus*	Larvae	Emerged	Partially salvageable	Partially salvageable
White fir	4,000	*P.g.*[2]	Young adults & emerged	--	Partially salvageable	Unsalvageable
		Platypus	Larvae	Emerged	Salvageable	Unsalvageable
		Melanophila	Larvae	Emerged	Partially salvageable	Unsalvageable
		Monochamus	Larvae	Emerged	Salvageable	Unsalvageable
	5,000	*P.g.*[2]	Young adults	Emerged	Salvageable	Partially salvageable
		Monochamus	Larvae, young adults	Prepupae, emerged	Salvageable	Unsalvageable
		Melanophila	Larvae	Emerged	Salvageable	Partially salvageable
		Platypus	Larvae, eggs	Young adults	Salvageable	Partially salvageable
		Xeris	Young larvae	Mature larvae, pupae	Salvageable	Partially salvageable
Red fir	7,000	*Sirex*	Larvae	Prepupae	Salvageable	Salvageable
		Melanophila	Prepupae	Emerged	Salvageable	Partially salvageable

[1]Partially salvageable = 50 percent of tree sound (heartwood); unsalvageable = uneconomical for salvage logging due to degrade.

[2]*D.v.* = *Dendroctonus valens*; *D.m.* = *D. monticolae*; *P.g.* = *Pseudohylesinus grandis*.

Blue stain introduced by bark beetles and flatheaded borers was by far the most important single cause of degrade. It caused an estimated 50 percent of the deterioration in the lower elevations in 1963 and an equal amount in the high elevations by the end of 1964.

The most serious degrade due to wood boring was caused by roundheaded borers; horntail wasps rank next in importance. These insects were most destructive to true firs.

The principal insect species causing deterioration as a direct result of their boring, in decreasing order of importance, were *Semanotus litigiosus* (Casey) in white fir and Douglas-fir, *Monochamus oregonensis* Lec. in white fir and red fir, *Platypus wilsoni* Swaine in all firs, several species of *Buprestis* and *Sirex californicus* (Ashmead) in Jeffrey pine, *Xeris morrisoni* (Cresson) in white fir, and *Sirex longicauda* Middlk. in red fir.

Conditions in the various tree species 1 and 2 years after the windthrow varied according to the host (table 5). These conditions apply to merchantable-size trees and constitute an over-all impression. Some deviations from these deterioration patterns were found in all species. For example, there was still some red fir above 7,000 feet elevation that was only slightly degraded at the end of 1964.

Moisture Contents of Downed Trees

Wood-boring insects presumably have certain minimum moisture requirements that are reflected in success or failure of larval development. Moisture did not seem to be a limiting factor in this study—even in the driest windthrown trees. As might be expected, the trees at higher elevations had the most moisture throughout this period. Also fir may have more moisture than pine. Both in 1963 and in 1964 average moisture content of several selected downed trees decreased as elevations decreased (table 6).

Biological Observations on *Xeris, Sirex,* and *Semanotus litigiosus*

Most of the horntail wasps were collected late in 1963. The genus *Xeris* was found in midsummer, but flights of *Sirex* were not common until late September 1963 (Wickman 1964). As mentioned earlier, no horntail wasp emergence had taken place when the study ended in October 1964, so the 1964 abundance curves (fig. 6) do not show a true picture of the significance of this family. Late-instar larvae were fairly common in fir and Jeffrey pine in October 1964. It is quite possible that these insects could ultimately build up a large population. From the economic standpoint, however, if the windthrow is salvaged and milled by the first summer after damage, then deterioration caused by horntail wasps should be of minor importance.

In contrast to the late siricid attack dates, one species of roundheaded borer *(S. litigiosus)* attacked extremely early in the 1963 season. White fir, cut from the Hatchet Mountain area in the summer of 1963, cold-decked at Redding, and milled into 2 by 4's, contained large numbers of young adults. These insects were found in mid-October 1963 and appeared ready to emerge. White fir logs checked on Plot 2 also contained adult *S. litigiosus*. None was trapped on the plots; the sticky traps were put out after the eggs were laid. The larvae were commonly found in 1963, but were not identified as *S. litigiosus*.

In 1964, *S. litigiosus* emerged from mid-March to mid-April. Larval development was completed under the bark by August. The larvae then burrowed into the wood to a maximum depth of 3 inches, but usually only 1½ inches, and constructed a pupal chamber. After a 2- to 3-week pupal period the young adults developed and remained in the pupal chambers over winter. This insect probably caused the major deterioration of windthrown white fir on the plots after the 1962 storm.

Table 6.--*Average moisture contents of selected windthrown trees in northern California, 1963 and 1964*

Plot	Trees sampled	Tree species	Elevation	Moisture content 1963	Moisture content 1964
	Number		*Feet*	*Percent*	*Percent*
1	1	White fir	5,000	220	69
2	2	White fir	4,000	130	93
3	1	Jeffrey pine	6,000	165	72
4	1	Red fir	7,100	235	162

Discussion

Insect caused damage on the windthrow areas was not as serious as expected from past reports of similar catastrophes. This was especially true of bark beetle populations. Past experience after pine windfall has shown that bark beetle populations can increase the season after wind damage, and spread to nearby standing trees when downed material is no longer available (Miller 1928; Struble 1948). This did not happen in the 1962 windfall areas. In fact many of the trees, especially at higher elevations, showed no evidence of bark beetle attacks.

Ips were by far the most prevalent bark beetles found on tops and small-diameter pines, but their damage potential to nearby standing trees is limited. No *Ips* top-killing was found in the plot areas, but serious top-killing has subsequently occurred around several windthrow areas. Some of the bark beetle attacks on windthrown trees were unsuccessful, and brood production was often below normal in 1963. But bark beetles were still the most important cause of deterioration because they introduced blue stain. Blue stain in pine can degrade logs up to 50 percent several months after bark beetle attacks (Johnson 1940).

Wood borers were scarce in most windfall areas in 1963 and, except for several species, almost nonexistent in 1964. But Shea and Johnson (1962) noted that windthrown Douglas-fir in Washington attracted ambrosia beetle attacks for 3 years. In California, trees down 3 years are usually too dry for such attacks. Some trees were attacked the second season, however, and, considering the slow drying of many of the study trees and the presence of larvae in the wood in October 1964, it seemed likely that wood borers would be emerging from some of the material in 1965 and possibly again in 1966.

There are two possible reasons for the light damage from wood borer and bark beetle activity. First, few insects—caused by lack of suitable breeding material before the storm; and, second, dilution of the population—caused by an overabundance of suitable breeding material after the storm. This explanation is all the more plausible since the plot (No. 2) with the heaviest insect activity was in an area logged a few years before the storm, and thus had a resident population breeding in the logging slash.

Natural enemies were also scarce. A few woodborer parasites were collected, but not enough to obtain much biological information. Bark beetle predators and parasites were fairly abundant in 1963. The black-backed three-toed woodpecker was an imporant predator of *Monochamus* on Plot 2 (Wickman 1965), but little other bird predation was seen.

The relationship of insect abundance and temperature was not too positive. There was even a tendency for roundheaded borers to show increasing activity as temperature decreased. For example, an increased number of roundheaded borers were evident during the early July 1963 cold snap. *S. litigiosus* can emerge and attack trees during cool weather of early spring, as shown by their activity on Plot 2 in 1963 and 1964.

This observation agrees with those made in Russia by Stark (1954), who found several species of flatheaded and roundheaded borers remaining in a site and ovipositing as long as the weather remained warm and stable. Activity declined and the insects dispersed when cold weather set in. But Stark also found a species of *Xylotrechus* (roundheaded borer) that showed increased activity during cool weather with light winds. It appears that individual species may have different temperature responses.

The below-normal temperatures in 1963 made it difficult to draw reliable conclusions on flight and attack periods in relation to temperatures. Generally, flatheaded and roundheaded borers attacked early in the season, during warm weather. Horntail wasps and *Platypus* ambrosia beetles attacked late in the season during a warm spell in late September 1963, coinciding with flights of these insects. When the study was ended in 1964, horntail wasps had not emerged.

Both collections and emergence data showed that flatheaded borers and ambrosia beetles preferred certain portions of the tree. The trap collections reflected quite well the attack sites for these types of insects. And the data agrees with that obtained by Johnson *et al.* (1961) for *Trypodendron* and flatheaded borers in windthrown Douglas-fir. Graham (1925) reported that flatheaded borers tended to breed in portions of the bole exposed to sunlight. He said that the distribution of insects in logs is regulated by many factors, of which food, moisture, and temperature appear the most important. Data from the present study indicated that attack patterns for flatheaded borers were at least associated with the temperature factors. It appeared that trees in a shaded cool environment suffered fewer insect attacks and thus slower deterioration than trees in exposed warmer sites.

The sticky-foot traps seemed to work very well for collecting visiting insects. And it appeared that —at least for flatheaded borers and ambrosia beetles—trap collections could be equated with portion of tree attacked. The Coleoptera, Hymenoptera, and Diptera collected in traps may indicate the attractancy of "Stickem" for some insects of these orders or the random movement of the insects.

The largest collections were made of *Melanophila gentilis* and *M. drummondi*. They were classified as wood borers in this study, but their "wood boring" is actually limited to a small amount of sapwood boring by a few individuals. They were studied because of the blue stain fungus they introduce (Johnson 1940) and of the hope that their attack habits may be representative of other members of the buprestid family. The largest collections of true wood borers were of ambrosia beetles, followed closely by *S. litigiosus*. The variety of wood-boring insects captured and the uncertainty of which species may be dominant in any given situation greatly complicates the study of tree deterioration by these insects. This uncertainty also makes it difficult to predict the kind of insect damage to expect in a similar situation in the future.

Although the damage resulting from insect activity studied here was not severe, this should not leave the impression that the insect potential in windthrown timber is of minor importance. The cool changeable weather during the summer of 1963 undoubtedly helped reduce insect activity and attacks. By the same token, this type of weather also retarded the drying of much of the windthrown material, especially at higher elevations, and prolonged the development of several species of wood borers. Under different circumstances deterioration and subsequent tree killing could be extremely serious. Further studies should be undertaken when favorable circumstances present themselves.

Summary

1. Insect-caused deterioration of windthrown conifers in northern California was studied for two seasons after the disastrous 1962 Columbus Day storm.

2. Damaged fir and pine growing at elevations from 4,000 to 7,000 feet were periodically dissected, observed, and had traps attached for catching attacking insects during the summers of 1963 and 1964.

3. At least 46 different species of insects causing tree degrade were caught, reared, or trapped during the study. Flatheaded borers, especially *Melanophila*, were the most numerous wood borers; *Ips* and *Dendroctonus* were the commonest bark beetles.

4. Adult activity was somewhat related to air temperatures, especially for *Melanophila* and *Sirex*, but the data were not sufficient to draw definite conclusions.

5. Flatheaded borers and ambrosia beetles collected on sticky-foot traps were compared with subsequent emergence holes to check the reliability of trap positions. Flatheaded borers tended to concentrate attacks on the top surface at the base of trees. Ambrosia beetles attacked both sides of the base. Traps reflected attack sites fairly well for these two groups of insects. Not enough other insects were caught for analysis.

6. Observations on tree deterioration suggested that blue stain introduced by bark beetles and flatheaded borers was the most important type of tree degrade. The most serious degrade due to wood boring was caused by roundheaded borers.

7. Four generalizations can be made about deterioration of the 1962 windthrow studied: Smaller trees suffered more degrade than larger; degrade was more severe below 5,000 feet elevation; exposed trees were attacked sooner than shaded trees; and there was no apparent difference in degrade of windthrown trees with roots in the ground versus those with roots broken off.

8. The study offered an opportunity to obtain biological information on several horntail wasps and the life history of an important roundheaded borer, *Semanotus litigiosus*.

9. Generally, degrade of windthrown trees due to insects was not as heavy as expected. This light

attack may have been due to low insect populations before the storm, dilution of the populations caused by an overabundance of breeding material after the storm, and unusually cool weather during the summer of 1963—the period initial insect attacks were expected.

10. Although the damage resulting from insect activity studied here was not severe, this should not leave the impression that the insect potential in windthrown timber is of minor importance. Under different circumstances, deterioration and subsequent tree killing could be extremely serious.

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THREE-PEE SAMPLING THEORY
and program 'THRP'
for computer generation of selection criteria

L. R. Grosenbaugh

U. S. FOREST SERVICE RESEARCH PAPER PSW-21

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Forest Service - U. S. Department of Agriculture

NOTICE
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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 VIRTUE OF ALREADY BEING ON PUNCHED CARDS. ON A MORE ELEMENTARY LEVEL, H. P. LUHN'S INGENIOUS 11-CHARACTER DOCUMENT IDENTIFIER (FAMILIAR TO USERS OF PERMUTED 'KWIC' INDICES) PROVIDES AN EXCELLENT TOOL FOR VISUAL, MECHANICAL, OR ELECTRONIC RETRIEVAL BY AUTHOR, YEAR, OR INITIALS OF THE FIRST THREE NON-TRIVIAL WORDS IN THE TITLE. THIS IDENTIFIER ALSO SERVES TO MATCH ANY PAGE WITH ITS APPROPRIATE DOCUMENT IN THE EVENT OF SEPARATION OR MIXUPS. SUCH A SYSTEM IS MUCH BETTER ADAPTED TO CUMULATIVE UPDATING OF INDICES THAN IS ANY ARBITRARY LOCAL SERIES OF NUMBERS THAT MUST BE RECYCLED PERIODICALLY.

FINALLY, COMPUTER-PROCESSED TEXT IS EASILY REVISED AND REPUBLISHED. THIS IS AN IMPORTANT CONSIDERATION IN FIELDS WHERE CHANGES AND NEW DEVELOPMENTS 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 AN EARLIER ONE (PSW-13).

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U.S.FOREST SERVICE RESEARCH PAPER PSW-21. (LATEST REVISION DATED 7-20-65)

PACIFIC SOUTHWEST FOREST AND RANGE EXPERIMENT STATION, BERKELEY, CALIFORNIA
FOREST SERVICE, U.S.DEPARTMENT OF AGRICULTURE

THREE-PEE SAMPLING THEORY AND PROGRAM 'THRP' FOR COMPUTER GENERATION OF SELECTION CRITERIA.

L.R.GROSENBAUGH

SUMMARY

SAMPLING WITH PROBABILITY PROPORTIONAL TO PREDICTION--3P SAMPLING--IS A NEW TECHNIQUE INVOLVING VARIABLE PROBABILITY. BASIC THEORY AND DERIVED FORMULAE ARE EXPLAINED IN THE CONTEXT OF SAMPLE-TREE-MEASUREMENT FOR APPRAISAL AND SALE OF STANDING TIMBER. A RELATIVE PROBABILITY IS ARBITRARILY ASSIGNED TO EACH TREE IN THE POPULATION AT THE TIME THAT IT IS MARKED FOR HARVEST. EACH PROBABILITY IS PAIRED WITH SOME NUMBER SUBSEQUENTLY DRAWN AT RANDOM FROM (AND REPLACED IN) AN APPROPRIATELY CONSTRUCTED POPULATION OF INTEGERS. THOSE TREES WITH PROBABILITY AS GREAT AS OR LARGER THAN ASSOCIATED RANDOM NUMBER SHOULD BE MEASURED AS SAMPLES. PROBABILITY RECORDS ARE NEEDED ONLY FOR MEASURED TREES, ALTHOUGH COMPLETE RECORDS IMPROVE PRECISION. NUMBER OF SAMPLE TREES TO BE MEASURED CANNOT BE RIGIDLY SPECIFIED IN ADVANCE.

TO PROVIDE THE ARTIFICIAL POPULATION OF NUMBERS APPROPRIATE TO A GIVEN 3P-SAMPLE DESIGN, COMPUTER PROGRAM 'THRP' HAS BEEN WRITTEN IN FORTRAN-4, WITH SUBROUTINE 'IRDM' IN 7090-MAP. A NOVEL FEATURE INVOLVES USE OF THE BOOLEAN LOGICAL OPERATOR 'EXCLUSIVE OR' TO OBTAIN A SINGLE NUMBER AS THE RANDOM RESULTANT OF TWO INDEPENDENT CYCLICAL PROCESSES. CONVENIENT FIELD DISPENSERS FOR COMPUTER-GENERATED INTEGERS ARE ILLUSTRATED.

================================ INTRODUCTION ================================

CONSIDERABLE IMPROVEMENT IN SAMPLING EFFICIENCY OVER THE PAST 25 YEARS HAS BEEN BASED ON NEW THEORY CONCERNING THE SELECTION OF SAMPLES WITH VARYING PROBABILITY. HANSEN AND HURWITZ DEVELOPED THE CONCEPT OF SAMPLING WITH PROBABILITY PROPORTIONAL TO SIZE ('P.P.S.' SAMPLING), AND TOGETHER WITH MADOW, WROTE A VERY USEFUL TEXT (*4) THAT SUMMARIZES MUCH OF THE THEORY APPROPRIATE TO P.P.S. SAMPLING.

FORESTERS HAVE APPLIED P.P.S. SAMPLING TO TREE POPULATIONS IN A NUMBER OF WAYS--LIST SAMPLING, CLUSTER SAMPLING OF AREA BY CONCENTRIC PLOTS OF DIFFERENT RADII FOR TREES OF DIFFERENT SIZE-CLASS, AND CLUSTER SAMPLING OF AREA BY CRITICAL DISTANCE FROM LINE OR POINT EXPRESSED AS A CONTINUOUS FUNCTION OF TREE DIAMETER OR HEIGHT. SPECIALLY GRADUATED TAPES OR OPTICAL GAUGES ESTABLISHING APPROPRIATE CRITICAL ANGLES (*1) FACILITATE DISCRIMINATION BETWEEN QUALIFYING AND NON-QUALIFYING TREES IN THE AREA SAMPLES.

HOWEVER, SUITABLE LISTS OF TREE POPULATIONS OR EVEN SIMPLE TREE ENUMERATIONS ARE RARELY AVAILABLE IN ADVANCE OF TREE SAMPLING BECAUSE OF EXPENSE, RAPID CHANGE, AND THE ALMOST INSUPERABLE DIFFICULTY OF ESTABLISHING CORRESPONDENCE BETWEEN LISTED OR ENUMERATED TREES AND INDIVIDUAL STANDING TREES IN EXTENSIVE FOREST POPULATIONS. RELATIVELY SMALL NUMBERS OF SAMPLE TREES PERMANENTLY RELOCATABLE FOR RESEARCH PURPOSES OR FOR ESTIMATING GROWTH AND MORTALITY OF WHOLE FORESTS ARE NOTABLE EXCEPTIONS.

IN CLUSTER SAMPLES OF AREA USING P.P.S. (PLOTS, LINES, POINTS), THE ONE OR MORE ACTUAL TREE DIMENSIONS CONSTITUTING 'SIZE' (OR RELATIVE PROBABILITY)

MUST BE MEASURED ON ALL OBVIOUSLY QUALIFYING TREES, IN ADDITION TO ALL VARIABLES OF INTEREST THAT DO NOT COINCIDE WITH 'SIZE'. EVEN DOUBTFULLY QUALIFYING TREES REQUIRE THE LINEAR MEASUREMENT OF BOTH TREE SIZE (PROBABILITY DIMENSION) AND DISTANCE BETWEEN TREE AND REFERENCE POINT OR LINE.

ALTHOUGH P.P.S. SAMPLING USING LISTS OR GEOMETRIC CLUSTERS HAS IMPROVED EFFICIENCY GREATLY OVER EARLIER TYPES OF FOREST SAMPLING WITH ESSENTIALLY EQUAL PROBABILITIES, MANY SITUATIONS OCCUR WHERE THE VARIABLE OF INTEREST (VOLUME, PRODUCT YIELD, VALUE, ETC.) IS ONLY WEAKLY CORRELATED WITH GEOMETRIC PROBABILITY DIMENSIONS CONVENIENTLY MEASURABLE ON STANDING TREES. ALSO, WHERE THE SAMPLE INVOLVES AN APPRECIABLE PORTION OF THE TREE POPULATION, TIME SPENT IN MEASUREMENTS NEEDED ONLY TO INCLUDE OR EXCLUDE INDIVIDUALS OR TO ESTABLISH PROBABILITY DIMENSIONS OF INCLUDED INDIVIDUALS OFTEN BECOMES EXCESSIVE.

SAMPLING WITH PROBABILITY PROPORTIONAL TO PREDICTION ('THREE-PEE', OR '3P', SAMPLING) WAS CONCEIVED BY THE AUTHOR TO MORE EFFICIENTLY HANDLE SUCH SITUATIONS IN THE ABSENCE OF SUITABLE LISTS. IT TAKES INTO ACCOUNT THE FOLLOWING FACTS--(1) SPEEDY OCULAR ASSESSMENT OF SOME QUANTITY ASSOCIATED WITH AN INDIVIDUAL TREE AT THE TIME IT IS VISITED AND MARKED FOR HARVEST IS CHEAP AND NEVER IMPOSES THE BURDEN OF PHYSICAL MEASUREMENT OF EITHER RELATIVE PROBABILITY DIMENSION OR ANY CRITICAL INCLUSION-EXCLUSION DISTANCE, (2) TALENTED ASSESSORS CAN QUICKLY MAKE BIASED OCULAR JUDGMENTS AT THE TIME OF MARKING THAT WILL BE HIGHLY CORRELATED WITH INDIVIDUAL TREE QUANTITIES IMPOSSIBLE TO MEASURE IN THE STANDING TREE (VOLUME AFFECTED BY DEFECT, END-PRODUCT YIELD, DOLLAR VALUE, ETC.), (3) CORRECTION OF SUCH BIASED JUDGMENT BY EQUAL-PROBABILITY TECHNIQUES INVOLVING REGRESSION OR RATIO ESTIMATES HAS BEEN UNSATISFACTORY BECAUSE OF ERRATIC VARIATION AND UNKNOWN FORM OF UNDERLYING FUNCTIONAL RELATIONSHIPS.

3P SAMPLING DIFFERS FROM PUBLISHED FORMS OF VARIABLE-PROBABILITY SAMPLING IN THE FOLLOWING WAYS --(1) UNLIKE LIST SAMPLING, 3P SAMPLING EMPLOYS A RANDOMLY VARYING NUMBER OF SAMPLES AND REQUIRES NO PRIOR ENUMERATION (LIST) OF THE POPULATION --(2) UNLIKE GEOMETRIC P.P.S. SAMPLING, 3P SAMPLING DOES NOT REQUIRE OBJECTIVE (AND EXPENSIVE) DETERMINATION OF INDIVIDUAL TREE DIMENSION AND/OR DISTANCE FROM SAMPLE LOCUS AS A PREQUISITE TO SAMPLE SELECTION --(3) COMPLETE AGGREGATION OF VARIABLE PROBABILITIES SUBSEQUENT TO SAMPLING A PREVIOUSLY UNENUMERATED, UNLISTED, UNSTRATIFIED POPULATION IS MORE FEASIBLE THAN BY ANY OTHER METHOD. THOUGH SUCH COMPLETE AGGREGATION IS NOT NECESSARY, IT GREATLY IMPROVES EFFICIENCY.

A CAREFUL REVIEW OF (*4) TOGETHER WITH MURTHY'S LATER SUMMARY (*8) OF MORE RECENT VARIABLE-PROBABILITY TECHNIQUES SUGGESTS THAT (*2) WAS THE FIRST PUBLICATION TO DEAL WITH THE UNIQUE ASPECTS AND ADVANTAGES OF 3P SAMPLING.

========================== THEORY OF 3P SAMPLING ==========================

FOR ALGEBRAIC PURPOSES, AN ASTERISK (*) DENOTES MULTIPLICATION, A DOUBLE ASTERISK (**) DENOTES EXPONENTIATION, AND A SLANT (/) DENOTES DIVISION. THESE OPERATORS ARE EXECUTED IN THE FOLLOWING ORDER--EXPONENTIATION PRECEDES MULTIPLICATION OR DIVISION WHICH PRECEDE ADDITION OR SUBTRACTION WITHIN ANY GIVEN SET OF PARENTHESES, AND THE SEQUENCE FOR EVALUATION OF PARENTHETICAL EXPRESSIONS IS FROM INNERMOST TO OUTERMOST. TO AVOID EXCESSIVE PARENTHESES, VARIABLES ENDING IN 'I' ARE ASSUMED TO BE SUBSCRIPTED VARIABLES HAVING INDIVIDUAL VALUES PECULIAR TO THE 'I'TH TREE. NO SPECIAL NOTATION WILL BE EMPLOYED WHERE SUBSCRIPT IMPLICATION IS OBVIOUS.

IN DEVELOPING 3P-SAMPLING THEORY, IT WILL BE CONVENIENT TO ADOPT A STANDARD LEGEND. ASSUME A FOREST POPULATION CONSISTING OF 'M' TREES, ASSOCIATED WITH EACH OF WHICH IS A PARTICULAR VARIABLE QUANTITY 'YI' THAT CAN BE OBJECTIVELY MEASURED. A RELATIVE PROBABILITY 'KPI' ESTABLISHED IN SOME ARBITRARY MANNER IS ALSO ASSOCIATED WITH EACH TREE. 'KPI' SHOULD BE AN INTEGER, HOPEFULLY CORRELATED WITH OR PROPORTIONAL TO 'YI', THE TREE VARIABLE OF MAXIMUM INTEREST. IF EACH TREE IN THE POPULATION IS VISITED, 'KPI' NEED NOT BE ESTABLISHED FOR A GIVEN TREE UNTIL AFTER SUBJECTIVELY GUESSING 'YI' JUST PRIOR TO APPLICATION OF THE SELECTION PROCESS AT THE PARTICULAR TREE. THERE IS NEVER ANY NEED TO ESTABLISH CORRESPONDENCE BETWEEN A STANDING TREE AND AN ENTRY ON A PREVIOUS RECORD OR LIST.

3P SAMPLING REQUIRES A RECTANGULAR PROBABILITY SET (EQUAL LIKELIHOOD), COMPOSED OF AN ARITHMETIC PROGRESSION OF INTEGERS WITH UNIT INTERVAL FROM ONE

TO 'KZ', AND 'KZ' MUST EXCEED THE LARGEST 'KPI' ASSIGNED TO ANY TREE IN THE POPULATION. LATER, IT WILL BE CONVENIENT TO CONSIDER 'KZ' AS THE SUM OF TWO COMPONENTS 'K' AND 'Z', SO THAT (K+Z)=KZ.

THE 3P-SELECTION PROCESS INVOLVES VISITING EACH OF THE 'M' TREES, CONCURRENTLY ESTABLISHING ITS 'KPI' AS AN INTEGER IN THE RANGE FROM ONE THROUGH (KZ-1), THEN DRAWING AN INTEGER AT RANDOM FROM THE SET OF 'KZ' ELEMENTS (FOLLOWED BY REPLACEMENT OF THE SELECTED INTEGER). THE INTEGER THUS DRAWN WILL BE DENOTED AS 'KP'. IF 'KP' EXCEEDS 'KPI', THE TREE IS REJECTED AND ITS 'YI' IS ARBITRARILY ASSUMED TO BE ZERO. OTHERWISE, THE TREE IS SELECTED AND ITS 'YI' IS ACTUALLY MEASURED. THE PROBABILITY THAT A GIVEN TREE WILL HAVE ITS 'YI' MEASURED IS THUS KPI/KZ.

NOW SUPPOSE ALL 'M' TREES IN THE POPULATION WERE GIVEN AN EQUAL OPPORTUNITY OF BEING CHOSEN TO BE THE ONLY TREE WHOSE 'YI' WAS TO BE MEASURED, WITHOUT REGARD TO THE OUTCOME OF THE FIRST SAMPLING. THE PROBABILITY THAT A PARTICULAR TREE WOULD BE SELECTED BY SUCH A SAMPLE IS 1/M, WHILE THE PROBABILITY THAT ANY TREE THUS SELECTED WOULD ALSO BE A TREE SELECTED FOR MEASUREMENT BY THE EARLIER DESCRIBED SAMPLING PROCESS IS KPI/(M*KZ), HENCEFORTH CALLED 'PI'. BY ITS NATURE, 'PI' MUST ALWAYS BE LESS THAN UNITY IF 'KZ' EXCEEDS 'KPI', AND MORE THAN ZERO IF 'KPI' IS AT LEAST ONE.

THE NUMBER OF MEASURED TREES 'N' COULD VARY FROM ZERO TO 'M' IF ONLY THE EARLIER SAMPLE WERE CONSIDERED (WITHOUT REPLACEMENT). HOWEVER, 'N' COULD ASSUME ONLY THE VALUES ZERO OR ONE IF SUCCESS IN BOTH SAMPLES WERE REQUIRED.

SINCE THE LATTER SITUATION IS SIMPLEST, CONSIDER THE EXPECTED VALUE OF YI/PI IN SUCH A SAMPLING SCHEME. REMEMBER THAT IF N=0, YI/PI IS ARBITRARILY SPECIFIED TO HAVE ZERO VALUE. OTHERWISE, N=1 AND YI/PI WILL BE DETERMINED BY MEASUREMENT OF 'YI'. THE EXPECTED VALUE OF YI/PI IN SUCH A MODEL IS

$$\sum^{M}(PI*(YI/PI) + (1-PI)*ZERO) = \sum^{M} YI$$

BUT YI/PI = M*KZ*YI/KPI, WHICH THUS PROVIDES AN UNBIASED ESTIMATE OF AGGREGATE 'YI' IN THE TREE POPULATION.

NOW SUPPOSE THE INITIAL 3P SAMPLE HAD NEVER BEEN REDUCED TO ZERO OR ONE SAMPLE TREE BY THE INDEPENDENT EQUAL-PROBABILITY SELECTION. HOWEVER, 'PI' AS ALREADY DEFINED STILL HAS MEANING. THERE WOULD NOW BE A SUM OF 'M' VALUES OF YI/PI AVAILABLE (SOME ARE ARBITRARILY ZERO). SINCE EACH HAS EXPECTED VALUE EQUAL TO $\sum^{M}$YI, THE SUM OF ALL 'M' VALUES HAS EXPECTED VALUE EQUAL TO M*$\sum^{M}$YI.

HENCE, (1/M)*$\sum^{M}$YI/PI HAS AN EXPECTED VALUE OF $\sum^{M}$YI, THE AGGREGATE 'YI' IN THE POPULATION. BUT (1/M)*$\sum^{M}$YI/PI = KZ*$\sum^{M}$YI/KPI, SO THIS EXPRESSION PROVIDES AN UNBIASED ESTIMATE OF AGGREGATE 'YI' IN THE POPULATION. SINCE ONLY THE 'N' VALUES OF MEASURED 'YI' ARE OF CONCERN (THE OTHERS ARE ARBITRARILY ASSUMED TO BE ZERO), THE AGGREGATE 'YI' IN THE POPULATION CAN BE ESTIMATED BY

```
=======                N
3PFIRST = KZ * ∑YI/KPI IF N=NONZERO
=======

          = ZERO            IF N=ZERO
```

INSTEAD OF MAKING AN ESTIMATE OF ZERO WHENEVER N=0, IT COULD BE SPECIFIED THAT THE ENTIRE PROCESS BE REPEATED WHENEVER AN OUTCOME OF ZERO SAMPLE TREES WAS SECURED. IF THE PROBABILITY OF OBTAINING AN OUTCOME OF N=0 IS CALCULATED AS PZ=(1-KPI/KZ)*(1-KPI/KZ)*...*(1-KPI/KZ) UNTIL ALL 'M' TREES HAVE BEEN ACCOUNTED FOR, THEN THE UNBIASED ESTIMATOR APPROPRIATE TO NONZERO 'N' (WITH REDRAW WHEN N=0) IS

```
========                       N
3PSECOND = (1-PZ) * KZ * ∑YI/KPI WITH REDRAW IF N=0
========
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'PZ' IS USUALLY SO NEARLY ZERO AS TO BE NEGLIGIBLE WHEN THE EXPECTED NUMBER OF SAMPLES IS 5 OR MORE. HENCE, THE MUCH MORE CONVENIENT '3PFIRST' ESTIMATOR

CAN BE USED IN MOST PRACTICAL SITUATIONS EVEN THOUGH A REDRAWING IS SPECIFIED FOR A ZERO OUTCOME.

THE TWO ESTIMATORS ABOVE ARE SIMPLE AND UNBIASED, BUT VARIATION IN 'N' IS DIRECTLY REFLECTED BY VARIATION AMONG THE ESTIMATES. NOTE THAT A SINGLE SET OF SAMPLE TREES IS SECURED WITHOUT REPLACEMENT, THAT NO A PRIORI OR A POSTERIORI LIST OR ENUMERATION OF INDIVIDUALS IN THE POPULATION IS REQUIRED (ONLY THAT EACH INDIVIDUAL BE GIVEN A KNOWN OPPORTUNITY TO BE INCLUDED IN THE SAMPLE).

AS LONG AS 'KZ' EXCEEDS THE LARGEST 'KPI' IN THE POPULATION, THE EXPECTED VALUES OF THE ESTIMATORS ARE EQUAL TO POPULATION VALUES. THIS IS EQUIVALENT TO SAYING THAT THE EXPECTED NUMBER OF SAMPLES TIMES THE LARGEST 'KPI' IN THE POPULATION SHOULD BE SMALLER THAN $\sum^{M}$KPI. MOREOVER, IT IS DESIRABLE THAT THE PRODUCT (N * (MAX KPI)) BE SMALLER THAN $\sum^{M}$KPI, SINCE OTHERWISE SAMPLE BLOW-UP FACTORS SMALLER THAN UNITY CAN OCCUR.

THE DISTRIBUTION OF 'N' IN A 3P SAMPLE CAN BE PREDICTED FROM STUDY OF THE WELL KNOWN POISSON SERIES (NOT THE POISSON EXPONENTIAL LIMIT). THE BERNOUILLI OR BINOMIAL SERIES IS A SPECIAL CASE OF THE POISSON SERIES IN WHICH ALL 'KPI' ARE THE SAME. THE EXPECTED NUMBER OF MEASURED TREES IN A 3P SAMPLE IS EQUAL TO THE PRODUCT OF 'M' TIMES THE SINGLE-DRAW EXPECTATION FOR THE ENTIRE POPULATION (OR ESN = M*$\sum^{M}$PI), WHICH CAN BE EXPRESSED AS

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=======
3PTHIRD = ESN = (1/KZ) * ΣKPI (sum to M)
=======
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$$3PTHIRD = ESN = (1/KZ) * \sum^{M} KPI$$

IF A REDRAW IS SPECIFIED WHEN N=0, THE EXPECTED NUMBER OF NONZERO SAMPLES 'ENZSN' IS

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========
3PFOURTH = ENZSN = ESN/(1-PZ)
========
```

AS WAS PREVIOUSLY NOTED, IN PRACTICE 'PZ' IS USUALLY SO CLOSE TO ZERO THAT THE TWO FORMULAE MAY BE USED INTERCHANGEABLY.

THE VARIANCE OF 'N' ABOUT 'ESN' FOR A POISSON SERIES IS DERIVED ON PAGE 149 OF RIETZ (*9), AND THE EXPRESSION GIVEN THERE CAN BE SHOWN TO BE ALGEBRAICALLY EQUIVALENT TO

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=======
3PFIFTH = ESN - (1+C**2) * (ESN**2)/M
=======
```

WHERE 'C' IS THE COEFFICIENT OF VARIATION (EXPRESSED AS A DECIMAL FRACTION) OF 'KPI' FOR THE ENTIRE POPULATION.

IN A BINOMIAL SERIES, (1+C**2) = 1, SO ESN - (ESN**2)/M MAY BE USED AS A SAFE UPPER BOUND FOR THE VARIANCE OF 'N' WHERE NOTHING IS KNOWN ABOUT THE VARIATION AMONG 'KPI'. IF ONLY THE 'N' SAMPLE VALUES OF 'KPI' ARE KNOWN, (1+C**2) CAN BE APPROXIMATED BY (1/N**2) * ($\sum^{N}$KPI) * $\sum^{N}$(1/KPI). WHERE ALL 'M' VALUES OF 'KPI' ARE KNOWN, (1+C**2) = M*$\sum^{M}$(KPI**2)/($\sum^{M}$KPI)**2.

IF IT BE SPECIFIED THAT REDRAWING WILL OCCUR WHEN AN OUTCOME OF N=0 IS SECURED, THE VARIANCE IS ABOUT 'ENZSN' RATHER THAN 'ESN', AND N=0 IS REJECTED. SUCH VARIANCE CAN BE COMPUTED AS 3PFIFTH/(1-PZ), MINUS PZ*ENZSN**2. AS NOTED EARLIER, 'PZ' IS USUALLY SO NEARLY ZERO AS TO MAKE THIS THE SAME AS '3PFIFTH'.

IN VIEW OF THE SPEED WITH WHICH OCULAR JUDGMENTS CAN ESTABLISH A MEANINGFUL 'KPI' FOR ANY TREE, IT MAY WELL BE FOUND FEASIBLE TO OBTAIN 'KPI' FOR ALL INDIVIDUALS IN A FOREST POPULATION, INSTEAD OF MERELY FOR SOME PORTION OF THE POPULATION. WHERE THIS IS DONE, MORE EFFICIENT ESTIMATORS OF AGGREGATE 'YI' FOR A POPULATION ARE AVAILABLE, SINCE THE FLUCTUATION CAUSED BY VARIATION IN 'N' ABOUT 'ESN' CAN BE LARGELY REMOVED.

FOR CONVENIENCE, THESE MORE EFFICIENT ESTIMATORS WILL BE DERIVED FROM '3PSECOND' EXPRESSIONS, ALTHOUGH ACCEPTANCE OF ZERO ESTIMATES WHEN N=0 WOULD

LEAD TO THE SAME END RESULT.

FROM '3PTHIRD' AND '3PFOURTH' IT IS OBVIOUS THAT ENZSN = $(1/KZ)*\sum^{M} KPI/(1-PZ)$, SO KZ = $(1/ENZSN)*\sum^{M} KPI/(1-PZ)$. SUBSTITUTING FOR 'KZ' IN '3PSECOND' GIVES $(\sum^{M} KPI/ENZSN) * \sum^{N} YI/KPI$, AND MULTIPLYING BY N/N AND REARRANGING GIVES A DIFFERENT FORM OF THE UNBIASED '3PSECOND' ESTIMATOR FOR AGGREGATE 'YI' IN THE POPULATION, THUS

$$3PSIXTH = (N/ENZSN) * (\sum^{M} KPI/N) * \sum^{N} YI/KPI$$

THE EXPECTED VALUE OF N/ENZSN IS UNITY, SO IF 'N' IS UNCORRELATED WITH THE REMAINDER OF THE EXPRESSION, OR IF 'N' COINCIDES WITH ENZSN, THE EXPECTED VALUE OF '3PSIXTH' IS

$$3PSEVENTH = (\sum^{M} KPI/N) * \sum^{N} YI/KPI$$

UNLESS COVARIANCE BETWEEN 'N' AND '3PSEVENTH' IS NEGATIVE AND LARGE, THE LATTER ESTIMATES WILL HAVE MUCH SMALLER DEVIATIONS FROM POPULATION VALUES THAN WILL CORRESPONDING '3PSECOND' ESTIMATES. THE CNLY POSSIBLE WAY LARGE NEGATIVE COVARIANCE BETWEEN 'N' AND '3PSEVENTH' COULD ARISE WOULD BE FOR 'KPI' TO BE STRONGLY AND NEGATIVELY CORRELATED WITH 'YI', A CIRCUMSTANCE THAT IS DIFFICULT TO IMAGINE WHEN THERE IS ANY REAL BASIS FOR OCULAR ASSESSMENT.

IT IS APPARENT THAT '3PSEVENTH' ESTIMATES ARE MERELY '3PSECOND' ESTIMATES ADJUSTED BY MULTIPLICATION BY ENZSN/N. IN COMBINING 2 OR MORE '3PSEVENTH' ESTIMATES OF THE SAME POPULATION, EACH SHOULD BE WEIGHTED BY ITS OWN 'N' AND DIVIDED BY AGGREGATE 'N' FOR ALL SAMPLES INVOLVED IN THE COMBINATION. SUCH A WEIGHTING PROCEDURE LEADS TO CUMULATIVE ESTIMATES APPROACHING POPULATION VALUES AS AGGREGATE 'N' GROWS LARGE, YET WHEN AGGREGATE 'N' IS SMALL AND AVERAGE 'N' DEVIATES EXCESSIVELY FROM 'ENZSN', THE ERRORS ARE USUALLY SMALLER

THAN IS THE CASE WITH '3PFIRST' OR '3PSECCND'.

SOME OBVIOUS IMPLICATIONS OF '3PSIXTH' AND '3PSEVENTH' FORMULAE FOLLOW. THE STRONGER THE POSITIVE CORRELATION BETWEEN LOG 'KPI' AND LOG 'YI', THE LESS VARIATION AMONG '3PSEVENTH' ESTIMATES. WHEN 'KPI' IS CONSTANTLY PROPORTIONAL TO 'YI', '3PSEVENTH' NEVER VARIES, REGARDLESS OF VARIATION IN 'N'. THUS, VARIATION IN 'N' HAS LITTLE EFFECT ON '3PSEVENTH' ESTIMATES WITH GOOD CORRELATION BETWEEN 'YI' AND 'KPI'.

THE EFFECT OF VARIATION IN 'N' ON '3PSEVENTH' ESTIMATES IS MUCH GREATER WHEN THERE IS ZERC CORRELATION BETWEEN 'YI' AND 'KPI', AS IN THE CASE OF FREQUENCY. HERE, EQUAL-PROBABILITY SAMPLES WOULD BE MUCH MORE EFFICIENT. IT IS INFORMATIVE TO CALCULATE SUCH 3P ESTIMATES OF FREQUENCY, EVEN THOUGH TRUE POPULATION VALUES OF FREQUENCY ARE ACTUALLY AVAILABLE, SINCE THE PERCENTAGE DEVIATION OF A FREQUENCY ESTIMATE FROM POPULATION VALUE CONSTITUTES AN OUTER BOUND FOR THE MUCH SMALLER DEVIATIONS APT TO OCCUR AMONG ESTIMATES OF VARIABLES BETTER CORRELATED WITH 'KPI'.

THE ADVANTAGE OBTAINED IN 3P SAMPLING WITH VERY SMALL OR ZERO VARIATION IN THE RELATIONSHIP BETWEEN 'YI' AND 'KPI' CAN BE SEEN EVEN MORE CLEARLY IN P.P.S. CLUSTER SAMPLING OF AREA, WHERE HORIZONTAL POINT-SAMPLES ARE MOST EFFICIENT FOR TOTAL BASAL AREA ESTIMATES, HORIZONTAL LINE-SAMPLES FOR SUM-OF-DIAMETER ESTIMATES, VERTICAL LINE-SAMPLES FOR AGGREGATE LINEAL FOOTAGE ESTIMATES, PLOT-SAMPLES FOR FREQUENCY ESTIMATES, ETC. ALL OF THE VARIATION IN SUCH P.P.S. SAMPLES IS ATTRIBUTABLE TO UNCONTROLLABLE VARIATION IN 'N'.

TO OBTAIN AN UNBIASED ESTIMATE OF THE VARIANCE OF ANY 3P ESTIMATE REQUIRES TWO OR MORE INDEPENDENT SETS OF SAMPLES (WITH REPLACEMENT). THE MOST EFFICIENT WAY TO OBTAIN MORE THAN ONE SET OF 3P SAMPLES IS TO COMPARE 'KPI' OF EACH TREE VISITED WITH 2 OR MORE RANDOM INTEGERS INSTEAD OF ONE. REGARDLESS OF HOW MANY

TIMES THE TREE QUALIFIES, IT NEED ONLY BE MEASURED ONCE, THOUGH ITS MEASURED 'YI' WILL BELONG TO MORE THAN ONE SET OF SAMPLES IF IT QUALIFIES MORE THAN ONCE. THIS TECHNIQUE CREATES INTERPENETRATING SETS OF 3P SAMPLES.

CALCULATION OF VARIANCE FOR SUCH SIMULTANEOUSLY ACQUIRED INDEPENDENT SETS OF SAMPLES IS STRAIGHTFORWARD--DEVIATIONS OF '3PFIRST' OR '3PSECOND' ESTIMATES ARE MEASURED FROM AN UNWEIGHTED MEAN, WHILE DEVIATIONS OF '3PSEVENTH' ESTIMATES SHOULD BE MEASURED FROM A WEIGHTED MEAN, AS EXPLAINED EARLIER. THE ORDINAL OF EACH SET OR SETS TO WHICH A GIVEN SAMPLE TREE BELONGS MUST, OF COURSE, BE RECORDED AT THE TIME THAT THE TREE QUALIFIES.

INDEPENDENT SETS OF SAMPLES AFFORD AN ADDITIONAL ADVANTAGE IN THAT THEY ALLOW ESTIMATION OF THE CORRELATION BETWEEN 'N' AND ANY OF THE 3P ESTIMATORS, WITH SUBSEQUENT ADJUSTMENT OF THE ESTIMATES IF CORRELATION IS STRONG AND AT THE SAME TIME DEVIATION OF MEAN 'N' FROM 'ENZSN' IS LARGE AND KNOWN. ORDINARILY, HOWEVER, '3PFIRST' OR '3PSECOND' ESTIMATORS SHOULD NOT BE EMPLOYED WHEN 'ENZSN' IS KNOWN, WHILE ADJUSTMENT NEEDED BY '3PSEVENTH' ESTIMATES OF ANY VARIABLE (EXCEPT POSSIBLY FREQUENCY) IS APT TO BE SO SMALL AS TO BE NEGLIGIBLE. WHERE ADJUSTMENTS ARE FOUND DESIRABLE, A LINEAR FUNCTION WILL USUALLY BE QUITE SATISFACTORY IN THE ZONE BETWEEN MEAN 'N' AND 'ENZSN', EVEN THOUGH THE RELATIONSHIP BETWEEN 'YI' AND 'KPI' IS NONLINEAR, ERRATIC, OR DIFFICULT TO FORMALIZE.

INDEPENDENT SETS OF SAMPLES AFFORD THE ONLY ESTIMATE OF VARIANCE AMONG '3PFIRST' AND '3PSECOND' ESTIMATES, BUT MUCH SIMPLER APPROXIMATE VARIANCES CAN BE CALCULATED FOR '3PSEVENTH' ESTIMATES. THE APPROXIMATIONS CAN BE RATIONALIZED AS FOLLOWS.

IF A FIXED NUMBER OF TREES 'N' BE SELECTED FROM 'M' TREES (WITH REPLACEMENT) FOR MEASUREMENT OF 'YI', EACH WITH PARTICULAR SINGLE-DRAW

PROBABILITY PI = KPI/$\sum^{M}$KPI, THEN THE EXPECTED VALUE OF EACH TI = YI/PI IS $\sum^{M}$YI, AND THE EXPECTED VALUE OF THE VARIANCE OF THE MEAN OF THESE 'N' ESTIMATES OF A TOTAL IS

========
$$3PEIGHTH = (1/N) * \sum^{M} PI*(TI-\sum^{M} YI)**2$$
========

NOW SUBSTITUTE SAMPLE ESTIMATE $\sum^{N}$TI/N FOR $\sum^{M}$YI, AND RECOGNIZE THAT 'PI' BECOMES THE CONSTANT 1/N IN A SELF-WEIGHTING PROBABILITY SAMPLE OF FIXED SIZE 'N'. TO CONVERT FROM ABSOLUTE TO RELATIVE VARIANCE, DIVIDE BY ($\sum^{N}$TI/N)**2. FINALLY, MULTIPLY BY N/(N-1) TO COMPENSATE FOR USING DEVIATIONS FROM THE SAMPLE MEAN INSTEAD OF DEVIATIONS FROM POPULATION MEAN. THE SAMPLE ESTIMATE OF THE RELATIVE VARIANCE OF A TOTAL BASED ON 'N' SAMPLES THEN BECOMES

=======
$$3PNINTH = (\sum^{N} TI**2)/(\sum^{N} TI)**2 - 1/N, \text{ ALL MULTIPLIED BY } N/(N-1)$$
=======

THIS IS AN UNBIASED ESTIMATE OF VARIANCE WHEN SAMPLING WITH 'N' FIXED AND WITH REPLACEMENT. MULTIPLICATION BY ($\sum^{N}$TI/N)**2 CONVERTS FROM RELATIVE TO ABSOLUTE UNITS. 3PNINTH IS A GOOD APPROXIMATION WHEN SAMPLING WITH 'N' FIXED BUT WITHOUT REPLACEMENT IF N/M AND MOST 'PI' ARE SMALL RELATIVE TO UNITY (*4). THE AUTHOR DEMONSTRATES IN THE NEXT SECTION THAT 3PNINTH IS A USEFUL APPROXIMATION EVEN WHERE 'N' IS VARIABLE AND WHERE N/M AND 'PI' ARE MUCH LARGER THAN WOULD USUALLY OCCUR IN PRACTICE.

IN MORE FAVORABLE SITUATIONS WHERE COMPUTERIZED TREE POPULATIONS WERE REPEATEDLY 3P-SAMPLED, SHARPNACK (*10) FOUND THAT, AS EXPECTED, 2/3 OF THE DEVIATIONS FROM POPULATION VALUES FELL BETWEEN FIDUCIAL LIMITS BASED ON THE ABOVE VARIANCE APPROXIMATIONS, ALTHOUGH DISTRIBUTIONS OF THE SAMPLE ESTIMATES WERE SOMEWHAT SKEWED.

================ EXPECTED VALUES FOR SOME 3P-SAMPLE ESTIMATES ================

THE MORE IMPORTANT FORMULAE DERIVED IN THE PRECEDING SECTION WERE STATED WITHOUT PROOF IN AN EARLIER PAPER (*2), ALONG WITH A SMALL NUMERICAL EXAMPLE ILLUSTRATING COMPUTATIONAL PROCEDURE FOR OBTAINING ESTIMATES FROM A SINGLE SET OF 2 MEASURED 3P-SAMPLE TREES DRAWN FROM A 9-TREE POPULATION.

IN ORDER TO INVESTIGATE PATTERNS OF VARIATION EXHIBITED BY 3P-SAMPLE ESTIMATES UNDER A VARIETY OF CIRCUMSTANCES, THE PRESENT PAPER COMPUTES 3P-SAMPLE ESTIMATES AND PROBABILITIES OF OCCURRENCE FOR ALL POSSIBLE OUTCOMES DRAWN FROM THE SAME 9-TREE POPULATION BY 3 DIFFERENT DESIGNS OR SAMPLING RATES. SEVERAL DIFFERENT TYPES OF 3P ESTIMATORS ARE COMPARED FOR EACH DESIGN. ANY TRIVIAL DIFFERENCE BETWEEN VOLUME ESTIMATES IN THE PRESENT PAPER AND THE EARLIER ONE CAN BE EXPLAINED BY THE FACT THAT VOLUMES OF THE 9 INDIVIDUAL TREES HAVE NOW BEEN ROUNDED TO THE NEAREST BOARD FOOT TO SIMPLIFY THE COMPUTATIONS.

IN THE 9-TREE POPULATION, 'KPI' IS OCULARLY ASSESSED VALUE TO THE NEAREST DOLLAR (BASED ON GUESSED BOARD-FOOT VOLUME AT 2 CENTS PER BOARD FOOT). TABLE 1 SHOWS ALL POSSIBLE SAMPLES THAT CAN BE DRAWN FROM THE 9-TREE POPULATION BELOW.

GUESSED KPI	ACTUAL FREQUENCY	ACTUALLY MEASURED BOARD-FOOT VOLUME
2	1	106
2	1	106
2	1	106
2	1	106
2	1	106
2	1	106
5	1	248
5	1	248
10	1	526
$32 = \sum^{M} KPI$	$9 = M$	$1658 = \sum^{M} YI$

TABLE 1. 3P-SAMPLE OCCURRENCES AND '3PSEVENTH' ESTIMATES FOR 9-TREE POPULATION

P=PROBABILITIES OF OCCURRENCE IF KZ EQUAL TO 32	20	11	SAMPLE SIZE =N	3PSEVENTH ESTIMATE T=FREQ. (NUMBER)	T=VOL. (BD.FT.)	COMPONENT ELEMENT REL. LIKELIHOODS =KPI
.33229816	.14946778	.00811378	0	REDRAW	REDRAW	NONE
.15104461	.14946778	.08113783	1	3.20	1683.20	10
.13291926	.09964519	.01081838	1	16.00	1696.00	2
.12307340	.09964519	.01352297	1	6.40	1587.20	5
.06041784	.09964519	.10818377	2	9.60	1689.60	2, 10
.05594245	.09964519	.13522972	2	4.80	1635.20	5, 10
.04922936	.06643012	.01803063	2	11.20	1641.60	2,5
.02215321	.02767922	.00601021	2	16.00	1696.00	2,2
.01139569	.01660753	.00563457	2	6.40	1587.20	5,5
.02237698	.06643012	.18030629	3	8.53	1655.47	2,5, 10
.01006964	.02767922	.06010210	3	11.73	1691.73	2,2, 10
.00820490	.01845281	.01001701	3	12.80	1659.73	2,2,5
.00517986	.01660753	.05634572	3	5.33	1619.20	5,5,10
.00455827	.01107169	.00751276	3	9.60	1623.47	2,5,5
.00196917	.00410062	.00178080	3	16.00	1696.00	2,2,2
.00372950	.01845281	.10017016	4	10.40	1665.60	2,2,5, 10
.00207194	.01107169	.07512762	4	8.00	1638.40	2,5,5,10
.00089508	.00410062	.01780803	4	12.80	1692.80	2,2,2, 10
.00075971	.00307547	.00417376	4	11.20	1641.60	2,2,5,5
.00072932	.00273375	.00296800	4	13.60	1668.80	2,2,2,5
.00009846	.00034172	.00029680	4	16.00	1696.00	2,2,2,2
.00034532	.00307547	.04173757	5	9.60	1649.92	2,2,5,5,10
.00033151	.00273375	.02968005	5	11.52	1671.68	2,2,2,5, 10
.00006753	.00045563	.00123667	5	12.16	1652.48	2,2,2,5,5
.00004475	.00034172	.00296800	5	13.44	1693.44	2,2,2,2, 10
.00003647	.00022781	.00049467	5	14.08	1674.24	2,2,2,2,5
.00000262	.00001519	.00002638	5	16.00	1696.00	2,2,2,2,2
.00003071	.00045563	.01236669	6	10.67	1657.60	2,2,2,5,5,10
.00001658	.00022781	.00494667	6	12.27	1675.73	2,2,2,2,5, 10
.00000338	.00003797	.00020611	6	12.80	1659.73	2,2,2,2,5,5
.00000119	.00001519	.00026382	6	13.87	1693.87	2,2,2,2,2, 10
.00000097	.00001012	.00004397	6	14.40	1677.87	2,2,2,2,2,5
.00000003	.00000028	.00000098	6	16.00	1696.00	2,2,2,2,2,2
.00000153	.00003797	.00206112	7	11.43	1663.09	2,2,2,2,5,5,10
.00000044	.00001012	.00043971	7	12.80	1678.63	2,2,2,2,2,5, 10
.00000009	.00000169	.00001832	7	13.26	1664.91	2,2,2,2,2,5,5
.00000001	.00000028	.00000977	7	14.17	1694.17	2,2,2,2,2,2, 10
.00000001	.00000019	.00000163	7	14.63	1680.46	2,2,2,2,2,2,5
.00000004	.00000169	.00018321	8	12.00	1667.20	2,2,2,2,2,5,5,10
.00000001	.00000019	.00001628	8	13.20	1680.80	2,2,2,2,2,2,5, 10
.0000000+	.00000003	.00000068	8	13.60	1668.80	2,2,2,2,2,2,5,5
.0000000+	.00000003	.00000679	9	12.44	1670.40	2,2,2,2,2,2,5,5,10
UNITY =	UNITY =	UNITY = TOTAL $\sum^{41}$P		POPULATION VALUES		
EXPECTED NUMBER OF SAMPLE TREES						
1.0000	1.6000	2.9091		9.0000	1658.00	
$\sum^{41}$P*N=$\sum^{8}$KPI/KZ=ESN				$\sum^{41}$(P*N*T)/$\sum^{41}$P*N=$\sum^{8}$Y		

SYMBOLS AND LEGEND FOR ALL TABLES ARE THE SAME AS IN PRECEDING SECTION.

THE 3 DIFFERENT RATES OF 3P SAMPLING RESULT FROM USING VALUES OF 'KZ' EQUAL TO 32, 20, 11. FOR THE LISTED POPULATION THIS MAKES 'ESN' EQUAL TO 1.0, 1.6, 2.9091, AND 'ENZSN' EQUAL TO 1.4977, 1.8812, 2.9329. EXPECTED VALUE OF VARIANCE ABOUT 'ESN' IS .8301, 1.1650, 1.4611, WHILE EXPECTED VALUE OF VARIANCE ABOUT 'ENZSN' IS .4979, .8408, 1.4033. THE EXAMPLE EMPLOYED TO ILLUSTRATE THE EARLIER PAPER HAD 'ESN' EQUAL TO 1.6, WHILE THE MAXIMUM 'ESN' POSSIBLE WITHOUT BIAS IS 2.9091 UNLESS THE SCALE USED IN ESTABLISHING 'KPI' IS MADE LARGER.

THE TOTAL NUMBER OF POSSIBLE COMBINATIONS INVOLVING 9 THINGS (OF WHICH 6 ARE IDENTICAL, 2 IDENTICAL, AND 1 UNIQUE) TAKEN 0, 1, 2, ... 9 AT A TIME IS (6+1)*(2+1)*(1+1) = 42 COMBINATIONS. THE BINOMIAL PROBABILITIES FOR EACH OF THE 7 CELLS IN THE FIRST VECTOR, THE 3 IN THE SECOND, AND THE 2 IN THE THIRD MUST BE CALCULATED PRIOR TO OBTAINING THE 3-VECTOR KRONECKER PRODUCT, WHOSE 42 TERMS ARE THE DESIRED INDIVIDUAL PROBABILITIES FOR THE 42 POSSIBLE OUTCOMES. HAD EACH OF THE 9 TREES DIFFERRED FROM THE OTHERS, THERE WOULD HAVE BEEN 2**9 = 512 PROBABILITIES IN THE KRONECKER PRODUCT. OBVIOUSLY, ONLY VERY SMALL POPULATIONS CAN BE ANALYZED IN THIS MANNER, EVEN ON HIGH-SPEED COMPUTERS.

TABLE 1 SHOWS THE 3 BASIC SETS OF PROBABILITIES AND THE 42 POSSIBLE OUTCOMES FOR '3PSEVENTH' FREQUENCY AND VOLUME ESTIMATES, AS WELL AS THE 'KPI' OF INDIVIDUAL SAMPLE TREES COMPRISING EACH OUTCOME. FOR CONVENIENCE, OUTCOMES HAVE BEEN ARRAYED BY NUMBER OF SAMPLE TREES ('N'). ALL SUBSEQUENT TABLES CAN BE DERIVED FROM TABLE 1.

TABLE 2 SUMMARIZES PROBABILITIES FOR EACH 'N' WITH CORRESPONDING EXPECTED VALUES FOR VARIOUS FREQUENCY ESTIMATORS ('3PFIRST', '3PSECOND', '3PSEVENTH'). THE ACCUMULATED CROSSPRODUCT OF THE LAST TWO COLUMNS DEMONSTRATES THAT WEIGHTS OF N/(AGGREGATE N) ARE APPROPRIATE FOR COMBINING SEVERAL SETS OF '3PSEVENTH' ESTIMATES INTO A SINGLE ESTIMATE WHICH WILL TEND TOWARD POPULATION VALUE AS NUMBER OF SETS APPROACHES INFINITY.

TABLE 3 DOES FOR VOLUME WHAT TABLE 2 DID FOR FREQUENCY.

IT IS APPARENT THAT ALTHOUGH '3PFIRST' AND '3PSECOND' ESTIMATES ARE UNBIASED, VARIATION IS MUCH GREATER THAN FOR '3PSEVENTH'. IT IS ALSO APPARENT THAT FREQUENCY ESTIMATES ARE ALWAYS POSITIVELY CORRELATED WITH 'N', EVEN IN THE CASE OF '3PSEVENTH' ESTIMATES. THIS IS NECESSARILY SO BECAUSE VARIABLE 'KPI' CAN HAVE ONLY ZERO CORRELATION WITH CONSTANT UNIT FREQUENCY. HOWEVER, THE RELATIONSHIP BETWEEN 'N' AND '3PSEVENTH' ESTIMATES WILL ALWAYS BE SLIGHT WHEN CORRELATION EXISTS BETWEEN 'KPI' AND 'YI', AS IS USUALLY THE CASE WITH VOLUME, VALUE, ETC. IN SUCH SITUATIONS THE SLOPE OF THE RELATION IN A PARTICULAR ZONE MAY BE POSITIVE OR NEGATIVE DEPENDING ON ACCIDENTAL CIRCUMSTANCES NOT INFERRABLE FROM ANY SINGLE SET OF SAMPLES.

TABLE 4 REARRAYS TABLE 1 BY MAGNITUDE OF '3PSEVENTH' FREQUENCY ESTIMATES AND SQUARES THE DEVIATIONS FROM POPULATION VALUE. THIS SQUARED ERROR (WEIGHTED BY PROBABILITY) IS SUBSEQUENTLY SUMMED TO OBTAIN EXPECTED VALUE OF VARIANCE AMONG '3PSEVENTH' ESTIMATES, ALTHOUGH THE VALUE THUS OBTAINED ALSO INCLUDES ANY BIAS PRESENT. THE LAST COLUMN GIVES THE INTERNAL APPROXIMATION FOR '3PSEVENTH' VARIANCE BASED ON VARIANCE WITHIN A SINGLE SAMPLE ('3PNINTH').

TABLE 5 REARRAYS TABLE 1 BY MAGNITUDE OF '3PSEVENTH' VOLUME ESTIMATES AND DOES FOR VOLUME WHAT TABLE 4 DID FOR FREQUENCY.

TABLE 2. RELATION BETWEEN 'N' AND EXPECTED VALUES OF FREQUENCY ESTIMATES USING SEVERAL DIFFERENT 3P ESTIMATORS AND RATES OF SAMPLING

3P SAMPLING RATE=KZ	SAMPLE SIZE =N	PROB. OF OCCURRENCE =P	3PFIRST ESTIMATED FREQ.=T	3PSECOND ESTIMATED FREQ.=T	3PSEVENTH ESTIMATED FREQ.=T	3PSEVENTH WEIGHTS =N*P
32	0	.33229816	.00	REDRAW	REDRAW	.00000000
	1	.40703727	8.35	5.57	8.35	.40703727
	2	.19913855	18.35	12.25	9.18	.39827710
	3	.05235882	29.62	19.78	9.87	.15707646
	4	.00828401	41.92	27.99	10.48	.03313604
	5	.00082820	55.01	36.73	11.00	.00414100
	6	.00005286	68.71	45.88	11.45	.00031716
	7	.00000208	82.79	55.28	11.83	.00001456
	8	.00000005	97.32	64.98	12.17	.00000041
	9	.0000000+	112.00	74.78	12.44	.0000000+
EXPECTED VALUES =		UNITY	9.00	9.00	8.75	1.0000=ESN
WEIGHTED VALUE OF $\sum^{9}$(P*N*3PSEVENTH)/$\sum^{9}$(P*N)				=	9.00	
20	0	.14946778	.00	REDRAW	REDRAW	.00000000
	1	.34875816	4.86	4.13	7.77	.34875816
	2	.31000725	11.00	9.36	8.80	.62001450
	3	.14434199	18.03	15.33	9.62	.43302596
	4	.03977606	25.77	21.92	10.31	.15910423
	5	.00684957	34.04	28.95	10.89	.03424785
	6	.00074700	42.69	36.31	11.38	.00448200
	7	.00005025	51.60	43.89	11.79	.00035175
	8	.00000191	60.72	51.65	12.14	.00001528
	9	.00000003	70.00	59.54	12.44	.00000027
EXPECTED VALUES =		UNITY	9.00	9.00	8.61	1.6000=ESN
WEIGHTED VALUE OF $\sum^{9}$(P*N*3PSEVENTH)/$\sum^{9}$(P*N)				=	9.00	
11	0	.00811378	.00	REDRAW	REDRAW	.00000000
	1	.10547918	1.69	1.68	4.92	.10547918
	2	.27308890	5.09	5.05	7.40	.54617780
	3	.31606468	9.06	8.98	8.77	.94819404
	4	.20054437	13.46	13.35	9.79	.80217748
	5	.07614334	18.17	18.02	10.57	.38071670
	6	.01782824	23.09	22.90	11.20	.10696940
	7	.00253055	28.14	27.91	11.69	.01771385
	8	.00020017	33.28	33.01	12.10	.00160135
	9	.00000679	38.50	38.19	12.44	.00006111
EXPECTED VALUES =		UNITY	9.00	9.00	8.38	2.9091=ESN
WEIGHTED VALUE OF $\sum^{9}$(P*N*3PSEVENTH)/$\sum^{9}$(P*N)				=	9.00	

TABLE 3. RELATICN BETWEEN 'N' AND EXPECTED VALUES OF VOLUME ESTIMATES USING SEVERAL DIFFERENT 3P ESTIMATORS AND RATES OF SAMPLING

3P SAMPLING RATE=KZ	SAMPLE SIZE =N	PROB. OF OCCURRENCE =P	3PFIRST ESTIMATED VOL.=T	3PSECOND ESTIMATED VOL.=T	3PSEVENTH ESTIMATED VOL.=T	3PSEVENTH WEIGHTS =N*P
32	0	.33229816	.0	REDRAW	REDRAW	.00000000
	1	.40703727	1658.4	1107.3	1658.4	.40703727
	2	.19913855	3314.6	2213.2	1657.3	.39827710
	3	.05235882	4974.8	3321.7	1658.3	.15707646
	4	.00828401	6640.7	4434.0	1660.2	.03313604
	5	.00082820	8312.0	5550.0	1662.4	.00414100
	6	.00005286	9987.8	6668.9	1664.6	.00031716
	7	.00000208	11666.8	7790.0	1666.7	.00001456
	8	.00000005	13349.7	8913.6	1668.7	.00000041
	9	.0000000+	15033.6	10038.0	1670.4	.0000000+
EXPECTED VALUES =		UNITY	1658.0	1658.0	1658.1	1.0000=ESN
WEIGHTED VALUE OF $\sum_0^9$(P*N*3PSEVENTH)/$\sum_0^9$(P*N)				=	1658.0	
20	0	.14946778	.0	REDRAW	REDRAW	.00000000
	1	.34875816	1037.1	882.1	1659.4	.34875816
	2	.31000725	2071.1	1761.6	1656.9	.62001450
	3	.14434199	3107.8	2643.3	1657.5	.43302596
	4	.03977606	4148.6	3528.6	1659.5	.15910423
	5	.00684957	5193.3	4417.1	1661.9	.03424785
	6	.00074700	6241.0	5308.2	1664.3	.00448200
	7	.00005025	7291.0	6201.3	1666.5	.00035175
	8	.00000191	8342.9	7095.9	1668.6	.00001528
	9	.00000003	9396.0	7991.6	1670.4	.00000027
EXPECTED VALUES =		UNITY	1658.0	1658.0	1658.2	1.6000=ESN
WEIGHTED VALUE OF $\sum_0^9$(P*N*3PSEVENTH)/$\sum_0^9$(P*N)				=	1658.0	
11	0	.00811378	.0	REDRAW	REDRAW	.00000000
	1	.10547918	574.8	570.2	1672.2	.10547918
	2	.27308890	1139.5	1130.3	1657.5	.54617780
	3	.31606468	1707.2	1693.4	1655.5	.94819404
	4	.20054437	2279.0	2260.5	1657.4	.80217748
	5	.07614334	2853.7	2830.5	1660.3	.38071670
	6	.01782824	3430.4	3402.6	1663.2	.10696940
	7	.00253055	4008.6	3976.1	1665.9	.01771385
	8	.00020017	4587.8	4550.6	1668.3	.00160135
	9	.00000679	5167.8	5125.9	1670.4	.00006111
EXPECTED VALUES =		UNITY	1658.0	1658.0	1658.7	2.9091=ESN
WEIGHTED VALUE OF $\sum_0^9$(P*N*3PSEVENTH)/$\sum_0^9$(P*N)				=	1658.0	

TABLE 4. SQUARED DEVIATIONS OF '3PSEVENTH' FREQUENCY ESTIMATES FROM POPULATION VALUE, WITH '3PNINTH' APPROXIMATIONS USING VARIATION WITHIN SAMPLE

P=PROBABILITIES OF OCCURRENCE IF KZ EQUAL TO 32	20	11	SAMPLE SIZE =N	3PSEVENTH ESTIMATED T=FREQ.	SQUARED DEVIATION (T-POP T)	APPROX.VAR. (3PNINTH ABSOLUTE)
.33229816	.14946778	.00811378	0	REDRAW	REDRAW	REDRAW
.15104461	.14946778	.08113783	1	3.20	33.6400	NONE
.05594245	.09964519	.13522972	2	4.80	17.6400	2.5600
.00517986	.01660753	.05634572	3	5.33	13.4689	1.0378
.12307340	.09964519	.01352297	1	6.40	6.7600	NONE
.01139569	.01660753	.00563457	2	6.40	6.7600	.0000
.00207194	.01107169	.07512762	4	8.00	1.0000	7.6800
.02237698	.06643012	.18030629	3	8.53	.2209	14.7911
.06041784	.09964519	.10818377	2	9.60	.3600	40.9600
.00455827	.01107169	.00751276	3	9.60	.3600	10.2400
.00034532	.00307547	.04173757	5	9.60	.3600	7.1680
.00372950	.01845281	.10017016	4	10.40	1.9600	10.8800
.00003071	.00045563	.01236669	6	10.67	2.7889	5.9164
.04922936	.06643012	.01803063	2	11.20	4.8400	23.0400
.00075971	.00307547	.00417376	4	11.20	4.8400	7.6800
.00000153	.00003797	.00206112	7	11.43	5.9049	4.8065
.00033151	.00273375	.02968005	5	11.52	6.3504	7.7824
.01006964	.02767922	.06010210	3	11.73	7.4529	18.2044
.00000004	.00000169	.00018321	8	12.00	9.0000	3.9314
.00006753	.00045563	.00123667	5	12.16	9.9856	5.5296
.00001658	.00022781	.00494667	6	12.27	10.6929	5.7458
.0000000+	.00000003	.00000679	9	12.44	11.8336	3.2553
.00820490	.01845281	.01001701	3	12.80	14.4400	10.2400
.00089508	.00410062	.01780803	4	12.80	14.4400	10.2400
.00000338	.00003797	.00020611	6	12.80	14.4400	4.0960
.00000044	.00001012	.00043971	7	12.80	14.4400	4.3886
.00000001	.00000019	.00001628	8	13.20	17.6400	3.4514
.00000009	.00000169	.00001832	7	13.26	18.1476	3.1347
.00004475	.00034172	.00296800	5	13.44	19.7136	6.5536
.00072932	.00273375	.00296800	4	13.60	21.1600	5.7600
.0000000+	.00000003	.00000068	8	13.60	21.1600	2.4686
.00000119	.00001519	.00026382	6	13.87	23.7169	4.5511
.00003647	.00022781	.00049467	5	14.08	25.8064	3.6864
.00000001	.00000028	.00000977	7	14.17	26.7289	3.3437
.00000097	.00001012	.00004397	6	14.40	29.1600	2.5600
.00000001	.00000019	.00000163	7	14.63	31.6969	1.8808
.13291926	.09964519	.01081838	1	16.00	49.0000	NONE
.02215321	.02767922	.00601021	2	16.00	49.0000	.0000
.00196917	.00410062	.00178080	3	16.00	49.0000	.0000
.00009846	.00034172	.00029680	4	16.00	49.0000	.0000
.00000262	.00001519	.00002638	5	16.00	49.0000	.0000
.00000003	.00000028	.00000098	6	16.00	49.0000	.0000

UNITY = UNITY = UNITY = TOTAL $\sum^{42} P$

EXPECTED NUMBER OF SAMPLE TREES

1.0000 1.6000 2.9091

$\sum^{42} P*N = \sum^{0} KPI/KZ = ESN$

TABLE 5. SQUARED DEVIATIONS OF '3PSEVENTH' VOLUME ESTIMATES FROM POPULATION VALUE, WITH '3PNINTH' APPROXIMATIONS USING VARIATION WITHIN SAMPLE

P=PROBABILITIES OF OCCURRENCE IF KZ EQUAL TO 32	20	11	SAMPLE SIZE =N	3PSEVENTH ESTIMATED T=VOL.	SQUARED DEVIATION (T-POP T)	APPROX.VAR. (3PNINTH ABSOLUTE)
.33229816	.14946778	.00811378	0	REDRAW	REDRAW	REDRAW
.12307340	.09964519	.01352297	1	1587.20	5012.64	NONE
.01139569	.01660753	.00563457	2	1587.20	5012.64	.00
.00517986	.01660753	.05634572	3	1619.20	1505.44	1024.00
.00455827	.01107169	.00751276	3	1623.47	1192.32	1315.27
.05594245	.09964519	.13522972	2	1635.20	519.84	2304.00
.00207194	.01107169	.07512762	4	1638.40	384.16	880.64
.04922936	.06643012	.01803063	2	1641.60	268.96	2959.36
.00075971	.00307547	.00417376	4	1641.60	268.96	986.45
.00034532	.00307547	.04173757	5	1649.92	65.29	661.09
.00006753	.00045563	.00123667	5	1652.48	30.47	710.25
.02237698	.06643012	.18030629	3	1655.47	6.40	1178.74
.00003071	.00045563	.01236669	6	1657.60	.16	499.71
.00820490	.01845281	.01001701	3	1659.73	2.99	1315.27
.00000338	.00003797	.00020611	6	1659.73	2.99	526.11
.00000153	.00003797	.00206112	7	1663.09	25.91	387.03
.00000009	.00000169	.00001832	7	1664.91	47.75	402.63
.00372950	.01845281	.10017016	4	1665.60	57.76	692.05
.00000004	.00000169	.00018321	8	1667.20	84.64	307.20
.00072932	.00273375	.00296800	4	1668.80	116.64	739.84
.0000000+	.00000003	.00000068	8	1668.80	116.64	317.07
.0000000+	.00000003	.00000679	9	1670.40	153.76	249.17
.00033151	.00273375	.02968005	5	1671.68	187.14	452.20
.00003647	.00022781	.00049467	5	1674.24	263.74	473.50
.00001658	.00022781	.00494667	6	1675.73	314.35	317.90
.00000097	.00001012	.00004397	6	1677.87	394.82	328.82
.00000044	.00001012	.00043971	7	1678.63	425.60	235.45
.00000001	.00000019	.00000163	7	1680.46	504.45	241.58
.00000001	.00000019	.00001628	8	1680.80	519.84	181.30
.15104461	.14946778	.08113783	1	1683.20	635.04	NONE
.06041784	.09964519	.10818377	2	1689.60	998.56	40.96
.01006964	.02767922	.06010210	3	1691.73	1137.71	18.21
.00089508	.00410062	.01780803	4	1692.80	1211.04	10.24
.00004475	.00034172	.00296800	5	1693.44	1255.99	6.55
.00000119	.00001519	.00026382	6	1693.87	1286.66	4.55
.00000001	.00000028	.00000977	7	1694.17	1308.27	3.34
.13291926	.09964519	.01081838	1	1696.00	1444.00	NONE
.02215321	.02767922	.00601021	2	1696.00	1444.00	.00
.00196917	.00410062	.00178080	3	1696.00	1444.00	.00
.00009846	.00034172	.00029680	4	1696.00	1444.00	.00
.00000262	.00001519	.00002638	5	1696.00	1444.00	.00
.00000003	.00000028	.00000098	6	1696.00	1444.00	.00

UNITY = UNITY = UNITY = TOTAL $\sum^{42} P$

EXPECTED NUMBER OF SAMPLE TREES

1.0000 1.6000 2.9091

$\sum^{42} P*N=\sum^{8} KPI/KZ=ESN$

TABLE 6. EXPECTED VALUES OF VARIANCE AMONG NONZERO '3PSECOND' AND '3PSEVENTH' ESTIMATES, COMPARED WITH EXPECTED ABSOLUTE VALUES OF TWO APPROXIMATIONS FOR VARIANCE AMONG '3PSEVENTH' ESTIMATES. THE FIRST ('3PNINTH') IS DERIVED FROM EXPECTED INTERNAL VARIANCE WITHIN '3PSEVENTH' SAMPLES, WHILE THE SECOND ('3PEIGHTH') IS DERIVED FROM EXPECTED INTERNAL VARIANCE WITHIN THE POPULATION WHEN SAMPLED WITH VARIABLE PROBABILITY AND REPLACEMENT.

SAMPLE SIZE =ENZSN (N VARIES IF 3P)	EXPECTED VARIANCE AMONG 3PSECOND ESTIMATES	EXPECTED VARIANCE AMONG 3PSEVENTH ESTIMATES	VARIANCE APPROXIMATIONS: N VARIES, NO REPLACE. (3PNINTH)	VARIANCE APPROXIMATIONS: N=ENZSN, REPLACE. (3PEIGHTH)
	AMONG FREQUENCY ESTIMATES			
1.4977	41.84	22.84	17.20	20.70
1.8812	39.76	15.97	16.13	16.48
2.9329	28.59	8.78	13.31	10.57
	AMONG VOLUME ESTIMATES			
1.4977	611502.9	1687.8	1273.2	1540.0
1.8812	654005.4	1316.9	1188.9	1226.0
2.9329	452001.3	598.3	966.5	786.4

N.B. HAD FAILURE OF SELECTION PROCESS TO OBTAIN ANY SAMPLES BEEN SPECIFIED AS EQUIVALENT TO ZERO ESTIMATE (WITHOUT REDRAW), EXPECTED VARIANCES AMONG SUCH '3PFIRST' FREQUENCY ESTIMATES WOULD BE 102.98, 60.98, 29.49 FOR 'ESN'=1.0, 1.6, 2.9091 RESPECTIVELY. CORRESPONDING EXPECTED VOLUME VARIANCES WOULD BE 2283921.4, 1252024.3, 478185.7.

TABLE 6 SUMMARIZES THE EXPECTED VALUES OF VARIANCES AMONG '3PSECOND' AND '3PSEVENTH' ESTIMATES (A FOOTNOTE GIVES '3PFIRST' VARIANCES). THEN EXPECTED VALUES FOR 2 APPROXIMATIONS OF '3PSEVENTH' VARIANCE ARE GIVEN. THE FIRST ('3PNINTH') IS CONVENIENT WHEN ONLY INTERNAL EVIDENCE FROM A SINGLE SET OF '3PSEVENTH' SAMPLES IS AVAILABLE. THE SECOND ('3PEIGHTH') IS CONVENIENT WHEN ALL VALUES FOR INDIVIDUAL 'YI' AND 'KPI' IN THE POPULATION ARE KNOWN, BUT WHEN IT IS IMPRACTICAL TO COMPUTE EXPECTED VALUES OF VARIANCE BECAUSE OF THE ASTRONOMICAL NUMBER OF POSSIBLE OUTCOMES.

IT IS INTERESTING TO NOTE FROM TABLES 4, 5, 6 THAT EVEN WITH A RIDICULOUSLY SMALL POPULATION AND RELATIVELY LARGE VALUES FOR KPI/KZ AND ENZSN/M, EXPECTED VALUES OF '3PNINTH' AND '3PEIGHTH' ARE USEFUL APPROXIMATIONS FOR THE EXPECTED VARIANCE AMONG '3PSEVENTH' ESTIMATES. WHEN 'KZ' IS EQUAL TO 32, 20, 11, OBSERVED SQUARED ERRORS OF '3PSEVENTH' FREQUENCY ESTIMATES EXCEED EXPECTED VARIANCES 46, 45, 33 PERCENT OF THE TIME. OBSERVED SQUARED FREQUENCY ERRORS EXCEED '3PNINTH' APPROXIMATIONS 54, 45, 33 PERCENT OF THE TIME. WHEN VOLUME REPLACES FREQUENCY, EXCEEDANCES OF EXPECTED VARIANCES OCCUR 0, 31, 38 PERCENT OF THE TIME, WHILE EXCEEDANCES OF '3PNINTH' APPROXIMATIONS OCCUR 44, 33, 29 PERCENT OF THE TIME. IN MOST CASES, '3PEIGHTH' APPROXIMATIONS ARE SLIGHTLY CLOSER TO EXPECTED VALUES THAN ARE '3PNINTH' APPROXIMATIONS.

IT IS ALSO INTERESTING TO NOTE IN TABLES 4 AND 5 THAT BOTH FREQUENCY AND VOLUME ESTIMATES TEND TO BE SOMEWHAT SKEWED. WHEN 'KZ' IS EQUAL TO 32, 20, 11, THEN '3PSEVENTH' FREQUENCY ESTIMATES BELOW POPULATION VALUE OCCUR IN 56, 54, 55 PERCENT OF THE CASES, RESPECTIVELY. '3PSEVENTH' VOLUME ESTIMATES ARE BELOW POPULATION VALUE IN 41, 46, 56 PERCENT OF THE CASES. THE MAGNITUDE AND DIRECTION OF SEPARATION BETWEEN PORULATION VALUE AND MEDIAN (I. E., THE FIFTIETH PERCENTILE) OBVIOUSLY DEPENDS BOTH ON SAMPLING RATE AND RELATION

BETWEEN 'KPI' AND 'YI'. SUCH ASYMMETRY USUALLY DIMINISHES AS 'ENZSN' INCREASES AND SHOULD NOT BE CONFUSED WITH BIAS.

A NUMBER OF INFERENCES BASED ON THE TWO PRECEDING SECTIONS CAN NOW BE SUMMARIZED.

(1) '3PFIRST' AND '3PSECOND' ESTIMATES ARE UNBIASED, BUT TEND TO DEVIATE MUCH MORE FROM POPULATION VALUES THAN DO '3PSEVENTH' ESTIMATES.

(2) '3PSEVENTH' ESTIMATES MAY INVOLVE A SMALL BIAS THAT COMPLETELY DISAPPEARS AS N/ENZSN APPROACHES UNITY OR AS VARIANCE OF YI/KPI APPROACHES ZERO.

(3) THE ONLY PRACTICABLE METHOD FOR OBTAINING UNBIASED ESTIMATES OF THE VARIANCE OF 3P SAMPLES FROM LARGE POPULATIONS IS TO OBTAIN INDEPENDENT, INTERPENETRATING SETS OF SAMPLES.

(4) WHEN SUCH INDEPENDENT SETS OF 3P SAMPLES HAVE BEEN SECURED AND WHEN, IN ADDITION, THE AGGREGATE SUM OF 'KPI' IS KNOWN FOR THE POPULATION, ESTIMATES CAN BE ADJUSTED FCR LARGE DIFFERENCES BETWEEN 'N' AND 'ENZSN' IF STRONG CORRELATION BETWEEN 'N' AND 3P ESTIMATES WARRANTS.

(5) WHEN SUCH INDEPENDENT SETS OF 3P SAMPLES ARE LACKING, '3PNINTH' AFFORDS A USEFUL APPROXIMATION OF THE VARIANCE OF '3PSEVENTH' ESTIMATES.

(6) THE SQUARED DIFFERENCE BETWEEN '3PSEVENTH' ESTIMATES AND POPULATION VALUES APPEARS TO BE SMALLER THAN THE EXPECTED OR THE APPROXIMATE VARIANCES IN ROUGHLY 2/3 OF THE CASES WHEN 'ENZSN' IS AT LEAST 3, THOUGH SOME ASYMMETRY IS APPARENT.

(7) MAGNITUDE AND DIRECTION OF SKEWNESS OF 3P ESTIMATES DEPEND ON 'KZ', THE SUM AND DISTRIBUTION OF 'KPI', AND THE RELATION BETWEEN 'KPI' AND 'YI'. SKEWNESS IS NOT SYNONYMOUS WITH BIAS.

================== SOME CONSIDERATIONS IN 3P-SAMPLE DESIGN ==================

IT WILL BE ASSUMED HENCEFORTH THAT IN MOST PRACTICAL SITUATIONS, 'ESN' AND 'ENZSN' ARE SO NEARLY IDENTICAL AS TO MAKE DISTINCTION UNNECESSARY, AND 'ESN' WILL BE USED EVEN THOUGH REDRAW WOULD USUALLY BE SPECIFIED WHEN N=0.

DESIGN OF 3P SAMPLES MAY BE SLIGHTLY INFLUENCED BY 'C', THE COEFFICIENT OF VARIATION AMONG 'KPI' IN THE POPULATION, AND BY 'M', THE NUMBER OF TREES IN THE POPULATION, BUT ASSUMING 'C' TO BE ZERO AND 'M' TO BE THE NEAREST ROUND NUMBER SUCH AS 1000, 10000, ETC. IS USUALLY SAFE.

THERE ARE, HOWEVER, TWO OTHER POPULATION PARAMETERS THAT MUST BE TENTATIVELY GUESSED IN ADVANCE WITH MORE ACCURACY IF 3P SAMPLING IS TO ACHIEVE DESIRED PRECISION WITH TOLERABLE RISK.

PROBABLY THE MOST IMPORTANT GUESS IS FOR $\sum^{M}$KPI, WHICH SHOULD BE WITHIN 20-30 PERCENT OF ITS ULTIMATE VALUE. IF A PRELIMINARY DIAGNOSTIC TALLY (*1) FOR EACH SALE AREA HAS BEEN MADE BY HORIZONTAL POINT-SAMPLING, THIS INFORMATION IS READILY AVAILABLE WITH ADEQUATE ACCURACY. SUCH RECONNAISSANCE REQUIRES ONLY ONE OR TWO MAN-DAYS OF EFFORT EVEN FOR SEVERAL THOUSAND ACRES.

THE OTHER IMPORTANT PARAMETER THAT MUST BE GUESSED IS THE COEFFICIENT OF VARIATION 'CV' OF THE PROPERLY WEIGHTED RATIOS YI/KPI APPROPRIATE TO THE PARTICULAR MEN WHO WILL BE ASSESSING 'KPI' WHEN THE TREES ARE MARKED FOR HARVEST. THIS DEPENDS ON THEIR SKILL, TRAINING, AND TALENT, BUT REASONABLY CONSCIENTIOUS ASSESSORS SHOULD HAVE NO DIFFICULTY IN ACHIEVING A 20 TO 30 PERCENT COEFFICIENT, AND TALENTED ASSESSORS HAVE BEEN ABLE TO ACHIEVE 15 PERCENT OR LESS. EXPERIENCE WITH PREVIOUS PERFORMANCE ALLOWS SPECIFYING A

'CV' LIKELY TO BE ACHIEVED. THE MOST CONVENIENT APPROXIMATION INVOLVES TAKING THE SQUARE ROUT OF N*3PNINTH FOR A 3P SAMPLE PREVIOUSLY COMPLETED BY THE PARTICULAR ASSESSORS.

WITH THESE GUESSES OR ASSUMPTIONS, THE FIRST STEP IN DESIGNING A '3PSEVENTH' SAMPLE IS TO COMPUTE 'ESN' THAT IS NEEDED FOR THE MAXIMUM TOLERABLE STANDARD ERROR 'TSE'. IF STANDARD ERROR OF PLUS OR MINUS 2 PERCENT CAN BE TOLERATED AND IF THE COEFFICIENT OF VARIATION FOR YI/KPI IS 20 PERCENT, TENTATIVE ESN = (CV/TSE)**2 = 100 TREES. THIS WILL USUALLY BE INCREASED BY ONE OR TWO TIMES THE STANDARC DEVIATION OF TENTATIVE 'ESN' TO DECREASE POSSIBILITY THAT 'N' LESS THAN TENTATIVE 'ESN' WOULD OCCUR. THUS, TENTATIVE 'ESN' MIGHT BE INCREASED TO 110 BY ADDING THE SQUARE ROOT OF '3PFIFTH'.

NOW THE NEW 'ESN' CAN BE USED IN CONJUNCTION WITH GUESSED $\sum^{M}$KPI TO OBTAIN RATE OF 3P SAMPLING, KZ = $\sum^{M}$KPI/ESN. IF $\sum^{M}$KPI WERE GUESSED AT 11000 (DOLLARS, HUNDREDS OF BOARD FEET, ETC.), AND IF 'ESN' WERE SPECIFIED AS 110 TREES, THEN KZ = 100 WOULD RESULT IN THE DESIRED RATE OF 3P SAMPLING.

HOWEVER, THIS DOES NOT SPECIFY WHAT TO DO IN THE CASE OF TREES ASSIGNED A 'KPI' EQUAL TO OR GREATER THAN 'KZ', NOR DOES IT GUARD AGAINST ANOTHER CONTINGENCY--SECURING SO MANY SAMPLE TREES THAT THE BLOW-UP FACTOR FOR THE LARGEST TREES SAMPLED BECOMES LESS THAN UNITY. THE AUTHOR HAS DEVISED A PRACTICAL SOLUTION TO THESE TWO RELATED PROBLEMS IN DESIGN. JUSTIFICATION FOR THIS SOLUTION PRESUMES AN UNDERSTANDING OF THE UNDERLYING PRINCIPLES DISCUSSED BELOW.

IF A FIXED NUMBER OF SAMPLES 'N' BE DRAWN WITH VARIABLE PROBABILITY AND WITHOUT REPLACEMENT, THE SAMPLE ESTIMATE WILL BE BIASED UNLESS 'PI' (EQUAL TO KPI/$\sum^{M}$KPI) FOR THE LARGEST INDIVIDUAL PROBABILITY IN THE POPULATION IS

SMALLER THAN 1/N. THE REASON IS THAT ESTIMATION FROM PROBABILITY SAMPLES ASSUMES THAT THE 'I'TH INDIVIDUAL WILL BE REPRESENTED BY SAMPLES PROPORTIONATELY TO ITS 'PI', YET IT IS IMPOSSIBLE FOR ONE INDIVIDUAL TO CONSTITUTE MORE THAN (1/N)TH PORTION OF ANY SINGLE SET OF 'N' SAMPLES DRAWN WITHOUT REPLACEMENT. FROM THIS, IT FOLLOWS THAT (N) * (MAX KPI) MUST BE SMALLER THAN $\sum^{M}$KPI FOR THE SAMPLE ESTIMATE TO BE UNBIASED.

IF A VARIABLE NUMBER 'N' OF 3P SAMPLES BE DRAWN WITHOUT REPLACEMENT, THE SAMPLE ESTIMATE WILL BE BIASED UNLESS KPI/KZ FOR THE LARGEST PROBABILITY IN THE POPULATION IS SMALLER THAN UNITY. THE REASON IS THAT ESTIMATION FROM 3P SAMPLES ASSUMES THAT KPI/KZ IS THE EXPECTED VALUE OF THE NUMBER OF APPEARANCES OF THE 'I'TH INDIVIDUAL IN A SINGLE SET OF 3P SAMPLES, YET IT IS IMPOSSIBLE FOR THE 'I'TH INDIVIDUAL TO APPEAR MORE THAN ONCE IN ANY SINGLE SET OF SAMPLES DRAWN WITHOUT REPLACEMENT. FROM THIS AND THE FACT THAT ESN = $\sum^{M}$KPI/KZ, IT FOLLOWS THAT (ESN) * (MAX KPI) MUST BE SMALLER THAN $\sum^{M}$KPI FOR THE SAMPLE TO BE UNBIASED. THIS IS THE 3P ANALOG OF THE FIXED-SAMPLE INEQUALITY DEVELOPED IN THE PRECEDING PARAGRAPH.

IT IS, MOREOVER, DESIRABLE THAT (N) * (MAX KPI) BE SMALLER THAN $\sum^{M}$KPI IN 3P SAMPLING, EVEN THOUGH ESTIMATES WHERE THIS CONDITION IS VIOLATED ARE NOT BIASED IN THE STRICT SENSE OF THE WORD (SINCE INDIVIDUALS UNDER-REPRESENTED WHEN 'N' IS LARGE ARE OVER-REPRESENTED WHEN 'N' IS SMALL).

TO PROVIDE A SAFEGUARD AGAINST THE DESIGNER'S IMPERFECT KNOWLEDGE OF THE DISTRIBUTION OF 'KPI' IN THE POPULATION, AND TO REDUCE THE ERRATIC EFFECTS OF SAMPLING OR REJECTING A FEW LARGE TREES WITH 'KPI' JUST BARELY SMALLER THAN 'KZ', IT IS DESIRABLE TO RESTRICT THE POPULATION SAMPLED TO SOMETHING LESS THAN THE COMPLETE POPULATION. WHEN THIS IS DONE, EVERY TREE IN THE EXCLUDED PORTION MUST BE MEASURED, AND THE ERROR-FREE TOTAL OF THESE (WITHOUT

INFLATION) MUST BE ADDED TO THE ESTIMATE FOR THE SAMPLED PORTION.

IT NOW BECOMES CONVENIENT TO SPLIT 'KZ' INTO TWO ADDITIVE PARTS 'K' AND 'Z' SUCH THAT (K+Z) = KZ. THE PROGRESSION OF INTEGERS STOPS WITH 'K', AND THE PROBABILITY SET IS COMPLETED WITH Z=(KZ-K) NULLS, WHICH CAN BE REPRESENTED BY MINUS ZEROS (-0) OR DOUBLE X'S (XX). ALL TREES ASSIGNED 'KPI' LARGER THAN 'K' MUST BE MEASURED WITHOUT RECOURSE TO ANY RANDOM SAMPLING PROCESS. TREES ASSIGNED 'KPI' EQUAL TO OR SMALLER THAN 'K' WILL BE SUBJECTED TO THE USUAL 3P-RANDOM-INTEGER COMPARISON, BUT WHEN PAIRED WITH NULL ELEMENTS WILL ALWAYS BE REJECTED AS SAMPLES. NO TREE CAN BE ASSIGNED A 'KPI' SMALLER THAN UNITY.

THE USE OF NULLS FACILITATES GUARDING AGAINST 'N' EXCEEDING THRESHOLD NB = $\sum^{M}$KPI/K, EVEN THOUGH SUCH SAMPLES WOULD NOT BE BIASED IN THE STRICT SENSE OF THE WORD. THERE IS A RATIO Z/K THAT SATISFIES THE EQUALITY (NB - ESN)**2 = 3PFIFTH. ASSUME C = 0 AS THE SAFE BINOMIAL UPPER BOUND FOR THE POISSON SERIES. SUBSTITUTING IDENTITIES GIVES (ESN * Z/K)**2 = ESN - (1/M) * ESN**2. IF 4 TIMES THE RIGHT-HAND SIDE OF THE EQUALITY IS USED AS THE LOWER BOUND FOR A SINGLE EXCLUDED TAIL INVOLVING PROBABILITIES AGGREGATING 1/40, AND IF IT BE RECOGNIZED THAT WE WOULD BE STILL HAPPIER IF THE RIGHT-HAND SIDE WERE SMALLER THAN THE LEFT-HAND SIDE, THEN IT CAN BE STATED THAT 'N' WILL EXCEED 'NB' LESS THAN 1 TIME IN 40 IF

```
=======
3PTENTH = (Z/K)**2 SHOULD EXCEED 4 * (1/ESN - 1/M)
=======
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THUS, AFTER HAVING DETERMINED 'KZ' THAT GIVES APPROXIMATELY THE DESIRED SAMPLING RATE IF THE ENTIRE POPULATION OF 'M' TREES INVOLVING $\sum^{M}$KPI COULD BE 3P-SAMPLED WITHOUT BIAS, A SMALLER LESS VARIABLE POPULATION OF TREES WITH MAXIMUM KPI=K IS DEFINED, AND ALL LARGER TREES ARE MEASURED. THIS ORDINARILY RESULTS IN MEASURING SOMEWHAT MORE TREES THAN WAS ORIGINALLY ANTICIPATED, BUT

WITH CONSIDERABLY LESS SAMPLING ERROR FOR THE TOTAL, SINCE THE SURE-TO-BE MEASURED TREES HAVE NO SAMPLING ERROR, YET OFTEN INVOLVE CONSIDERABLE VOLUME.

IF THE SAMPLE DESIGN SPECIFIES SEVERAL INDEPENDENT INTERPENETRATING SETS OF SAMPLES INSTEAD OF A SINGLE SET, THE TOTAL NUMBER OF SAMPLES NEEDED TO GET THE DESIRED 'TSE' MUST BE DIVIDED BY THE PLANNED NUMBER OF SETS BEFORE CALCULATION OF 'KZ' AND 'K', SINCE THESE PARAMETERS GOVERN EACH INDIVIDUAL SET.

IT IS OBVIOUS THAT THE TECHNIQUE OUTLINED ABOVE FOR DESIGNING 3P SAMPLES INVOLVES EDUCATED GUESSES AND APPROXIMATE ANSWERS, YET EXPERIENCE HAS SHOWN THAT SPECIFICATION OF 'KZ' AND 'K' FOLLOWING THE PROCEDURES DISCUSSED LEADS TO ESTIMATES THAT ACHIEVE THE DESIRED OBJECTIVE IF THE EDUCATED GUESSES DO NOT ERR BADLY. CUSHIONS AGAINST BAD LUCK AND IMPERFECT KNOWLEDGE HAVE BEEN INCORPORATED INTO THE CALCULATIONS OF BOTH 'KZ' AND 'K'.

THE EXPECTED VALUE OF $\sum^{M}$KPI FOR A 3P SAMPLE CAN BE CALCULATED EXACTLY AS (KZ)*(ESN - EXPECTED VARIANCE OF ESN), WHICH HELPS FLAG SAMPLES DEVIATING EXCESSIVELY FROM EXPECTATION EVEN WHEN VARIANCE CAN ONLY BE APPROXIMATED.

THE USE OF 3P SAMPLES WHERE THE $\sum^{N}$KPI IS NOT COMPLETELY ACCUMULATED DURING THE SAMPLING PROCESS WILL NOT BE DISCUSSED AT LENGTH. OPPORTUNITIES OF THIS SORT ARISING IN FORESTRY INVOLVE 3P SUBSAMPLING OF PRIMARY LIST, AREA, OR CLUSTER SAMPLES SELECTED WITH KNOWN PROBABILITIES OFTEN UNRELATED TO THE AGGREGATE OF INDIVIDUALS COMPRISING THE PRIMARY UNIT. SINCE THE SAMPLING VARIANCE CAN NEVER BE LESS THAN VARIANCE AMONG THE PRIMARY UNITS WHEN COMPLETELY MEASURED, THE ADVANTAGE OF 3P SUBSAMPLING WOULD CONSIST ONLY OF A GREAT REDUCTION IN COST WITH POSSIBLY ONLY A MODERATE INCREASE IN VARIATION AMONG ESTIMATES OF PRIMARY SAMPLING UNITS. AN EXAMPLE MIGHT BE DENDROMETRY APPLIED TO A 3P SAMPLE OF TREES ON ONE-ACRE PLOT-SAMPLES.

================== 3P-RANDOM-INTEGER GENERATION BY COMPUTER ===================

THE BASIC PROBABILITY SET FOR A 3P SAMPLE WAS EXEMPLIFIED BY A DECK OF CARDS CONTAINING KZ = (K+Z) ELEMENTS IN THE AUTHOR'S EARLIER PAPER (*2). THIS WAS DONE TO SIMPLIFY EXPOSITION, ALTHOUGH THE PAPER HINTED AT MORE SUITABLE MECHANISMS.

FOR FIELD USE, ESPECIALLY WHERE (K+Z) MIGHT CONTAIN HUNDREDS OR THOUSANDS OF ELEMENTS, LISTS OF RANDOM INTEGERS ARE THE OBVIOUS ANSWER. HOWEVER, USING SUCH LISTS AS PUBLISHED WOULD BE INTOLERABLE IN 3P SAMPLING, SINCE NUMBERS LARGER THAN 'KZ' WOULD HAVE TO BE MENTALLY SKIPPED, AND SINCE THE USER WOULD HAVE TO REMEMBER THAT NUMBERS BETWEEN 'K' AND 'KZ' REPRESENTED NULLS, NOT ACTUAL NUMBERS.

JUST AS COMPUTATION OF 3P-SAMPLE ESTIMATES WOULD HAVE BEEN IMPRACTICAL BEFORE THE DAY OF HIGH-SPEED COMPUTERS, SO WOULD THE PREPARATION OF INDIVIDUAL TAILOR-MADE LISTS OF RANDOM NUMBERS WITH SPECIFIED MAXIMUM AND WITH NULLS INTERSPERSED WITH NUMBERS IN THE RATIO Z/K. HIGH-SPEED COMPUTER PROGRAM 'STX' ACCOMPLISHING THE FIRST JOB HAS ALREADY BEEN DESCRIBED IN REFERENCE (*3), WHILE PROGRAM 'THRP' FOR ACCOMPLISHING THE SECOND JOB IS DESCRIBED BELOW. NULLS INTERSPERSED WITH INTEGERS WILL BE REPRESENTED BY (-0) INSTEAD OF BY THE EARLIER (X) OR (XX) TO SIMPLIFY PRINTING FORMAT.

MONTE CARLO METHODOLOGY AND GENERATION OF STRINGS OF PSEUDO-RANDOM NUMBERS HAVE BEEN THE SUBJECT OF NUMEROUS PUBLICATIONS. A NUMBER OF COMPUTER PROGRAMS FOR SUCH GENERATORS WERE SCREENED BY THE AUTHOR, AND NONE WERE FOUND SATISFACTORY FOR 3P SAMPLING, WHERE TREES ON THE GROUND ARE USUALLY VISITED

IN A NOTABLY NON-RANDOM SEQUENCE. EXCESSIVELY LONG RUNS (SERIAL CORRELATION) CONSTITUTED THE MOST UNSATISFACTORY CHARACTERISTIC OF THE GENERATORS TRIED.

AFTER THE AUTHOR HAD EMPIRICALLY DISCARDED A NUMBER OF GENERATORS AS UNSUITABLE, HULL AND DOBELL'S EXCELLENT ARTICLE (*6) SUBSTANTIATED THE UNSUITABILITY OF MANY OF THESE, AND INDICATED SOME PROMISING LEADS. SINCE THE AUTHOR INTUITIVELY FELT THAT THE MIXED CONGRUENTIAL METHOD HAD THE MOST PROMISE, HE TRIED THE GENERATOR (2**8+1) * X + F, MODULO 2**35, WHICH GAVE THE LEAST GROUNDS FOR SUSPICION IN (*6). 'X' IS THE PREVIOUSLY GENERATED NUMBER, WHILE 'F' IS A CONSTANT THAT IS RELATIVELY UNIMPORTANT AS LONG AS IT IS ODD. AFTER TRIAL OF SEVERAL CONSTANTS, THE AUTHOR ADOPTED 29 327 845 667. 29 327 871 111 HAS THEORETICAL MERIT AMONG NUMBERS PRIME TO 257.

RESULTS WERE STILL UNSATISFACTORY, SO 2 ADDITIONAL OPERATIONS WERE INCORPORATED INTO THE GENERATOR. FIRST, 23 RANDOM 12-DIGIT OCTAL MASKS WERE STORED AND SINGLY COMBINED WITH GENERATED INTEGERS IN THE BOOLEAN 'EXCLUSIVE OR' OPERATION. 7-BIT CIRCULAR ROTATION OF EACH MASK PROVIDED 828 DIFFERENT MASKS BEFORE RECYCLING. IT SHOULD BE NOTED THAT 'EXCLUSIVE OR' WITH A GIVEN MASK WILL TRANSFORM 2**35 INTEGERS INTO 2**35 DIFFERENT INTEGERS WITHOUT REPETITION.

SECOND, A RANDOM PERMUTATION OF THE SEQUENCE OF NUMBERS 1 THROUGH 500 WAS STORED AND USED ON ALTERNATE PAGES OF OUTPUT EITHER TO SPECIFY ORDER IN THE PRINT ARRAY CORRESPONDING TO THE GENERATED PROGRESSION, OR TO SPECIFY ORDER IN THE GENERATED ARRAY CORRESPONDING TO THE PRINT PROGRESSION. THIS WAS INTENDED TO FURTHER DISPERSE NONRANDOM STRINGS OF NULLS WHICH MIGHT SURVIVE THE 'EXCLUSIVE OR' INTERACTION WITH THE RANDOM MASK.

PRIOR TO THE PERMUTATION, ALL GENERATED INTEGERS (MOD 2**35) WERE RIGHT-ADJUSTED SO THEY RETAINED THE SAME NUMBER OF BIT POSITIONS AS DID (KZ-1),

WHICH NUMBER IS THE LOGARITHM OF 'KZ' TO THE BASE 2. ANY NUMBER AFTER ADJUSTMENT THAT WAS LARGER THAN (KZ-1) WAS REPLACED BY A NEWLY GENERATED INTEGER, UNTIL AN ARRAY OF 500 INTEGERS LESS THAN 'KZ' WAS OBTAINED. NULL (-0) THEN REPLACED (+0) AND ALL INTEGERS LARGER THAN 'K'. OBVIOUSLY, THIS PROCEDURE CAN GENERATE A RECTANGULAR POPULATION FROM ZERO TO 'K' IF 'KZ' IS SET EQUAL TO (K+1). SAMPLING WITH EQUAL PROBABILITY WOULD REQUIRE SETTING K=1.

THIS GENERATOR HAS APPARENTLY PROVIDED SATISFACTORY LISTS FOR A WIDE VARIETY OF TRYING SITUATIONS. ALTHOUGH THE AUTHOR COULD FIND NO EARLIER PUBLICATIONS ADVOCATING USE OF 'EXCLUSIVE OR' AS A SECONDARY GENERATING FUNCTION TOGETHER WITH THE INPUT OF RANDOM NUMBERS AS MASKS AND AS PERMUTED SUBSCRIPTS, HE WAS INTERESTED TO NOTE LATER THAT MCLAREN AND MARSAGLIA (*7) CONCLUDED INDEPENDENTLY THAT NONE OF A LARGE NUMBER OF MIXED CONGRUENTIAL AND MULTIPLICATIVE CONGRUENTIAL GENERATORS THEY SCREENED WERE SATISFACTORY. THE SOLUTIONS THEY RECOMMENDED WERE--(1) INPUTTING A LIST OF RANDOM NUMBERS AND HAVING EACH SUCH NUMBER GENERATE ITS OWN REPLACEMENT, SERIATIM (2) USING OUTPUT FROM ONE GENERATOR AS INPUT TO A SECOND GENERATOR. THEIR EXPERIENCE SEEMS TO BEAR OUT THE AUTHOR'S, AND THEIR SOLUTIONS, THOUGH DIFFERENT, ARE ALONG THE SAME LINES AS HIS.

HOW TO USE 'THRP' TO GENERATE CRITERIA FOR 3P SAMPLING SPECIFIED BY 'K' AND 'KZ' IS EXPLAINED IN APPENDICES A AND B. HOWEVER, TWO FEATURES MIGHT BE MENTIONED HERE. ON THE BOTTOM RIGHT OF EACH PAGE OF 500 INTEGERS AND NULLS ARE TWO FIGURES--THE SUM OF NONNULL INTEGERS, AND THE NUMBER OF NONNULL INTEGERS. ON THE LAST PAGE, THESE FIGURES ARE TOTALLED FOR ALL PAGES AND LABELLED 'KSUM' AND 'NK', ALONG WITH THE TOTAL NUMBER OF GENERATED ITEMS, LABELLED 'NKZ'. BELOW THESE TOTALS ARE THE SUM OF INTEGERS EXPECTED FOR 'NK' NONNULL ITEMS, THE NUMBER OF NONNULL ITEMS EXPECTED AMONG 'NKZ' TOTAL ITEMS

(WITH SPECIFIED K/KZ), AND THE TOTAL NUMBER OF ITEMS REQUESTED TO BE GENERATED.

THUS, IT IS POSSIBLE TO SCREEN EITHER INDIVIDUAL PAGES OR SETS OF PAGES BEFORE SAMPLING STARTS. PAGES OR SETS DIFFERING EXCESSIVELY FROM EXPECTATION CAN BE DISCARDED BEFORE USE, IF DESIRED, WITHOUT BIASING THE SAMPLE ESTIMATES.

FIELD USE OF RANDOM CRITERIA IN FOREST SAMPLING HAS SUFFERED GREATLY FROM LACK OF SUITABLE DISPENSERS IN THE PAST. CHEAP BIASED DEVICES INVOLVING MARBLES, DICE, SHORT-PERIOD REPEATING SEQUENCES OF NUMBERS, COUNTERS OR TALLIES WITH FIXED SAMPLING INTERVALS, PROBABILITY SETS EXHAUSTED BEFORE REPLACEMENT OR RESHUFFLE, ETC., HAVE TENDED TO GIVE RANDOM SAMPLING A BLACK EYE.

EVEN WHERE OTHERWISE BLAMELESS LISTS OF RANDOM NUMBERS HAVE BEEN EMPLOYED, FOREKNOWLEDGE OF THE NEXT RANDOM NUMBER HAS OFTEN INFLUENCED THE SEQUENCE IN WHICH TREES WERE VISITED OR THE ACTION TAKEN AT A PARTICULAR TREE. WHEN ENUMERATION SEQUENCE OR INDIVIDUAL ASSESSMENT IS SUBJECTIVE, FOREKNOWLEDGE OF THE FORTHCOMING RANDOM CRITERION CAN BIAS SAMPLE ESTIMATES JUST AS SURELY AS LOADING DICE AGAINST OR IN FAVOR OF PARTICULAR OUTCOMES. THOUGH LISTS OF GENUINELY RANDOM NUMBERS IN THE CUSTODY OF A RECORDER AND UNSEEN BY ENUMERATORS OR ASSESSORS SHOULD RESULT IN NO BIAS, SUCH PROCEDURE IS FREQUENTLY NOT FEASIBLE.

CONSEQUENTLY, THE AUTHOR FELT THAT WIDESPREAD SATISFACTORY APPLICATION OF 3P SAMPLING REQUIRED FINDING OR DEVELOPING SUITABLE DISPENSERS FOR THE TAILOR-MADE LISTS OF COMPUTER-GENERATED CRITERIA. HE ORIGINALLY HOPED TO ADAPT SMALL DOUBLE-ROLLER MAP DISPLAY CASES TO THE JOB, BUT THE MANUFACTURER OF THE ONLY MODEL OF WHICH HE WAS AWARE HAD GONE OUT OF BUSINESS.

TO ILLUSTRATE THE SORT OF THING NEEDED, HE MADE THE CRUDE DEVICE SHOWN IN FIGURE 1A. THE DIMENSIONS WERE DETERMINED BY ODDS AND ENDS AVAILABLE, SUCH AS LINT-PICKER CYLINDERS AND HONEYCOMB FRAME, BUT A DEVICE HANDLING 1, 2, 5,

OR 10 COLUMNS WOULD HAVE BEEN PREFERABLE TO THE 3 COLUMNS SHOWN.

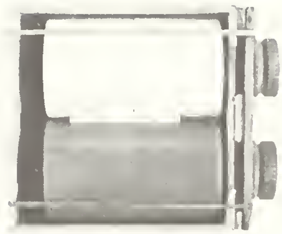
THE AUTHOR NEXT LOCATED THE PROGRAMMED LEARNING DEVICE SHOWN IN FIGURE 1B. IT IS MADE FOR THE NATICNAL INSTITUTE OF EDUCATION, WATERFORD, CONNECTICUT BY THE EDUCATIONAL AIDS PUBLISHING CORP., CARLE PLACE, L.I., N.Y. ALTHOUGH IT CAN HANDLE THE FULL 10-COLUMN COMPUTER SHEET, A METAL, WOOD, OR PLASTIC OUTER SHELL WOULD BE BETTER THAN ITS PRESENT CARDBOARD CONTAINER. FURTHERMORE, THE CONTAINER COULD BE NARROWER, AND A BETTER BRAKE THAN RUBBER BANDS AROUND BOTH ROLLERS COULD BE DEVISED. HOWEVER, IT IS SUITABLE FOR TEMPORARY USE WHERE THE DISPENSER CAN BE PROTECTED FROM MOISTURE.

FINALLY, CLEMENT MESAVAGE OF THE U.S. FOREST SERVICE'S SOUTHERN FOREST EXPERIMENT STATION BECAME INTERESTED IN THE PROBLEM AND DEVOTED MUCH PERSONAL AS WELL AS OFFICIAL EFFORT TO DEVELOPMENT OF THE PRODUCTION MODEL SHOWN IN FIGURE 1C. IT HANDLES 5 COLUMNS (A COMPUTER HALF-PAGE), AND 20 HALF-PAGES CAN BE SPLICED TOGETHER WITH RUBBER CEMENT TO PROVIDE 5000 3P CRITERIA. THE DISPENSER IS MANUFACTURED BY GRANNAN INDUSTRIES, 844 HIGHWAY 62 EAST, MOUNTAIN HOME, ARKANSAS. LISTS ARE PRINTED SO THAT A 4-CHARACTER IDENTIFIER AT BOTTOM OF EACH CULUMN NOT ONLY SERVES AS A BASE AND HELPS ALIGN THE SPLICE, BUT IT ALSO PROVIDES NON-DETACHABLE BRIEF IDENTIFICATION OF THE PARTICULAR JOB OR AREA TO WHICH THE CRITERIA ARE APPROPRIATE.

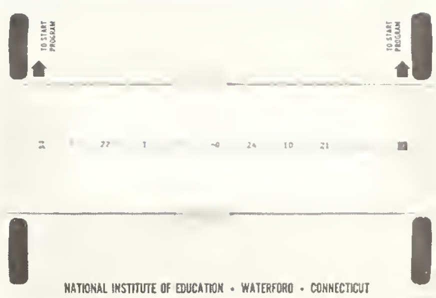
ALL IN ALL, IT SEEMS TO BE THE MOST SUITABLE AND CONVENIENT DISPENSER OF 3P CRITERIA THAT IS CURRENTLY AVAILABLE. OF THE 5 COLUMNS, ALL CAN BE USED AT EACH TREE WHEN 5 INTERPENETRATING INDEPENCENT SAMPLES ARE DESIRED--AND 5 IS A FAIRLY SATISFACTORY NUMBER FOR MANY PURPOSES--OR FEWER CAN BE USED. WHEN ONLY 1 NUMBER IS NEEDED PER TREE, A NEW CRITERION SHOULD BE ROTATED INTO VIEW AT EACH TREE VISITED UNTIL A COLUMN HAS BEEN EXHAUSTED. THEN THE NEXT COLUMN CAN BE USED BY ROTATING IN THE OPPCSITE DIRECTION, ETC. THE IMPORTANT THING

FIGURE 1. RANDOM INTEGER DISPENSERS THAT DISPLAY ONE LINE OR ONE NUMBER AT A TIME FROM A LIST OF NUMBERS GENERATED BY COMPUTER FOR ANY DESIRED RATE OF 3P SAMPLING.

(A)



(B)



(C)

(A) AUTHOR'S EARLY HOME-MADE DEVICE (3 COLUMNS).
(B) NATIONAL INSTITUTE OF EDUCATION'S PROGRAMMED LEARNING DEVICE (10 COL.).
(C) MESAVAGE'S PRODUCTION MODEL (5 COLUMNS).

IS THAT ROTATION EXPOSING THE FORTHCOMING 'KP' SHOULD NEVER OCCUR UNTIL AFTER 'KPI' FOR THE CORRESPONDING TREE HAS BEEN ASSIGNED AND RECORDED.

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================================= APPENDIX A =================================

LISTING OF FORTRAN-4 VERSION OF

PROGRAM THRP

AND 7090-MAP VERSION OF

SUBROUTINE IRDM

```
$IBFTC BLB3    DECK                                                       BLB3    0
C  BLB3----INPUT-OUTPUT OPTIONS AND CONSTANTS FOR THRP (11-11-64)         BLB3    1
C          RANDOM NUMBER GENERATOR FOR 3P SAMPLING, BY L.R.GROSENBAUGH.   BLB3    2
C      SPECIFY LOGICAL NUMBER OF DESIRED INPUT TAPE (MRE) AND             BLB3    3
C      OUTPUT TAPE (MPR).  IF REGULAR SYSTEM OUTPUT TAPE IS USED,         BLB3    4
C      'MEOF' SHOULD BE SPECIFIED TO BE ZERO,  OTHERWISE TO BE ONE.       BLB3    5
C      'LEFT' AND 'KFIX' ARE CONSTANTS NEEDED BY GENERATING FUNCTION.     BLB3    6
      BLOCK DATA                                                          BLB3    7
      COMMON /B3P/ MRE,MPR,MEOF,LEFT,KFIX,NARG,MASK,L,LIM,K,KZ,M          BLB3    8
      DATA MRE/-1/,MPR/-3/,MEOF/0/,LEFT/8/,KFIX/29327845667/              BLB3    9
      END                                                                 BLB3   10

$IBMAP B3P     DECK                                                       B3P     0
*  MAP DECK 'B3P' SHOULD REPLACE FORTRAN-4 DECK 'BLB3' AHEAD OF DECK      B3P     1
*  'THRP' ON 7040-7044 IF BLOCK DATA IS NOT ACCEPTABLE.                   B3P     2
*                                                                         B3P     3
        DEC -1,-3,0,8,29327845667                                         B3P     4
        END                                                               B3P     5
```

```
$IBFTC THRP    DECK                                                     THRP
C BC THRP--WITH IRDM, GENERATES INTEGERS (WITH REPLACEMENT) SUITABLE FORTHRP
C        --SPECIFIED 3P-SAMPLE DESIGN--BY L. R. GROSENBAUGH--(11-11-64).THRP
C  INPUT-OUTPUT TAPES ARE SPECIFIED EARLY IN 'BLB3' OR /B3P/.  USER     THRP
C      SPECIFIES LOGICAL NUMBER OF DESIRED INPUT TAPE (MRE) AND         THRP
C      OUTPUT TAPE (MPR).  IF REGULAR SYSTEM OUTPUT TAPE IS USED,       THRP
C      'MEOF' SHOULD BE SPECIFIED TO BE ZERO,  OTHERWISE TO BE ONE.     THRP
C  FOR EACH SALE, 2 DATA CARDS MUST BE PUNCHED TO CAUSE DRAWING (WITH   THRP
C      REPLACEMENT) AND LISTING OF RANDOM INTEGERS APPROPRIATE AS       THRP
C      CRITERIA FOR A SPECIFIED 3P-SAMPLE DESIGN.  THE 3P-SAMPLE        THRP
C      UNIVERSE CONSISTS OF A TOTAL POPULATION OF 'KZ' CARDS, OF WHICH  THRP
C      'K' ARE INTEGERS RANGING IN VALUE FROM ONE TO 'K' WITH UNIT      THRP
C      INTERVAL, AND 'KZ MINUS K' ARE NULLS REPRESENTED BY -0 (XX'S OR  THRP
C      FACE CARDS ARE SYNONYMS FOR NULLS).                              THRP
C  SEE 1964. SOC. AMER. FORESTERS PROC. 1963, PAGES  36- 42,            THRP
C      'SOME SUGGESTIONS FOR BETTER SAMPLE-TREE-MEASUREMENT' FOR BASIC  THRP
C      THEORY AND FIELD PROCEDURE.                                      THRP
C  SEE 1964 U.S.FOREST SERVICE RESEARCH PAPER PSW-13 'STX--FORTRAN 4    THRP
C      PROGRAM FOR ESTIMATES OF TREE POPULATIONS FROM 3P SAMPLE-TREE-   THRP
C      MEASUREMENTS' FOR SUBSEQUENT PROCESSING OF 3P-SAMPLE DATA.       THRP
C  FIRST DATA CARD SHOULD BE BLANK IN COLUMNS 1-4, WITH FULL            THRP
C      IDENTIFICATION OF SALE AREA IN COLUMNS 5-64, AND BRIEF CODED     THRP
C      IDENTIFICATION OF SALE AREA IN COLUMNS 73-76 (SAME CARD AS FIRST THRP
C      CONTROL CARD IN PROGRAM 'STX').                                  THRP
C  SECOND DATA CARD SHOULD BE BLANK IN COLUMNS 1-4, WITH ANY 12-DIGIT   THRP
C      OCTAL NUMBER (NO 8'S OR 9'S) IN COLUMNS 5-16, DIFFERENT FOR EACH THRP
C      SALE.  THIS IS INITIAL ARGUMENT 'L' FOR STARTING THE GENERATOR.  THRP
C      COLUMNS 18-22 SHOULD CONTAIN 'LIM', THE TOTAL NUMBER OF TREES    THRP
C      EXPECTED TO BE MARKED FOR SALE.  THIS NUMBER OF TREES OR ITEMS   THRP
C      (LIM) SHOULD BE A MULTIPLE OF 500, SINCE EACH PRINTED PAGE OF    THRP
C      SAMPLE CRITERIA (INTEGERS) WILL HAVE 10 COLUMNS OF 50 ITEMS EACH.THRP
C      COLUMNS 24-27 SHOULD CONTAIN 'K' SPECIFIED BY THE 3P DESIGN.     THRP
C      COLUMNS 29-33 SHOULD CONTAIN 'KZ'(ALSO KNOWN AS 'K+Z' OR 'PRBS').THRP
C  PAIRS OF CARDS FOR MANY SALES MAY BE PROCESSED DURING ONE MACHINE    THRP
C      RUN, BUT THE PAIR FOR THE LAST SALE SHOULD BE FOLLOWED BY A CARD THRP
C      PUNCHED 9999 IN COLUMNS 1-4.                                     THRP
C  EACH PAGE OF LISTED INTEGERS WILL HAVE ITS SUM AND NUMBER OF NONNULL THRP
C      ITEMS PRINTED AT BOTTOM-RIGHT.                                   THRP
C  LAST PAGE OF EACH SALE CONTAINS TOTAL SUM, TOTAL NUMBER OF NONNULLS, THRP
C      AND GRAND TOTAL NUMBER OF NONNULLS PLUS NULLS.  BELOW APPEARS    THRP
C      EXPECTED SUM FOR NUMBER OF NONNULLS ACTUALLY APPEARING,EXPECTED  THRP
C      NUMBER OF NONNULLS GIVEN 3P DESIGN WITH SPECIFIED 'LIM', AND     THRP
C      'LIM' AS SPECIFIED.                                              THRP
C  QUICK COMPARISON OF PAGE TOTALS AND GRAND TOTALS WITH EXPECTATIONS   THRP
C      AND SPECIFICATIONS ALLOWS REJECTION OF LISTS DEVIATING           THRP
C      IN AN IMPROBABLE MANNER OR EXCESSIVELY.                          THRP
C                                                                       THRP
      COMMON /B3P/ MRE,MPR,MEOF,LEFT,KFIX,NARG,MASK,L,LIM,K,KZ,M        THRP
      COMMON /LUK/JS,NUM,MNU                                            THRP
      DIMENSION ALFATH(10),JS(500),NUM(500),MNU(500)                    THRP
```

```
  1 FORMAT (72X,I8/2X,10(3X,A4),I8)
  20FORMAT (2H1 ,10A6,6H PAGE ,I4/2X,2HL=,O12,6H, LIM=,I5,4H, K=,I4,
  215H, KZ=,I5,1H,,A4/2X)
  3 FORMAT (2X,10I7)
  40FORMAT (2H1 ,10A6,6H PAGE ,I4/2X,2HL=,O12,6H, LIM=,I5,4H, K=,I4,
  415H, KZ=,I5,1H,,A4/2X/2X,A4,6X,11HKSUM       =,I12,16H,       NK
  42 =,I5,11H,       NKZ=,I5/2X,21HEXPECTED  NK*(K+1)/2=,I12,16H,
  43NKZ*K/KZ=,I5,11H,       LIM=,I5)
  5 FORMAT (I4,10A6,8X,A4)
  6 FORMAT (I4,O12,1X,I5,1X,I4,1X,I5)
  7 JPAGE=1
    NK=0
    NKZ=0
    KSUM=0
    KSUB=0
    NKSUB=0
    NONSAM=-0
    READ  (MRE,5) KREENO,ALFATH,CDID
    IF (KREENO .NE. 0) GO TO 33
  8 READ  (MRE,6) KREENO,L,LIM,K,KZ
    IF (KREENO .NE. 0) GO TO 33
  9 AKZ=FLOAT(KZ)
    AM=37.-1.44269504*ALOG(AKZ)
    M=INT(AM)
    CALL MSET
 10 CALL IGEN
 18 WRITE (MPR,2) ALFATH,JPAGE,L,LIM,K,KZ,CDID
    JPAGE=JPAGE+1
    IFLAG=MOD(JPAGE,2)
    I=0
    DO  29  I=1,500
    IF (IFLAG .EQ. 0) GO TO 23
 22 II=JS(I)
    III=I
    GO TO 24
 23 III=JS(I)
    II=I
 24 NKZ=NKZ+1
    IF (NUM(II) .EQ. 0) GO TO 26
 25 IF (NUM(II) .LE. K) GO TO 27
 26 MNU(III)=NONSAM
    GO TO 29
 27 MNU(III)=NUM(II)
    KSUB=KSUB+NUM(II)
    NKSUB=NKSUB+1
 29 CONTINUE
    WRITE (MPR,3) MNU
 310WRITE (MPR,1) KSUB,CDID,CDID,CDID,CDID,CDID,CDID,CDID,CDID,CDID,
 311CDID,NKSUB
    NK=NK+NKSUB
    KSUM=KSUM+KSUB
    KSUB=0
```

```
      NKSUB=0
      IF (NKZ .LT. LIM) GO TO 10
   32 JEKSUM=(NK*(K+1))/2
      JENK=(NKZ*K)/KZ
     OWRITE (MPR,4) ALFATH,JPAGE,L,LIM,K,KZ,CDID,CDID,KSUM,NK,NKZ,
     1JEKSUM,JENK,LIM
      GO TO 7
   33 IF (MEOF .EC. 0) GO TO 35
   34 END FILE MPR
   35 RETURN
      END
```

```
$IBMAP IRDM    DECK                                                     IRDM
*  IRDM---- CONTINUOUS RANDOM INTEGER GENERATOR FOR THRP--------------- IRDM
*         ---BY L. R. GROSENBAUGH (7040-7094 MAP-F4 VERSION OF 11-11-64)IRDM
*                                                                       IRDM
*                                                                       IRDM
*  RANDOM INTEGERS SMALLER THAN A SPECIFIED MAXIMUM 'KZ' ARE GENERATED  IRDM
*      WITH REPLACEMENT BY A 4-STAGE PROCESS.                           IRDM
*  SEVERAL PARAMETERS MUST BE READ BEFORE 'CALL MSET' CAN READY THE     IRDM
*  GENERATING FUNCTION FOR OPERATION.  AMONG THESE PARAMETERS---------- IRDM
*      'L' IS OCTAL STARTING ARGUMENT (MOD 2**35) FOR GENERATOR.        IRDM
*      'KZ' IS MAXIMUM DECIMAL INTEGER THAT MUST NOT BE EQUALLED OR     IRDM
*      EXCEEDED.                                                        IRDM
*      'M' IS 37 MINUS TOTAL DECIMAL NUMBER OF BITS IN (KZ-1).          IRDM
*  THEN 'CALL IGEN' INITIATES ACTUAL GENERATION OF 500-ITEM BATCHES OF  IRDM
*  RANDOM NUMBERS AND NULLS APPROPRIATE TO THE SPECIFIED PARAMETERS.    IRDM
*      FIRST-STAGE INTEGERS ARE SUCCESSIVELY GENERATED BY THE MIXED     IRDM
*      CONGRUENTIAL METHOD, ALTHOUGH SLIGHT MODIFICATION WOULD ALLOW    IRDM
*      USE OF THE MULTIPLICATIVE CONGRUENTIAL METHOD (SEE 1964 JOUR.ACM.IRDM
*      11, PAGES 31-40).  A LEFT SHIFT AND ADDITIVE CONSTANT OPTIMUM    IRDM
*      FOR MODULUS 2**35 HAVE BEEN EMPLOYED, BUT ARE EASILY CHANGED.    IRDM
*  SECOND-STAGE TREATMENT OF 35-BIT FIRST-STAGE INTEGER IS TO 'ERA' IT  IRDM
*      WITH AN INDEPENDENT SEQUENCE OF MASKS THAT ARE PROGRESSIVELY     IRDM
*      CHANGED BY FIVE 7-BIT ROTATIONS OF EACH OF 23 RANDOM 36-BIT      IRDM
*      PATTERNS, RESULTING IN 828 DIFFERENT RANDOM MASKS BEFORE CYCLE   IRDM
*      REPEATS.                                                         IRDM
*  THIRD-STAGE TREATMENT IS TO TRUNCATE RIGHT-HAND BITS IN EXCESS OF    IRDM
*      NUMBER NEEDED TO EXPRESS 'KZ-1', AND TO GENERATE A REPLACEMENT   IRDM
*      WHEN THE RIGHT-ADJUSTED RESIDUAL EQUALS OR EXCEEDS 'KZ'.         IRDM
*  STAGES 1-3 ARE REPEATED UNTIL A SET OF 500 QUALIFYING INTEGERS ARE   IRDM
*      OBTAINED, RANGING FROM 0 THROUGH (KZ MINUS ONE).                 IRDM
*  FOURTH-STAGE TREATMENT (IN THRP) IS TO REARRANGE THESE 500 INTEGERS  IRDM
*      SO AS TO FURTHER REDUCE ANY OBVIOUS SERIAL CORRELATION, AND TO   IRDM
*      TRANSFORM +0 AND ALL NUMBERS LARGER THAN 'K' TO -0,THUS YIELDING IRDM
*      A SET OF CRITERIA APPROPRIATE TO THE 3P-SAMPLE DESIGN SPECIFIED  IRDM
*      AS 'K,KZ'.                                                       IRDM
*                                                                       IRDM
       ENTRY   MSET                                                     IRDM
       ENTRY   IGEN                                                     IRDM
 MSET  SAVE    1,2,4                                                    IRDM
       CAL L                                                            IRDM
       STO NARG                                                         IRDM
       CAL LEFT                                                         IRDM
       STA SHIFT                                                        IRDM
       CAL M                                                            IRDM
       STA MCUT                                                         IRDM
       CAL KNUM                                                         IRDM
       STA NEWP                                                         IRDM
       ADD FIHUN                                                        IRDM
       STA STOP                                                         IRDM
       STZ INDX                                                         IRDM
```

```
        RETURN  MSET
IGEN    SAVE     1,2,4
        CLA NEWP
        STA STORE
        STO RLOD
LOAD    CLA INDX
        SUB ONE
        TPL *+2
        ADD TWTHR
        STO INDX
        ADD KNPA
        STA NMSK
        STA MUTA
        STA FINI
NMSK    LDQ **
        CLA RLOD
        ADD FIVE
        STO RLOD
LOOP    RQL 7
        STQ MASK
        CAL NARG
SHIFT   ALS **
        ADD NARG
        ADD KFIX
        STO NARG
        ORA MASK
        SLW ORA
        CAL MASK
        ANA NARG
        COM
        ANA ORA
        ALS 2
MCUT    ARS **
        CAS KZ
        TRA LOOP
        TRA LOOP
*
STORE   STO **
        CLA STORE
        ADD ONE
        STA STORE
        CAS STOP
        TRA FINI
        TRA FINI
        TRA GOON
GOON    CAS RLOD
        TRA MUTA
        TRA MUTA
        TRA LOOP
MUTA    STQ **
        TRA LOAD
FINI    STQ **
```

```
       TOV  *+1                                                      IRDM 102
       RETURN    IGEN                                                IRDM 103
*                CONSTANTS                                           IRDM 104
 STOP  STO       **                                                  IRDM 105
 NEWP  STO       **                                                  IRDM 106
 KNPA  PZE       NPAT                                                IRDM 107
 KNUM  PZE       NUM                                                 IRDM 108
 ONE   DEC  1                                                        IRDM 109
 TWO   DEC  2                                                        IRDM 110
 FOUR  DEC  4                                                        IRDM 111
 FIVE  DEC  5                                                        IRDM 112
 SIX   DEC  6                                                        IRDM 113
 TWTHR DEC  23                                                       IRDM 114
 FIHUN DEC  500                                                      IRDM 115
 NPAT  OCT  201450075226,214546337146,322724516102,303667607764      IRDM 116
       OCT  304170563342,221625507015,777210313005,431320677112      IRDM 117
       OCT  504765671151,233717444633,717372135702,375415045242      IRDM 118
       OCT  706156152034,516724654017,526040760510,543414754156      IRDM 119
       OCT  321113461357,241256504205,505761377112,252344415135      IRDM 120
       OCT  117000633423,404766555015,610746200174                   IRDM 121
*                ERASABLES                                           IRDM 122
 INDX  PZE       0                                                   IRDM 123
 RLOD  PZE       0                                                   IRDM 124
 ORA   PZE       0                                                   IRDM 125
*                LABELLED CONTROL SECTIONS                           IRDM 126
       USE       .DUMY.                                              IRDM 127
 B3P   CONTRL    B3P                                                 IRDM 128
       USE       B3P                                                 IRDM 129
       EVEN                                                          IRDM 130
 MRE   BSS       1                                                   IRDM 131
 MPR   BSS       1                                                   IRDM 132
 MEOF  BSS       1                                                   IRDM 133
 LEFT  BSS       1                                                   IRDM 134
 KFIX  BSS       1                                                   IRDM 135
 NARG  BSS       1                                                   IRDM 136
 MASK  BSS       1                                                   IRDM 137
 L     BSS       1                                                   IRDM 138
 LIM   BSS       1                                                   IRDM 139
 K     BSS       1                                                   IRDM 140
 KZ    BSS       1                                                   IRDM 141
 M     BSS       1                                                   IRDM 142
       USE       PREVIOUS                                            IRDM 143
 LUK   CONTRL    LUK                                                 IRDM 144
       USE       LUK                                                 IRDM 145
       EVEN                                                          IRDM 146
 JS    DEC  426,36,333,460,154,308,235,96,110,293,221,361,62,476,109  IRDM 147
       DEC  210,281,420,30,306,445,273,48,475,104,170,437,277,38,353  IRDM 148
       DEC  153,237,465,256,61,287,413,441,369,298,99,428,302,204,116 IRDM 149
       DEC  51,320,463,179,55,483,334,95,234,363,487,253,197,409,303  IRDM 150
       DEC  231,435,209,300,18,357,480,143,205,350,255.91,3,131,489   IRDM 151
       DEC  399,174,371,453,118,394,97,346,271,307,31,123,243,384,452 IRDM 152
       DEC  29,343,217,391,102,328,196,142,35,368                     IRDM 153
```

```
       DEC 337,229,493,94,263,317,198,486,75,449,45,279,472,416,245          IRDM 154
       DEC 323,200,57,191,17,370,496,133,260,73,398,240,4,172,339            IRDM 155
       DEC 64,274,187,468,354,165,500,462,137,396,44,121,365,83,289          IRDM 156
       DEC 230,20,152,473,405,92,332,458,406,290,301,212,114,444,356         IRDM 157
       DEC 77,481,351,146,250,52,159,422,349,295,49,359,393,19,265           IRDM 158
       DEC 285,74,314,126,7,167,86,236,372,451,479,68,132,386,103            IRDM 159
       DEC 257,459,10,93,331,26,276,149,203,166                              IRDM 160
       DEC 484,325,98,215,366,259,33,115,192,410,233,58,145,378,454          IRDM 161
       DEC 224,117,139,56,9,266,431,194,319,228,84,141,443,186,129           IRDM 162
       DEC 282,13,490,71,383,78,344,288,85,305,326,402,63,379,429            IRDM 163
       DEC 106,246,442,69,72,381,42,269,291,193,338,244,15,330,81            IRDM 164
       DEC 464,177,299,268,482,340,155,28,313,6,180,264,296,251,144          IRDM 165
       DEC 222,432,469,100,67,446,248,310,352,220,101,440,286,364,400        IRDM 166
       DEC 461,335,185,79,439,8,297,455,50,242                               IRDM 167
       DEC 380,309,188,284,408,128,347,54,423,367,336,411,122,414,11         IRDM 168
       DEC 329,202,447,466,183,488,70,125,283,164,168,438,470,135,24         IRDM 169
       DEC 87,207,434,169,477,112,377,278,404,173,65,395,448,324,206         IRDM 170
       DEC 456,252,390,2,485,151,304,499,12,43,311,412,467,348,225           IRDM 171
       DEC 418,82,261,182,34,201,373,175,424,134,108,497,318,127,178         IRDM 172
       DEC 327,23,388,199,14,105,39,374,171,158,232,53,213,1,189             IRDM 173
       DEC 321,292,219,478,345,474,226,37,214,415                            IRDM 174
       DEC 272,397,430,176,355,249,59,392,124,450,41,294,76,190,258          IRDM 175
       DEC 421,218,494,358,407,136,239,457,90,107,471,387,162,275,254        IRDM 176
       DEC 138,21,376,80,401,315,267,5,150,160,316,66,403,247,22             IRDM 177
       DEC 60,382,130,498,227,280,184,433,40,223,161,385,16,425,322          IRDM 178
       DEC 195,147,113,89,119,342,241,492,216,262,156,32,46,389,417          IRDM 179
       DEC 27,157,211,270,341,88,419,148,312,360,120,375,163,362,495         IRDM 180
       DEC 140,436,47,427,111,25,208,181,491,238                             IRDM 181
NUM    BSS      500                                                          IRDM 182
MNU    BSS      500                                                          IRDM 183
       USE      PREVIOUS                                                     IRDM 184
       END                                                                   IRDM 185
```

N.B. INSTRUCTIONS ABOVE ARE COMPATIBLE WITH IBM 704-709-7040-7044-7090-7094, EXCEPT FOR MACROS 'ENTRY', 'SAVE', AND 'RETURN' NOT AVAILABLE TO 704 SAP. LITTLE MODIFICATION IS NEEDED TO ADAPT 'IRDM' TO 704, ALTHOUGH 'THRP' MUST BE CONVERTED FROM FORTRAN-4 TO FORTRAN-2, AND THE 3 MACROS ABOVE MUST EACH BE REPLACED BY APPROPRIATE LINKAGE. 'IRDM' MAKES NO USE OF INDEX REGISTERS, SO IT MAY BE USED WITH MINIMUM 7040, WHICH LACKS SUCH REGISTERS.

INSTRUCTIONS ABOVE ALSO AVOID USE OF INSTRUCTION 'ERA' (BOOLEAN 'EXCLUSIVE OR') NOT AVAILABLE ON 704-7040-7044. HOWEVER, USERS OF 709-7090-7094 CAN ADVANTAGEOUSLY REPLACE 'ORA MASK' ON CARD IRDM 75 WITH 'ERA MASK' AND DELETE CARDS IRDM 76 THROUGH IRDM 80 OR ELSE PUNCH AN ASTERISK (*) IN COLUMN ONE OF EACH OF THEM.

================================== APPENDIX B ==================================

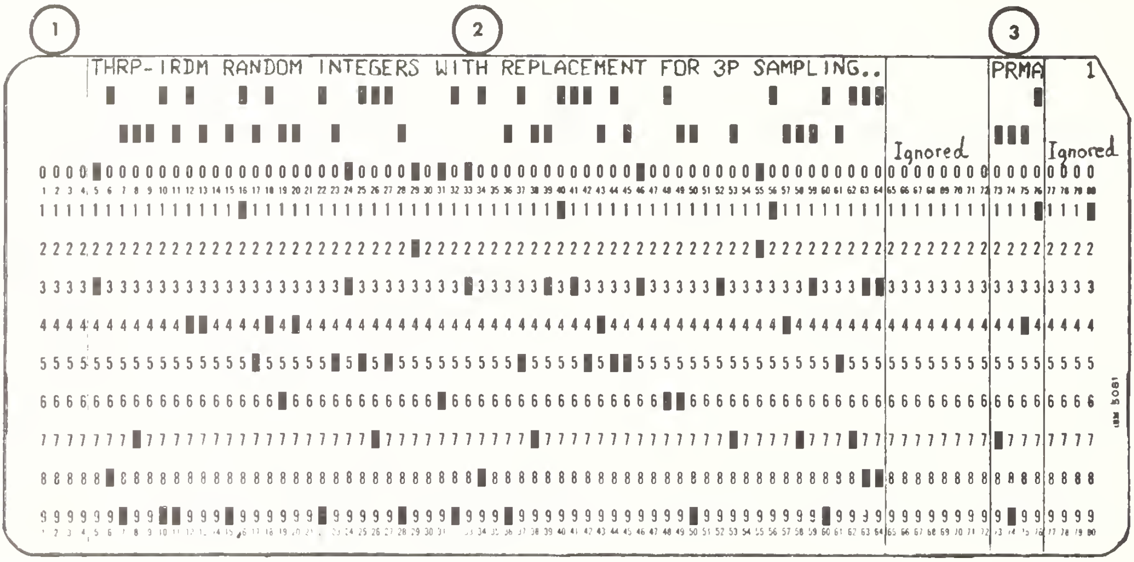
ILLUSTRATION OF INPUT TO PROGRAM 'THRP'

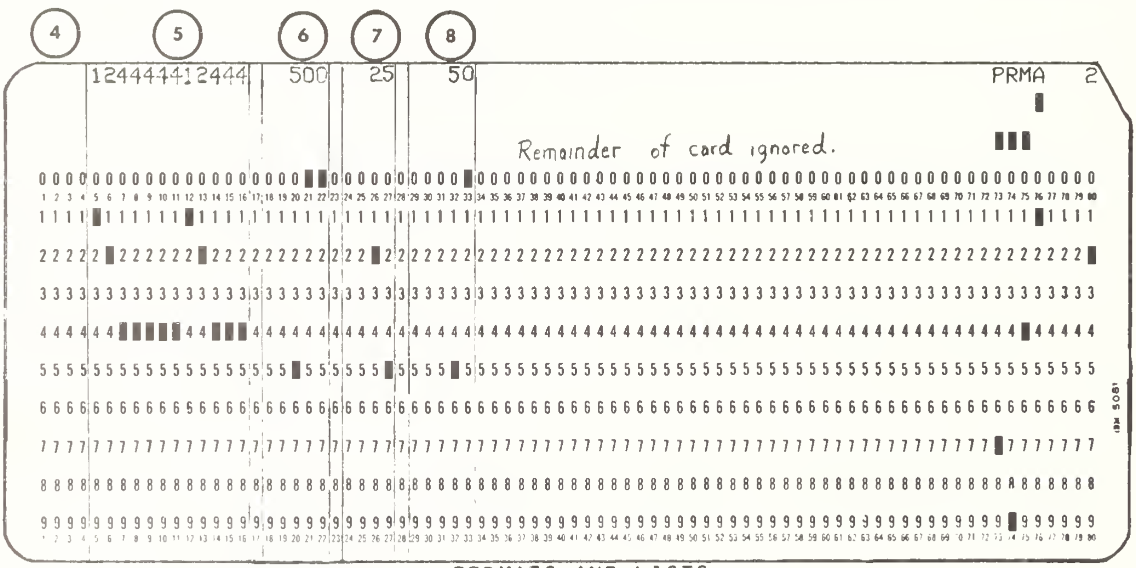
WITH PRINTED OUTPUT RESULTING

INPUT CECK

```
$JOB    (IDENTIFICATION, ETC.)
$IBJOB THRP     MAP
$USE            BLB3(B3P)
$USE            IRDM(LUK)
$IBFTC BLB3     DECK                                                       BLB3    0
$IBFTC THRP     DECK                                                       THRP    0
$IBMAP IRDM     DECK                                                       IRDM    0
$ENTRY          THRP
$DATA
    THRP-IRDM RANCOM INTEGERS WITH REPLACEMENT FOR 3P SAMPLING..          PRMA    1
    124444412444   500   25    50                                          PRMA    2
9999
$EOF
```

FIGURE 2. PARAMETER CARDS CONTROLLING AND DESCRIBING RANDOM INTEGER GENERATION





FORMATS AND LISTS

```
5 FORMAT (I4,10A6,8X,A4)                                   THRP   58
  READ   (MRE,5) KREENO,ALFATH,CDID                        THRP   67

6 FORMAT (I4,O12,1X,I5,1X,I4,1X,I5)                        THRP   59
8 READ   (MRE,6) KREENO,L,LIM,K,KZ                         THRP   69
```

FIGURE 2 (CONTINUED).

LEGEND
======

1 =KREENO= ALWAYS BLANK.

2 =ALFATH= NAME OF SALE AREA OR JOB.

3 = CDID = BRIEF JOB IDENTIFIER FOR PRINTING AT BOTTOM OF EACH PAGE.

4 =KREENO= ALWAYS BLANK.

5 = L = OCTAL STARTING ARGUMENT FOR GENERATOR--MAY BE ZERO OR ANY 12-DIGIT NUMBER LACKING 'EIGHTS' OR 'NINES'.

6 = LIM = TOTAL NUMBER OF RANDOM INTEGERS DESIRED (INCLUDING NULLS). ENOUGH EXTRAS ARE ALWAYS PRINTED TO FILL THE LAST PAGE.

7 = K = MAXIMUM NONNULL INTEGER INCLUDED IN 3P-PROBABILITY SET.

8 = KZ = (K+Z) OR THE MAXIMUM NONNULL INTEGER PLUS THE NUMBER OF NULLS (-0) COMPRISING THE 3P-PROBABILITY SET.

SEVERAL PAIRS OF CARDS FOR SEVERAL DIFFERENT JOBS CAN BE PROCESSED IN THE SAME RUN. THE LAST PAIR OF CARDS ON ANY RUN SHOULD ALWAYS BE IMMEDIATELY FOLLOWED BY A PROGRAM-END CARD PUNCHED 9999 IN COLUMNS 1-4.

THE FIRST PARAMETER CARD OF A 'THRP' JOB IS IDENTICAL WITH THE FIRST CARD USED LATER TO PROCESS THE SAMPLE DATA BY PROGRAM 'STX'(*3).

========================
RESULTANT OUTPUT FOLLOWS.

FIGURE 3. 'THRP' PRINTOUT FROM ILLUSTRATORY TEST INPUT
THRP-IRDM RANDOM INTEGERS WITH REPLACEMENT FOR 3P SAMPLING.. PAGE 1
L=124444412444, LIM= 500, K= 25, KZ= 50,PRMA

-0	24	-0	-0	-0	18	-0	19	-0	17
-0	4	24	-0	18	-0	-0	-0	2	-0
-0	18	-0	-0	24	16	14	-0	-0	11
1	6	16	20	-0	14	1	13	-0	8
6	-0	-0	22	4	-0	-0	3	-0	-0
20	20	6	-0	-0	6	17	-0	-0	19
-0	2	-0	5	-0	9	-0	-0	-0	8
18	-0	8	-0	-0	2	-0	2	-0	-0
12	6	25	-0	9	-0	-0	19	-0	-0
22	-0	19	8	4	-0	20	-0	-0	9
-0	7	-0	-0	18	4	-0	-0	18	22
19	12	-0	25	15	-0	-0	-0	-0	8
21	-0	-0	13	-0	2	-0	-0	11	-0
-0	-0	-0	-0	5	-0	-0	5	10	15
-0	1	23	-0	14	25	-0	25	12	21
20	18	6	-0	17	25	-0	-0	2	6
-0	6	5	-0	6	-0	13	-0	12	-0
5	15	-0	6	15	-0	-0	-0	-0	-0
-0	-0	-0	-0	-0	-0	-0	11	3	5
6	-0	24	12	3	-0	20	-0	10	-0
1	-0	14	-0	-0	-0	24	13	-0	-0
24	-0	-0	-0	-0	2	18	2	9	-0
-0	-0	20	-0	8	-0	15	23	16	23
-0	-0	14	12	-0	-0	19	24	-0	-0
-0	17	-0	-0	-0	4	-0	-0	-0	22
-0	-0	25	22	-0	25	5	-0	-0	-0
-0	10	25	20	-0	-0	4	5	-0	4
-0	11	18	-0	-0	11	14	18	-0	-0
14	-0	17	13	4	14	-0	-0	-0	-0
3	12	1	9	-0	-0	-0	-0	-0	11
-0	25	-0	23	20	-0	-0	17	3	-0
-0	7	-0	7	20	1	17	24	-0	-0
-0	10	19	-0	23	-0	22	23	8	-0
-0	10	-0	4	-0	25	22	13	18	15
6	13	25	-0	-0	7	23	-0	-0	23
3	-0	18	19	-0	-0	18	-0	-0	-0
-0	23	-0	13	14	6	-0	1	-0	-0
14	-0	-0	-0	23	14	11	19	-0	-0
13	-0	-0	8	20	12	-0	20	21	-0
-0	24	-0	10	1	5	-0	-0	-0	14
18	-0	2	-0	-0	-0	11	7	-0	15
-0	-0	-0	6	-0	9	17	8	-0	11
8	-0	-0	-0	22	-0	-0	-0	-0	10
-0	-0	9	-0	12	3	17	25	-0	15
-0	-0	11	-0	15	8	8	8	5	16
5	-0	-0	-0	21	-0	10	17	-0	-0
-0	8	23	-0	-0	-0	-0	23	-0	20
-0	-0	-0	22	-0	-0	10	-0	3	-0
-0	-0	14	-0	14	-0	16	-0	15	25
-0	-0	-0	9	25	-0	20	-0	-0	12
PRMA	PRMA	PRMA	PRMA	PRMA	PRMA	PRMA	PRMA	PRMA	PRMA

3304
248

FIGURE 3. (CONTINUED)
THRP-IRDM RANDOM INTEGERS WITH REPLACEMENT FOR 3P SAMPLING.. PAGE 2
L=124444412444, LIM= 500, K= 25, KZ= 50,PRMA

PRMA	KSUM =	3304,	NK =	248,	NKZ=	500
EXPECTED	NK*(K+1)/2=	3224,	NKZ*K/KZ=	250,	LIM=	50C

Emergency Revegetation to Rehabilitate Burned Watersheds in Southern California

E. S. Corbett and L. R. Green

U. S. FOREST SERVICE RESEARCH PAPER PSW-22

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

1965

Contents

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LISLE R. GREEN is in charge of the Station's research on fuel hazard reduction by converting chaparral to grass cover, with headquarters at Riverside, Calif. Born in Ogden, Utah, he holds bachelor's (1941) and master's (1948) degrees in range management from Utah State University. He has been on the Berkeley station's research staff since 1948, except for 5 years when he taught range management and soil science at California State Polytechnic College.

A wildfire denuded most of the San Dimas Experimental Forest in 1960. Before the fire the watersheds grew a dense cover of chaparral, consisting mostly of chamise *(Adenostoma fasciculatum)* with lesser amounts of ceanothus *(Ceanothus* spp.*)*, white sage *(Salvia apiana)*, black sage *(S. mellifera)*, manzanita *(Arctostaphylos glauca* and *A. glandulosa)*, California buckwheat *(Eriogonum fasciculatum)*, and scrub oak *(Quercus dumosa)*. The fire was extremely hot. It consumed all of the lighter vegetation and most of the heavy brush stems (fig. 1). And it left the soil in a loose powder-dry condition—unshielded from the wind and from heavy rains that usually occur in winter. Experience has shown that the removal of the vegetation cover by fire may greatly increase flood and erosion damage in the chaparral-covered mountains of southern California (Rowe *et al.* 1954).

To test "first-aid" treatments aimed at reducing the damage, an emergency research program was started at once.[1] The treatments included both vegetative and physical measures. This paper discusses the results of vegetative treatments in the first four years after the fire: the establishment and growth of artificially seeded species, the regrowth of native vegetation, and the effects of plant growth on watershed rehabilitation.

Physical measures have been described in detail elsewhere, along with some preliminary findings of the research program (Krammes and Hill 1963; Rice *et al.* 1965). These measures were of three types: contour trenches built by bulldozers to intercept storm runoff and enhance its infiltration; small check dams of soil cement to stabilize channels; and rows of barley planted on closely spaced contours to stabilize side slopes. Because the barley planting was designed to create physical barriers to overland flow, this treatment was considered a physical measure in the experimental design. In the analysis of preliminary findings, such "side slope stabilization" appeared to be the most effective physical measure in reducing erosion. In this report, however, we consider the barley planting primarily as part of the plant cover.

Erosion Control Treatments

Experimental Design

In testing the vegetative treatments to control erosion, we used 25 watersheds, each 2 to 9 acres in size. From this group we randomly selected eight watersheds for testing annual grasses, eight for testing perennials, and four—left unseeded—for controls. Twelve of these 20 watersheds received one of the physical treatments. These 20 (table 1) are designated the "main treatment group watersheds" throughout this paper. The other five watersheds were given more than one physical treatment, and one of these was also seeded to annual grass.

In southern California, broadcast sowing of annual grasses is the most widely used method of rehabilitating burned watersheds. Four of the watersheds were broadcast sown by helicopter to a "low-density" mixture of 2 pounds of Wimmera 62 ryegrass *(Lolium rigidum)* and ½ pound of blando brome *(Bromus mollis)* per acre. Five (including one not in the main group) were sown to a "high-density" mixture of 16 pounds of Wimmera ryegrass and 4 pounds of blando brome per acre. Annual ryegrass is hardy, germinates well under local winter temperatures, and the seed is not ex-

[1] Since 1947 research at the San Dimas Experimental Forest has been conducted in cooperation with the California Division of Forestry. Other agencies that assisted in the emergency research program described in this paper were the California Department of Water Resources, Los Angeles County Fire Department, and Los Angeles Flood Control District.

Figure 1.—Typical watershed conditions after the fire of July 1960, at the San Dimas Experimental Forest.

Table 1.--*Experimental design of erosion control treatments--main treatment group watersheds*

Vegetative treatment	No physical treatment	Contour trenches	Channel checks	Side-slope stabilization
No seeding	XX	XX	XX	XX
Low density annuals	XX	XX	XX	XX
High density annuals	XX	XX	XX	XX
Low density perennials	XX	XX	XX	XX
High density perennials	XX	XX	XX	XX

pensive (Hellmers 1957). On California's foothill ranges seeds of annual plants start to germinate after the first rains of ½ to 1 inch (Bentley and Talbot 1951). Schultz *et al.* (1955) found that about 2 inches of rain were necessary to start germination in heavy ashes from a brush fire. Rainfall must occur at frequent intervals after germination to assure continuous growth.

Perennial grasses, slower growing than annuals, are recommended as permanent cover on areas where chemical spraying will be used to kill the brush. They are often used on fuel-breaks and for increasing the grazing capacity of brushlands. Four watersheds were broadcast seeded to a "low-density" mixture of perennial and annual grasses; it included 1 pound each of pubescent wheatgrass *(Agropyron trichophorum)* and Harding grass *(Phalaris tuberosa* var. *stenoptera)*; ½ pound each of intermediate wheatgrass *(A. intermedium)*, tall wheatgrass *(A. elongatum)*, big bluegrass *(Poa ampla)*, and smilo grass *(Oryzopsis miliacea)*; and ¼ pound of blando brome per acre. Four watersheds were seeded to a "high-density" mixture totaling 20 pounds per acre: Harding grass, 6 pounds; pubescent wheatgrass, 4 pounds; tall and intermediate wheatgrasses, smilo, and big bluegrass, 2 pounds each; and Wimmera 62 ryegrass and blando brome, 1 pound each. These mixtures are designated as the perennial grass treatments.

All the watersheds were sown on November 27, 1960. The watersheds sown with perennials were also sprayed with 2,4-D and 2,4,5-T, during the springs of 1961, 1962, and 1964, to aid in perennial grass establishment by reducing competition from brush species. The two annuals—ryegrass and blando brome—were added to provide some additional ground cover until the slower developing perennials could take over.

The average cost of helicopter sowing on large areas was about $1.00 per acre plus cost of seed (Bentley *et al.* 1961). Cost of annual grass seed was moderate: 12 cents per pound for Wimmera 62 ryegrass and 60 cents for blando brome (table 2). The low density mixtures cost 54 cents per acre for annual grasses and $2.85 for the perennial grasses; the per acre cost of the high density mixes was $4.32 for annuals and $13.32 for perennials.

The side slope stabilization treatment was installed on nine watersheds, five of which were in the main treatment group. The contour rows of barley were hand planted in furrows 2 feet apart, cut into the soil with hoes, between December 1960 and mid-January 1961. Barley at 150 pounds per acre and 16–20 ammonium phosphate fertilizer at 140 pounds per acre were distributed in the furrows and covered with soil. The cost of this treatment was about $140 per acre.

Sampling Methods

Vegetation cover was determined by ocular estimates on permanent 4-square foot-quadrats. The quadrats were subdivided into 1-foot squares to increase the accuracy of the estimates. They were distributed in a stratified (on aspect) random fashion in the watersheds. Vegetation estimates consisted of the percentage of soil within the quadrats covered by a vertical projection of actual foliar density. Areas sampled within the watersheds ranged from 96 to 240 square feet. The estimates for each strata were weighted by the areas of the aspects in the watershed.

Estimates of percent cover on each quadrat were made for the following categories: (a) sown annual grass, (b) sown perennial grass, (c) planted barley, (d) native grasses, (e) native broadleaves, (f) brush seedlings, (g) brush sprouts, (h) dead brush stems, and (i) litter. The vegetation surveys were made in April–May 1961, February and July 1962, May–June of 1963 and 1964. In the May–June 1964 survey we sampled only 13 of the 25 watersheds.

Results and Discussion

Broadcast Seeding of Grasses

The establishment of seeded species was extremely poor during the winter of 1960–1961. One reason was scanty rainfall (fig. 2). During the 2-month period immediately following the November 27 sowing, only 0.06 inch of rain fell. Throughout the remainder of the hydrologic year only 4.23 inches fell—bringing the total to 39 percent of the 35-year average. Furthermore, above-normal temperatures and high winds dried the soil and desiccated seedlings during late fall and early winter.

Since the aim of the study was to test the effect of grass cover and not seeding techniques, the ex-

Table 2.--*Cost of seed per acre, by species and treatment*

Species	Estimated 1960 cost per lb.	Low density annuals (2½ lbs. seed per acre)	High density annuals (20 lbs. seed per acre)	Low density perennials and annuals (4¼ lbs. seed per acre)	High density perennials and annuals (20 lbs. seed per acre)
	Dollars				
Harding	0.90	0	0	0.90	5.40
Pubescent wheatgrass	.60	0	0	.60	2.40
Tall wheat-grass	.40	0	0	.20	.80
Intermediate wheatgrass	.60	0	0	.30	1.20
Smilo	.80	0	0	.40	1.60
Big blue	.60	0	0	.30	1.20
Blando	.60+	.30	2.40	.15	.60
Wimmera	.12	.24	1.92	0	.12
Totals	--	.54	4.32	2.85	13.32

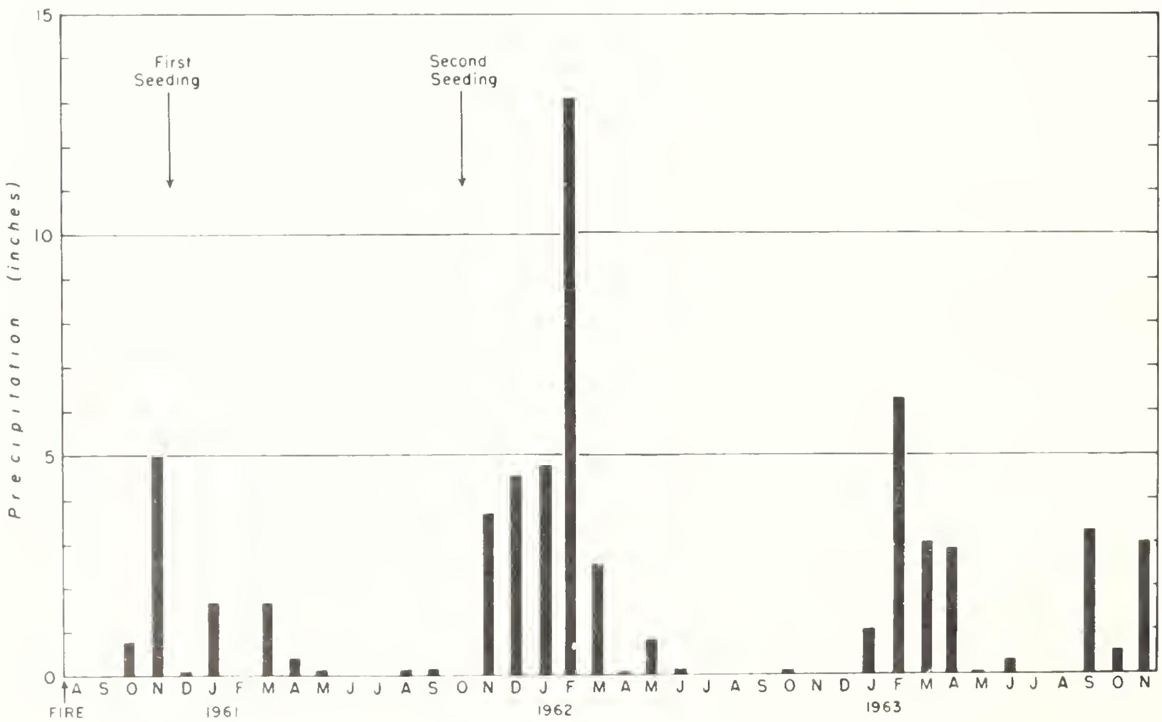

Figure 2.—Precipitation regime after the fire of July 1960.

perimental watersheds were broadcast seeded again less than a year later, in October 1961. The purpose of reseeding was to establish a sufficient cover of seeded species for experimental testing.

In the spring following the first sowing, watersheds seeded with "high-density" annuals had only a 2.2 percent cover of seeded grasses; the watersheds seeded with "low-density" annuals only 1.3 percent (fig. 3 [2]). The watersheds sown with perennials had less than 1 percent cover in all samples. Because the second seeding was followed by substantial rainfall in late fall and winter, the cover of seeded grass was measurably improved. The grass covers in the watersheds with "high-density" and "low-density" annual grass seedings were 10.0 and 4.8 percent, respectively, in February 1962. The maximum cover in a single "high-density" annual watershed was 12.9 percent. Seeded cover in the perennial-sown watersheds was only 2.6 percent, most of which was accounted for by annual species. Later in the spring the seeded grass cover in the watersheds with the "high-density" perennial mixture was 6.2 percent, the bulk of which was still annual grass.

In the annual-sown watersheds the grass cover decreased gradually over the next 2 years, while in the perennial-sown watersheds, the cover increased as the perennial species began to take hold. In most cases annual species still contributed a substantial amount of cover in the perennial-sown watersheds (fig. 3), where sown grass did not have to compete with the native vegetation. The perennial grasses have done the best under low density rates of sowing where the amounts of annual grass seed included was low. The seeded grass cover (excluding barley) in the watersheds with the side slope stabilization treatment was about 50 percent lower than in those without it.

Barley Plantings

Barley emerged within 10 days of planting, and quickly established rows. It provided 6.4 percent cover in the spring of 1961 and reached a maximum of 18.8 percent in the summer of 1962 (table 3). It also retained its row effect very well during this period (fig. 4). Rice *et al.* (1965) attributed a 65-percent reduction in debris yield during the hydrologic year 1961–1962 to the barley treatment.

After reaching its peak, the barley cover declined rapidly. This decrease was probably due to loss of fertilizer effectiveness, failure of soil to cover seed, and rodents destroying seeds. Competition from native herbaceous and brush species also took its toll—especially on the drier sites. Even in these areas, however, rows of dead barley stubble remained (fig. 5).

The close spacing of the barley rows helped prevent detached soil particles from moving down slope any great distance. The soil particles became trapped among the barley plants and gradually built up a series of small terraces, giving the watershed side slopes a miniature step-like effect. This helped to reduce serious rill and gully erosion from runoff-producing storms. The barley treatment also aided in protecting the soil from rain drop impact—thus lowering the probability of soil detachment—and helped to increase the infiltration capacity. On such critical erosion source areas as dry erosion chutes and unstable soil banks, however, this treatment, as well as any other type of vegetative measure, is difficult to install successfully without some type of mechanical aid.

Growth of Native Species

Within 10 days after the fire, sprouts of native species started emerging from the crowns of many burned shrubs (Plumb 1961). By December, herbaceous species, where present, were still in the cotyledon stage or not much beyond it. The charred brush stems probably provided about as much cover then as the new sprout foliage. Sprouting was more prevalent on areas of deep soils where moisture conditions were the most favorable.

By the spring of 1961, the native vegetation provided about 10 percent cover on all watersheds without the side slope stabilization treatment (fig. 6), and 5 percent on watersheds that had this treatment. The plant species occurring most often on the plots were short-lobed phacelia *(Phacelia brachyloba)*, whispering bells *(Emmenathe penduliflora)*, broom deervetch *(Lotus scoparius)*, hoaryleaf ceanothus seedlings, and morning glory *(Convolvulus occidentalis)*. Herbicidal spraying kept the native vegetation in the perennial-sown watersheds in check from 1961 through 1964 (that is, the natives never exceeded 10.5 percent cover).

[2] Graphs in this paper indicate the trends from one sampling period to the next and do not represent the actual vegetative cover for each month throughout the year.

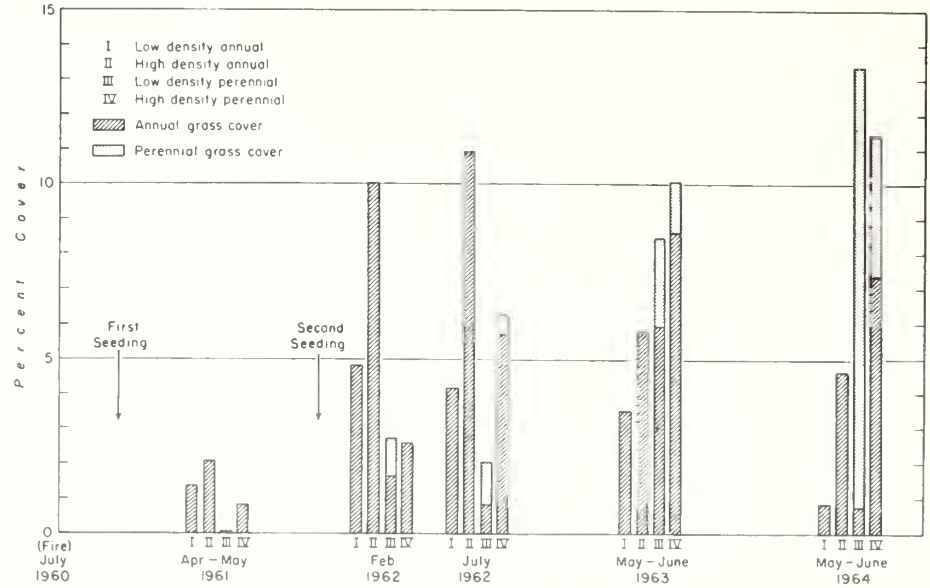

Figure 3.—Percent of soil covered by sown grasses in the seeded watersheds without the side slope stabilization treatment.

Figure 4.—A new and second crop of barley had developed in the original rows on the experimental watersheds when this photo was taken in January 1962.

Table 3.--*Development of barley in eight experimental watersheds seeded in December 1960-mid-January 1961*

Date of survey	Row length[1]	Density[2]	Cover
	Ft./acre	*Stems/in.*	*Percent*
April-May 1961	15,060	4.1	6.4
February 1962	13,550	6.1	12.6
July 1962	14,930	6.0	18.8
August 1963	2,780	7.7	3.8

[1]Actual length of barrier created by barley plants in the watersheds.
[2]Density of existing barley rows.

Figure 5.—Vegetation recovery three years after the fire in a watershed that received both the side slope stabilization treatment and a high density rye-grass seeding. Lack of native vegetation is evident in the spaces between the brush sprouts.

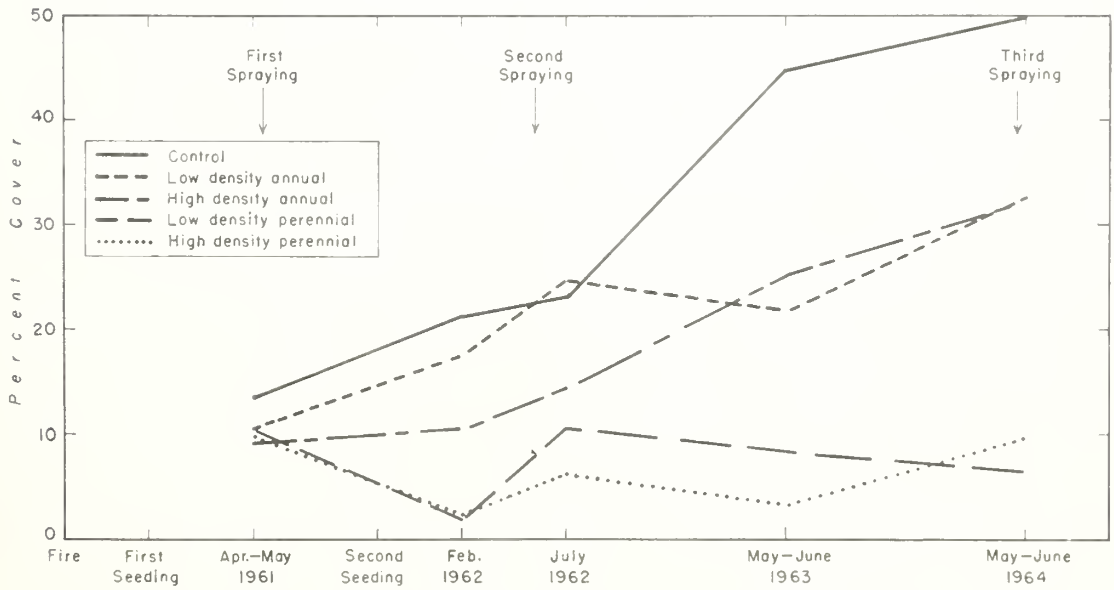

Figure 6.—Percent of soil covered by native species (native grasses, broadleaves, seedlings, and sprouts) in the main treatment group watersheds without the side slope stabilization treatment.

In the control watersheds, cover from native species increased from 12.3 percent in the spring of 1961 to 49.8 percent in 1964 (fig. 7). The watersheds sown with low density annuals had a native cover similar to that in the controls until 1962, when the rate of increase leveled off. Competition from the seeded grass in the watersheds sown with high density annuals slowed the establishment of native vegetation until 1963, when the annual grasses began to decline. The seeded grass cover in the watersheds sown with low density annuals was not great enough to affect establishment of native vegetation substantially in the first two years.

Recovery of native vegetation was significantly suppressed by the barley plantings. Control watersheds without barley had from 7.3 percent (spring 1961) to 23.7 percent (spring 1963) more native cover than watersheds with this treatment (fig. 8). When the barley began to fade out in 1963, the native species in the barley-sown watersheds began to respond more vigorously. In all barley-treated watersheds, the native cover was held back by about 40 percent during the first 2 years. This development was readily apparent by comparing two adjacent watersheds—one with and one without the barley treatment (figs. 5, 7).

The first two years after the fire, cover provided by the barley more than made up for its effect in holding back the native vegetation in the control watersheds (fig. 9). When the barley deteriorated, however, the live vegetation was greatest in the watersheds without the barley treatment. The amount of live vegetative cover could be important in areas where mass slumping of soil is likely because plants with live, deep vigorous root systems would be needed to maintain soil stability.

Litter and Dead Stems

Since the first vegetation sample was taken in 1961, the dead vegetative cover (primarily litter) has been gradually increasing. This cover averaged 1.3 percent in 1961 and 9.5 percent in 1964 in the main treatment group watersheds. A large amount of litter was added in 1963 and 1964 in the side-slope stabilized watersheds—primarily from barley.

Total Vegetative Cover

Vegetative cover was uniformly low after the first rainy season, which was 61 percent below normal. Including seeded grasses, native species, and litter and dead stems, total cover averaged only 12.5 percent in the spring of 1961, and differences between treatments were small—within 2 percent cover (fig. 10).

The following year, after another seeding and appreciable rainfall, cover in the unsprayed watersheds increased to about 30 percent. The perennial-sown watersheds still had a low cover of vegetation in February 1962—about 9 percent, but increased to 16 percent by the summer.

The annual-seeded watersheds never had a significantly greater vegetative cover than the controls. In the third and fourth years after the fire, the total vegetative cover was highest in the control watersheds. There was no significant difference in total vegetative cover between the high and low density annual watersheds and between the high and low density perennial watersheds. Table 4 lists the significance of differences among the various seeding treatments.

The importance of each type of vegetation in the makeup of total cover varied among the watershed groups. In the control watersheds without side slope stabilization, vegetative cover is provided mainly by the native species (fig. 11C). In the annual-sown watersheds the native species were a little slower in responding, seemingly because of competition from the seeded grass (fig. 11A). When the annual grasses began to decline after 2 years, the native species increased their cover more rapidly. Litter and dead stems provided gradually increasing cover in all watersheds. In the sprayed perennial-sown watersheds (fig. 11B), the seeded grass cover was slow in becoming established; not until the third and fourth years after the fire did the cover show signs of increasing appreciably. In the four control watersheds with the side slope stabilization treatment, barley held back the recovery of the native vegetation and added appreciably to the litter cover (fig. 11D).

Effects on Watershed Rehabilitation

There have been only six analyzable storms to evaluate the treatments since the fire on the Experimental Forest. Five of them have been reported by Krammes and Hill (1963) and Rice *et al.* (1965). The sixth storm, on January 20–22, 1964, produced 3.76 inches of rain. Rainfall intensities

Figure 7.—Recovery of native vegetation in one of the control watersheds three years after the fire.

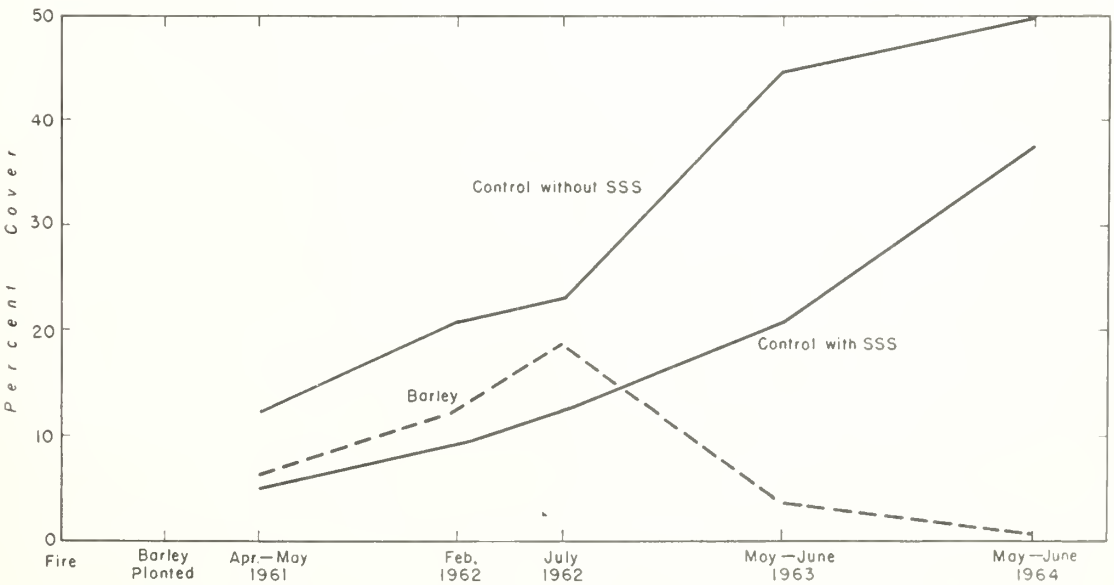

Figure 8.—Percent of soil covered by native species (native grasses, broadleaves, seedlings, and sprouts) on all the unseeded watersheds, with and without the side slope stabilization treatment; and barley cover in the watersheds with side slope stabilization treatment.

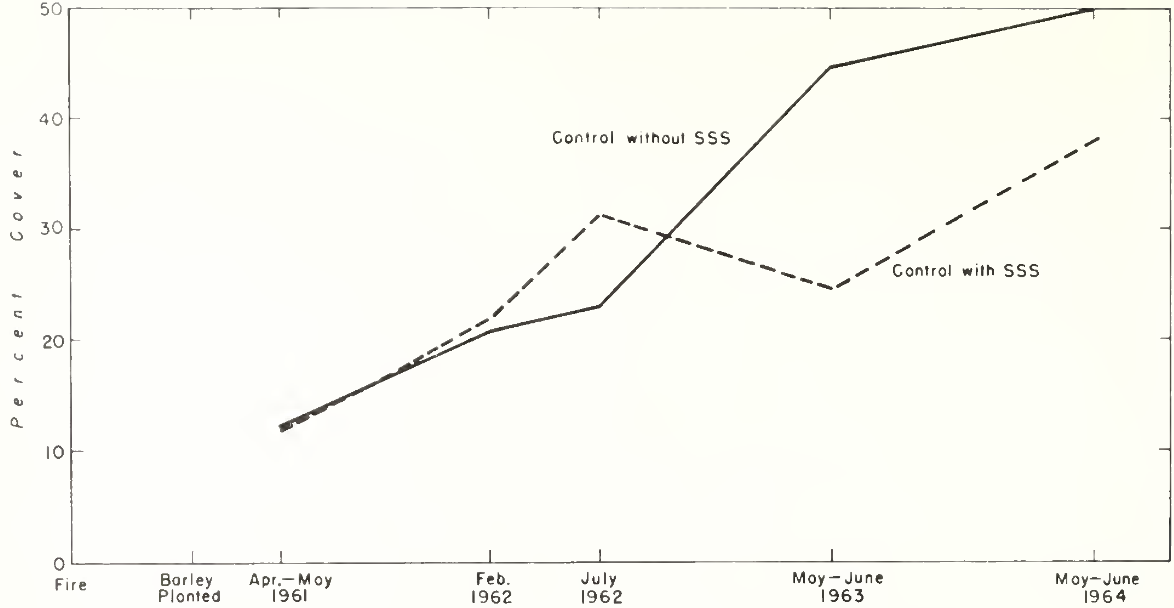

Figure 9.—Percent of soil covered by live vegetation (planted barley and native species) on all the unseeded watersheds with and without the side slope stabilization treatment.

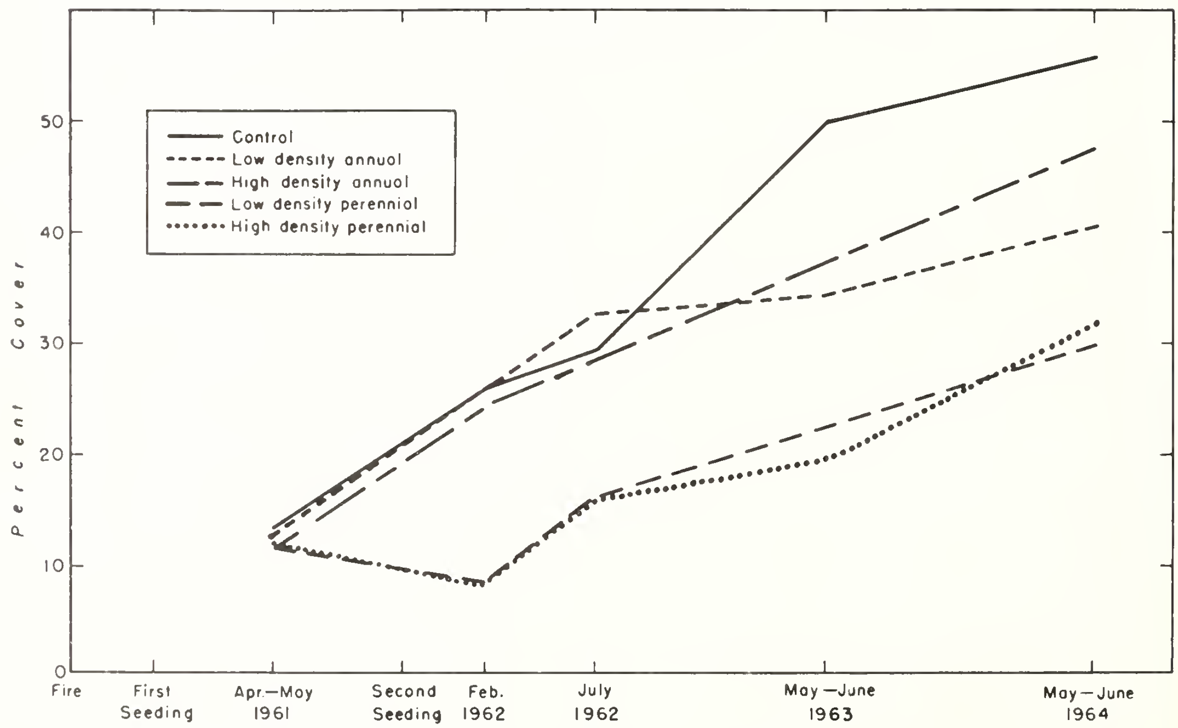

Figure 10.—Percent of soil covered by all vegetation (dead and alive) in the main treatment group watersheds without the side slope stabilization treatment.

Table 4.--*Statistical significance of differences in total vegetative cover among watershed groups*[1]

Watersheds compared	Date surveyed				
	April-May 1961	Feb. 1962	July 1962	May-June 1963	May-June[2] 1964
Control-high density annual	([3])	([3])	([3])	0.05	([3])
Control-low density annual	([3])	([3])	([3])	.05	.05
Control-high density perennial	([3])	0.01	0.05	.01	.05
Control-low density perennial	([3])	.01	.05	.01	.01
High density annual-low density annual	([3])	([3])	([3])	([3])	([3])
High density annual-high density perennial	([3])	.01	.05	.01	([3])
High density annual low density perennial	([3])	.01	.05	.05	([3])
Low density annual high density perennial	([3])	.01	.05	.01	([3])
Low density annual-low density perennial	([3])	.01	.05	.05	([3])
High density perennial-low density perennial	([3])	([3])	([3])	([3])	([3])

[1]On the basis of Duncan's new multiple-range test.

[2]This analysis was less sensitive than the previous ones owing to the reduction in the number of watersheds sampled.

[3]Not significant.

were as follows:

Duration (minutes)	*Inches per hour*
5	1.51
10	1.24
15	1.09
20	.92
30	.82
60	.66

Although this storm was similar in amount and intensity to some of those occurring during the winter of 1961–62, the peak flows (mean average response) were only 18 percent as great. Seven of the 20 main treatment group watersheds had no flows during this storm; 2 years before all watersheds had measurable peak flows. During this period the total vegetative cover doubled. The trends in flood peaks corresponded well with the total vegetative amounts (fig. 10).

Analysis of the four largest storms in the winter of 1961–62 (Rice *et al.* 1965) suggests that a substantial grass cover established the first year after a fire can help reduce erosion measurably. In watersheds with the "high-density" annual sowing, the seeded grass (10 percent cover) was associated with a 16-percent reduction in debris even though it had no apparent effect on flood peaks. "Low-density" annuals had little or no effect.

In watersheds seeded with perennial mixtures, the seeded species apparently could not compensate for the reduction in native species caused by herbicidal sprays. The total vegetative cover in perennial-seeded watersheds was 13 to 30 percent lower than in the unseeded control watersheds for 3 years after the first spraying. Rice *et al.* (1965) found that watersheds seeded to "low-density" perennials tended to have higher flood peaks and greater debris yields than the other watersheds the first two years after the fire. "High-density" perennial watersheds showed little difference from unseeded watersheds in those years. Since then, however, flood peaks from all the perennial watersheds

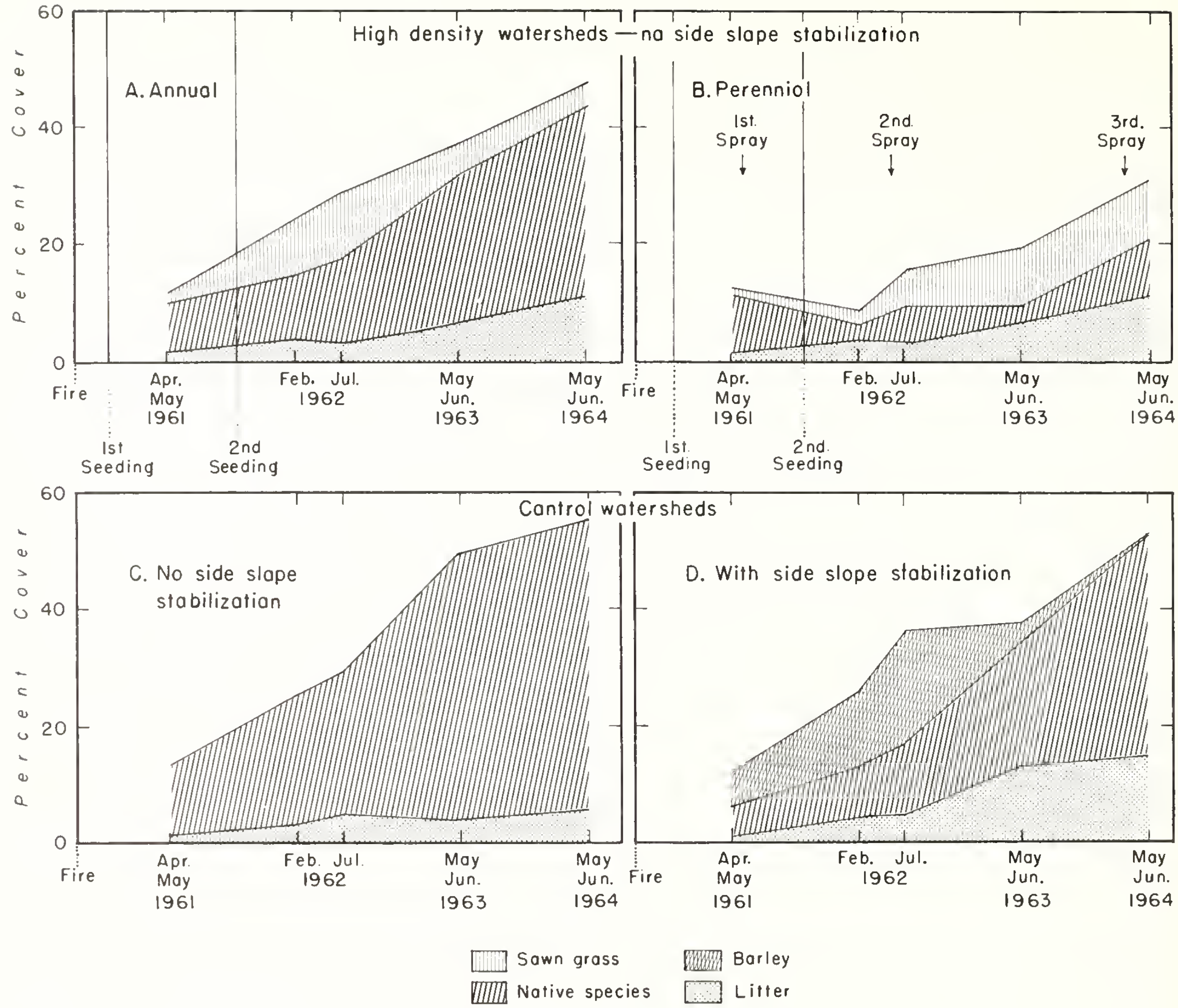

Figure 11.—Relative contribution of the various vegetative components in the various watershed groups.

have been greater than peaks from unseeded watersheds.

Unfavorable weather the first year after the fire unquestionably reduced the effectiveness of seeded grasses in the experimental watersheds. The best seedbed conditions for establishing a grass cover existed that year. In Monroe Canyon at slightly lower elevations than the experimental watersheds, annual grasses were sown *before* the November rains in 1960. By the end of the first growing season, deep soils in this area had a 16.6 percent grass cover on north-facing slopes, and 2.6 percent on the drier south slopes. One year later the grass had increased to 53.1 percent on north slopes and to 24.3 percent on south slopes. The experimental watersheds were first sown *after* the November 1960 rains. And rainfall remained scanty the rest of that season. "High-density" seeding with annuals—the most successful broadcast seeding—produced only 2.2 percent cover the first year; even after a second seeding, it provided only 10 percent cover the next year. Thus, timing of the seeding may be a critical factor in the rehabilitation of burned watersheds.

Even if moisture is adequate for germination, several factors can inhibit grass establishment when no rain follows seeding. Growth of grass may be limited by deficient precipitation or low temperatures, or both, after germination. Strong winds can blow large amounts of seed from the hillside; harvester ants, rodents, birds, and other wildlife can destroy much seed. But rainfall tends to cover the seed with ash and soil, protecting it from such losses. The longer the interval between the time of seeding and the first good rain, the greater the loss is likely to be.

Despite these hazards, an effort to establish grasses seems worthwhile. For some erosion control problems, grasses may be more advantageous than many native plants—even though the aerial parts of natives are much larger. The grasses have fine, fibrous root systems that occupy the upper layers of soil. And the numerous grass plants are more uniformly distributed than native species in the watersheds. These are advantages when the problem is to bind down surface soil. Where mass slumping of soil is a problem, plants that put down deep roots have the advantage, for they can help bind the soil mantle to the underlying parent material. Such species as Eastwood manzanita *(Arctostaphylos glandulosa),* the oaks *(Quercus* spp.*),* and christmasberry *(Photinia arbutifolia)* would be desirable native plants in this situation (Hellmers *et al.* 1955). Where both surface erosion and mass movement of soil may occur, as on road fills, a mixture of deep-rooted woody shrubs and fibrous-rooted plants would be recommended. Besides the grasses, some native plants with shallow branching roots would help in this situation; for example, such species as bush monkeyflower *(Mimulus longiflorus),* California buckwheat, white sage, and thickleaf yerbasanta *(Eriodictydon crassifolium* var. *nigrescens).*

A grass cover may be helpful in reducing another problem: the hydrophobic characteristic of some chaparral soils. A water-repellent property of soil is commonly associated with both burned and unburned chaparral watersheds and is generally thought to result from an organic coating on soil particles. This property may be responsible for increasing surface runoff and erosion potential in southern California mountains. Van't Woudt (1959), in describing Zunker's (1930) work, showed that water-repellent soils were commonly associated with native heath vegetation, but were not found on adjacent areas which had been in a grass cover for 20 years or more. In examining burned chaparral watersheds in southern California, Krammes and DeBano (1965) found large areas of non-wettable soils. Sample sites where the soils did not demonstrate this hydrophobic characteristic were usually occupied by a grass cover.

Summary and Conclusions

The testing of emergency erosion control measures after a wildfire burned the San Dimas Experimental Forest has been in progress since late 1960. Twenty-five small watersheds were treated with various "first aid" measures including grass seeding to reduce debris production and flood peak flows. Precipitation through 1964 was 66 percent of the 35-year average.

The total vegetative cover in the seeded watersheds was never significantly higher than in the unseeded controls. The seeded vegetation (sown grasses and planted barley) had a substantial effect, which varied directly with percent cover, on holding back the recovery of native species. But the grass cover established in the watersheds so treated might have provided better protection from surface soil erosion than a like area of some native species because of the rooting habits and uniform distribution of the grass plants and their possible effects on the existing areas of hydrophobic soils.

The benefit of grass cover was illustrated the second winter after the fire when, in four large storms, the "high-density" annual grass seedings were associated with a 16 percent reduction in debris. Owing to the low cost of the annual grass seedings and the speed with which it can be applied, land managers appear justified in trying to establish a grass crop. But this treatment should not be taken as a cure-all. In many instances a combination of vegetative and physical measures may be most appropriate—especially in critical erosion areas of a watershed.

The total vegetative cover in the watersheds sown with perennials which were sprayed with herbicides to aid in grass establishment, was far below the total in other treatments. The perennial grasses did not compensate for the reduction in native species during the first four years.

Barley planted in closely spaced rows on contour proved to be the most successful emergency treatment. Barley row length and density, and the resulting percent cover, stayed high for two years. But the barley stand began to deteriorate in the third and fourth years and storms were too few to test the treatment during this period.

The mean average peak flow from 20 treated watersheds in one 1964 storm was only 18 percent as great as the average peak produced from three storms of similar size in 1961–62. The total vegetative cover had doubled in the intervening 2 years, from 21.2 to 42.6 percent. "Healing" of the watersheds during this period has thus had a considerable effect on reducing the flood potential.

In selecting a vegetative treatment for use to control erosion on burned watersheds, several factors must be kept in mind. A good grass cover established a year or two after a fire can help reduce the amount of erosion. There is a risk (high in southern California), however, that establishment of a grass crop will be poor owing to critical and variable climatic conditions. Row plantings of barley have proved effective in controlling erosion, but are more expensive than broadcast seedings. Use of this treatment on critical erosion areas in a watershed and broadcast seedings on the other portions will help to minimize cost yet establish a sound erosion control program. If down-stream values are high, a combination of vegetative treatments and physical structures may be required to provide the needed protection. The most successful erosion control program is one that can prevent soil movement on the slopes from starting and concentrating in stream channels.

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GPO 971-876

Estimated Demand for Lumber and Plywood in Hawaii by the Year 2000

George D. Frazier

U. S. FOREST SERVICE RESEARCH PAPER PSW-23 1965

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

CONTENTS

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Forest resources form one of Hawaii's most valuable natural assets. There are about 1.1 million acres of commercial forest land in the State. In 1961 this land was estimated to carry more than 722 million board feet of standing sawtimber.[1] Yet much of the timber products are now imported. Can the timberlands of Hawaii provide at least part of the Islands' needs both now and in the future?

The future of the timber products industry in Hawaii will depend on future demands for lumber and plywood and on the availability of timber raw materials. Availability of raw materials will hinge on a sound forestry program. In planning investments—both public and private—in such a program, estimates of the future needs in timber products are essential. To obtain a picture of the consumption pattern in Hawaii, we gathered information on the types and species of timber products used, the proportion of lumber to plywood used, and the proportion of hardwoods to softwoods used.

We projected future demands by correlating total lumber consumption with population changes. But this correlation explained only 56 percent of the variation in lumber consumption. And so we developed individual regression equations for hardwood and softwood use. A simple multiple correlation coefficient showed that 85 percent of the variation in hardwood consumption was associated with population changes. In contrast, population changes explained only 32 percent of the variation in softwood lumber consumption. Other factors were examined to explain the variations. A prediction of plywood consumption by the year 2000 was not attempted statistically. Historical trends of plywood use in Hawaii were compared with the trend in use on the United States mainland as an indication of what might happen in the future.

This paper is the first of a series examining the present and potential markets for Hawaii-produced timber. It reviews the consumption of timber and plywood during the period 1951–61. It forecasts expected consumption of lumber and plywood in Hawaii by the year 2000. It reports the composition of past lumber consumption and the expected changes in the proportion of hardwood and softwood consumed by the year 2000.

Consumption Pattern 1951-1961

The apparent consumption of lumber in Hawaii varied between 78.5 and 93.6 million board feet during the period 1951–61 (table 1). ("Apparent consumption" as used in this paper is the 3-year moving average of lumber imports plus the estimated annual production of lumber in Hawaii.) Consumption generally increased between 1954 and 1959, but it has declined rather sharply since 1959 (fig. 1).

In contrast to the decline in lumber consumption, plywood use has risen markedly since 1957. "Apparent consumption" of plywood is the 3-year moving average of imports only; Hawaii does not have a plywood industry. In 1958 an estimated 2.3 million square feet of plywood (3/8-inch surface measure basis) were imported into the State. Imports increased until they reached a high of 16.1 million square feet in 1960. Although plywood consumption declined in 1961, it still was nearly six times greater than that reported in 1957 (fig. 1).

The consumption of timber products depends greatly upon population levels. Other things being equal, an increasing population will cause an increased consumption of all goods and service—

[1] Nelson, Robert E., and Wheeler, Philip R. Forest resources in Hawaii—1961. Hawaii Forestry Div., Honolulu, in cooperation with Pacific SW. Forest & Range Expt. Sta. U.S. Forest Serv. 48 pp., illus. 1963.

including lumber and plywood. More people will require more houses, more furniture, and more products and services that use lumber and plywood in their manufacture and delivery. Since 1954 population in Hawaii has increased at a nearly constant rate (fig. 2). The expected growth in population was used in projecting expected lumber and plywood consumption. In the projection, we assumed that . . .

- The general level of economic activity in the State during the past 10 years would continue in the next 35 to 40 years.
- Consumer's tastes and preferences as to lumber and plywood in housing and other goods made from wood would not undergo radical change.
- No major technical changes in the uses of wood and wood products or in wood products manufacturing would take place in the next 35 to 40 years.
- The same level of military preparedness and the same state of world affairs and the world economy would persist in the next period as it has since the early 1950's.

Table 1.--*Apparent consumption of lumber and plywood, State of Hawaii, 1951-61, and population*

Year	Population[1]	Lumber: 3-year moving average of imports[2]	Lumber: Annual production[3]	Lumber: Total apparent consumption	Plywood: 3-year moving average of imports[4]
		Thousands of board feet			*M sq. ft.*
1950	472,780	--	--	--	--
1951	471,853	78,938	303	79,241	--
1952	462,494	89,118	303	89,421	--
1953	468,301	78,984	322	79,306	--
1954	474,391	78,133	323	78,456	1,881
1955	491,899	82,190	326	82,516	1,373
1956	512,200	84,733	476	85,209	1,318
1957	538,296	87,948	531	88,479	2,301
1958	560,448	88,307	843	89,150	9,319
1959	580,505	92,696	928	93,624	14,041
1960	595,024	86,837	1,078	87,915	16,079
1961	612,763	77,793	[5] 1,000	78,793	12,212
1962	635,888	--	--	--	--

[1]Hawaii Dept. of Health. Civilian population--State of Hawaii. 1950-63 (midyear). Rev. Sept. 13, 1963.

[2]Hawaii Board of Harbor Commissioners. Annual report for each year.

[3]Estimated koa lumber used in furniture and cabinet manufacturing. 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.)

[4]There is no plywood production in Hawaii. Thus the 3-year moving average of imports is apparent consumption. U.S. Army Corps of Engineers, Pacific Regional Statistical Office. Report prepared for the U.S. Forest Service, Jan. 17, 1964, converted from short tons to square feet, 3/8-inch basis. (1 short ton 1,777.8 square feet, 3/8-inch basis.) 1961 and 1962 include foreign plywood import data from U.S. Bureau of Census. U.S. imports of merchandise for consumption. Dist. No. 32, annual summaries.

[5]Estimated by the author

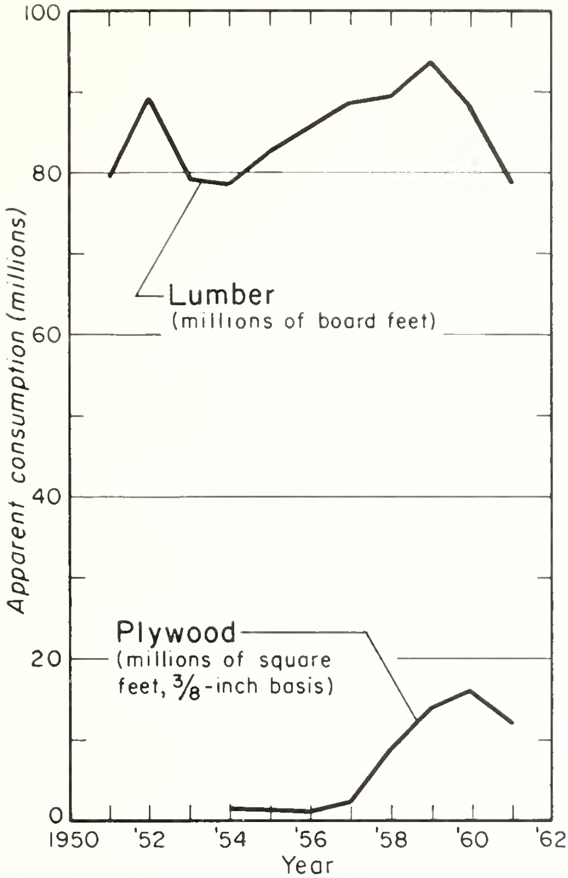

Figure 1. — *Apparent consumption of lumber and plywood, Hawaii, 1951-61.*

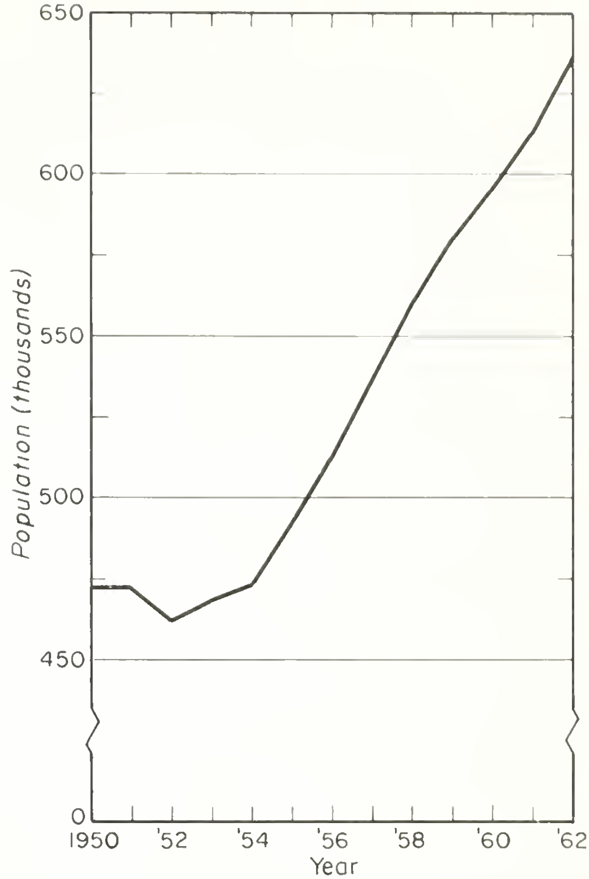

Figure 2.—*The population, State of Hawaii, 1950-62. (Source: Hawaii Dept. of Health, Research Planning and Statistical Office. Civilian Population — State of Hawaii. 1950-63 (midyear). Rev. Sept. 13, 1963).*

Expected Lumber Demand

We estimate that the consumption of lumber in the year 2000 will be 103 million board feet. By then Hawaii's population is expected to reach 1,000,000. The error of this forecast is estimated to be 25 million board feet at the 95-percent level of confidence. Therefore, the estimated consumption by the year 2000 is expected to be between 78 and 128 million board feet.[2]

[2] The usefulness and validity of a confidence statement depends upon the validity of the model used in prediction. When a prediction and its confidence statement are desired for a given value of the independent variable greatly beyond the limits of the observed data, it is assumed that the relationships of the model will continue to hold for all values of the independent variable beyond the observed data.

The data do not show a high degree of correlation between population and lumber consumption. Only 56 percent of the variation in lumber consumption is associated with population changes—in this case, increases in population (fig. 3).

In analyzing the data, one year was discarded—1952. The 1952 data were influenced by heavy lumber imports directly related to the Capehart housing project for military dependents. It was assumed that there will not be many projects of this type in the future.

Demand for Hardwoods

The present composition of forest products demand and what it might be in the future are of par-

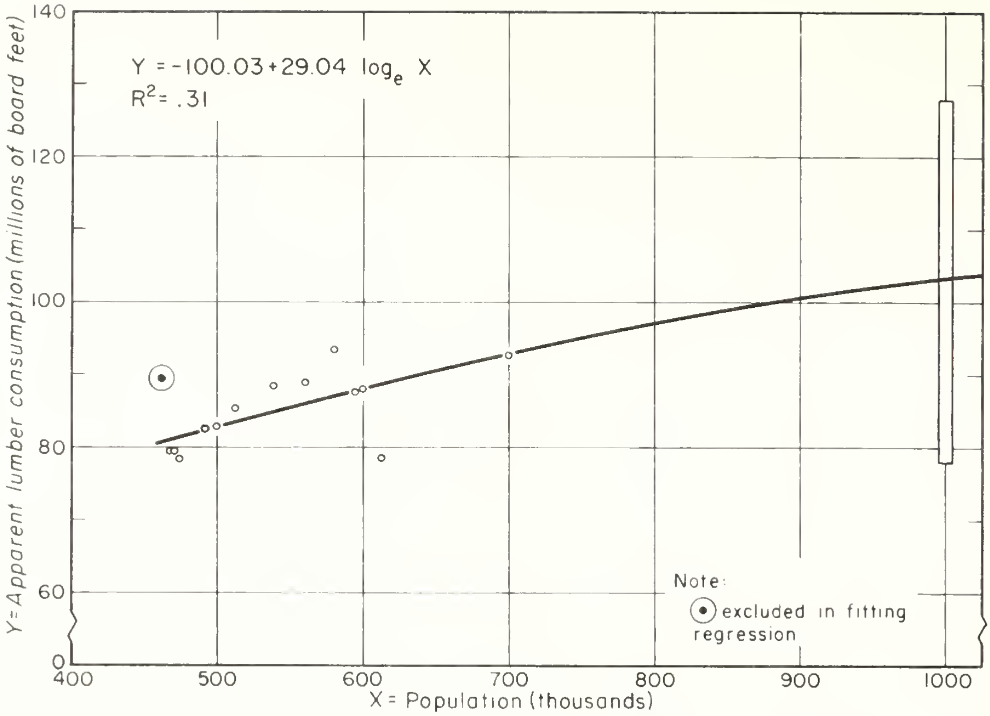

Figure 3. — *The relationship between total lumber consumption and population, State of Hawaii.*

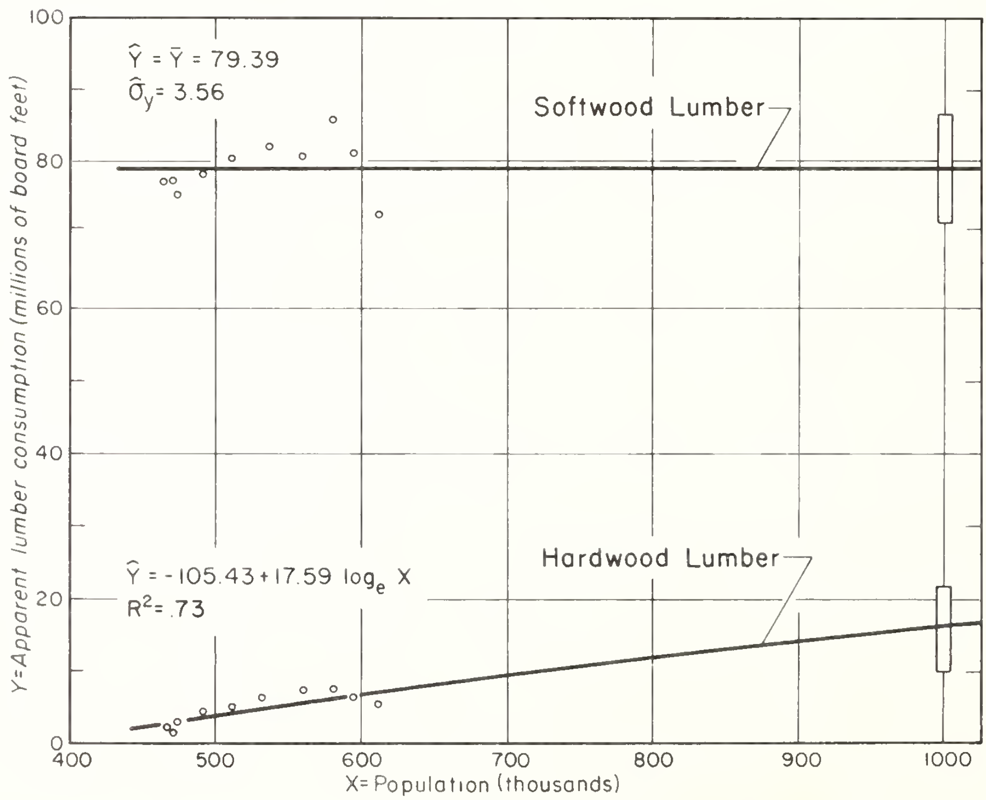

Figure 4. — *The estimated consumption of softwood and hardwood lumber, State of Hawaii.*

Table 2.--*Composition of apparent lumber consumption in Hawaii, 1951-61*[1]

Year	Total apparent lumber consumption	Hardwood species	Softwood species
	Thousands of board feet		
1951	79,241	1,519	77,722
1952	89,421	1,772	87,649
1953	79,306	2,205	77,101
1954	78,456	2,973	75,483
1955	82,516	4,176	78,340
1956	85,209	4,907	80,302
1957	88,479	6,306	82,173
1958	89,150	7,192	81,958
1959	93,624	7,494	86,130
1960	87,915	6,489	81,426
1961	78,793	5,507	73,286

[1]Apparent consumption of hardwood lumber was estimated on the basis of the 3-year moving average of hardwood lumber imports to which was added the estimated production of lumber in Hawaii. This production is all hardwood species as reported by Ernesto dela Cruz Lucas. Evaluation of market data as a guide for forest development in Hawaii. 1963. (Unpublished master's thesis on file, Agricultural Economics, Graduate School, Univ. of Hawaii, Honolulu, Hawaii.)

ticular importance in planning a forestry program in Hawaii. Except for the years 1960 and 1961, hardwood consumption has grown steadily (table 2). This increase has closely paralleled the growth in population during the period (fig. 4). Eighty-five percent of the increase in hardwood lumber use was associated with changes in population.

By the year 2000, hardwood lumber consumption in Hawaii is expected to reach 16.1 million feet. The error of this prediction at the 5 percent probability level indicates that the range of expected consumption is between 9.9 and 22.3 million feet. If this projection is correct, hardwood lumber consumption will increase in the next 30 to 40 years by two to four times the present level of consumption. On a per capita basis, hardwood consumption is expected to rise four times the 1950–52 level, and 1½ times the current level (table 3).

Hardwood lumber markets in Hawaii have been dominated by three species: Philippine mahogany, oak, and koa (table 4). Although the importance of Philippine mahogany has declined relative to other hardwood species since the mid-1950's, it still comprises a large part of the total volume. The relative importance of both domestic and Japanese oak species has also dropped; oak species now comprise only an estimated 13 percent of the total hardwood lumber market in Hawaii.

Since 1959, consumers have shifted to other hardwood species, including such imported woods as teak, Japanese ash, and maple. Other preferred hardwoods include such mainland species as ash, alder, walnut, and maple. This trend shows that consumers are willing to try new hardwood species. If the trend continues it could have an important bearing on the market introduction and acceptance of Hawaii-grown hardwood species.

Demand for Softwoods

Between 1951–61, consumption of softwood lumber in Hawaii remained relatively constant. It varied from a low of 73 million board feet to a high of 86 million board feet. If average annual consumption for this period is used as an estimate of future demand, softwood lumber use by the year 2000 will be 79.4 million board feet. This constant rate of consumption in the face of an expanding population would mean a sharp drop in per capita use to 60 percent of the 1960–61 level (table 5).

A regression equation correlating softwood lumber use with population changes showed that only 32 percent of the variation in consumption was

Table 3.--*Estimated per capita consumption of hardwood lumber in Hawaii, 1950-2000*

Population	Implicit years	Hardwood lumber consumption per capita	Estimated total hardwood lumber ccnsumption from regression
		Bd. ft.	*MM bd. ft.*
470,000	1950-52	6	2.796
500,000	1955	8	3.885
600,000	1960-61	12	7.092
1,000,000	2000	16	16.078

Table 4.--*Species composition of hardwood lumber consumption in Hawaii, 1951-61*[1]

Year	Philippine 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.)

Table 5.--*Estimated per capita consumption of softwood lumber in Hawaii, 1950-2000*

Population	Implicit years	Softwood lumber consumption per capita	Average softwood lumber consumption 1951-61
		Bd. ft.	*MM bd. ft.*
470,000	1950-52	169	79.4
500,000	1955	159	79.4
600,000	1960-61	132	79.4
1,000,000	2000	79	79.4

explained by population changes. This figure is not significantly different statistically from zero at the 5 percent level of probability. Thus other factors were investigated in an attempt to explain this variation in use.

Softwood lumber is used chiefly in construction—particularly in houses and other dwellings. Three types of activities account for most of this use: (a) new construction because of an expanding population; (b) new construction to replace older housing; and (c) maintenance and repair of existing dwelling units.

Few data are available on the age of houses in Hawaii. In general the average age of houses there is probably low because of the high level of building activity since the early 1950's. The U.S. Bureau of the Census[3] found that 36 percent of the housing units in Hawaii were built between 1950 and 1960. In contrast only 27.5 percent of the housing units in the United States mainland were built during that decade.

Softwood lumber use in new housing will depend largely on the rate of population growth. If the population increases at a constant rate each year, annual consumption of softwoods would be expected to be relatively constant. Since 1954 Hawaii's population growth has remained relatively constant (fig. 2). Although softwood consumption in individual years has fluctuated rather sharply, these changes are probably the result of the construction industry's inability to respond directly to demands for more housing.

In all likelihood, softwood lumber consumption in the next 35 to 40 years will not rise drastically in Hawaii because of dwelling unit replacements or because of maintenance and repair work on houses. The most important factor affecting annual lumber consumption will be the rate of increase in the State's population.

[3] U.S. Bureau of the Census. U.S. Census of housing 1960. Vol. 1, States and small areas, United States summary. Final report HC(1)-1. U.S. Government Printing Office, Washington, D. C. 1963.

Implications for the Lumber Industry

Total consumption of lumber in Hawaii is expected to be between 78 and 128 million board feet by the year 2000. Hardwood consumption by then is expected to be about 16.1 million board feet; softwood consumption by then would be about 79.4 million board feet. By summing the two individual estimates, total lumber consumption is estimated to be 95.5 million board feet—an estimate well within the expected range of total lumber consumption of 78 to 128 million board feet (table 6). The two figures differ because of differences in estimation procedures. The predictions indicate an 11 percent increase in total lumber use. Little change is expected in softwood consumption, but hardwood consumption is expected to jump by nearly 150 percent.

These estimates provide forest managers with some basis for planning future timber programs in Hawaii. The present timber resource consists chiefly of hardwood species. In developing a resource base for the future, Hawaii can continue its present program of emphasizing hardwoods, or it can re-evaluate its program and consider other

Table 6.--*Lumber consumption in Hawaii, 1959-61, compared with the expected consumption in the year 2000*

Years	Total consumption	Softwoods	Hardwoods
	Millions of board feet		
1959-61	86.8	80.3	6.5
2000	[1] 95.5	[1] 79.4	[1] 16.1

[1] Calculated from individual regressions for hardwood lumber consumption and softwood lumber consumption. Total lumber consumption of 95.5 million board feet (estimated by summing the individual estimates) is well within the expected range of total lumber consumption of 78 to 128 million board feet. The expected values differ (103 million versus 95.5) because of the differences in estimation procedures.

species—both hardwood and softwood. Or it can, in view of these estimated needs for the future, decide to depend on other timber-producing areas for providing its lumber and other wood products.

Hawaii's timber products industry now provides only about one-sixth of the hardwood lumber requirements of the State. If the industry maintains only its present share of the market, it must expand more than 2½ times its present production of about 1 million board feet a year. Provided the proper economic environment and the proper resource base, there is no reason to assume that the industry could not expand even more and develop into a major supplier of the State's hardwood lumber needs.

Expected Plywood Demand

Estimating plywood demand in Hawaii was much more difficult to handle statistically for several reasons. First, the data are relatively unreliable. Second, the consumption data are available for only 7 years. Third, the consumption of plywood in Hawaii has been undergoing severe changes because cement manufacturing was introduced into the islands during this period, causing a rapid increase in the demand for plywood for concrete forms. For these reasons no statistical analyses were attempted to provide predictor equations.

Some insight into the level of demand that might exist by the year 2000 may be obtained by reviewing the consumption of plywood on the United States mainland. Since 1951, per capita consumption of softwood plywood there has risen by 2½ times (table 7).

Per capita consumption of plywood in Hawaii, on the other hand, has increased by five to six times. It is unlikely that this rate of increase will continue indefinitely. Rather it is reasonable to assume that the timber industry in Hawaii had to do some "catching up." We assumed that per capita consumption in Hawaii will continue to rise at a faster rate than that for the rest of the United States, but that it is unlikely the per capita consumption in Hawaii will equal that of the mainland by the year 2000.

As a preliminary estimate for the year 2000, we assumed that per capita consumption will be 40 square feet (on a 3/8-inch basis). At this level of consumption, the total estimated plywood demand by the year 2000 would be 40,000,000 square feet—an increase of about twice the 1961 level of consumption.

Table 7.--*Per capita consumption of softwood plywood in the United States mainland and in Hawaii, 1951-61*[1]

Year	Softwood plywood consumption: United States mainland	Softwood plywood consumption: Hawaii
	Square feet (3/8-inch basis)	
1951	19.3	--
1952	20.1	--
1953	24.0	--
1954	24.4	4.0
1955	31.8	2.8
1956	32.1	2.6
1957	32.8	4.3
1958	37.0	16.6
1959	43.1	24.2
1960	42.9	27.0
1961	49.9	19.9

[1]Source: Hair, Dwight, and Ulrich, Alice H. The demand and price situation for forest products--1964. U.S. Dept. Agr. Misc. Pub. 983, tables 1 and 8. 1964.

Summary and Conclusions

Past consumption of lumber in Hawaii indicates that markets using hardwood species have expanded more rapidly than softwood markets. A continuation of these trends would indicate that by the year 2000 the consumption of hardwood lumber in Hawaii would increase from two to four times the present level of use. In contrast, softwood lumber production is expected to remain relatively constant. Although the hardwood consumption in Hawaii is lower than softwood consumption, it now exceeds current hardwood lumber production in the State. If the predicted consumption by the year 2000 is realized, the present industry in Hawaii will have to grow to about 2½ times its present size to maintain its relative position in the hardwood lumber market. The expected consumption in 2000 provides a base for expanding the present industry in terms of its present level.

If the Hawaii timber products industry is to take part in this expected increase in market demands, it must (a) provide the species and products desired by the market; (b) provide these products at an accepted level of quality and in the amounts desired by the market; and (c) provide these products at competitive prices.

To encourage the continued development of the Hawaii timber products industry requires a forestry program that will provide the raw materials needed, in the quantities desired by the industry, and at a price that the industry can pay and still compete in the consumer market.

GPO 971-805

Natural Regeneration in Relation to Environment in the Mixed Conifer Forest Type of California

H. A. Fowells and N. B. Stark

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

Contents

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The study they report here was begun by Duncan Dunning, then Silviculturist at the Station. H. A. Fowells carried out the study under Dunning's supervision from 1934 to 1941 and later summarized most of the data. N. Stark deserves much credit for assembling the data for publication.

To provide information on factors affecting natural regeneration in the mixed conifer type in California, the Forest Service started in 1931 an intensive study on the Stanislaus-Tuolumne Experimental Forest in the Sierra Nevada of California. The specific objective of the study was to determine the environmental factors favoring or inhibiting the establishment of reproduction of the major species of the mixed conifer type. These species are ponderosa pine (*Pinus ponderosa* Laws.), sugar pine (*P. lambertiana* Dougl.), white fir (*Abies concolor* [Gord. and Glend.] Lindl.), and incense-cedar (*Libocedrus decurrens* Torr.).

Some phases of the study have been reported, and observations of research workers and others at the experimental forest have helped formulate silvicultural practices for the type. But this paper is the first publication of the results giving in detail some of the environmental factors which directly or indirectly affected the establishment of reproduction.

Method of Study

Five study areas were selected on the experimental forest, located within the Stanislaus National Forest at 120° 01′ W. longitude, 38° 30′ N. latitude, at an elevation of about 5,200 feet. The study areas were in the drainage of the South Fork of the Stanislaus River, with two on the south-facing slope in a sugar pine-ponderosa pine type and three on the north-facing slope in a sugar pine-fir type. The general area is of high site quality, with some mature trees exceeding 200 feet in height and 7 feet in diameter. The climate of the area is characterized by dry summers, an average annual precipitation of about 36 inches with heavy snowfall, long-term temperature extremes of −12°F. and 101°F., and a frost-free season of 112 days.[1] Soils are derived from granite or diorite and were classified in the Holland and Olympic series.

In each of the five study areas a site factor plot was established, with a rodent-proof fence enclosing 2,000–2,500 square feet. The fence extended 18 inches below the ground surface and was about 5 feet high, topped with 8 inches of thin sheet metal. A description of each study area follows:

Study Area 1.—Located on a north slope at 5,280 feet elevation, about 75 feet above the level of the river and 525 feet lower than the ridge. The ground slopes 17 percent to the northwest. The area was clearcut in 1927. Only a few white firs, 1 and 3 chains to the east of the area, remained. The logging left considerable debris, and the slash was not burned. The debris was removed from the enclosure before the study began, and no weeds were allowed to grow on the bare mineral soil (fig. 1). The area received full sunlight except between the dates of July 27 to September 4, when a slight amount of shade was cast in the early morning by a large white fir.

Study Area 2.—Located on a partially logged area at 5,525 feet elevation. It lies 400 feet above the river on a 17 percent northwest slope. Timber on the area was selectively cut in 1928, and logging slash was burned. The remaining debris was raked off to expose mineral soil. Partial shade fell on this area from the trees left after logging (fig. 2).

Study Area 3.—Located on a clearcut south slope at 5,290 feet elevation and 100 feet above

[1] Stark, N. **Thirty-year summary of climatological measurements from the central Sierra Nevada.** Berkeley, Calif., Pacific SW. Forest & Range Expt. Sta. U.S. Forest Serv. Res. Note PSW-36, 15 pp., illus. 1963.

Figure 1.—*Study area 1 as it looked about 1933.*

Figure 2.—*Study area 2 as it looked about 1933.*

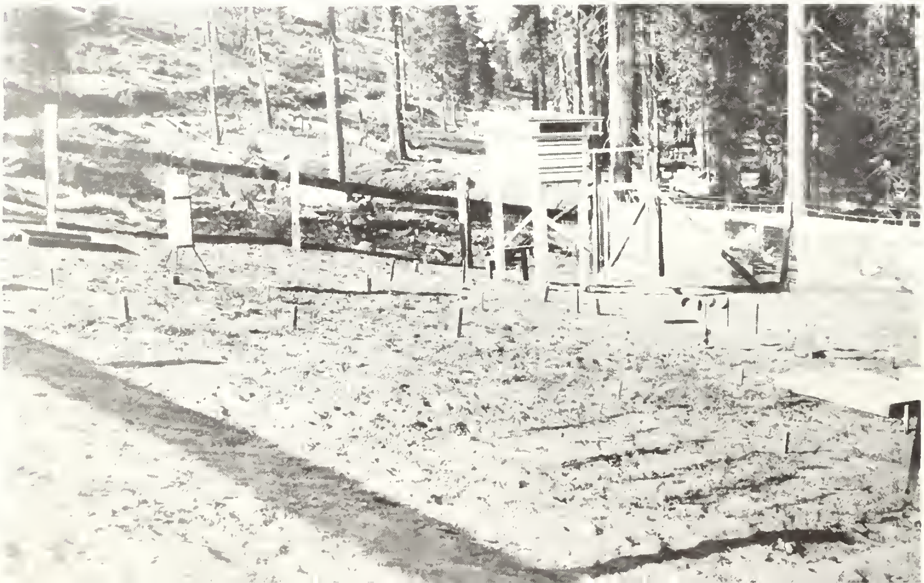

Figure 3.—*Study area 3 as it looked about 1934.*

Figure 4.—*Study area 4 as it looked about 1934.*

Figure 5.—*Study area 5 as it looked about 1934.*

the river. The ground slopes 24 percent to the south. The timber was cut in 1927. Although some slash was burned, the area was covered with logging debris which was raked to expose mineral soil (fig. 3). During summer days study area 3 received full sunlight except that weak shade fell on the area between 7 and 8 a.m. in early summer.

Study Area 4.—Located in an uncut stand on a south slope at 5,220 feet elevation, 30 feet above the river. The ground slopes 22 percent to the south. The litter was undisturbed (fig. 4). The area is shaded considerably in the morning, whereas full sunlight reaches the ground through part of the afternoon.

Study Area 5.—Located in a heavily shaded, uncut, north slope stand at 5,400 feet elevation, 25 feet above the river. The ground slopes 20 percent to the north. No litter was removed (fig. 5). Except for pinpoints of early morning sun, heavy shade from a dense stand of white fir poles and old sugar pines blanketed this station.

Soils in all five areas are fine sandy loams. Soil acidity varied from pH 4.8 to pH 5.5. The approximate proportions of soil fractions and wilting points as determined with sunflowers are given in table 1. From 10 to 16 wilting-point determinations were made for each sample depth at each study area.

Table 1.--*Sand, silt, and clay fractions and wilting points of soil at specified depths, Stanislaus-Tuolumne Experimental Forest*

Study area		Soil depth	Fine gravel	Sand	Silt	Clay	Wilting point
			Soil fraction, mm.				
			1 mm	.05-.5 mm	.005-.05 mm	.005 mm	
		In.	*Percent*				
1	Clearcut north slope	0- 3	3.2	74.6	12.2	10.0	6.6
		6- 8	2.9	75.5	11.9	9.7	6.9
		11-13	2.4	70.6	12.8	14.2	6.8
		18-21	2.2	71.9	11.9	14.0	6.2
2	Partially cut north slope	0- 3	3.6	74.5	13.5	8.4	7.4
		6- 8	3.3	76.4	12.2	8.1	7.3
		11-13	3.4	75.4	12.4	8.8	7.1
		18-21	2.7	74.3	12.7	10.3	6.7
3	Clearcut south slope	0- 3	2.6	75.1	11.4	10.9	6.2
		6- 8	2.5	77.6	9.9	10.0	6.5
		11-13	3.2	77.7	8.8	10.3	5.9
		18-21	3.2	74.1	7.6	15.1	5.7
4	Uncut south slope	0- 3	3.6	76.3	11.5	8.6	6.2
		6- 8	3.2	76.6	9.5	10.7	5.3
		11-13	2.6	77.8	9.4	10.2	5.0
		18-21	3.4	75.3	9.7	11.6	4.4
5	Uncut north slope	0- 3	3.6	73.6	14.1	8.7	8.8
		6- 8	2.6	75.9	14.6	6.9	8.2
		11-13	2.1	74.0	15.0	8.9	8.2
		18-21	2.1	72.8	15.0	10.1	8.3

Climatic Measurements

At each study area the following data were recorded:

1. Air temperatures within a louvered shelter (standard U.S. Weather Bureau type) at 4.5 feet above ground, recorded by a hygrothermograph and checked daily by maximum and minimum thermometers.

2. Relative humidity in the shelter by a hygrothermograph, checked daily by a psychrometer; and evaporation from black and white Livingston porous cup atmometers set at 8 inches above the ground, during the frost-free period.

3. Wind movement (miles per day) at 15 inches above ground by 4-cup anemometer. Wind was also measured at 8.5 feet above ground at study area 4 with a 3-cup anemometer.

4. Light intensity in foot-candles—in full sunlight, partial shade, and full shade—taken with a photronic cell.

5. Soil temperatures were measured with soil thermographs and checked by "Sixes" type thermometers. Temperatures were recorded at depths of ¼, 3, and 7 inches below the surface of the bare mineral soil in the study areas. The surface of the soil was bare in areas 1, 2, and 3 but covered with litter in areas 4 and 5. Consequently soil temperatures in study areas 1, 2, and 3 are not strictly comparable with those in areas 4 and 5.

6. Soil moisture was determined by the gravimetric method weekly or at 10-day intervals from May through October for most of 8 years. Samples were taken from 0 to 3, 6 to 8, 11 to 13, and 18 to 21 inches depth in the five stations.

7. Precipitation was estimated during the growing season with standard 8-inch rain gages.

Daily observations were made between 8 and 10 a.m. and charts of recording instruments were changed on Monday morning.

Seedling Observations

Replicate groups of seed spots of the four species (sugar pine, ponderosa pine, white fir, and incense-cedar) were set out each fall to provide seedlings for study. For several years equal numbers of seeds were planted in each spot to provide germination comparisons. Later, more seeds of the poorly germinating incense-cedar and white fir were planted to provide comparable numbers of seedlings for observation.

Seedlings were counted every 2 or 3 days during the period of germination and severe losses. Later, checks were made at weekly intervals. The losses were recorded by cause whenever it was possible to determine the cause with reasonable certainty. Principal causes of loss were:

1. Frost.—Seedlings collapse, with brown discoloration spreading from tip of cotyledons into the stem. Ultimately the seedlings wither.

2. Rodents.—Mice and pine squirrels clip off the cotyledons of pine when the seed coat is still attached, or they scratch out seedlings in search of seed; gophers burrow beneath seedlings, severing the roots (tops of a group of seedlings turn brown).

3. Insects.—Cutworms (*Euxoa excellans infelix* [Sm.]) kill seedlings by cutting their stems near the ground surface. The severed tops generally are pulled into the ground as the insect larvae feed on them. Partially eaten plants often are found protruding from the soil. Most cutworm damage occurs at night during the first month after seed germination.

4. Heat.—High soil surface temperatures cause heat lesions and killing of the cambial layer; the stems become constricted and may topple. Damage decreases as the seedlings develop woody stems.

5. Drought.—Seedlings turn brown and wither as soil moisture is depleted to the wilting point.

6. Fungi.—Damping-off organisms produce lesions on young stems at ground level, or lower.

7. Miscellaneous causes.—When none of the above causes could be identified, this category was used.

Total height of seedlings was measured at the end of each growing season for several years.

Root penetration was measured periodically by lifting seedlings to determine whether the roots were reaching depths where the soil moisture was above the wilting point.

Internal stem and surface soil temperatures were measured with thermocouples during the early part of the season when succulent stems would be most susceptible to heat damage.

Seedling survival was recorded annually for 5 years.

Environmental Differences Among Study Areas

The areas differed with respect to air temperature, precipitation, evaporation, wind movement, light intensity, soil temperature, and soil moisture, but many of the differences between areas appear minor in the averages presented here (tables 2–11).[2] Nevertheless, the differences were sufficient to produce environments favorable to different species.

It is rarely possible, however, to isolate from the data summaries one factor of the climatic environment to show its effect on the seedling. Excessively high or low temperatures which occurred when seedlings were young could be related to responses, but such occurrences are masked in the presentation of average figures in the summaries.

Air temperature.—Air temperatures have relatively little direct effect on the germination, growth, or survival of seedlings. The effect more commonly is observed indirectly in the relationship to soil temperatures and moisture.

Precipitation.—Dryness of the summer season is indicated by May-to-October precipitation (table 3). In terms of moisture which might become available to seedlings, however, the average monthly amounts of precipitation are misleading. For example, June precipitation was so dispersed that in only 2 of 8 years did it wet the soil more than a few inches below the surface. Penetration of moisture into the bare mineral soil occurred at the rate of about 1 inch per tenth-inch precipita-

[2] For a complete summary of the climatological data, see N. Stark, *op. cit.*

tion. Rainfall during July and August was ineffective in wetting the soil. Precipitation in September was effective only twice in 8 years. One of these months occurred in a year when precipitation was effective in June. Thus, in 5 of 8 years drought existed for a 4-month period—June, July, August, and September.

Wind movement.—Anemometers of the type used do not record low wind velocities accurately. Data on daily wind movement (table 4) should be considered on a comparative rather than an actual basis.

Evaporation.—The integration of several climatological factors is reflected in the amount of water evaporated from the white spherical Livingston atmometers (table 5). These instruments were in operation only from the middle of June to the middle of September because of the dangers of freezing before and after those dates.

Radiation and light intensity.—Black spherical Livingston atmometers were operated concurrently with the white atmometers from 1938 to 1941. The radiant solar energy occurring in the five study areas is related inversely to the ratio of the evaporation from the white spheres to that from the black spheres for the same periods of exposure. These ratios are given in table 6.

Irradiation.—Light intensity was measured photoelectrically in full sunlight, in part shade caused by the crowns of trees, and in full shade caused by the boles of trees. The measurements were taken on consecutive clear days during the latter part of August. A few measurements taken in full sunlight in mid-June gave intensities of about 10,000 foot candles.

Soil temperatures.—Soil temperatures at study areas 1, 2, and 3 differed noticeably from those at areas 4 and 5 (tables 8–10), but it must be remembered that measurements at 4 and 5 are not strictly comparable.

Soil moisture content.—Moisture apparently was available to the seedlings at depths of 6 inches or deeper during the summer at all study areas except number 4. Here the moisture content of the soil was reduced to near or below the wilting point, determined with sunflowers, for a period of a month or more each summer. In fact, near the end of the dry season in 1937, the moisture content of the soil in this area was close to or below the wilting point for the complete soil layer of 30 to 40 inches. Surprisingly, moisture was available below 6 inches in study area 5 during the growing season.

As an example of the seasonal trends, soil moisture contents in the 5 areas are given in table 11 for the year 1937.

Germination, Survival, and Growth in Relation to Environment

Germination.—Ponderosa pine germinated best of the four species. Sugar pine ranked second, incense-cedar third, and white fir last. Highest germination of ponderosa pine occurred in the south-facing open plot (area 3), but highest germination of the other species occurred on the partially cut, north-facing plot (area 2). Germination of all species on the uncut plots on both slopes (areas 4 and 5) was appreciably lower than at the other three areas.

First-year survival.—In the 8-year period, sugar pine seedlings had the highest first-year survival—42.8 percent. Survival rates of ponderosa pine, incense-cedar, and white fir were 27.3, 11.6, and 11.1 per cent, respectively.

For all species combined, the highest first-year survival was on the open north-facing plot (area 1). Survival at the end of the first year was:

Study area	*Survival percent*
1	35.1
2	31.5
3	28.4
4	6.0
5	16.9

However, the environments of the five areas affected the survival of some species more than others. Although 30 to 40 percent of the pines survived on the open south-facing slope, no white firs and only 18 percent of the incense-cedars survived on this plot. Ponderosa pine had the poorest survival under the dense white fir-sugar pine stand on the north-facing slope (table 12).

Table 2.--*Average maximum and minimum air temperatures, Stanislaus-Tuolumne Experimental Forest, May-October, 1934-41*

Month	Study area									
	1 Clearcut north slope		2 Partially cut north slope		3 Clearcut south slope		4 Uncut south slope		5 Uncut north slope	
	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.
	°F.									
May	67.8	34.3	66.1	40.7	66.8	34.8	66.1	34.7	63.6	38.9
June	74.1	38.7	72.7	46.3	73.3	38.9	72.4	39.0	70.8	44.7
July	82.0	42.7	80.8	52.7	81.7	43.2	81.2	42.7	77.6	50.6
August	83.2	42.8	80.7	53.5	83.1	43.3	82.7	42.2	78.3	51.5
September	75.4	37.9	72.5	47.8	75.9	38.4	75.3	36.8	71.5	45.8
October	63.8	31.5	61.5	39.6	64.9	31.8	63.8	31.1	59.8	38.0

Table 3.--*Average monthly precipitation, Stanislaus-Tuolumne Experimental Forest, May-October, 1934-41*

Month	Study area				
	1 Clearcut north slope	2 Partially cut north slope	3 Clearcut south slope	4 Uncut south slope	5 Uncut north slope
	Inches				
May	1.17	0.95	1.10	1.06	0.67
June	.84	.82	.82	.67	.56
July	.13	.12	.09	.10	.08
August	.04	.03	.03	.02	.02
September	1.11	1.05	1.06	.71	.72
October	2.52	2.46	2.65	2.24	2.14

Table 4.--*Average daily wind movement, Stanislaus-Tuolumne Experimental Forest, May-October, 1934-41*

Month	Study area				
	1 Clearcut north slope	2 Partially cut north slope	3 Clearcut south slope	4 Uncut south slope	5 Uncut north slope
	Miles				
May	28.5	20.5	23.9	14.9	7.7
June	25.4	18.2	21.1	11.6	6.8
July	22.6	16.9	21.8	11.2	4.8
August	22.6	15.9	22.0	12.3	5.0
September	20.7	15.8	20.0	11.7	3.4
October	15.1	11.2	15.0	9.8	1.8

Table 5.--*Average daily evaporation from white atmometers, Stanislaus-Tuolumne Experimental Forest, June-September, 1934-41*

Month	Study area				
	1 Clearcut north slope	2 Partially cut north slope	3 Clearcut south slope	4 Uncut south slope	5 Uncut north slope
	Cubic centimeters				
June	36.1	39.0	38.4	27.5	24.9
July	40.2	42.8	42.7	30.4	27.2
August	41.3	41.6	45.6	32.6	29.3
September	35.0	35.1	38.6	28.2	25.0

Table 6.-- *Ratio of evaporation from white atmometers to evaporation from black atmometers, Stanislaus-Tuolumne Experimental Forest, June-September, 1938-41*

Month	Study area				
	1 Clearcut north slope	2 Partially cut north slope	3 Clearcut south slope	4 Uncut south slope	5 Uncut north slope
June	0.68	0.78	0.73	0.74	0.94
July	.72	.81	.75	.76	.94
August	.73	.86	.74	.80	.96
September	.75	.84	.76	.83	.95

Table 7.--*Light intensity at midday, by degree of shade, Stanislaus-Tuolumne Experimental Forest, late August, 1934-41*

Degree of shade	Study area				
	1 Clearcut north slope	2 Partially cut north slope	3 Clearcut south slope	4 Uncut south slope	5 Uncut north slope
	Foot-candles				
Full sun	6,200	6,100	6,800	6,800	5,900
Part shade	--	470	--	810	450
Full shade	--	320	--	330	160

Table 8.--*Average monthly maximum and minimum soil temperatures, 1/4-inch depth, Stanislaus-Tuolumne Experimental Forest, May-October, 1934-41*

Month	Study area									
	1 Clearcut north slope		2 Partially cut north slope		3 Clearcut south slope		4 Uncut south slope		5 Uncut north slope	
	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.
	°F.									
May	99	35	94	39	106	38	66	47	53	43
June	117	39	115	46	123	42	76	50	59	47
July	132	43	129	52	138	45	92	54	71	53
August	130	41	125	50	142	44	92	54	72	54
September	109	34	105	44	110	38	81	48	64	49
October	79	30	70	36	92	34	59	41	49	41

Table 9.--*Average monthly maximum and minimum soil temperatures, 3-inch depth, Stanislaus-Tuolumne Experimental Forest, May-October, 1934-41*

Month	Study area									
	1 Clearcut north slope		2 Partially cut north slope		3 Clearcut south slope		4 Uncut south slope		5 Uncut north slope	
	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.
	°F.									
May	72	46	64	46	74	48	54	47	49	44
June	82	53	75	55	82	54	60	52	54	49
July	90	60	82	63	90	62	67	57	60	55
August	87	58	78	61	91	61	67	58	61	56
September	74	48	70	52	78	52	60	51	57	52
October	57	38	49	40	63	42	48	42	47	44

Table 10.--*Average monthly maximum and minimum soil temperatures, 7-inch depth, Stanislaus-Tuolumne Experimental Forest, May-October, 1934-41*

Month	Study area									
	1 Clearcut north slope		2 Partially cut north slope		3 Clearcut south slope		4 Uncut south slope		5 Uncut north slope	
	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.
	°F.									
May	61	51	54	49	64	54	52	50	45	44
June	70	59	64	57	71	61	56	54	50	49
July	77	66	72	66	78	69	62	60	57	55
August	74	65	68	64	78	70	62	61	58	56
September	63	56	59	56	70	63	57	56	54	52
October	50	44	46	43	67	50	48	47	46	45

Table 11.--Soil moisture content, oven dry weight basis, at four depths, Stanislaus-Tuolumne Experimental Forest, May 21-November 26, 1937

Date	Study area 1 Clearcut north slope				Study area 2 Partially cut north slope				Study area 3 Clearcut south slope				Study area 4 Uncut south slope				Study area 5 Uncut north slope			
	Depth in inches				Depth in inches				Depth in inches				Depth in inches				Depth in inches			
	0-3	6-8	11-13	18-21	0-3	6-8	11-13	18-21	0-3	6-8	11-13	18-21	0-3	6-8	11-13	18-21	0-3	6-8	11-13	18-21
	Percent																			
5/21	10.4	14.5	15.2	16.9	27.8	18.0	18.1	18.7	9.8	13.6	14.1	16.4	13.2	15.7	14.8	9.5	28.0	19.6	21.3	20.4
5/28	7.9	14.6	14.9	15.1	15.4	17.0	17.5	17.8	6.0	13.1	12.1	13.2	14.3	15.4	14.2	9.3	16.0	19.2	20.9	20.2
6/4	10.0	13.6	14.1	15.4	15.8	15.2	15.7	16.2	6.3	11.7	12.0	11.1	15.0	13.3	13.5	10.4	15.8	18.2	20.1	20.2
6/11	10.7	15.0	14.4	15.4	20.3	16.3	16.0	16.0	7.4	10.6	10.4	10.8	16.9	12.8	11.6	10.5	15.4	18.0	19.2	20.1
6/18	11.5	14.8	14.6	14.4	27.2	20.3	19.2	17.1	11.6	10.9	11.4	11.1	11.3	10.7	12.1	11.4	24.5	18.6	18.7	19.6
6/25	6.1	14.0	14.1	14.5	14.0	16.4	15.8	16.1	7.4	10.9	10.7	11.0	9.0	9.6	11.4	9.6	16.3	17.4	19.3	19.4
7/2	4.1	13.2	14.0	13.3	8.5	14.7	15.1	15.2	3.9	10.9	11.2	10.9	9.5	9.3	8.3	7.4	10.9	16.6	17.3	17.8
7/9	3.5	12.5	13.4	14.3	4.3	13.2	13.7	13.5	2.4	10.4	10.8	10.4	4.5	7.4	6.8	5.6	4.8	16.2	16.7	17.9
7/16	7.2	13.0	13.9	14.6	6.2	14.5	13.6	14.0	3.3	10.3	11.1	10.8	2.8	7.7	7.2	7.6	10.0	15.0	16.3	17.0
7/22	7.5	13.8	14.0	13.0	6.3	12.6	12.4	13.0	2.8	11.2	11.1	11.4	4.5	6.9	6.3	6.0	7.5	13.5	14.3	16.1
7/30	3.1	11.9	13.1	12.2	5.6	10.7	11.6	12.2	3.2	10.8	11.0	10.5	5.5	6.6	6.0	5.5	8.3	12.8	13.0	14.2
8/6	4.6	12.0	12.6	12.6	6.3	10.1	11.7	10.9	3.0	9.1	10.7	10.5	4.8	6.1	5.8	5.4	7.5	12.6	12.5	13.2
8/13	1.8	9.2	11.9	11.9	4.3	8.5	10.0	9.8	2.1	8.8	10.2	10.0	3.2	5.9	5.5	5.1	6.8	11.4	10.6	10.6
8/20	2.2	9.2	11.4	15.3	4.0	8.2	9.5	10.0	2.3	9.3	10.8	10.5	3.5	5.1	5.1	4.8	5.5	10.3	10.2	9.7
8/27	2.0	10.4	12.0	14.5	2.7	7.4	9.5	9.7	2.0	9.9	10.5	10.5	2.4	6.2	5.6	5.1	4.1	10.2	9.9	10.1
9/3	1.9	11.3	13.5	15.1	5.2	9.2	9.7	9.2	2.3	10.1	9.8	10.0	1.7	5.5	5.8	5.4	3.2	10.0	10.5	10.6
9/10	2.2	10.8	11.3	12.3	3.8	7.6	9.2	9.4	2.2	8.4	10.5	10.6	5.8	5.2	5.1	5.1	4.1	10.0	10.4	10.1
9/17	1.8	11.4	15.8	12.6	3.2	7.4	9.0	9.3	2.0	7.2	9.9	10.0	2.1	4.7	5.0	5.0	3.2	10.7	10.4	10.2
9/24	3.2	10.7	11.4	11.0	3.4	8.1	8.2	8.2	2.0	8.5	9.9	9.7	1.9	5.3	4.9	4.7	3.9	9.4	10.2	10.1
10/1	3.9	11.2	12.3	12.3	5.3	8.7	8.5	7.7	2.8	8.2	9.1	9.8	3.9	5.1	4.8	4.8	6.6	9.9	11.3	11.3
10/3	21.2	15.4	--	--	30.2	20.0	--	--	20.6	7.7	--	--	13.9	14.0	--	--	12.7	10.3	--	--
10/8	11.3	13.4	13.8	13.2	23.4	17.9	16.9	12.9	9.8	10.2	9.5	9.2	13.2	11.1	5.0	5.4	22.2	9.6	9.4	9.4
10/15	20.0	19.7	13.0	10.9	25.6	20.2	18.9	10.1	16.8	13.5	9.7	9.8	12.9	6.3	5.5	3.6	12.7	9.8	10.0	10.4
10/22	8.8	13.6	15.5	10.8	12.1	17.4	16.4	16.5	7.1	10.4	10.6	11.3	10.4	10.5	5.8	5.7	11.3	10.0	10.1	10.8
10/29	8.2	15.1	14.0	13.9	20.1	15.4	14.4	14.1	4.6	12.2	12.0	11.1	9.1	7.7	6.4	5.9	19.3	11.2	11.2	10.9
11/5	5.3	13.8	15.2	12.8	9.4	12.7	12.0	13.1	2.8	10.4	10.2	9.9	7.3	6.2	5.5	5.0	7.9	10.8	10.2	10.1
11/8	42.4	21.9	19.8	17.6	38.2	23.6	19.7	19.0	38.7	20.8	18.7	19.4	28.5	18.4	19.5	18.6	56.5	11.6	11.7	10.6
11/26	20.5	19.8	16.7	19.9	27.6	20.2	20.3	20.2	30.7	23.2	19.8	19.7	27.9	20.0	16.7	19.9	44.2	27.1	23.2	23.3

Causes of first-year mortality.—Cutworms and drought were the two greatest causes of loss.[3] During the 8-year period cutworms killed 30 percent and drought killed 25.5 percent of all the seedlings which started in the five study areas. Cutworms showed a preference for incense-cedar, taking 52 percent of the seedlings. Other losses to cutworms were white fir, 31 percent; ponderosa pine, 29 percent; and sugar pine, 10 percent. Insect-caused losses were greater on the north-facing slope than on the south-facing slope.

Losses from drought differed but little by species, ranging from 20 to 29 percent. Incense-cedar was apparently the most resistant, but the differences among the species may not have been significant.

Losses from drought did vary appreciably among the five study areas. The losses were: area 1, 8 percent; area 2, 19 percent; area 3, 24 percent; area 4, 50 percent; and area 5, 44 percent. The very low loss in area 1 and relatively low losses in areas 2 and 3 can be explained partly by the amount of available moisture and by the root development of the seedlings. Moisture was always available there below a depth of 6 inches. Clearing of vegetation in areas 1 and 3 decreased the use of moisture, and evaporation did not reduce the soil moisture content must below the surface. Soil moisture contents were lower in area 2, with partial timber cover, but still did not reach the wilting point below 6 inches. There is evidence that reduction to the wilting point as determined by sunflower does not necessarily indicate inavailability of moisture to pine seedlings.[4] Although moisture appeared to be available at study area 5, roots may not have penetrated deeply enough to reach the moisture (table 13).

[3] Fowells, H. A. **Cutworm damage to seedlings in California pine stands.** Jour. Forestry 38:590–591. 1940.

[4] Fowells, H. A., and Kirk, B. M. **Availability of soil moisture to ponderosa pine.** Jour. Forestry 43:601–604. 1945.

Table 12.--*First-year survival, by species and study area, Stanislaus-Tuolumne Experimental Forest, 1934-41*

Species	Study area				
	1 Clearcut north slope	2 Partially cut north slope	3 Clearcut south slope	4 Uncut south slope	5 Uncut north slope
	Percent				
Ponderosa pine	48.6	26.7	30.9	2.4	4.0
Sugar pine	51.5	60.7	37.5	13.2	36.0
Incense-cedar	8.8	13.6	17.8	0.0	11.1
White fir	1.3	19.9	0.0	1.0	18.5

Table 13.--*Root penetration of current year seedlings, Stanislaus-Tuolumne Experimental Forest, mid-July, 1940*

Species	Study area				
	1 Clearcut north slope	2 Partially cut north slope	3 Clearcut south slope	4 Uncut south slope	5 Uncut north slope
	Inches				
Ponderosa pine	14.4	8.6	9.2	7.0	5.1
Sugar pine	17.2	17.0	--	9.0	6.9

Rodents, frost, and heat were only minor causes of loss under the conditions of study, in which screen covers protected the seedlings in the early part of the season. But even with the protection of screens, rodents took 6 percent of the seedlings; without screens, they probably would have taken all the seed planted.

Measurements of temperatures showed that minimums were higher and maximums were lower under the screens.[5] Nearly all the losses from frost occurred in the cleared areas. White fir and sugar pine were the most susceptible to frost injury. In the cleared area on the south-facing slope, 18 percent of the sugar pine and 26 percent of the white fir were killed by frost, but only 3.5 percent of the ponderosa pine and 6 percent of the incense-cedar. Average losses from frost at all study areas were: ponderosa pine, 1.3 percent; sugar pine, 8.0 percent; white fir, 9.9 percent; and incense-cedar, 2.4 percent.

Although protective screens covered the seedlings during the early part of the season, they were removed after the seedlings shed their seed coats. Surface-soil temperatures—or actually temperatures at ¼-inch depth—sometimes reached 160°F. at area 3, but very few seedlings were killed by heat lesions. Only about 1 percent of the seedlings in area 3, a small fraction of a percent in areas 1 and 2, and none in areas 4 and 5 were killed by high surface-soil temperatures. Of areas 1, 2, and 3, number 2 had the fewest hours per year during which the surface-soil temperature exceeded 130°F. (table 14). No temperatures over 130° were recorded in areas 4 and 5, partly because of the overhead shade and partly because of the placement of the elements beneath litter and in the soil.

A stem temperature of about 130°F. is considered to be lethal to very young seedlings.[6] Temperatures were measured in the stems of ponderosa and sugar pine seedlings several months old with a copper-constantan thermocouple drawn into a glass capillary. Internal temperatures of sugar pine seedlings averaged 125° when the soil-surface temperature averaged 135°, and the temperatures of ponderosa pine seedlings averaged 134° with a soil-surface temperature of 136°.

Fungi also were a negligible cause of first-year loss (tables 15 and 16).

Subsequent survival.—After 5 years, survival of sugar pine was best; ponderosa pine, second; incense-cedar, third; and white fir poorest (fig. 6). Considering all species together, highest survival after 5 years was in areas 3 and 2; lowest in areas 4 and 5, the heavily timbered sites (fig. 7). The rapid drop in survival in area 1 resulted from loss of sugar pine seedlings which had been attacked by an unidentified tip insect.

It is of interest that the best survival of sugar pine occurred in area 2, the partially cut plot where minimum air temperatures were higher than in the other study plots. Also, only in this plot did any white fir survive as long as 5 years. Sugar pine and white fir were the most sensitive

[5] Fowells, H. A., and Arnold, R. K. **Hardware cloth seed-spot screens reduce high surface soil temperatures.** Jour. Forestry 37:821–822. 1939.

[6] Baker, Frederick S. **Effect of excessively high temperatures on coniferous reproduction.** Jour. Forestry 27: 949–975. 1929.

Table 14.--*Hours per year during which soil temperatures at 1/4 inch exceeded 130°F., Stanislaus-Tuolumne Experimental Forest, 1934-41*

Years	Study area		
	1 Clearcut north slope	2 Partially cut north slope	3 Clearcut south slope
1934	17	12	150
1935	88	0	152
1936	56	0	189
1937	33	0	380
1938	48	8	246
1939	136	63	198
1940	161	43	380
1941	52	23	194

to frost. Best survival of ponderosa pine and incense-cedar occurred in area 3, the cleared, south-facing plot. But survivals of ponderosa pine in areas 1 and 2 were 19 and 15 percent, respectively. No ponderosa pine seedlings survived for 5 years in areas 4 and 5, the heavily timbered areas.

Seedling growth.—The heights attained by seedlings in 5 years is not meaningful in terms of site potential. All the plots are in an area classed as site 1. But the heights do reflect the competition imposed by the overstory and additionally by the neighboring seedlings in spots or rows. After 8 years ponderosa pine seedlings averaged 50 inches tall in area 3, 35 inches in area 1, but only 5 inches in area 2, the partially cut plot. Also after 8 years sugar pine seedlings averaged 30 inches tall in area 3, 16 inches in area 1, but only 7 inches in area 2. Growth of these species in areas 4 and 5 was negligible. Too few seedlings of incense-cedar and white fir survived for a period of 5 years or more to provide an estimate of height.

Table 15.--*Percent of first-year seedlings killed, by species and by cause of mortality, Stanislaus-Tuolumne Experimental Forest, 1935-42*

Species	Frost	Rodent	Insect	Fungi	Heat	Drought	Misc.
Ponderosa pine	1.3	7.3	29.4	1.6	0.5	27.8	4.8
Sugar pine	8.0	5.1	9.9	.2	0.0	28.8	5.1
White fir	9.9	8.3	30.7	4.0	0.0	25.1	10.8
Incense-cedar	2.4	4.8	52.0	3.1	0.0	19.8	6.2

Table 16.--*Percent of first-year seedlings killed, by study area and by cause of mortality, Stanislaus-Tuolumne Experimental Forest, 1935-42*

Cause of loss	Study area				
	1 Clearcut north slope	2 Partially cut north slope	3 Clearcut south slope	4 Uncut south slope	5 Uncut south slope
Frost	5.8	1[illegible].9	8.6	2.7	0.5
Rodent	3.6	4.2	14.3	2.9	4.1
Insect	42.4	36.5	18.4	22.6	24.6
Fungi	1.9	1.9	1.0	7.8	.9
Heat	.1	.2	1.0	0.0	0.0
Drought	8.0	18.9	23.3	49.7	44.0
Misc.	3.3	4.9	5.2	8.2	8.8

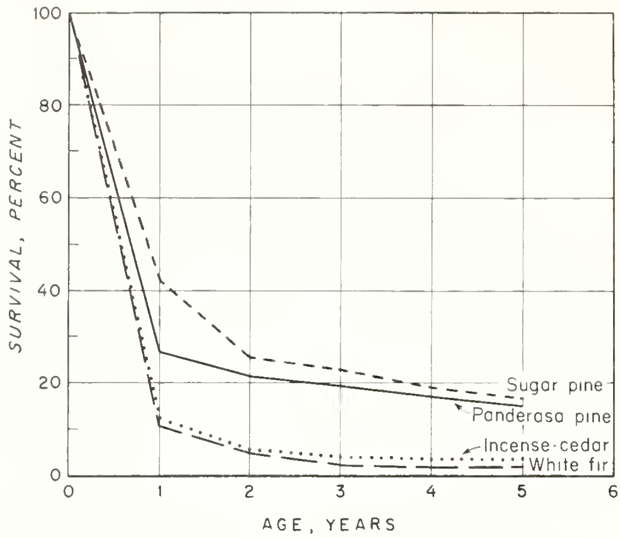

Figure 6.—*Survival rates for ponderosa pine, sugar pine, white fir, and incense-cedar combined for five study areas for a period of 5 years. (Based on survival records of more than 10,000 seedlings.)*

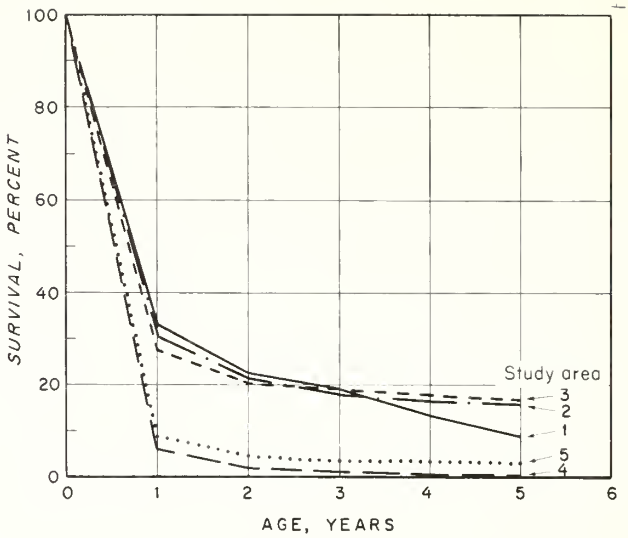

Figure 7.—*Combined survival rates of four species in five study areas for a period of 5 years. (Based on survival records of more than 10,000 seedlings.)*

Implications for Silviculture

The results of the study have had important implications in the development of silvicultural practices in the mixed conifer type in California. First and most important is that the study demonstrated that climatic factors in this region are not so severe as to preclude natural regeneration. Despite the 4-month drought, soil moisture was nearly always available to seedlings—provided competition from other plants was minimized.

Locally, low temperatures influenced the species composition of the reproduction. Sugar pine and white fir were favored by a light overstory which prevented frosts. However, the overstory held back growth of the seedlings severely. Careful removal of the overstory, as in a shelterwood system, would be necessary to capitalize on this type of advance reproduction. Insects apparently play an important part in determining species composition. Incense-cedar might have been a much greater component of the stand if cutworms had not selectively taken this species.

The study showed that sugar pine is not as difficult to regenerate as many had believed on the basis of the scarcity of sugar pine seedlings. With rodent protection, the first-year and five-year survival of sugar pine was higher than survival of any other species. The good survival of sugar pine—and of ponderosa pine—with rodent protection suggested the need for some form of rodent control as a prerequisite to obtaining satisfactory regeneration of the pines.

Although complete clearing created conditions leading to high surface-soil temperatures, particularly on south-facing slopes, stem insolation does not appear to be a critical factor in survival.

The many years of observation of environmental factors and seedling responses can lead only to the conclusion that regeneration of the pines is favored by removal of the overstory, understory, and ground competition, by soil disturbance, and by protection of the seed from rodents.

GPO 972-035

Residents of Butte County, California: Their Knowledge and Attitudes Regarding Forest Fire Prevention

William S. Folkman

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Contents

The Author

WILLIAM S. FOLKMAN is responsible for studies of the sociological problems in the prevention of man-caused forest fires. He joined the Pacific Southwest Station staff in 1962 after a career in sociological research and teaching with several universities and the U. S. Department of Agriculture's Agricultural Marketing Service and Economic Research Service in Washington, D. C. A native of Ogden, Utah, he holds a bachelor's degree in agriculture from Utah State Agricultural College, a master's degree in sociology from the University of Utah, and a doctorate in rural sociology from Cornell University. He has also studied at the American Graduate School of the University of Copenhagen in Denmark and at the University of Strasbourg in France.

Demands for recreational use of land, lakes, and rivers in forested areas are expanding at phenomenal rates. This growth has been stimulated by an increasing population, widening mobility, rising standards of living, increased personal income, more leisure time, and changing patterns of use of leisure time. The pressure for desirable residential sites has forced many families into intimate and continued contact with wildland areas. The increased tempo of electric power line and highway construction, as well as the traditional occupational uses of the forest, has brought expanding numbers of workers into the forests.

The greater use, mainly by urban-oriented forest publics, raises problems for those responsible for the management and protection of forests. Foremost among these problems is that of man-caused forest fires. Fortunately, the number of such fires does not increase in a geometric, or even arithmetic, progression with the number of people. Nevertheless, just staying abreast of the problem requires continued effort.

As in so many other situations the State of California presents a larger-than-life size reflection of this national problem. The highly touted Mediterranean-type climate coupled with the rugged and scenic terrain is, perhaps, largely responsible. Many people have been attracted by these qualities, and such qualities encourage them to spend much time out of doors. This has brought many people into a precarious contact with the high-risk forest environment created by this same combination of climatic and physical conditions.

Firefighting research has brought significant improvements in materials and techniques for combating fires. In fire prevention, some success has been achieved by an engineering approach. Experiments with fire retardant sprays for roadsides, fireproofing practices in campgrounds, clearing of fuels from around forest residences, and similar practices have resulted in improved means of modifying the environment around the forest publics.

Behavioral studies in fire prevention research are expected to lead to more effective means of modifying human behavior itself, rather than the environment, to achieve further reductions in fire starts. It is recognized, however, that an acceptable degree of control of wildfire will require a continued attention to all these approaches to the problem.

This paper reports on one aspect of a continuing study concerned with modifying human behavior with regard to the use of fire in high hazard wildland areas.[1] The study seeks to identify groups of people representing different degrees of risk from a fire prevention standpoint. It will aid in determining the direction of further studies, as well as serve as a benchmark from which to measure the effects of later program changes. This work is sponsored jointly by the California Division of Forestry and the Pacific Southwest Forest and Range Experiment Station.

Previous Studies

Use patterns stemming from frontier times have perpetuated the practice of essentially free and unlimited access to wildland areas, whether privately or publicly owned. The Forest Service policy traditionally has been that the National Forests belong to the American people and only under exceptional conditions or situations is restriction placed on entry. As a consequence, even the gross number of people visiting a given forest, or man-

[1] Herrmann, W. W., Callahan, R. B., Gray, David, and Porter, Seymour. **A research design for the prevention of man-caused forest fires, 1959-1960 Progress Report.** Los Angeles: Univ. So. Calif. 1961.

agement unit, is known only in the most general terms. Information regarding who these people are and what they do in the forest is very limited. Recent reports of the Outdoor Recreation Resources Review Commission[2] relieve some of this information gap for recreational uses. But its data are on a national basis, with only limited regional reporting.

Several studies, two dating back to the late 1930's, have been made in the Southeast and Ozark regions of the United States.[3] Without exception, they relate woods burning to the culture of the area. Burning was an important tool in land clearing. It was thought to improve grazing, control ticks, snakes, and other undesirable wildlife. Such burning was once a widely accepted practice. But of late, it is largely confined to a relatively small segment of the economically deprived, for whom it seems to serve as a means for expressing frustration and hostility, although, for some, a real or fancied economic advantage may be involved.

Except for the research conducted at the Pacific Southwest Station in recent years, there appears to have been no study of the behavioral aspects of man-caused fires outside the South. The results thus far indicate that in California the starting of wildfires is not culturally supported as it has been in the Southeast, although under certain conditions culturally patterned evasion of fire regulations is accepted in much the same way that traffic violations are.

To further test some of the research findings arising from the Station's earlier studies and to evaluate the effectiveness of various educational efforts, we selected a county to serve as a laboratory. A number of important considerations suggested a county as a unit of study. It is the smallest practical unit having some administrative autonomy and uniformity while still representative of the fire prevention problem. Butte County, in northern California, was selected after careful attention was given to the criteria set up for a test county. It has all of the major wildland uses, such as lumbering, recreation, and grazing; it includes both Forest Service and California Division of Forestry protection jurisdiction and its forests are essentially typical of the wildland areas of the State.

People from outside the county, of course, do visit the wildlands in Butte County, and thereby contribute to the local fire problem. The decision to confine the study to Butte County residents consequently requires some justification. In addition to the obvious difficulties of adequately sampling and interviewing forest users while they are at large in the forest, or of tracing them to their diverse home areas, there are positive reasons for confining the study to county residents. The study of a resident population provides an opportunity to determine how various types of wildland users compare with their neighbors who do not make use of these areas. Here we are concerned with their relative numbers, differences in socio-economic characteristics, levels of knowledge and attitudes regarding fire use and abuse, and other information. Both nonresidents and residents are exposed to the limited fire prevention education which may be conducted in the wildlands. But an effective fire prevention program requires a sustaining effort back home—something that could not be controlled for the nonresidents.

Such a program involves stepped up exposure to fire prevention messages through the various mass media; experimental changes in the frequency or method of personal contacts made by fire prevention personnel; and special work with schools, service organizations, and other groups whose members conceivably are exposed to the wildland environment through their occupational or recreation interests.

A necessary first step, and the focus of this study, was to determine the current level of attitudes and understanding of the residents of Butte County as they pertain to fire prevention. These levels were to be related to the amount and type of use of the wildland and other characteristics of the respondents. Such a benchmark is essential to measure the effects of future efforts in the county.

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[2] **ORRRC Study Reports.** Vols. 1 through 27. U. S. Government Printing Office, Washington, D.C. 1962.

[3] Hansbrough, Thomas R. **Analysis of man-caused fires in Louisiana.** 1961. (Unpublished doctor's thesis on file at Louisiana State Univ., Baton Rouge, La.).

Kaufman, Harold F. **Social factors in the reforestation of the Missouri Ozarks.** 1939. (Unpublished master's thesis on file at Univ. Missouri, Columbia, Mo.).

Shea, John P. **The psychologist makes a diagnosis.** 1939. (Unpublished rpt. on file at U.S. Forest Serv., Washington, D.C.).

Morris, John B. **Preliminary investigation of human factors in forest fires.** 1958. (Unpublished rpt. on file at Southern Forest Expt. Sta., U. S. Forest Serv., New Orleans, La.)

Method of Study

A representative sample of the resident population of Butte County was interviewed to obtain the data whereby the necessary benchmark could be established. An area sampling design was developed for the county, including urban and other presumably low risk areas and those where exposure to the high hazard areas is more direct and sustained. The sample was also designed to represent all age groups 14 years of age or over and not just household heads. The sample consisted of 851 potential respondents, about 1.4 percent of the eligible population. From this sample 761 completed the questionnaires, an attrition of 11 percent.

Failure to find respondents at home, in spite of repeated callbacks, accounted for about one-third of the non-response. Another one-third was due to refusals. Change of residence between time of listing and interviewing was responsible for 15 percent of the non-response. The remainder—a similar proportion—was attributable to serious illness or other barriers to communication. Non-response did not seem to effect the representativeness of the sample.

The representativeness of the sample was confirmed by relating comparable items (such as age. marital status, grades of school completed, and income) from the 1960 population census. Only in income did the parent population and the sample show a significant difference. Higher income groups appear to be over-represented in the sample. While it is possibly true that lower income groups actually were under-represented, the economic well-being of the county had improved markedly in the 4 years between the time of the national census and interviewing for this study. This might account for at least part of the difference.

The field work for the survey and some of the analysis were done in cooperation with the Survey Research Center, University of California, Berkeley. Interviewing was done by experienced interviewers furnished and supervised by the Survey Research Center. Experiment Station personnel participated in training the interviewers.

The series of questions used to measure the current levels of knowledge regarding fire risk, approved fire safety practices, and fire control regulations was developed in earlier, Station-supported research by the University of Southern California, modified in line with our most recent experience.[4] Attitudes associated with these areas of knowledge were measured by a series of questions, some of which were developed by the group at the University of Southern California, some by the Experiment Station, but none previously used in a study.

Findings

Exposure to the High Risk Forest Environment

To assess the degree of risk a particular type of wildland user represents, it is necessary to consider (a) the type of activity he engages in, (b) the season of the year when this takes place, (c) where it takes place, (d) how often it takes place, (e) the knowledge he possesses regarding safe use of fire in the vulnerable areas, and (f) his desire to use this knowledge consistently and properly.

Hunting, for example, is generally a solitary and back country sport. The typical hunter does not stay in an improved campground where hazards have been removed. He does not spend his time by a stream where a flipped cigarette has a fair chance of landing in water. He is not apt to camp near many other hunters who might put out any fire he may carelessly leave burning. In contrast to the skier, he puts himself in the most hazardous part of the wildland during the most hazardous season of the year. Indications are that he has a comparatively good knowledge of safe fire use.[5] But because of these other factors the hunter still constitutes a significant fire risk.

Other wildland users, for some different and some similar reasons, also constitute fire risks.

[4] Folkman, William S. **Levels and sources of forest fire prevention knowledge of California hunters.** U.S. Forest Serv. Res. Paper PSW-11. Pacific SW. Forest & Range Expt. Sta., Berkeley, Calif. 1963.

[5] Folkman, *op. cit.* p. 7.

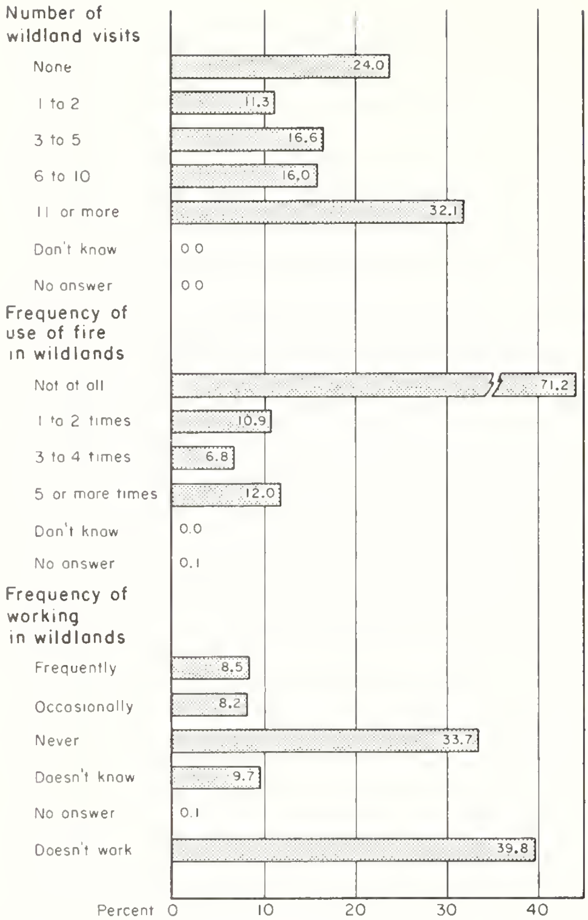

Figure 1.—Percentage distribution of certain wildland activities of Butte County residents, 1964.

Even the person whose only contact with wildland is driving through on a paved road may be a source of uncontrolled fire if he throws a lighted cigarette or match through the open window of his car. If he stops and pulls off the road he may unknowingly increase his potential for starting a fire. According to the response to one item in the Knowledge section of the questionnaire, 16 percent of the respondents were unaware that a fire can be started by exhaust sparks or sparks made by contact of metal parts of the car with rocks.

The results of this survey show that a rather high proportion of Butte County residents were exposed to the high risk environment of the wildlands of the county at some time or other, and thus in some degree must be considered as potential fire starters (fig. 1). Three-fourths of the respondents were in these wildlands at least once during the year preceding the interview. Nearly one-third were in areas of high fire danger on more than 10 occasions during this period. Many of these persons who were exposed to this highly inflammable environment used fire in these areas—whether for cooking, warming, recreational purpose, or in connection with their work. (This is aside from smoking as a use of fire.) Twenty-nine percent of the respondents admitted using fire in the wildland areas at least once, 12 percent five or more times. Some under-reporting is possible because some respondents may have felt that an admission of use would be self-incriminating even though the use may have been entirely legitimate. The number reporting positively to a later question as to whether they had a campfire permit corresponds closely with the number reporting having used fire.

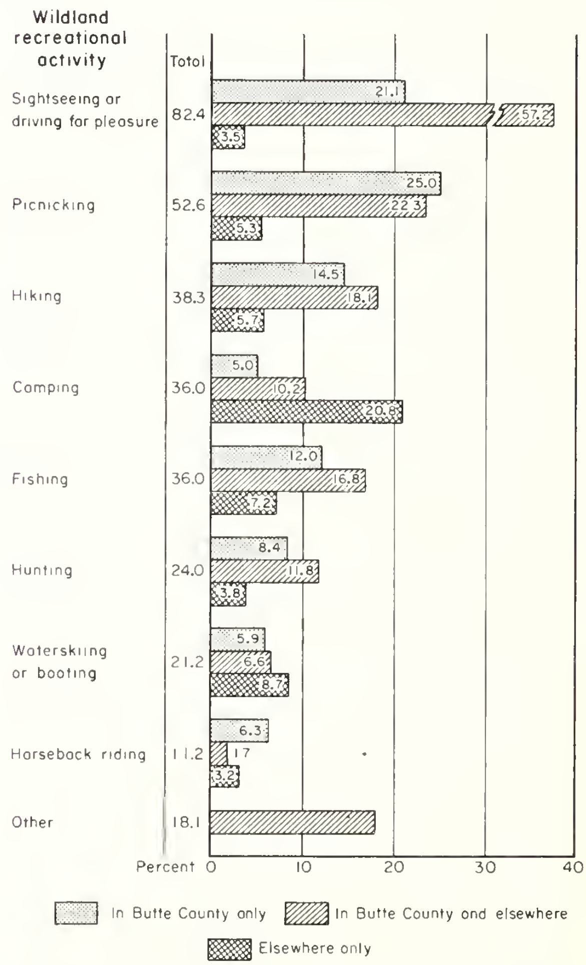

Figure 2.—Percentage distribution by type of wildland recreation engaged in by Butte County residents, 14 years of age and over, 1964.

Most of the wildland use is for recreational purposes, but 17 percent of the respondents reported that their work occasionally took them into the wildland areas of the county. One-half of these said that their work required them to be in these areas *frequently*.

It is a rare individual who does not get out into the wildlands in Butte County at some time during the year, if only for a pleasure drive or sightseeing excursion. Four out of five of the respondents reported having engaged in this activity (fig. 2). The next most frequent activity in terms of proportion participating, was picnicking, with half of the respondents involved. Hiking, the third most often reported, was cited by 38 percent. The other recreational activities, in order of frequency of mention, were fishing, camping, hunting, and water sports. Other miscellaneous activities, ranging from swimming to gold panning and bottle hunting, occupied the attention of 18 percent of the respondents.

The extent of participation in outdoor recreational activities by Butte County residents resembles that of people elsewhere in the West and throughout the United States (table 1). The only major difference is that hiking seems to be much more popular in Butte County than it does elsewhere.

As might be expected, there was a rather close interrelationship among some of the wildland activities. Campers, fishers, and hikers, for example, were also engaged to a significant extent in all other activities covered in the questionnaire. Picnickers and hunters tended to be involved in other outdoor activities to a slightly less degree, while horseback riders and water sports enthusiasts appeared to have even narrower interests.

When type of activity is related to frequency of use of fire, campers most often used fire, followed by those in the miscellaneous "other activities" category and hunters. Persons reporting these other activities used fire between 6 and 10 times on the average. Persons driving for pleasure and picnicking reported the lowest frequency of use of fire, but even these averaged between three and five occasions when they used fire in the wildland areas during the year.

Socio-economic Relationships

To be able to relate wildland activity to the characteristics of those involved has value to the wildland manager who is concerned with implementing a fire prevention program. By more precisely defining the publics he must deal with, he can more efficiently and effectively operate his

Table 1.--*Participation in outdoor recreational activities of Butte County residents compared with national and regional participation*[1]

Activity	Percent participation		
	United States	West	Butte County
Camping	8	17	36
Sightseeing Driving for pleasure	42 52	55 56	82
Fishing	29	30	36
Hiking	6	9	38
Horseback riding	6	11	11
Hunting	[2]13	[2]14	24
Picknicking	53	54	53
Boating Waterskiing	22 6	23 9	21
Other activity	--	--	18

[1]Data for the United States and Western Region are from: Outdoor Recreation Resources Review Commission. National Recreation Survey. ORRRC Study Report 19, 394 pp., 1962. In a number of ways the data are not comparable. The national survey included respondents 12 years of age and over; the Butte County survey included those 14 years of age and over. The national survey data reported are for the period from June through August (except for hunting which is for September through December); the Butte County data are for the entire year.

[2]Period reported is September through December.

Table 2.--*Wildland activity related to certain socio-economic characteristics, Butte County, 1964*

Characteristic	Number of respondents	Total number of wildland visits					
		None	1-2	3-5	6-10	11+	Total
		Percent					
Age last birthday:							
10-24	168	10.7	10.7	20.2	13.7	44.7	100.0
25-34	102	19.6	11.8	11.8	23.5	33.3	100.0
35-49	190	20.5	10.5	17.4	20.0	31.6	100.0
50-64	173	25.5	11.0	18.5	12.1	32.9	100.0
65 and over	127	48.0	13.4	11.8	12.6	14.2	100.0
Not reported	1	100.0	--	--	--	--	100.0
Total	761	24.0	11.3	16.6	16.0	32.1	100.0
Sex:							
Male	369	16.8	8.1	15.2	19.8	40.1	100.0
Female	392	30.9	14.3	17.8	12.5	24.5	100.0
Total	761	24.0	11.3	16.6	16.0	32.1	100.0
Marital status:							
Single	141	16.3	10.6	13.5	15.6	44.0	100.0
Married	521	22.3	11.3	17.8	17.5	31.1	100.0
Widowed, divorced, or separated	99	44.5	12.1	14.1	9.1	20.2	100.0
Total	761	24.0	11.3	16.6	16.0	32.1	100 0
Years of schooling completed:							
0-7	79	43.0	13.9	7.6	11.4	24.1	100.0
8	113	38.1	8.0	22.1	9.7	22.1	100.0
Some high school	196	21.4	15.3	17.9	13.8	31.6	100.0
High school graduate	176	15.3	9.6	16.5	20.6	38.1	100.0
Some college	134	17.2	10.4	16.4	17.2	38.8	100.0
College graduate	63	22.2	7.9	14.3	25.4	30.2	100.0
Total	761	24.0	11.3	16.6	16.0	32.1	100.0
Occupational status:							
Employed:							
Fulltime	284	14.4	9.2	18.3	19.4	38.7	100.0
Part time	116	24.1	13.8	12.1	17.2	32.8	100.0
Not employed:							
Retired or disabled	100	49.0	13.0	10.0	10.0	18.0	100.0
Housewife	169	33.2	13.6	17.1	11.8	24.3	100.0
Student	90	8.9	7.8	23.3	18.9	41.1	100.0
Other	2	50.0	50.0	--	--	--	100.0
Total	761	24.0	11.3	16.6	16.0	32.1	100.0
Occupation:							
Professional, technical	48	16.7	12.5	8.3	22.9	39.6	100.0
Farmer, farm manager	18	5.6	16.7	16.7	33.3	27.7	100.0
Manager, official, proprietor	47	10.6	6.4	19.1	17.1	46.8	100.0
Clerical worker	67	11.9	16.4	17.9	17.9	35.9	100.0
Sales worker	33	12.1	9.1	15.2	33.3	30.3	100.0
Craftsman, foreman	50	10.0	6.0	16.0	26.0	42.0	100.0
Operative	52	23.1	11.5	9.6	13.5	42.3	100.0
Service worker	69	20.3	10.1	27.5	15.9	26.2	100.0
Farm laborer	33	27.2	6.1	15.2	18.2	33.3	100.0
Laborer	37	16.2	5.4	24.3	8.1	46.0	100.0
Not employed, retired	303	36.3	12.9	15.5	11.2	24.1	100.0
Not reported	4	25.0	25.0	--	--	50.0	100.0
Total	761	24.0	11.3	16.6	16.0	32.1	100.0

Table 2.--*Wildland activity related to certain socio-economic characteristics, Butte County, 1964, continued*

Characteristic	Number of respondents	Total number of wildland visits					
		None	1-2	3-5	6-10	11+	Total
		Percent					
Family income:							
Under $1,500	61	44.2	16.4	9.8	6.6	23.0	100.0
$1,500-$2,999	97	35.1	16.5	23.7	7.2	17.5	100.0
$3,000-$4,499	101	31.6	11.9	9.9	12.9	33.7	100.0
$4,500-$5,999	100	25.0	19.0	12.0	15.0	29.0	100.0
$6,000-$7,999	132	15.2	6.8	18.2	23.5	36.3	100.0
$8,000-$9,999	82	9.8	9.8	18.3	24.4	37.7	100.0
$10,000-$14,999	98	11.2	8.2	19.4	21.4	39.8	100.0
$15,000 and over	26	11.5	11.5	19.2	19.2	38.6	100.0
Not reported	64	35.8	1.6	18.8	9.4	34.4	100.0
Total	761	24.0	11.3	16.6	16.0	32.1	100.0
Residence:							
City	364	25.0	11.0	17.0	17.3	29.7	100.0
Suburb	144	12.5	9.0	19.4	16.0	43.1	100.0
Small town or village	139	31.7	12.2	14.4	12.2	29.5	100.0
Open country, farm	68	29.4	16.2	8.8	23.5	22.1	100.0
Open country, nonfarm	46	21.7	10.9	21.7	6.5	39.2	100.0
Total	761	24.0	11.3	16.6	16.0	32.1	100.0

program—using a broad gauge "shot gun" approach where necessary and narrowing in with specialized programs where feasible in special situations.

But the interrelatedness of certain outdoor activities mentioned earlier must continue to be kept in mind. Certain portions of the publics who are engaged in one activity also engage in other activities—some picnickers also fish and hike, many campers participate in a wide range of activities—so there is considerable overlap among the various wildland users.

Participation in wildland activities might be expected to be related to the social and economic characteristics of the participants. Wildland recreational activities have predetermining characteristics which condition participation in them, as pointed out in an ORRRC Report.[6] These characteristics include: time required to engage in the activity, monetary costs of engaging, level of physical activity involved, level of skill required, level of prestige or status achieved through participation, and the level of continuous learning enabled by participation, and others. That they are differentially distributed by age and sex, by type of occupation, by level of education, and so forth is to be expected. Work in wildland areas also might be expected to be influenced by such variables, but not necessarily in the same way.

The length of time a person had lived in Butte County was not significantly related to his rate of use of the wildlands. Whether he was native to the area or had moved there from another part of the State or elsewhere likewise was unrelated to such use. (Two-fifths of the respondents had always lived in Butte County, nearly one-third were from some other county in northern California, while the remaining 27 percent were nearly equally divided between former residents of southern California and other States.)

The location of former residence as to city, small town, or open country was also unrelated to wildland activity.

Looking first at a gross measure of wildland activity—total number of wildland visits during the year before the survey—we found that the proportion reporting no visits increased with age. The opposite was true of those reporting more than 10 visits per year (table 2). Males were found to have more wildland activity than females; marital status, related as it is to age, showed a similar relationship. Those who were single (mostly the younger respondents) often used the wildlands whereas the widowed, divorced, or separated (a

[6] Folkman, *op. cit.* p. 4.

state developing more frequently with advances in age) did not. A high level of wildland activity was associated with higher educational attainment.

People who were employed, especially those working full time, were inclined to have a higher rate of wildland activity than those not employed. An exception is students, who had the highest rate of activity of any occupational status category. People whose occupation fell in the manager-proprietor category were found to be most active in the wildlands; nonfarm laborers, craftsmen, and professional workers were next most active. Service workers and farmers were the least active of any of the occupational groupings.

Wildlands activity is positively tied to income. The greater the total income of a family, the more likely a person is to have a high rate of activity.

Persons living in the suburbs had the highest activity rate; nonfarm residents of the open country ranked next. Those living in small towns or villages, as well as those living on farms, had the largest proportion reporting no wildland activity at all.

Relationships between participation in specific wildland activities and various social and economic characteristics are similar to those shown for total wildland activity (table 3).

In addition to the social and economic characteristics mentioned earlier, the survey also obtained information regarding the mass media channels used by the respondents as well as their organization ties. This information will also be used in later experiments in which exposure to fire prevention messages will be varied and methods of personal contact will be studied.

Although it sometimes seems that present day radio programming caters exclusively to a youthful audience, radio appeared to have a much broader audience in Butte County. Only 13 percent of the sample were in the teenage category, but three-fourths of the people interviewed said they listened to the radio daily, about one-third spending 2 or more hours per day listening (table 12, appendix). Only 10 percent said they did not listen at all. Local stations were listened to primarily, but a rather large minority said they listened to nonlocal (mostly Sacramento) stations most often. Seventy percent felt that radio gives adequate coverage of the local fire situation.

Television viewing was considerably more popular than radio listening (table 13, appendix). Three out of five reported 2 or more hours per day of viewing time. Most people (62 percent) watched the one local channel, but in parts of the county where reception is satisfactory some watched Sacramento channels or the Redding channel. The appraisal of the adequacy of fire situation coverage by television stations was similar to that of radio.

The *Chico Enterprise Record*, the *Oroville Mercury*, and the *Sacramento Bee* are the newspapers with the widest coverage in Butte County, but five others were reported with some frequency (table 14, appendix). Newspaper coverage of the local fire situation was rated adequate by a slightly higher proportion than so rated radio or television coverage.

As is true in other parts of the country, most people in Butte County were not affiliated with any organized groups (table 15, appendix). Twenty-eight percent reported that they belonged to some religious organization. This was the most frequently mentioned type of membership, followed by membership in business and fraternal organizations.

Knowledge about Fire Prevention

Knowledge about fire prevention and fire behavior was measured by a 20-item multiple choice test (table 16, appendix). The items were selected from those used in the previously mentioned hunter study,[7] with several items eliminated and several others revised according to previous experience.

The mean score (percent of items answered correctly) of the Butte County residents on the knowledge test was 58 percent (table 4). This contrasts with a score of 54 percent correct for those who reportedly had not been in the wildlands at all during the previous year, and 65 percent for those whose work took them into the wildlands frequently.

The pattern of relationship between knowledge scores and various socio-economic variables was similar to that shown between wildland activity and these same variables.

The following characteristics were found to relate to knowledge: Male respondents, those in the younger age groups, those with higher educational achievement and higher incomes, all showed significantly higher knowledge scores than did their opposite numbers.

Average knowledge scores in this survey are

[7] Folkman, *op.cit.* pp. 16–22.

Table 3.--*Relationship of wildland activities to certain socio-economic characteristics, Butte County, 1964*

Item	Working	Camping (Butte County)	Camping (outside county)	Fishing	Hiking	Horse-back riding	Hunting	Picnicking	Sight-seeing, driving for pleasure	Water skiing, boating
Number reporting participation	458	116	236	274	292	86	183	401	627	164
Age	X	X	X	X	X	X	O	X	X	X
Marital status	X	X	X	X	X	X	X	X	--	X
Education	X	--	X	--	X	--	--	X	X	X
Job status	X	X	X	X	X	X	X	X	X	X
Type of work	X	--	X	O	X	--	X	--	--	--
Family income	X	--	-	X	O	--	--	X	X	X
Sex	X	X	X	X	--	--	X	--	--	O
Race	--	--	--	O	--	--	--	--	X	--
Present residence	--	--	O	--	--	--	--	--	O	--
Previous residence	--	--	--	--	--	--	--	--	--	--
Migratory status	--	--	--	--	--	--	--	--	--	--

(X indicates significance at 0.001 level)
(O indicates significance at 0.01 level)
(-- indicates no significance)

Table 4.--*Fire prevention knowledge score related to types of wildland activity, Butte County, 1964*

Activity	Number reporting activity	Mean score (percent correct)
Total	761	58
Frequency of wildland use:		
Not at all	183	54
1-2 times	86	60
3-5 times	126	61
6-10 times	122	62
11 or more times	244	62
Work in wildlands:		
Frequently	65	65
Occassionally	62	63
Never	256	59
Camping:		
In Butte County	116	64
Outside Butte County	236	61
Fishing	274	61
Hiking	291	62
Hunting	183	62
Picnicking	400	60
Sightseeing or driving for pleasure	627	60
"Other" activities	138	63

Table 5.--*Matrix of varimax rotated factor weights for the 18 attitude items in test instrument*

Attitude items	Dimensions				
	I	II	III	IV	V
1	0.077	0.123	0.564	-0.081	-0.145
2	.034	.336	.099	.055	.770
3	.097	-.109	.726	.050	.037
4	.001	.363	-.180	.552	.037
5	.266	.152	.453	.287	.144
6	.161	.093	.684	.126	-.110
7	-.026	-.033	.017	.824	.035
8	-.178	.432	.042	.559	-.011
9	.703	-.080	.071	.154	-.048
10	.399	-.002	.191	.109	-.379
11	-.313	.546	.114	.197	.082
12	.547	.290	.148	-.013	-.282
13	.697	-.140	.051	-.060	-.166
14	.619	.007	.182	-.187	.138
15	.057	.536	-.072	.174	.133
16	.453	-.210	.232	-.220	-.021
17	-.035	.748	-.080	-.020	-.072
18	.270	.218	.260	-.095	-.579
Proportion of total communality accounted for by factor[1]	.130	.102	.100	.089	.072

[1]Total of all five factors is .493.

all well below the 79 percent achieved on the similar test administered to the licensed hunters of California in 1960.[8] On the basis of their high scores in the previous study, we anticipated that hunters would do equally as well in this one. On the basis of these data however, it would seem that the level of fire prevention knowledge of hunters differs little from that of other users of the wildland areas.

Several factors may be responsible for this wide difference between the two tests of what is essentially the same instrument. In the earlier study a mailed questionnaire was used; in the later study it was administered during a personal interview. The former situation would provide a more relaxed, unhurried atmosphere and an opportunity to resort to references or consultants while responding to the questions. This was not possible in the present survey. The earlier study sampled a State-wide population, while the present study is confined to one county.

About 3 out of 5 of the respondents in Butte County reported that they had observed a forest fire close at hand. Nearly a third of them said they had actually helped fight such a fire. Such intimate acquaintance with uncontrolled fire tends to be related to knowledge about fire prevention.

In California, fire danger is quite high throughout the dry season of the year, getting progressively higher as the season advances. But within this general pattern, there are usually one or more periods of relatively short duration when weather conditions produce a situation where the fire danger becomes extremely critical. Then, within a few days it returns to about where it was before. People who knew of this, and who in their own estimation were more aware of such critical fire situations, had higher scores on the knowledge test.

A list of 12 possible sources of fire prevention information was given on the questionnaire, and the respondents were asked to check the sources from which they had received most of their information. An average of three sources were selected. Television, forest ranger, and newspapers were the most frequently mentioned sources, with 39 percent of the respondents selecting each of them. Smokey Bear (36 percent) and radio (33 percent) were the next most frequently reported sources of knowledge. This represents considerable difference in the ranking of information sources from that found in the hunter study[9] where signs and Smokey Bear were among the top three and newspapers were down in seventh place. The nature of the Butte County sample, with a more normal distribution by age, sex, education, etc., probably affected the ranking, as did the more restricted area sampled. The use of signs for fire prevention purposes, for example, is much more prevalent in southern California than it is in this area.

Butte County residents were more familiar with burning permits (61 percent) than they were with campfire permits (47 percent). One-fourth in each instance had a vague idea of what they were, while 13 percent and 25 percent, respectively, did not know. Thirty-six percent of the respondents (or other family member) had obtained a burning permit during the past year, as compared to 29 percent who got a campfire permit.

Butte County experienced nearly 300 reportable forest fires during the year preceding the survey. Most people were of the opinion that there were fewer. Twenty-nine percent estimated under 50 fires. One-third of those interviewed would not hazard a guess. Only 13 percent overestimated the number of fires.

Eighty-one percent felt that fire prevention information was readily available in the county.

Attitudes Regarding Fire Prevention

Attitudes are elusive, frustrating things to research. However, their considered importance in determining human behavior is such as to force the attempt.[10] Being an internal condition, or mind set, an attitude cannot be measured directly. There is considerable justification, however, for maintaining that these opinions reasonably reflect existing attitudes regarding fire prevention.

To measure attitudes, respondents were asked 18 questions (table 17, appendix). This portion of the questionnaire consisted of statements to which a respondent could answer on a five-place scale with expressions ranging from "strongly agree" to "strongly disagree." To probe various

[8] Folkman, *op. cit.* p. 7.

[9] Folkman, *op. cit.* p. 9.

[10] This persistent relationship to action is, in fact, the central focus of the psychologist's definition of attitude: "An individual's attitude toward something is his predisposition to perform, perceive, think and feel in relation to it." See Newcomb, Theodore. **Social psychology.** New York: Dryden Press. 1950. p. 118.

dimensions of attitude thought to be held about fire prevention, we included certain items, such as the nature of the problem, views about appropriate policy as to the problem, and how important it is to the individual. This was the first time the questionnaire had been used, and analysis showed the need for some changes in future use.

Principal component analysis with varimax rotation revealed five factors that accounted for 49.3 percent of the total commonality of the attitude questions (table 5).[11] The significant items comprising these factors were as follows:

I. Implementing Fire Prevention Program[12]
  1. More space in school textbooks should be given to fire prevention. (9)[13]
  2. I would like to see school children bring home fire prevention literature from school. (13)
  3. Fire Prevention people should establish closer relationships with the Boy Scouts and similar organizations. (14)
  4. Everyone should be required to attend a meeting at least once every 3 years where he would get information in fire prevention. (12)
  5. Fire prevention efforts in forests is money well spent. (16)
  6. Applicants for campfire permits should be required to pass an examination just as they do for a driver's permit. (10)

II. Salience of Fire Problem
  1. Forest fire danger in this area is highly overrated. (17)
  2. Schools should not be permitted to use school time for instruction in forest fire prevention. (11)
  3. Rangers should have much more important things to do than going around checking on forest visitors. (15)
  4. Fire prevention literature is a waste of taxpayer's money. (8)

III. Enforcement of Fire Regulations
  1. People who are careless with fire should be severely punished. (3)
  2. I should report people who break fire prevention rules in forest or brush areas. (6)
  3. Fire prevention instruction should be given to each person applying for a campfire permit. (1)
  4. Observing fire prevention rules is more important than obeying traffic regulations. (5)

IV. Assessment of Fire Prevention Program
  1. "Smokey Bear" does a poor job alerting the public to fire dangers. (7)
  2. Fire prevention literature is a waste of taxpayers' money. (8)
  3. Preventing forest fires is none of my concern. (4)

V. Regulation of Forest Use
  1. The National Forests belong to the public and people should be free to come and go as they please in them. (2)
  2. All persons entering a forest area should be required to register. (18)
  3. Applicants for campfire permits should be required to pass an examination just as they do for a driver's permit. (10)

Factor I, which accounts for more of the total commonality than any other factor, inexplicably is significantly related to only 3 of the 28 variables examined. The items making up this factor indicate that it is concerned with attitudes toward the means of implementing a fire prevention program. Failure of the factor to relate to the variables examined may mean that there is a highly unified feeling regarding this matter that transcends social and cultural differences.

Factor II, which appears to measure the importance which the respondents attach to the fire problem, was found to be significantly related to 25 of 28 different characteristics of these people (tables 6–9, appendix). The nature of the relationships indicates that those with the most frequent and varied contact with wildland areas and those who have had the most intimate experience with wildfire are most strongly concerned about the fire

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[11] For a discussion of this method of analysis see, for example, Harmon, H. H. **Modern factor analysis.** 471 pp. Chicago: University of Chicago Press, 1960. Commonality refers to the extent to which the common factors account for the total unit variance of the variable. A cluster structure analysis method developed by R. C. Tryon, Psychology Department, University of California, Berkeley (BC TRY System of Factor and Cluster Analysis, U.C. Computer Center Library, Berkeley), was also used, but it proved less satisfactory in defining meaningful dimensions.

[12] Titles used in the various sets are primarily for identification and should not be considered as providing definitive descriptions or definitions of the content of the sets.

[13] Numbers in parentheses following items represent numbering used in the questionnaire.

problem. This concern also increases as amount of schooling and income increases.

Factor III, which relates to the enforcement of fire regulations, and Factor IV, which relates to the assessment of the fire prevention program, were found to be related to 12 and 8 of the 28 variables, respectively. In the main, these relationships were similar to those shown with Factor II.

Factor V contributed very little to the total commonality and probably should not be included in future uses of the test instrument. It would appear to be probing some other dimension quite unrelated to fire prevention—possibly personality factors or political orientation.

The stability of the variables making up each of the dimensions will need to be investigated in future studies.

Questions in other parts of the questionnaire touched upon other aspects of fire prevention attitudes and related areas. It is quite apparent from these responses that Butte County residents are quite sensitive to the fire problem in their county, if not in their immediate locality. Eighty-eight percent of them felt that there was a moderate to great forest fire problem in the county. Most felt optimistic that this problem could be reduced.

In spite of such examples as the 1961 Bel Air Fire, however, 77 percent felt that their homes were in little or no danger from such a fire. Nearly one-third of their homes have brush or dry grass-covered land next to at least one side of their property. Many of these are built in a natural setting, with the brush and grass left essentially undisturbed. Residents in these more vulnerable localities were inclined to feel the fire problem somewhat more keenly (see Factor II, table 9, appendix).

An uncontrolled fire that burned timber was felt to be a very serious matter by 96 percent of the respondents. A brush fire was considered to be a very serious matter by 81 percent. But only 52 percent felt the same way about a grass fire.

Less than 1 percent of the people considered the fire control laws of California to be too strict. Over half felt they were about right, but two out of five said the laws were not strict enough. About the same proportion that felt the laws were about right also felt the enforcement of the laws in Butte County was about as it should be. Only one person felt that enforcement was too strict.

Nearly two-thirds of the respondents felt that the schools were doing a satisfactory job in fire prevention education for the children (one-fifth considered it excellent). Fourteen percent said the schools were doing a poor job, while 24 percent said they did not know.

Characteristics of High Risk Residents

A particularly serious problem to those responsible for fire prevention is people who have limited knowledge of fire behavior and fire prevention methods, and who have a low estimate of the seriousness of the forest fire problem in the area, but who are frequent users of the wildlands. To get some idea of the number of such persons, and to see in what ways they differ from others, the sample was first divided into quartiles on the basis of their knowledge scores, then further divided on the basis of their rating on Factor II (Salience of the Fire Problem) of the attitude scale. Those who fell in either the highest or lowest quartile on both these points were further divided on the basis of their wildland activity score. Of those who were in the lowest fourth on the basis of their knowledge-attitude scores, 14 were in the highest third in terms of their wildland activity scores. This may seem a rather insignificant number, but this represents about 2 percent of the total sample—projected to a total population basis, 1,000 to 1,200 persons in the county. These people were compared on a number of characteristics with those equally low in knowledge and attitude scores, but with little wildland activity, as well as with those with high scores and with the total sample (tables 10–15, appendix).

The small numbers involved makes the reported proportions subject to a high degree of variance. It is with this understanding that the major differences of the high risk group from the total sample are listed. These high risk people tended to be young (under 25 years of age), unmarried, and with a limited amount of schooling for their age. Equal numbers of each sex were involved. They may still have been in school, but if not, they were more apt to have only a part-time job in the operative, clerical, or laborer occupations. Few of them were the chief income earner for their family, and the total income for their families tended to be in the low to medium range. Their residential characteristics did not differ too markedly from the general population. However, they were mainly city or open country non-farm residents. Most of them formerly lived in small towns. They appeared to spend less time than average listening to the radio, but their TV watching was higher than average. They were low in organizational membership except for religious and youth organizations.

In contrast, those with a similar high wildland activity level, but with high "knowledge-attitude" scores, had a more normal age distribution (except for a deficiency in the 65 years of age and over category). They were predominantly married males and had higher than average years of schooling completed. They were employed full time, and their occupations were distributed across the full range of categories similar to that of the whole population. Their incomes tended to be higher than average and a high proportion lived in the suburbs.

Those whose wildland activity is minimal had equally distinctive characteristics, but because of their limited use of the wildlands they are not of direct concern to the fire prevention problem.

Summary and Conclusions

This paper reports data from a study of a representative sample of residents of Butte County, California. It relates the knowledge and attitudes regarding the use and abuse of fire in wildland areas with the various characteristics of wildland users and non-users.

Three-fourths of the respondents were found to make some use of the wildlands of the county. Nearly one-third admitted that their activity there involved the use of fire.

With use of the wildlands so widespread, it is difficult to give a meaningful description of the "typical" wildland user. But the most frequent users tended to be young (under 25 years of age), unmarried, male, and relatively well educated. They were employed full time in one of a wide range of occupations (excepting farming and the services), or were still in school. They came from suburban families with higher than average incomes.

Those persons most involved in wildland activities had the highest level of knowledge about proper fire use. Level of knowledge was also related to a number of socio-economic variables and to actual experience with forest fires.

Frequent users of wildlands who scored in the highest quartile on both the knowledge and attitude scales differed from other frequent users by being middle-aged, married, and employed full-time (few were students).

Response to attitude items indicated a strong and relatively uniform, positive feeling toward fire prevention. This was intensified by personal experience with wildfire and with extent of experience in wildland areas. There were also differences attributable to the socio-economic characteristics of the respondents.

Of particular importance to the fire prevention problem is a relatively small number who, although they are frequent users of the wildlands, have little knowledge of proper fire use and are indifferent to the problem. This group, scoring in the lowest quartile on both the knowledge and attitude scales, averages even younger in age than the other frequent users. Females were equally represented. Their low level of schooling for their age indicates a high proportion of dropouts and retardations. If not still in school, they tended to have low-paying part-time jobs.

Fire control administrators may well feel that the general level of knowledge regarding proper fire use in wildland areas should be improved. It is apparent that there are identifiable groups, or categories, of people within the general population who—in terms of their present levels of knowledge and attitude and in terms of their risk potential—are in particular need of improvement. It remains to be demonstrated to what extent a comprehensive action program can effectively change these levels. And, finally, it remains to be seen to what extent such changes will result in changes in the actual behavior of wildland users and a consequent reduction in fire starts.

Appendix

Table 6.--*Analysis of variance relating five attitude dimensions with selected wildland experience characteristics, Butte County, 1964*

Characteristic	Number	Attitude dimensions[1] I	II	III	IV	V
Frequency of working in wildlands:						
Frequently	64	0.486	0.532	0.494	0.491	0.494
Occassionally	60	.499	.518	.487	.503	.482
Never	237	.511	.513	.500	.501	.489
Significance level		(2/)	(2/)	(2/)	(2/)	(2/)
Total number of wildland visits:						
None	154	.502	.467	.513	.488	.516
1-2	78	.493	.478	.495	.509	.507
3-5	120	.498	.496	.495	.504	.502
6-10	119	.513	.521	.489	.503	.499
11 or more	234	.495	.524	.503	.507	.493
Significance level		(2/)	.001	(2/)	(2/)	(2/)
Total recreational activity in wildlands[3]						
0	139	.500	.478	.486	.491	.508
1	124	.501	.486	.500	.498	.508
2	133	.505	.513	.488	.499	.510
3	122	.504	.515	.504	.507	.503
4	69	.495	.524	.517	.533	.465
5	49	.492	.539	.507	.508	.491
6	16	.506	.525	.494	.538	.517
7	5	.442	.556	.529	.590	.501
Significance level		(2/)	.001	(2/)	(2/)	(2/)
Frequency of use of fire in wildlands:						
None	490	.501	.496	.499	.501	.508
1	48	.489	.477	.522	.510	.510
2	34	.513	.514	.538	.514	.522
3	26	.487	.505	.497	.501	.476
4	18	.484	.510	.497	.485	.449
5 or more	88	.500	.534	.484	.500	.472
Significance level		(2/)	.05	(2/)	(2/)	.01
Personal experience with forest fire—						
Observed forest fire close at hand:						
Yes	419	.500	.520	.487	.498	.498
No	282	.500	.473	.520	.507	.509
Significance level		(2/)	.001	.001	(2/)	(2/)
Ever forced to evacuate area endangered by fire:						
Yes	62	.483	.529	.490	.505	.494
No	643	.501	.498	.501	.501	.503
Significance level		(2/)	.05	(2/)	(2/)	(2/)
Ever had property destroyed:						
Yes	45	.587	.534	.495	.477	.512
No	655	.501	.500	.501	.502	.501
Significance level		(2/)	.05	(2/)	(2/)	(2/)

NOTE: Footnotes at end of table

Table 6.--*Analysis of variance relating five attitude dimensions with selected wildland experience characteristics, Butte County, 1964, continued*

Characteristic	Number	Attitude dimensions[1]				
		I	II	III	IV	V
Ever helped fight fire:						
Yes	218	0.498	0.518	0.488	0.491	0.489
No	485	.501	.493	.506	.506	.508
Significance level		([2])	.01	.05	([2])	.05

[1]Individual items were scored on a 5-place scale with "Strongly agree" given a weight of 1, and "Strongly disagree" a weight of 5, so that the more positive the response the lower the score. Items making up Factors II and IV are all negative statements, however, so that a negative response represents a positive attitude. Scores for these two dimensions are thus the reverse of those for the other dimensions. (Reverse scoring these negative items did not affect the stability of the dimensions.)

[2]Not significant.

[3]Represents a summation of different types of activities engaged in (camping, fishing, picnicking, etc.) in wildland areas of county.

Table 7.--*Analysis of variance relating five attitude dimensions with selected knowledge and attitude characteristics, Butte County, 1964*

Characteristic	Number	Attitude dimensions[1]				
		I	II	III	IV	V
Knowledge of what a campfire permit is:						
Knows	346	0.506	0.524	0.492	0.502	0.491
Has vague idea	183	.493	.500	.519	.504	.510
Incorrect answer	27	.503	.482	.488	.510	.513
Significance level		(2/)	.01	.05	(2/)	(2/)
Assessment of forest fire danger to home:						
Serious danger	26	.511	.511	.502	.492	.494
Some danger	130	.478	.520	.499	.507	.519
Little or no danger	548	.504	.496	.501	.501	.498
Significance level		.05	.05	(2/)	(2/)	(2/)
Awareness of extreme fire situations in area:						
Yes	609	.499	.511	.500	.500	.501
No	95	.503	.439	.502	.513	.505
Significance level		(2/)	.001	(2/)	(2/)	(2/)
Personal awareness of critical fire situations compared to other people:						
More aware	221	.488	.531	.478	.498	.496
Less aware	38	.487	.475	.518	.519	.534
Same as others	444	.506	.488	.510	.502	.502
Significance level		(2/)	.001	.001	(2/)	(2/)
Significance of different types of forest fire—						
Feel that timber fire is:						
Very serious matter	673	.499	.505	.498	.503	.501
Moderately serious	29	.503	.433	.549	.496	.515
Not very serious	1	.437	.405	.562	.467	.473
Not serious at all	1	.735	.207	.715	.208	.553
Significance level		(2/)	.001	.01	.05	(2/)
Feel that brush fire is:						
Very serious matter	483	.496	.508	.491	.500	.505
Moderately serious	187	.504	.490	.526	.510	.495
Not very serious	23	.533	.457	.516	.501	.491
Not serious at all	6	.557	.508	.486	.529	.437
Significance level		(2/)	.05	.001	(2/)	(2/)
Feel that grass fire is:						
Very serious matter	360	.494	.513	.488	.500	.506
Moderately serious	287	.505	.493	.516	.504	.499
Not very serious	47	.514	.467	.501	.510	.491
Not serious at all	4	.502	.432	.588	.561	.530
Significance level		(2/)	.01	.01	(2/)	(2/)
Feeling regarding enforcement of fire control laws:						
Too strict	1	.273	.359	.496	.451	.593
Not strict enough	276	.478	.514	.494	.505	.514
About right	382	.512	.491	.505	.499	.494
Significance level		.001	.01	(2/)	(2/)	.05

[1]See Table 6 for explanation of method of determining dimensions.
[2]Not significant.

Table 8.--*Analysis of variance relating five attitude dimensions with selected personal characteristics, Butte County, 1964*

Characteristic	Number	Attitude dimensions[1/]				
		I	II	III	IV	V
Age:						
14-24	165	0.492	0.501	0.539	0.542	0.506
25-34	97	.503	.512	.513	.521	.514
35-49	182	.511	.521	.495	.488	.515
50-64	153	.505	.498	.473	.477	.484
65 and over	107	.482	.463	.477	.481	.488
Significance level		(2/)	.001	.001	.001	.05
Marital status:						
Single	135	.492	.496	.532	.532	.502
Married	483	.504	.511	.497	.496	.502
Widowed, divorced, or separated	87	.490	.456	.470	.485	.503
Significance level		(2/)	.001	.001	.001	(2/)
Sex:						
Male	341	.503	.509	.497	.493	.479
Female	364	.497	.494	.503	.510	.523
Significance level		(2/)	.05	(2/)	.05	.001
Years of schooling:						
0-4	22	.458	.415	.479	.481	.549
5-7	42	.492	.421	.474	.467	.506
8	100	.489	.471	.495	.498	.496
Some high school	185	.486	.488	.506	.513	.503
High school graduate	169	.510	.520	.501	.497	.500
Some college	128	.512	.539	.506	.513	.493
College graduate	33	.516	.526	.514	.498	.512
Post graduate	36	.538	.569	.493	.491	.518
Significance level		(2/)	.001	(2/)	(2/)	(2/)
Occupational status:						
Employed full time	271	.511	.519	.497	.495	.481
Employed part time	106	.482	.500	.500	.505	.517
Retired or disabled	80	.484	.463	.473	.468	.494
Housewife	156	.498	.490	.497	.499	.535
Student	90	.503	.499	.542	.550	.497
Other	2	.445	.523	.482	.596	.577
Significance level		(2/)	.001	.001	.001	.001
Occupation:						
Professional, technical	46	.522	.538	.516	.510	.505
Farmer, farm manager	16	.523	.485	.480	.489	.437
Manager, official, proprietor	45	.508	.529	.485	.493	.501
Clerical worker	64	.502	.516	.520	.527	.496
Sales worker	32	.502	.513	.480	.528	.480
Craftsman, foreman	49	.511	.532	.482	.503	.487
Operative	50	.484	.508	.512	.457	.467
Service worker	66	.509	.508	.515	.527	.510
Farm laborer	28	.496	.477	.484	.499	.507
Laborer	35	.480	.495	.528	.493	.473
Not applicable not employed	270	.494	.480	.494	.496	.520
Significance level		(2/)	.01	(2/)	.05	.01
Chief income-earner of household:						
Yes	345	.504	.500	.487	.486	.484
No	360	.495	.502	.513	.516	.519
Significance level		(2/)	(2/)	.001	.001	.001

NOTE: Footnotes at end of table

Table 8.--*Analysis of variance relating five attitude dimensions with selected personal characteristics, Butte County, 1964, continued*

Characteristic	Number	Attitude dimensions[1]				
		I	II	III	IV	V
Family income:						
Under $1,500	54	0.484	0.453	0.475	0.494	0.494
$1,500-$2,999	86	.477	.468	.500	.497	.512
$3,000-$4,499	96	.489	.503	.486	.499	.509
$4,500-$5,999	96	.495	.499	.509	.504	.502
$6,000-$7,999	124	.503	.520	.507	.514	.500
$8,000-$9,999	78	.495	.533	.472	.502	.498
$10,000-$14,999	93	.520	.518	.515	.503	.487
$15,000-$19,999	17	.507	.549	.542	.493	.533
$20,000 and over	85	.551	.523	.483	.440	.501
Significance level		([2])	.001	.05	([2])	([2])

[1]See table 6 for explanation of method of determining dimensions.
[2]Not significant.

Table 9.--*Analysis of variance relating five attitude dimensions with selected residence characteristics, Butte County, 1964*

Characteristic	Number	Attitude dimensions[1]				
		I	II	III	IV	V
Residence:						
City	347	0.507	0.497	0.503	0.498	0.493
Suburb	135	.499	.520	.507	.505	.508
Small town or village	125	.472	.507	.491	.503	.517
Open country, farm	55	.500	.485	.507	.509	.504
Open country, nonfarm	43	.526	.477	.481	.508	.511
Significance level		.01	.05	(2/)	(2/)	(2/)
Place last lived:						
Always lived here	68	.491	.519	.516	.519	.505
Elsewhere, Butte County	233	.502	.491	.502	.499	.497
Other county, N. Calif.	216	.506	.496	.493	.498	.501
Other county, S. Calif.	91	.493	.521	.498	.507	.522
Other state	96	.490	.506	.505	.499	.496
Significance level		(2/)	(2/)	(2/)	(2/)	(2/)
Fire risk rating of residential environment:						
Res. lot surrounded by built-up or cultivated land on all sides	493	.504	.497	.501	.501	.498
Res. lot adjacent to brush- and/or dry grass-covered land on at least one side	156	.491	.502	.499	.503	.517
Res. built in "natural" setting, surrounded or nearly surrounded by brush- and/or dry grass-covered land	56	.484	.531	.496	.508	.497
Significance level		(2/)	.05	(2/)	(2/)	(2/)

[1]See table 6 for explanation of method of determining dimensions.
[2]Not significant.

Table 10.--*Comparison of persons with extreme levels of wildland activity and fire prevention knowledge and attitude scores by selected socio-economic characteristics, Butte County, 1964*

Characteristic	Wildland activity				All respondents
	Highest third		Lowest third		
	Knowledge-attitude scores		Knowledge-attitude scores		
	Lowest quartile	Highest quartile	Lowest quartile	Highest quartile	
n=	(14)	(43)	(42)	(10)	(761)
	Percent				
Age:					
14-24	50.0	23.3	9.5	10.0	23.4
25-34	14.3	16.3	9.5	--	13.8
35-49	7.1	34.9	14.3	40.0	25.8
50-64	7.1	23.3	26.2	30.0	21.7
65 and over	21.5	2.3	38.1	20.0	15.2
Not reported	--	--	2.4	--	.1
Total	100.0	100.0	100.0	100.0	100.0
Sex:					
Male	50.0	62.8	23.8	40.0	48.5
Female	50.0	37.2	76.2	60.0	51.5
Not reported	--	--	--	--	--
Total	100.0	100.0	100.0	100.0	100.0
Marital status:					
Single	50.0	23.3	14.3	10.0	18.5
Married	50.0	74.4	52.4	80.0	68.5
Widowed, divorced, or separated	--	2.3	33.3	10.0	13.0
Not reported	--	--	--	--	--
Total	100.0	100.0	100.0	100.0	100.0
Race:					
White	85.8	97.7	88.1	100.0	97.5
Negro	7.1	--	7.1	--	1.3
Other	7.1	2.3	4.8	--	1.2
Not reported	--	--	--	--	--
Total	100.0	100.0	100.0	100.0	100.0
Years of schooling completed:					
0-4	7.1	--	14.3	--	3.7
5-7	35.8	--	19.0	--	6.7
8	21.4	4.6	21.4	10.0	14.8
Some high school	28.6	20.9	23.8	20.0	25.8
High school graduate	--	42.0	14.3	20.0	23.1
Some college	7.1	18.6	2.4	20.0	17.6
College graduate	--	4.6	4.8	10.0	4.7
Post graduate	--	9.3	--	20.0	3.6
Not reported	--	--	--	--	--
Total	100.0	100.0	100.0	100.0	100.0
Occupational status:					
Employed, full time	14.3	55.9	19.1	60.0	37.3
Employed, part time	21.4	16.3	7.1	10.0	15.3
Retired or disabled	7.1	4.6	35.7	--	13.1
Housewife	21.4	11.6	35.7	30.0	22.2
Student	35.8	11.6	2.4	--	11.8
Other	--	--	--	--	.3
Not reported	--	--	--	--	--
Total	100.0	100.0	100.0	100.0	100.0

Table 10.--*Comparison of persons with extreme levels of wildland activity and fire prevention knowledge and attitude scores by selected socio-economic characteristics, Butte County, 1964, continued*

Characteristic	Wildland activity: Highest third, Knowledge-attitude scores: Lowest quartile	Wildland activity: Highest third, Knowledge-attitude scores: Highest quartile	Wildland activity: Lowest third, Knowledge-attitude scores: Lowest quartile	Wildland activity: Lowest third, Knowledge-attitude scores: Highest quartile	All respondents
n=	(14)	(43)	(42)	(10)	(761)
	Percent				
Occupation:					
Professional, technical	--	9.3	--	20.0	6.3
Farmer, farm manager	--	2.3	--	10.0	2.4
Manager, official, proprietor	--	7.0	--	--	6.2
Clerical worker	7.1	11.7	2.4	--	8.8
Sales worker	--	7.0	--	--	4.3
Craftsman, foreman	--	9.3	2.4	10.0	6.6
Operative	14.3	9.3	9.5	10.0	6.8
Service worker	--	4.6	9.5	20.0	9.1
Farm laborer	7.1	4.6	--	--	4.3
Laborer	7.1	9.3	2.4	--	4.9
Not employed, retired	64.4	21.0	73.8	30.0	39.8
Not reported	--	4.6	--	--	.5
Total	100.0	100.0	100.0	100.0	100.0
Percent of respondents who are chief income-earner of household:	28.6	55.8	50.0	50.0	49.4
Family income:					
Under $1,500	7.1	2.3	28.9	10.0	8.0
$1,500-$2,999	14.3	2.3	33.3	--	12.8
$3,000-$4,499	35.8	11.7	11.9	30.0	13.3
$4,500-$5,999	14.3	16.3	7.1	20.0	13.1
$6,000-$7,999	7.1	27.9	7.1	10.0	17.3
$8,000-$9,999	--	16.3	--	20.0	10.8
$10,000-$14,999	7.1	11.6	2.4	10.0	12.9
$15,000-$19,999	--	4.6	--	--	2.5
$20,000 and over	--	--	--	.9	.9
Not reported	14.3	7.0	9.5	--	8.4
Total	100.0	100.0	100.0	100.0	100.0

Table 11.--*Comparison of persons with various levels of wildland activity and fire prevention knowledge and attitude scores by selected residential characteristics, Butte County, 1964*

Characteristic	Wildland activity: Highest third, Knowledge-attitude scores: Lowest quartile	Wildland activity: Highest third, Knowledge-attitude scores: Highest quartile	Wildland activity: Lowest third, Knowledge-attitude scores: Lowest quartile	Wildland activity: Lowest third, Knowledge-attitude scores: Highest quartile	All respondents
n=	(14)	(43)	(42)	(10)	(761)
	Percent				
Length of residence in neighborhood:					
Less than 1 year	21.4	25.6	11.9	30.0	18.4
1-2 years	7.1	9.3	9.5	10.0	17.5
3-5	21.5	18.6	11.9	10.0	17.6
6-10	14.3	14.0	31.0	10.0	12.2
10 or more	35.7	32.6	35.7	40.0	34.3
Not reported	--	--	--	--	--
Total	100.0	100.0	100.0	100.0	100.0
Place last lived:					
Elsewhere, Butte County	42.9	39.6	31.0	10.0	32.3
Other county, N. Calif.	28.6	23.3	45.3	40.0	31.0
Other county, S. Calif.	14.3	14.0	7.1	30.0	12.9
Other state	7.1	14.0	9.5	10.0	14.4
Always lived here	7.1	9.3	7.1	10.0	9.3
Not reported	--	--	--	--	.1
Total	100.0	100.0	100.0	100.0	100.0
Present residence:					
City	57.2	41.9	52.4	20.0	47.8
Suburb	14.3	27.9	4.8	10.0	18.9
Small town or village	7.1	18.6	31.0	50.0	13.3
Open country, farm	7.1	4.6	4.8	20.0	8.9
Open country, nonfarm	14.3	7.0	7.1	--	6.1
Not reported	--	--	--	--	--
Total	100.0	100.0	100.0	100.0	100.0
Former residence:					
City	28.6	46.5	50.0	70.0	46.7
Small town	42.9	27.9	19.0	10.0	25.1
Open country	21.9	16.3	23.9	10.0	18.8
Not applicable (always lived in area)	7.1	9.3	7.1	10.0	9.3
Not reported	--	--	--	--	.1
Total	100.0	100.0	100.0	100.0	100.0
Fire risk rating of residential environment:					
Res. lot surrounded by built up or cultivated land on all sides	42.9	51.2	78.6	70.0	69.4
Res. lot adjacent to brush-and/or dry grass-covered land on at least one side	42.9	32.6	16.7	--	22.3
Res. built in "natural" setting surrounded, or nearly surrounded by brush-and/or dry grass-covered land	14.3	16.3	4.8	30.0	8.3
Not reported	--	--	--	--	--
Total	100.0	100.0	100.0	100.0	100.0

Table 12.--*Comparison of persons with various levels of wildland activity and fire prevention knowledge and attitude scores by their radio-listening characteristics, Butte County, 1964*

Characteristic	Wildland activity				All respondents
	Highest third		Lowest third		
	Knowledge-attitude scores		Knowledge-attitude scores		
	Lowest quartile	Highest quartile	Lowest quartile	Highest quartile	
n=	(14)	(43)	(42)	(10)	(761)
	Percent				
Station listened to most frequently:					
KAOR, Oroville	21.4	16.3	4.8	--	10.0
KHSL, Chico	28.7	27.9	23.8	10.0	28.8
KPAY, Chico	14.3	23.4	16.7	40.0	20.0
KFPK, Sacramento	--	9.3	14.3	20.0	10.5
Other Sacramento stations	7.1	4.6	7.1	--	5.6
San Francisco stations	7.1	9.3	4.8	10.0	5.4
Other local stations	7.1	--	2.4	--	3.9
Other stations	--	2.3	--	--	1.3
Don't know, or no answer	--	2.3	2.4	10.0	1.2
Don't listen to radio	14.3	4.6	23.8	10.0	10.1
Both KHSL, KPAY equally	--	--	--	--	3.2
Total	100.0	100.0	100.0	100.0	100.0
Hours of listening per day:					
2 or more	14.3	27.9	33.3	30.0	32.6
1-2	35.7	34.9	23.9	30.0	25.8
Less than 1	14.3	25.6	9.5	20.0	16.8
Usually only once or twice a week	21.4	7.0	9.5	10.0	14.8
Not at all	14.3	4.6	23.8	10.0	10.0
Don't know, or no answer	--	--	--	--	--
Total	100.0	100.0	100.0	100.0	100.0
Feel radio gives adequate coverage of local fire situation	71.4	60.5	64.3	80.0	70.4

Table 13.--*Comparison of persons with various levels of wildland activity and fire prevention knowledge and attitude scores by their television viewing characteristics, Butte County, 1964*

Characteristic	Wildland activity: Highest third — Knowledge-attitude scores: Lowest quartile	Wildland activity: Highest third — Knowledge-attitude scores: Highest quartile	Wildland activity: Lowest third — Knowledge-attitude scores: Lowest quartile	Wildland activity: Lowest third — Knowledge-attitude scores: Highest quartile	All respondents
n=	(14)	(43)	(42)	(10)	(761)
	Percent				
Channel watched most frequently:					
Channel 12, Chico	85.7	44.2	71.4	50.0	61.5
Channel 3, Sacramento	--	16.3	4.8	10.0	9.2
Channel 10, Sacramento	--	2.3	--	--	1.8
Channel 13 Sacramento	--	--	--	--	.8
Sacramento, channel unspecified	--	2.3	2.4	--	1.2
Chico and other channel equally	14.3	11.6	7.1	20.0	10.2
Channel 7, Redding	--	14.0	4.8	10.0	7.5
Other	--	2.3	--	--	.7
Don't know or no answer	--	--	--	--	.5
Don't watch television	--	7.0	9.5	10.0	6.6
Total	100.0	100.0	100.0	100.0	100.0
Hours of watching per day:					
2 or more	71.5	55.8	60.0	50.0	59.6
1-2	21.4	23.3	21.4	30.0	19.6
Less than 1	--	11.6	--	--	6.3
Usually only once or twice a week	7.1	2.3	9.5	10.0	7.9
Not at all	--	7.0	9.5	10.0	6.6
Don't know or no answer	--	--	--	--	--
Total	100.0	100.0	100.0	100.0	100.0
Feel television gives adequate coverage of local fire situation	78.6	41.9	73.8	70.0	67.3

Table 14.--*Comparison of persons with various levels of wildland activity and fire prevention knowledge and attitude scores by their newspaper subscriptions, Butte County, 1964*

Item	Wildland activity				All respondents
	Highest third		Lowest third		
	Knowledge-attitude scores		Knowledge-attitude scores		
	Lowest quartile	Highest quartile	Lowest quartile	Highest quartile	
n=	(14)	(43)	(42)	(10)	(761)
	Percent				
Chico Enterprise Record	42.9	44.2	42.9	50.0	47.8
Oroville Mercury	42.9	37.2	9.5	--	24.7
Sacramento Bee	7.1	27.9	14.3	10.0	19.4
San Francisco Chronicle	--	18.6	2.4	--	9.7
San Francisco Examiner	7.1	18.6	9.5	20.0	10.6
Paradise Post Weekly	--	2.3	2.4	10.0	3.4
Gridley Herald	--	2.3	11.9	40.0	6.3
Appeal Democrat	--	--	7.1	10.0	4.1
Other	7.1	7.0	4.8	10.0	7.0
Feel newspaper gives adequate coverage of local fire situation	78.6	55.8	76.2	70.0	76.6

Columns do not add as some respondents recorded more than one paper.

Table 15.--*Comparison of persons with various levels of wildland activity and fire prevention knowledge and attitude scores by organizational membership, Butte County, 1964*

Organization	Wildland activity				All respondents
	Highest third Knowledge-attitude scores		Lowest third Knowledge-attitude scores		
	Lowest quartile	Highest quartile	Lowest quartile	Highest quartile	
n=	(14)	(43)	(42)	(10)	(761)
	Percent				
Civic	--	23.3	--	10.0	10.9
Business, union, or farm	7.1	25.6	9.5	--	18.5
Fraternal	7.1	20.9	9.5	20.0	18.7
Religious	35.7	20.9	31.0	40.0	27.9
Youth	14.3	--	2.4	--	4.5
Outdoor club and conservation	--	9.3	--	--	4.6
Social	7.1	7.0	2.4	10.0	3.8
Veterans	--	4.6	--	--	2.6
Other	--	9.3	2.4	--	2.4

Columns do not add as some respondents reported more than one organization.

Table 16.--*Items comprising the knowledge test, showing percentage distributions of responses to individual items*

(n=761)	*Percent*
1. Green trees and shrubs of California:	
Are very difficult to burn	19.6
Will not burn at all	1.6
Will catch fire and burn very rapidly	43.4*
Will burn only in the hot summer months	27.7
Do not know	7.7
2. If you take extra gasoline for your camp stove, you should carry it in:	
A glass jar or jug	1.6
A safety can	72.2*
A container in which flammable liquids are purchased	21.9
A plastic container such as is used in the kitchen	1.7
Do not know	2.6
3. The safest method for lighting cigarettes in the forest area is to use:	
Book-type safety matches	19.3
Strike anywhere, stick-type matches	1.2
Stick-type safety matches	8.3
A cigarette lighter	65.4*
Do not know	5.8
4. The surest way to put out a campfire, assuming all these methods are available, is to:	
Pour water on it	7.1
Completely cover with dirt	34.3
Pour water on it and stir thoroughly	56.6*
Spread out the embers and let it burn itself out	1.2
Do not know	.8
5. If you are negligent with your campfire or warming fire and it escapes to the property of another, whether privately or publicly owned, you are:	
Not liable for damages	.5
Criminally liable, but not civilly liable	4.3
Civilly liable, but not criminally liable	15.7
Both criminally and civilly liable	32.2*
Liable, but don't know which	37.6
Do not know	9.7
6. If you drive your car off the road in dry grass areas:	
Exhaust sparks can start a fire	18.3
Sparks made by contact of metal parts of the car with rocks can set fires	3.7
Both 1 and 2 are correct	61.8*
Neither 1 or 2 are correct	5.0
Do not know	11.2
7. A sign in a National Forest that reads "Closed Area" means:	
That you may enter, but not smoke in the area	3.3
You may enter, but not build any campfires in the area	6.4
You may not enter the area	74.3*
You may not hunt or shoot within the area	5.6
Do not know	10.4
8. Windy weather:	
Tends to put out fires	.3
Affects only poorly built fires	.6
Makes necessary more precautions with fires	97.1*
Has little or no influence on fires	.4
Do not know	1.6

*Indicates correct response

Table 16.--*Items comprising the knowledge test, showing percentage distributions of responses to individual items, continued*

(n=761)	*Percent*
9. Prevention of man-caused forest fires ultimately depends upon:	
More and better trained personnel	6.4
More and better equipment	4.1
Public cooperation and recognition of personal responsibility	80.2*
Better techniques of fire fighting with the equipment we have	5.1
Do not know	4.2
10. When you are in a National Forest area in California, the law permits you to:	
Never smoke or build campfires	2.4
Smoke, but never build campfires	1.8
Smoke and build campfires only in areas so designated, during specified periods	85.4*
Smoke and build campfires only during the wet season	3.3
Do not know	7.1
11. "Humidity" is a measure of:	
Temperature of the air	7.5
Amount of rainfall that has fallen in last 24 hours	2.9
Percent of cloudiness during the daylight hours	.9
Amount of moisture in the air	81.2*
Do not know	7.5
12. "Watersheds" are:	
Areas where rain falls or snow melts to supply water to springs and creeks	47.1*
Structures over railroads for protection against heavy snow and rain	6.7
Buildings with gutters that run water to a cistern	3.4
Lakes and reservoirs which collect the water runoff from forests	20.4
Do not know	22.4
13. The time of day that forest fires typically will spread most rapidly:	
Sundown to midnight	8.8
Midnight to sunrise	4.3
10:00 a.m. to sundown	58.0*
Sunrise to 10:00 a.m.	4.5
Do not know	24.4
14. A fire is more apt to start where there is:	
Low temperature and low humidity	1.6
High temperature and low humidity	62.6*
High temperature and high humidity	21.9
Low temperature and high humidity	3.0
Do not know	10.9
15. A fire in the rotten vegetation found on the forest floor:	
Burns very rapidly--almost like a dry gunpowder train	18.6
Smolders slowly as in punk or cotton with little or no visible smoke	49.5*
Burns slowly along the top of the ground with easily detected production of smoke	17.1
Will not burn at all	1.8
Do not know	13.0
16. The chief cause of forest fires in Butte County is:	
Lightning	17.5
Campfires	5.9
Children playing with matches	3.0
Smokers' cigarettes and matches	58.8*
Do not know	14.8

*Indicates correct response

Table 16.--*Items comprising the knowledge test, showing percentage distributions of responses to individual items, continued*

(n=761)	*Percent*
17. The term "forest fire" means a fire which is burning out of control on lands covered wholly or in part by:	
Timber only	7.1
Timber and brush only	22.9
Timber, brush, and grass only	25.2
Timber, brush, grass, grain, or other flammable vegetation	39.5*
Do not know	5.3
18. The people responsible for starting most forest fires are:	
Hunters	12.4
Hikers	4.5
Campers	45.6
Local residents	10.4*
Do not know	27.2
19. Of the approximately 3,000 forest fires in California each year, what percent are human caused:	
10 percent	6.2
50 percent	19.4
70 percent	26.8*
90 percent	25.3
Do not know	22.3
20. Campfire permits are required for the use of:	
Gasoline or propane type camp stoves	2.2
Fire grates and charcoal burners	1.2
Open campfires	28.6
All of these	58.7*
Do not know	9.3

*Indicates correct response

Table 17.--*Items comprising the attitude test, showing percentage distributions of responses to individual items*

(n=761)	Percent
1. Fire prevention instruction should be given to each person applying for a campfire permit:	
Strongly agree	60.0
Agree	35.2
Undecided	2.5
Disagree	2.0
Strongly disagree	.3
Don't know, or no answer	--
2. The National Forests belong to the public and people should be free to come and go as they please in them:	
Strongly agree	15.9
Agree	31.3
Undecided	9.8
Disagree	30.5
Strongly disagree	12.1
Don't know, or no answer	.4
3. People who are careless with fire should be severely punished:	
Strongly agree	40.0
Agree	46.3
Undecided	10.2
Disagree	3.0
Strongly disagree	.1
Don't know, or no answer	.4
4. Preventing forest fires is none of my concern:	
Strongly agree	2.1
Agree	3.8
Undecided	1.4
Disagree	42.2
Strongly disagree	50.1
Don't know, or no answer	.4
5. Observing fire prevention rules is more important than obeying traffic regulations:	
Strongly agree	6.2
Agree	14.8
Undecided	38.5
Disagree	34.0
Strongly disagree	5.2
Don't know, or no answer	1.3
6. I should report people who break fire prevention rules in forest or brush areas:	
Strongly agree	29.0
Agree	59.7
Undecided	8.7
Disagree	2.2
Strongly disagree	.3
Don't know, or no answer	.1
7. "Smokey Bear" does a poor job of alerting the public to fire dangers:	
Strongly agree	2.3
Agree	4.9
Undecided	5.3
Disagree	58.8
Strongly disagree	28.7
Don't know, or no answer	--
8. Fire prevention literature is a waste of taxpayers' money:	
Strongly agree	2.5
Agree	2.0
Undecided	4.3
Disagree	61.9
Strongly disagree	29.2
Don't know, or no answer	.1

Table 17.--*Items comprising the attitude test, showing percentage distributions of responses to individual items, continued*

(n=761)	*Percent*
9. More space in school textbooks should be given to fire prevention:	
Strongly agree	17.0
Agree	48.9
Undecided	21.2
Disagree	8.5
Strongly disagree	.9
Don't know, or no answer	3.5
10. Applicants for campfire permits should be required to pass an examination just as they do for a driver's permit:	
Strongly agree	16.2
Agree	44.7
Undecided	13.0
Disagree	24.0
Strongly disagree	1.8
Don't know, or no answer	.3
11. School should not be permitted to use school time for instruction in forest fire prevention:	
Strongly agree	1.6
Agree	4.7
Undecided	4.7
Disagree	64.1
Strongly disagree	24.4
Don't know, or no answer	.5
12. Everyone should be required to attend a meeting at least once every three years, where he would get information and instruction in fire prevention:	
Strongly agree	14.4
Agree	40.2
Undecided	13.9
Disagree	27.5
Strongly disagree	3.7
Don't know, or no answer	.3
13. I would like to see school children bring home fire prevention literature from school:	
Strongly agree	16.8
Agree	68.6
Undecided	7.9
Disagree	5.4
Strongly disagree	.9
Don't know, or no answer	.4
14. Fire prevention people should establish closer relations with the Boy Scouts and similar organizations:	
Strongly agree	23.8
Agree	62.6
Undecided	10.2
Disagree	2.5
Strongly disagree	.4
Don't know, or no answer	.5
15. Rangers should have much more important things to do than going around checking on forest visitors:	
Strongly agree	2.5
Agree	8.9
Undecided	7.6
Disagree	62.2
Strongly disagree	18.3
Don't know, or no answer	.5
16. Fire prevention efforts in forests are money well spent:	
Strongly agree	39.0
Agree	57.1

Table 17.--*Items comprising the attitude test, showing percentage distributions of responses to individual items, continued*

(n=761)	*Percent*
16. Fire prevention efforts in forests are money well spent, contd:	
Undecided	2.8
Disagree	.6
Strongly disagree	.1
Don't know, or no answer	.4
17. Forest fire danger in this area is highly overrated:	
Strongly agree	2.0
Agree	5.4
Undecided	18.4
Disagree	56.2
Strongly disagree	16.3
Don't know, or no answer	1.7
18. All persons entering a forest area should be required to register:	
Strongly agree	19.6
Agree	45.0
Undecided	11.3
Disagree	21.4
Strongly disagree	2.4
Don't know, or no answer	.3

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