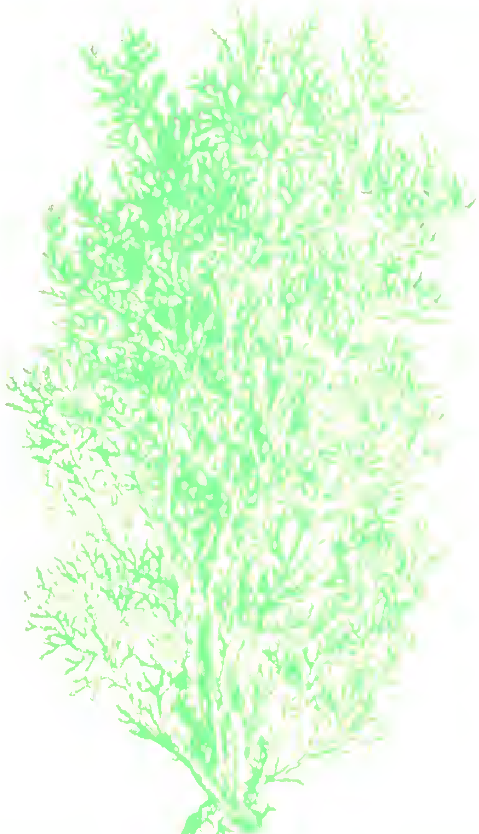


USDA FOREST SERVICE
RESEARCH PAPER INT-61 1969

INTERMOUNTAIN FOREST & RANGE EXPERIMENT STATION
Ogden, Utah

COVER: Original drawing of chamise, by Bryan Owen, Staff Artist, Northern Forest Fire Laboratory, Missoula, Montana.

USDA FOREST SERVICE
RESEARCH PAPER INT-61
1969

SEASONAL CHANGES IN HEAT CONTENT AND ETHER EXTRACTIVE CONTENT OF CHAMISE

C. W. Philpot

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
FOREST SERVICE
U. S. DEPARTMENT OF AGRICULTURE
OGDEN, UTAH 84401
JOSEPH F. PECHANEC, DIRECTOR

THE AUTHOR

CHARLES W. PHILPOT received his bachelor's and master's degrees in forestry from the University of California in 1961 and 1962, respectively. From 1960 to 1966 he studied fuel moisture and related variables as part of the Pacific Southwest Forest and Range Experiment Station's research on the factors that influence forest fire behavior. In 1966 he transferred to the Northern Forest Fire Laboratory, Missoula, Montana, where he is responsible for fuel chemistry research.

INTRODUCTION

Knowledge of the variations in heat content of wildland fuels is important in predicting fire behavior or assessing the relative flammability of different fuel complexes. The heat content of the fuel, and the availability of this heat content, partly determines the intensity with which the fuel burns. (Intensity is usually expressed as the rate of heat release per unit area per unit time; that is, B.t.u. per square foot per second.) Heat content availability also affects the fire's rate of spread. Studies are now underway to determine the effect of heat content changes on flammability.[1] Several species are being sampled seasonally to acquire data on fuels that differ in heat content.

The relation of heat content to ether extractive content is a part of this study. "Ether extractives" is a broad term that covers various waxes, oils, terpenes, and fats present in most plant fuels in varying amounts. Because these compounds do not undergo the complex pyrolytic reactions prior to combustion that are characteristic of the carbohydrate constituents of fuels (primarily cellulose), the extractives are more readily available. Also, much of the extractive material appears to be deposited on or near the surface of the plant parts, especially the leaves. The extractives collectively contain about twice the heat content of the extracted fuel. All indications are that extractives could play an important role in fire spread and intensity and that their seasonal variation is partly responsible for variation in heat content of fuels.

The specific effect of extractive content on fire behavior and flammability is presently an open question. In a study of herbicidal treatment on fire intensity, the U. S. Forest Service, Rocky Mountain Forest and Range Experiment Station (1963), found that chemically dried manzanita (*Arctostaphylos pungens* H.B.K.) did not burn as readily as untreated manzanita, although its moisture content was much lower. The treated material contained about one-half as much ether extractives as the untreated material. On the other hand, Mutch (1964) found the ignition time for powdered ponderosa pine (*Pinus ponderosa* Laws.) to be much longer than that of powdered sphagnum moss (*Sphagnum* sp.), although the pine had over four times more extractives than the moss. (The higher density of the pine may have influenced these results.) Pilot ignition time for both fuels, however, was increased by the removal of extractives. Philpot and Mutch (1968) found that guava (*Psidium guajava* L.) leaves that had been treated with herbicide did not burn as fast as leaves that had died naturally. The treated leaves were found to have 18 percent less extractives, as well as other chemical differences.

[1] *Defined for these studies as a combination of ignitibility, combustibility, and sustainability.*

Table 1. — The heat content of various species

Species	Anatomical portion	High heat value	Source
		B.t.u./lb.	
Basswood (*Tilia americana*)	xylem	8,341	Fons et al. (1960)
Bitterbrush (*Purshia tridentata*)	leaves		Short et al. (1966)
Spring		8,703	
Summer		7,933	
Fall		8,647	
Longleaf pine (*Pinus palustris*)	xylem	8,771	Fons et al. (1960)
Magnolia (*Magnolia grandiflora*)	xylem	8,561	Fons et al. (1960)
Manzanita (*Arctostaphylos viscida*)	leaves	9,208	Countryman (1964)
	twigs	8,676	
Manzanita (*Arctostaphylos pungens*)	leaves	9,070	Davis (1968)
Maple (*Acer saccharum*)	xylem	8,543	Fons et al. (1960)
Mountain mahogany (*Cercocarpus montanos*)	leaves		Short et al. (1965)
Spring		8,483	
Summer		8,309	
Fall		8,395	
Pinyon pine (*Pinus monophylla*)	leaves	9,480	Countryman (1964)
	stems	8,718	
Ponderosa pine (*Pinus ponderosa*)	needles	9,449	Mutch (1964)
Sagebrush (*Artemisia tridentata*)	leaves		Short et al. (1965)
Spring		8,527	
Summer		8,777	
Fall		9,094	
Sphagnum moss (*Sphagnum* spp.)		7,918	Mutch (1964)
White fir (*Abies concolor*)	xylem	8,660	Fons et al. (1960)

The heat contents of most wildland fuels are quite similar, as shown in table 1. This fact has led many to conclude that chemical composition and heat content changes of fuels are relatively unimportant, compared to their physical properties. However, some studies have been made; Richards (1940) found an increase of 1,300 B.t.u./lb. for snowbrush (*Ceanothus velutinus* Dougl.) during the fire season (fig. 1). A corresponding increase in extractives from 5.2 percent in June to 11.5 percent in September was also noted. Richards concluded that the heat content change would have a minor effect on burning rate as compared with moisture changes. Several range ecology studies have also found corresponding seasonal trends in extractives and heat content (Short, Dietz, and Remmenga 1966; Dietz, Udall, and Yeager 1962) (fig. 2). The relationship between heat content and extractives is supported by evidence that plant parts with high extractive content, such as pine needles or chaparral leaves, have higher heat contents than stems and xylem.

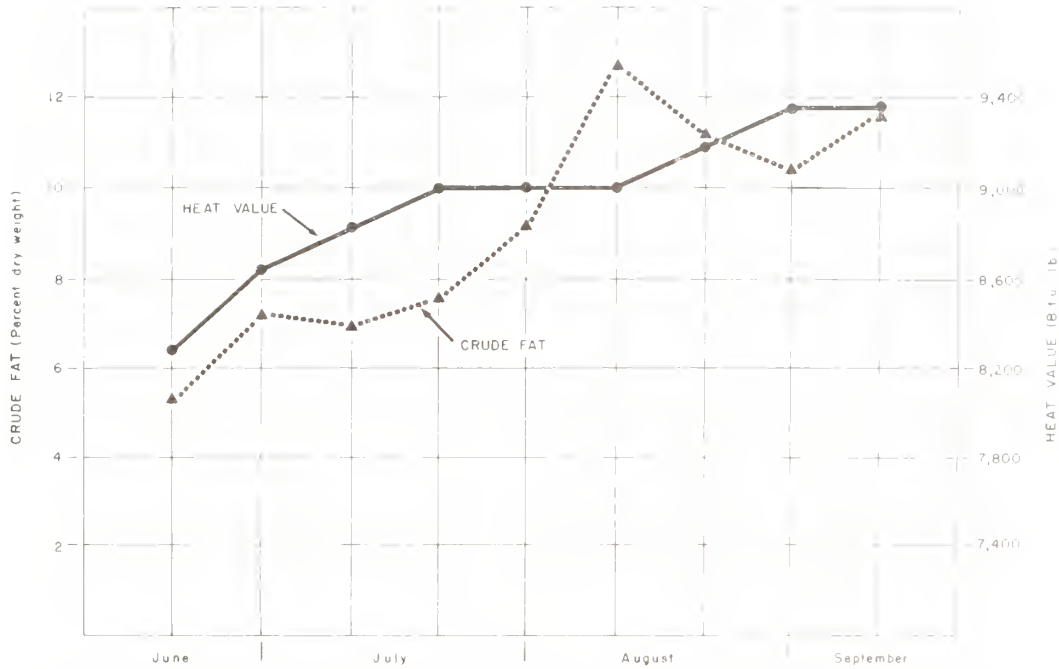


Figure 1. — The relationship between crude fat and heat of combustion of snowbrush. (Adapted from Richards.)

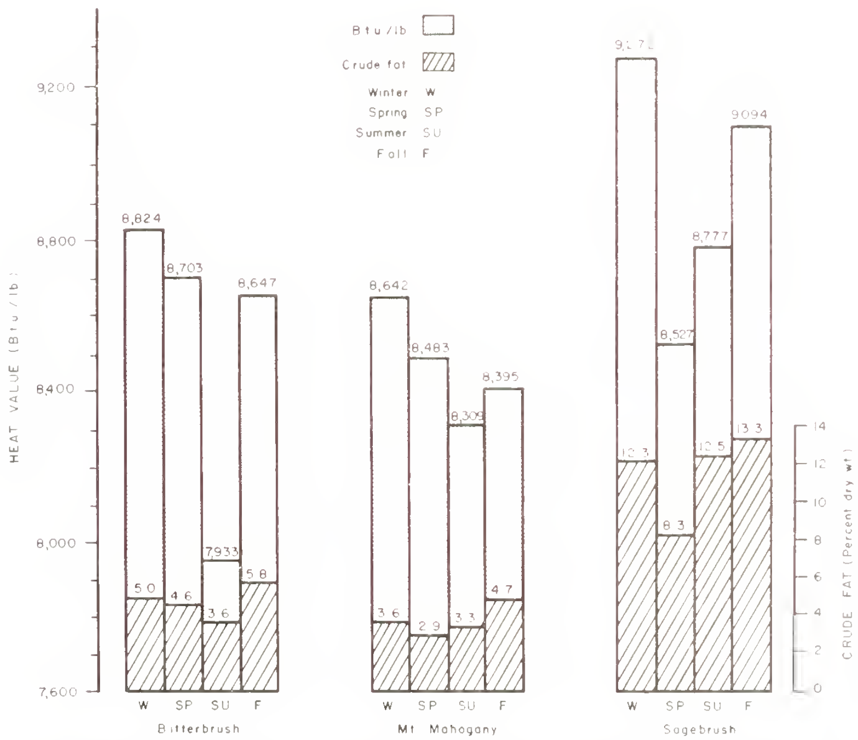


Figure 2. — Data from Dietz, Udall, and Yeager showing crude fat and heat content of three Colorado brush species.

CHAMISE

Chamise has been studied more extensively than most other wildland fuels. Because of its growth habit, physical makeup, moisture relations, and chemical characteristics, chamise is an extremely hazardous fuel — probably the most serious single fuel problem in California brushlands.

This species makes up about 50 percent of the chaparral fuel type in California and up to 70 percent in southern California (Leonard and Carlson 1957). Chamise often occurs in pure stands and deteriorates rapidly upon maturity and during periods of drought, losing its leaves and dying back. About one-third of mature chamise stands are dead material.

The needlelike leaves of chamise are arranged in groups of 10-15 per node on very small stems (fig. 3) and their surface area-to-volume ratio (σ) is 184 $in.^2/in.^3$ High values of σ imply rapid preheating and ignition and high burning rates. The leaves make up 67 percent of the total plant surface area but only 16 percent of the volume and 10 percent of the weight.[2] The form of the plant is generally conducive to rapid burning because several stems arise from the soil surface and branch into many smaller stems that support the leaves. All of this relatively small fuel becomes available for combustion under moderate burning conditions.

Figure 3. — Chamise stem with leaves.

The seasonal moisture trends of this species were determined by Olsen (1960). He found the moisture content of the foliage to be highest during active growth and lowest during late September and fall months. This trend generally coincides with fire season severity (Buck 1951). The moisture content of all aerial parts of this plant falls as low as 60 percent dry weight in September (Dell and Philpot 1965).

The chemical characteristics of chamise have not been studied to any great extent. Its approximate heat content is known, but not how this changes with time and location. The extractive content of the leaves is quite high, and by our own measurements has reached 13 percent dry weight. The seasonal changes in inorganic constituents, which may indicate changes in flammability, are currently being investigated at the Northern Forest Fire Laboratory.

[2] *Countryman, C. M., and C. W. Philpot. The physical characteristics of chamise as a wildland fuel. Pacific Southwest Forest and Range Exp. Station. (In preparation.)*

METHODS OF ANALYSIS

The chamise samples were obtained from the 4,500-ft. level, southwest exposure, on the North Mountain Experimental Area in southern California.[3] Two sets of data are included in this paper: the 1963 samples representing three dates and the much more complete 1966-67 samples representing eight dates. The leaves and stems (¼ inch or less) were clipped from each of three randomly picked plants in the same six subplots at each sample date during 1966-67 and were imme-

[3] *Cooperatively managed by the Riverside Fire Laboratory of the USDA Forest Service and the California Division of Forestry.*

diately placed in a styrofoam box with dry ice and airshipped frozen to the Northern Forest Fire Laboratory. There the material was freeze-dried to prevent volatile loss and was ground to 40 mesh in a Wiley mill. For the 1963 sampling, the complete plants were harvested on each sample date and all of the leaves removed. A subsample of all dates was then taken for analysis. The mineral and ether extractive contents were determined by standard methods (ASTM 1956a, 1956b). I extracted the samples with diethyl ether at a rate of 10 siphonings per hour for 8 hours. The weight change of the thimble was found to be more reliable than the weight of the flask because some extractives were apparently lost while the ether was being evaporated.

The heat content of the leaves and stems was determined for all of the 1963 samples and 14 of the 1966-67 samples. Heat contents for extracted leaves and stems were determined for only 14 of the 1966-67 samples picked at random. Heat content of extractives was determined directly (ASTM 1966) for some 1963 samples, but was calculated for the fourteen 1966-67 samples. All heat contents are expressed on an ash-free basis. Karl Fischer titrations were used for the moisture determinations necessary to convert data to a dry weight basis (ASTM 1962).

RESULTS

The extractive content of chamise leaves and small stems varied seasonally (figs. 4 and 5). The highest content for leaves (12 percent) was recorded for the fall and the lowest (8.5 percent) for the spring. A similar trend occurred in the stems, with a range of 4.3 percent to 8.9 percent. Duncan's New Multiple Range Test was used to test for significant differences between means on different dates (Steele and Torrie 1960). The results of this test (table 2) show the seasonal trend to be significant at the 5 percent level. The 1963 data were tested separately and the October value was found to be different from that for May. Apparently the 1963 data show a relationship similar to the 1966-67 data.

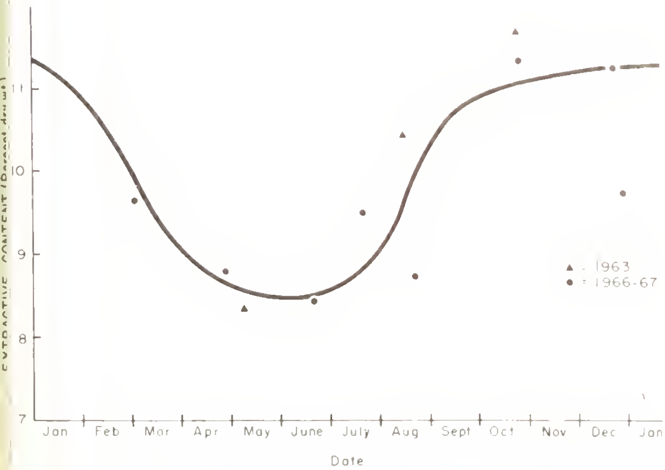


Figure 4. — Seasonal trend in ether extractives of chamise leaves.

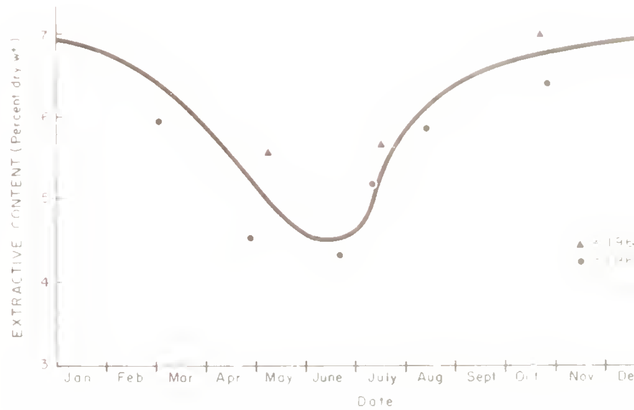


Figure 5. — Seasonal trend in ether extractives of chamise stems.

Table 2. — The significance of seasonal means for extractive content as determined by Duncan's New Multiple Range Test

Date of sampling	Code for sample	Samples having significant difference (P = 0.05) in mean extractive content			
		Leaves	Mean[1]	Stems	Mean[1]
10/26/66	A	BCDEFGH	11.34	DEFH	8.29
12/22/66	B	ACDEFGH	11.24	DEFH	6.65
3/ 2/67	C	ABE	9.66	DEH	5.94
4/27/67	D	AB	8.80	ABCGH	4.54
6/21/67	E	ABCFH	8.44	ABCFGH	4.33
7/12/67	F	ABE	9.57	ABEH	5.19
8/12/67	G	AB	8.72	DEH	5.83
12/28/67	H	ABE	9.72	ABCDEFG	8.29

[1] *Percent dry weight, ash free.*

The regression between extractive content and heat content of the total fuel, ash free, was determined by using data from two out of the six samples per sample date. These subsamples were picked randomly; data for these are presented in table 3. A portion of the 1963 data is also included in this analysis. Figures 6 and 7 show the relationships for leaves and stems. The coefficient of determination, r^2, is 0.72 for leaves and 0.58 for stems. The equations for the lines are

Leaves: $\overline{Y} = 8{,}000 + 169X$

Stems: $\overline{Y} = 8{,}800 + 101X$

where Y = high heat content (B.t.u./lb., ash free)

and X = ether extractive content (percent dry weight, ash free).

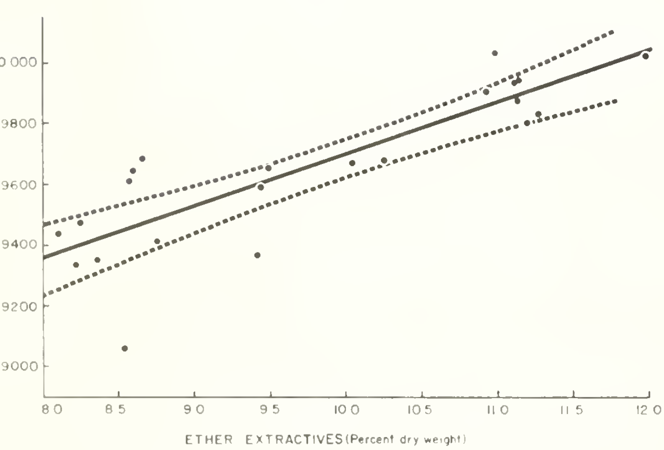


Figure 6. — The relationship between the extractive content of the leaves and total ash-free heat content.

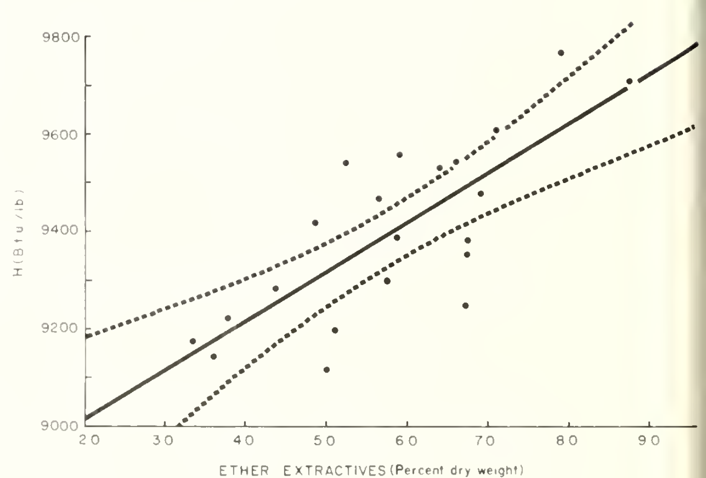


Figure 7. — The relationship between the extractive content of the stems and total ash-free heat content.

Table 3. — Data from randomly selected samples used for heat content determinations

Date of sample	Ether extractive content	High heat content, ash free (H_{tot})	Heat content of extracted fuel (H_{ex})	Difference H_{tot} and H_{ex} (ΔH)	Heat content of extractives (H_{ext})[1]
	Percent	B.t.u./lb.	B.t.u./lb.	B.t.u./lb.	B.t.u./lb.
			LEAVES		
5/63	8.76	9,413			
5/63	8.54	9,062			
7/63	11.28	9,826			
7/63	9.42	9,367			
10/63	11.94	10,026			
10/63	10.99	10,027			
10/66	10.93	9,904	9,161	743	15,959
10/66	11.14	9,871	9,063	808	16,316
12/66	11.14	9,937	9,194	743	15,864
12/66	11.20	9,354	9,800	775	15,945
3/67	8.57	9,611	9,014	596	15,980
3/67	9.44	9,592	8,930	662	15,943
4/67	8.25	9,473	9,034	439	14,355
4/67	8.60	9,615	9,078	567	15,671
6/67	8.22	9,337	8,969	368	13,145
6/67	8.36	9,353	8,866	487	14,691
7/67	9.50	9,655	9,123	532	14,723
7/67	10.26	9,677	9,031	646	15,327
8/67	8.66	9,686	9,059	627	16,299
8/67	8.10	9,436	8,736	700	17,378
			STEMS		
5/63	5.87	9,387			
5/63	5.01	9,118			
7/63	6.72	9,249			
7/63	6.74	9,353			
10/63	5.75	9,300			
10/63	8.75	9,709			
10/66	6.39	9,531	8,919	612	18,496
10/66	7.10	9,608	8,990	618	17,694
12/66	6.91	9,479	8,905	574	17,212
12/66	7.90	9,766	8,900	866	19,862
3/67	5.11	9,198	8,939	259	14,007
3/67	6.75	9,383	8,809	574	17,313
4/67	4.86	9,419	8,862	557	20,323
4/67	5.24	9,541	8,712	829	24,533
6/67	3.35	9,177	8,738	440	21,871
6/67	3.60	9,144	8,771	373	19,132
7/67	3.78	9,222	8,846	376	18,793
7/67	4.37	9,284	8,837	447	19,065
8/67	5.64	9,467	8,882	585	19,254
8/67	5.90	9,559	8,991	568	18,618

[1] *Calculated from H_{tot}, H_{ex}, and extractive content.*

The level of significance for both regression lines according to the F test is >99.5 percent for both sets of data. Dashed lines on the figures indicate 95 percent confidence bands.

The variability of these data prompted us to determine the heat content of the extracted fuel to see if a seasonal trend was present. These data are also presented in table 3. The extracted leaves gained approximately 171 B.t.u./lb. from spring to fall. The stems gained 148 B.t.u./lb.

Assuming that the difference between the heat content of the total fuel and the heat content of the extracted fuel, ΔH, is due solely to extractives, we plotted ΔH against extractive content (figs. 8 and 9). The coefficient of determination, r^2, is 0.60 for leaves and 0.44 for stems. The data were determined to fit a linear line and the equations are

Leaves: $\bar{Y} = 156 + 82.2X$
Stems: $\bar{Y} = 120 + 78.0X.$

The level of significance of the regression line is >99.0 percent according to the F test.

This relationship is complicated by the likelihood of seasonal variation in the heat content of the extractives themselves. Therefore it was necessary to determine this for the samples. The heat content of the ether extractives was calculated by the following relationship:

$$(1 - \text{fraction ext.}) \cdot (H_{ex}) + \text{fraction ext.} \cdot (H_{ext}) = H_{tot}$$

where

fraction ext.	=	extractive content (fraction dry weight)
H_{ex}	=	heat content of the extracted fuel (B.t.u./lb.)
H_{ext}	=	heat content of the extractives (B.t.u./lb.)
H_{tot}	=	heat content of the total fuel (B.t.u./lb.).

Heat content of the extractives calculated from 14 samples was

Leaves: $\bar{X} = 15{,}564$
Range = 3,933 (13,445 − 17,378)
Stems: $\bar{X} = 19{,}012$
Range = 7,321 (17,212 − 24,533).

The average heat content of leaf extractives from three of the 1963 plants was found to be 15,679 B.t.u./lb. by actual measurement.

There is a direct relationship for leaves between extractive content and heat content of the total fuel (H_{tot}). This implies a seasonal trend in H_{ext} for leaves. For stems, the trend does not appear to be the same, since the values remain fairly constant during summer and fall.

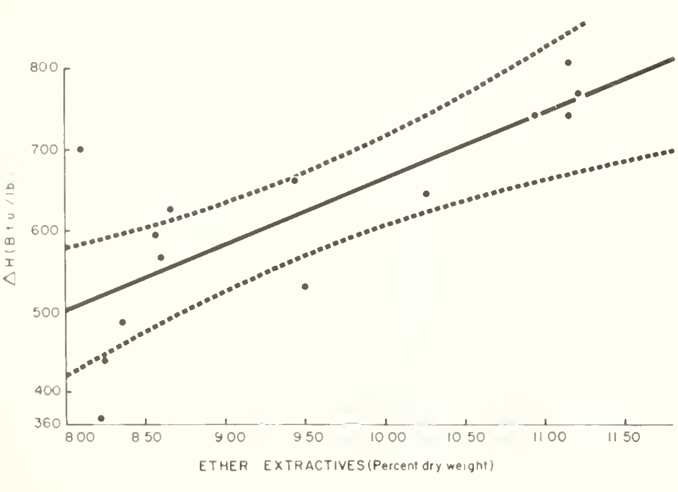


Figure 8. — The relationship between ΔH and the extractive content of the leaves.

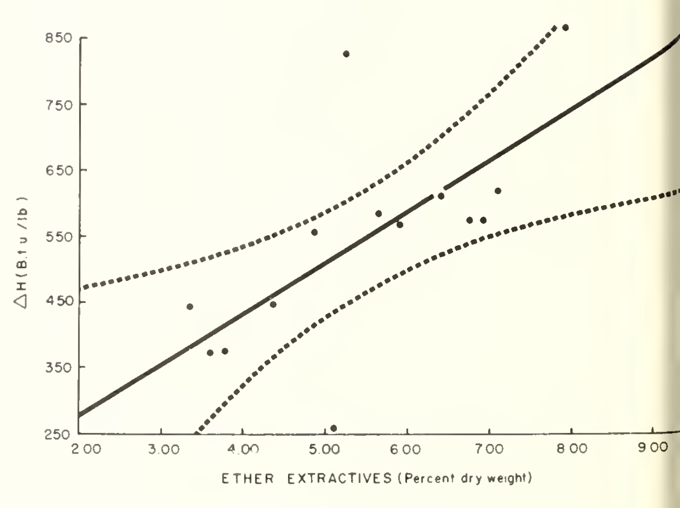


Figure 9. — The relationship between ΔH and the extractive content of the stems.

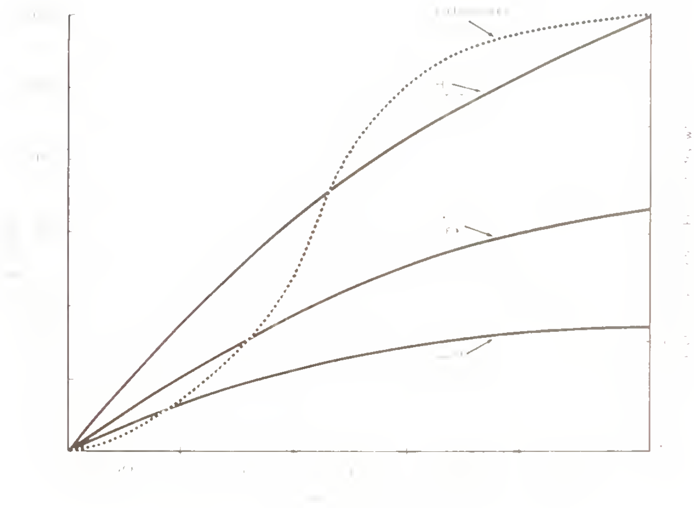


Figure 10. — Calculated heat content trends.

CONCLUSIONS

This study shows the following relationships for chamise:

1. The ether extractive content of the leaves ranged from a low of about 8.5 percent in the spring to about 12 percent in the fall for leaves and from 4.3 percent (spring) to 8.9 percent (fall) for stems. The dip at spring is probably partly due to new leaf flush and stem elongation. This new plant material has a lower extractive content.

2. The heat content of the total fuel, leaves, and small stems is directly related to their ether extractive content. The heat content of leaves increased 600 B.t.u./lb. and that of stems increased 465 B.t.u./lb. from May to October.

3. The heat content of the leaves and stems after extraction increased during the same period. Increase for leaves was about 171 B.t.u./lb.; and for stems, about 148 B.t.u./lb.

4. The computed heat content of the ether extractives was much higher from the stems and varied with time of year. It was at its highest for leaves at the end of the fire season. Values as high as 17,378 B.t.u./lb. for leaves and 24,533 B.t.u./lb. for stems were found. This variation implies a significant compositional change with season in the compounds making up the extractives.

The change in heat content of the leaves during the fire season (June through October) can be summarized graphically using the equations and data from this study (fig. 10).

The effect of this change will not be known until further research establishes the relation between flammability and extractives. An increase in flammability would be expected because of the increase in heat content. We found a direct relation between extractive content and the burning rate of aspen leaves (Philpot 1969). Also, if part of the extractives added to the leaves is deposited on the surface, rate of spread may be enhanced. However, the change probably is not very important from a fire hazard standpoint if the added heat content is not more available than the rest of the fuel within a specific species.

LITERATURE CITED

American Society for Testing and Materials.
1956a. Method of test for ash in wood, D1102-56, Philadelphia, Pa.

American Society for Testing and Materials.
1956b. Standard method of test for ether solubility of wood, D1108-56, 3 pp.

American Society for Testing and Materials.
1962. Tentative method of test for water using Karl Fischer Reagent, E203-62T.

American Society for Testing and Materials.
1966. Method of test for gross calorific value of solid fuel by adiabatic bomb calorimetry, D2015-66.

Buck, Charles C.
1951. Inflammability of chaparral depends on how it grows. U. S. Forest Serv., California Forest and Range Exp. Sta., Misc. Pap. 2, 2 pp.

Countryman, C. M.
1964. Mass fires and fire behavior. U. S. Forest Serv. Res. Pap. PSW-19, 55 pp.

Davis, James R.
1968. Freeze drying for preparing Arizona chaparral plants for energy analysis. USDA Forest Serv. Res. Note RM-106, 2 pp.

Dell, John D., and C. W. Philpot.
1965. Moisture content of various size components of live and dead chamise. U. S. Forest Serv. Res. Note PSW-83, 6 pp.

Dietz, Donald R., Robert H. Udall, and Lee E. Yeager.
1962. Chemical composition and digestibility by mule deer of selected forage species; Cache La Poudre Range, Colorado, Colorado Game and Fish Dep. Tech. Pub. 14, 88 pp.

Fons, W. L., H. D. Bruce, W. Y. Pong, and S. S. Richards.
1960. Project fire model — summary progress report. U. S. Forest Serv., Pacific Southwest Forest and Range Exp. Sta. 55 pp., illus.

Leonard, O. A., and C. E. Carlson.
1957. Control of chamise and brush seedlings by aircraft spraying. California Div. Forest., Range Improvement Studies, No. 2, 27 pp., illus.

Mutch, R. W.
1964. Ignition delay of ponderosa pine needles and sphagnum moss. J. Appl. Chem. 14: 271-275.

Olsen, James M.
1960. 1959 green fuel moisture and soil moisture trends in Southern California. U. S. Forest Serv., Pacific Southwest Forest and Range Exp. Sta. Res. Note 161, 8 pp.

Philpot, C. W.
1969. The effect of reducing ether extractives on the burning rate of aspen leaves. USDA Forest Serv. Res. Note INT-92, 6 pp., illus.

Philpot, C. W., and R. W. Mutch.
1968. The flammability of herbicide-treated guava foliage. USDA Forest Serv. Res. Pap. INT-54, 9 pp.

Richards, Leon W.
1940. Effect of certain chemical attributes of vegetation on forest flammability. J. Agr. Res. 60:833-838.

Short, H. L., Donald R. Dietz, and E. E. Remmenga.
1966. Selected nutrients in mule deer browse plants. 33 pp. Ecology 47(2): 222-229, illus.

Steele, G. D., and J. H. Torrie.
1960. Principles and procedures of statistics, p. 107. New York: McGraw-Hill Book Co., 481 pp.

U. S. Forest Service.
1963. Annual Report, Rocky Mountain Forest and Range Experiment Station, 22 pp.

Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field Research Work Units are maintained in:

- Boise, Idaho
- Bozeman, Montana (in cooperation with Montana State University)
- Logan, Utah (in cooperation with Utah State University)
- Missoula, Montana (in cooperation with University of Montana)
- Moscow, Idaho (in cooperation with the University of Idaho)
- Provo, Utah (in cooperation with Brigham Young University)

FOREST SERVICE CREED

The Forest Service of the U. S. Department of Agriculture is dedicated to the principle of multiple use management of the Nation's forest resources for sustained yields of wood, water, forage, wildlife, and recreation. Through forestry research, cooperation with the States and private forest owners, and management of the National Forests and National Grasslands, it strives — as directed by Congress — to provide increasingly greater service to a growing nation.

EXCLOSURES AND NATURAL AREAS ON RANGELANDS IN UTAH

W. A. Laycock

RESEARCH PAPER INT-62, 1969

FOREST SERVICE
U S
DEPARTMENT OF AGRICULTURE

Intermountain Forest & Range Experiment Station

Ogden, Utah

COVER: This exclosure on the Beaver District of the Fishlake National Forest is typical of the many two-part exclosures found throughout Utah. In this exclosure, cattle were excluded, while deer were permitted behind the fence in the area on the right. Both cattle and deer were excluded in the area on the left. Note lack of aspen reproduction where deer were permitted and abundant reproduction where they were excluded.

USDA Forest Service
Research Paper INT-62
1969

EXCLOSURES AND NATURAL AREAS ON RANGELANDS IN UTAH

W. A. Laycock

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401
Joseph F. Pechanec, Director

FOREWORD

The following members of the Research Committee of the Utah Section of the American Society of Range Management assisted materially in the compilation of this list: Mont E. Lewis, Chief, Branch of Range Studies and Training, Regional Office, Intermountain Region, USDA Forest Service, Ogden, Utah; Homer D. Stapley, Biologist (Big Game and Furbearers), Division of Fish and Game, Department of Natural Resources, State of Utah, Salt Lake City; A. T. Bleak, Range Scientist, Crops Research Laboratory, Agricultural Research Service, Utah State University, Logan; and Lamar R. Mason, Range Conservationist, USDA Soil Conservation Service, Salt Lake City.

Most of the information on individual protected areas was furnished by rangers and other staff members on the National Forest and Bureau of Land Management districts and staff members of the Division of Fish and Game, Utah Department of Natural Resources.

The author, who joined the Station in 1958, is Plant Ecologist and Leader of the Mountain Herbland, Brush, and Aspen Ranges Research Work Unit and is stationed in Logan at the Forestry Sciences Laboratory, maintained in cooperation with Utah State University. He was formerly stationed at Provo and at the U.S. Sheep Station Experimental Range in Dubois, Idaho. He received the degrees of bachelor and master of science in range management from the University of Wyoming and a doctoral degree in plant ecology from Rutgers University. Beginning in July 1969, he took a year's leave of absence to serve as a Senior Research Fellow with the New Zealand National Research Advisory Council assigned to the New Zealand Forest Service's Forest and Range Experiment Station at Rangiora.

CONTENTS

INTRODUCTION

Exclosures, natural areas, and other types of areas that have received either little or no use by domestic livestock have long been used as reference areas by range managers and scientists. The importance of exclosures in range management was discussed by Williams (1962) and a summary of the importance of natural areas in the evaluation of the grazing resources of North America was presented by Anderson (1966).

The need for a listing of exclosures and natural areas in any specific area has been recognized. For the land manager, knowledge of an existing exclosure may make erection of additional exclosures unnecessary. For the research worker, such a list may provide locations of areas relatively undisturbed by domestic livestock for ecological studies.

A list of all livestock and big game exclosures in Wyoming was published by Williams (1963). Young (1958) prepared a list of 36 big game exclosures in Utah but the list was not intended to be a complete inventory, did not include livestock exclosures or natural areas, and has not been updated.

Because of the need for knowledge about exclosures and natural areas, the American Society of Range Management initiated a "Reference Area" program. Included among this program's objectives is the compilation of a comprehensive list of existing exclosures and natural areas on rangelands in North America. Anderson (1966) described the goals of this program.

The list presented here is part of the "Reference Area" program and it includes all known fenced areas in Utah protected from grazing by either livestock or big game as well as larger "natural areas" that are thought to have received little or no use by domestic livestock because of natural barriers or inaccessibility. In addition, some watershed basins along the Wasatch front from which grazing has been excluded for many years are also included.

The exclosures and natural areas are grouped under the agency which administers or controls the land on which they occur and are further subdivided under districts in the case of the National Forests and Bureau of Land Management. Where an agency other than the land managing agency was involved in the construction, maintenance, or record-keeping, the cooperating agency is indicated in parentheses by the following abbreviations after the name of the exclosure:

- ARS: Agricultural Research Service
- IF&RES: Intermountain Forest and Range Experiment Station (USDA Forest Service)
- SCS: Soil Conservation Service
- UF&G: Utah Division of Fish and Game
- UofU: University of Utah
- USU: Utah State University

Information about the same exclosure reported by more than two agencies (usually the Utah Division of Fish and Game and another agency) was merged as accurately as possible, although conflicting information was sometimes encountered. If a conflict in name occurred, both names are given. Conflicts about size, date of establishment, location, etc., were resolved by contacting the agencies involved or by using the information thought to be most accurate. However, some errors undoubtedly exist in the list and corrections will be welcomed.

Information for each exclosure or natural area is abstracted using the following sequence:

- Numbers are merely used for indexing purposes (natural areas are indicated by an asterisk to the left of the number and a complete listing of the numbers of all natural areas is included in the index by date of establishment)
- Name of exclosure
- Legal description (quarter section, section, township, range)
- County
- Elevation
- Date established
- Vegetation type or major species
- Number of parts and size of each
- Type of animal excluded
- If vegetation in an exclosure has been sampled, this is indicated by a "V." If photographs have been taken of the exclosure this is indicated by a "P."
- Information about some individual exclosures or natural areas has been published in theses at universities and in scientific journals. References to these publications appear in parentheses at the end of the abstracts where appropriate.

The 529 exclosures and natural areas are numbered consecutively and indexes by county, date of establishment, elevation, types of animals excluded, and vegetation type or species present are presented at the end.

FUTURE STUDIES AND ADDITIONAL EXCLOSURES

Those who wish to study any of the exclosures listed should obtain permission from the land management agency responsible for the exclosure and also any other cooperating agency indicated before studies or sampling are initiated inside or in the immediate vicinity of the exclosure. This will assure that new studies do not conflict with or possibly destroy the value of any ongoing research or administrative studies.

Anyone having knowledge of additional natural areas, fenced study plots, or exclosures is urged to contact the author or some other representative of the Utah Section of the American Society of Range Management. When new exclosures are built they should also be reported in a similar manner (see fig. 1). Likewise, the destruction of existing exclosures should be reported. If enough corrections and additional information are received in the next 5 years, a supplement to this list may be issued.

The forms supplied for each exclosure (fig. 1) contained more information than is included in each abstract. These forms and maps of each ranger district, etc., with the location of the exclosures marked, are now filed in the American Society of Range Management Depository Library at Utah State University. Permission to examine the records should be obtained from the Chairman of the Range Science Department.

INVENTORY OF EXCLOSURES AND NATURAL AREAS IN UTAH
Research Committee, Utah Section, American Society of Range Management

NAME OF EXCLOSURE: ____________________

LOCATION: Quarter section____, Section____, Township____, Range____, County____

Ownership of Land____________________

ALTITUDE:__________ EXPOSURE:__________ SLOPE (%)__________

GENERAL DESCRIPTION OF AREA: ____________________

____

DATE ESTABLISHED: ____________________

Subsequent Alterations: ____________________

SIZE AND DIMENSIONS: ____________________

TYPE OF ANIMALS EXCLUDED: ____________________

TYPE AND HEIGHT OF FENCE:__________ In Good Repair?__________

VEGETATION TYPE AND/OR MAJOR SPECIES:____________________

____

Cultural treatments (seeding, spraying, etc.) if any:____________________

VEGETATION SAMPLING:

Has vegetation been sampled in exclosure?______ On grazed range outside?______

If so, when, and by what methods?____________________

Where are records located?____________________

PHOTOGRAPHS: Have photographs been taken of the Exclosure?_____ Grazed range?_____

If so, when?____________________

Black and White__________ Color transparency__________

Where are photos or negatives filed?____________________

GEOLOGICAL FORMATION:__________ SOIL TYPE:__________

Soil Depth:__________ Has profile been described?__________

GENERAL COMMENTS:____________________

____

____

REPORTED BY:__________ Title:__________ Date:__________

Figure 1.--Example of form used to report exclosure information.

ASHLEY NATIONAL FOREST

Altonah District

1. Jackson Park: SE1/4, sec. 26, T. 3 N., R. 4 W.; Duchesne; 10,700'; dry meadow; 16' X 16'; cattle; P.

2. Lake Ford Canyon: SW1/4, sec. 34, T. 2 N., R. 5 W.; Duchesne; 7,600'; sagebrush; 16' X 16'; cattle.

3. Lake Fork Mountain - Bear Park: NW1/8, sec. 13, T. 2 N., R. 5 W.; Duchesne; 10,500'; grass; 16' X 16'; cattle.

4. Lower Yellowstone: SW1/4, sec. 33, T. 2 N., R. 4 W.; Duchesne; 7,900'; 1951; sagebrush (sprayed), seeded grass (smooth brome and crested wheatgrass); 3 X 3 chains; cattle.

5. Miners Gulch: NE1/4, sec. 36, T. 2 N., R. 7 W.; Duchesne; 7,500'; sagebrush; 16' X 16'; sheep and cattle.

6. Ottosen Basin: NW1/4, sec. 6, T. 3 N., R. 6 W.; Duchesne; 10,800'; meadow; 16' X 16'; sheep.

7. Power Plant, Yellowstone: NW1/4, sec. 27, T. 2 N., R. 4 W.; Duchesne, 7,800'; sagebrush (sprayed), grass; 16' X 16'; cattle.

8. Yellowstone - Swift Creek: SE1/4, sec. 4, T. 2 N., R. 4 W.; Duchesne; 8,100'; 1950; sagebrush; 3 X 3 chains; cattle.

Duchesne District

9. Anthro Mountain Pilot Planting: SW1/4, sec. 14, T. 6 S., R. 5 W.; Duchesne; 8,100'; 1955; sagebrush, seeded grass (wheatgrasses); 1 acre; cattle; V.

10. Cottonwood Ridge Pilot Planting Plot: SE1/4, sec. 17, T. 6 S., R. 6 W.; Duchesne; 8,800'; 1956; sagebrush, seeded grass (wheatgrasses, smooth brome); 1 acre; cattle; V; P.

11. Sowers Canyon Experimental Reseeding: N1/2, sec. 31, T. 6 S., R. 6 W.; Duchesne; 7,800'; 1958; seeded grass (smooth brome, wheatgrasses); rabbitbrush; 40 acres; cattle; V; P.

12. Timber Canyon: NW1/4, sec. 20, T. 5 S., R. 9 W.; Duchesne; 7,800'; 1943; sagebrush; 1/2 acre; cattle, sheep.

13. Trail Hollow Pilot Planting: NE1/4, sec. 33, T. 2 N., R. 9 W.; Wasatch; 9,500'; 1955; sagebrush, seeded grass (wheatgrasses, smooth brome, mountain brome); 1 acre; sheep; V.

Manila District

14. Death Valley Game (UF&G): NE1/4, sec. 24, T. 2 N., R. 19 E.; Daggett; 7,800'; 1951; sagebrush, mountain brush; 100 sq. ft.; deer, cattle; V; P.

15. Dowd's Hole: Sec. 30, T. 2 N., R. 20 E.; Daggett; 7,700'; 1922; sagebrush, bluegrass; 1/10 acre; sheep, cattle; V.

ASHLEY NATIONAL FOREST

Manila District

16. Dowd Mountain Game (UF&G): Sec. 24, T. 2 N., R. 19 E.; Daggett; 8,000'; 1950; sagebrush, mountain brush; 1/4 acre; sheep; V.

17. Dutch John Game (UF&G): Sec. 4, T. 2 N., R. 22 E.; Daggett; 6,400'; 1959; mountain mahogany; in 2 parts:
    a. 1 acre; cattle; V; P;
    b. 1 acre; cattle; deer; V; P.

18. Hickerson Park: Sec. 19, T. 2 N., R. 18 E.; Daggett; 9,000'; 1922; meadow; 20' X 20'; cattle, horses; V.

19. Long Park: Sec. 14, T. 2 N., R. 18 E.; Daggett; 8,500'; 1923; sagebrush, bluegrass; 16' X 16'; cattle, horses; V.

20. Meadow Park: Sec. 2, T. 1 N., R. 20 E.; Daggett; 8,000'; 1929; sagebrush; 1/10 acre; sheep, goats; V.

21. Sheep Creek Park: Sec. 36, T. 2 N., R. 18 E.; Daggett; 8,600'; 1924; sagebrush, bluegrass; 1/10 acre; cattle, horses; V.

Roosevelt District

22. Bennion Park Study Plot: SE1/4, sec. 11, T. 3 N., R. 2 W.; Duchesne; 10,000'; 1923; grass; 16' X 16'; cattle, sheep.

23. Farm Creek Proper Use: NE1/4, sec. 15, T. 2 N., R. 1 W.; Duchesne; 8,000'; 1956; sagebrush (sprayed), grass; 1 acre; cattle; V; P.

24. Farm Creek Study Plot: NW1/4, sec. 23, T. 2 N., R. 1 W.; Uintah; 7,000'; 1922; seeded grass (crested wheatgrass, smooth brome); 16' X 16'; cattle, sheep.

25. Kidney Lake: NE1/4, sec. 28, T. 5 N., R. 3 W.; Duchesne; 12,000'; 1956; alpine grass; 1 acre; sheep; V; P.

26. Lake Mountain Study Plot (UF&G): NW1/4, sec. 32, T. 2 S., R. 19 E.; Uintah; 9,000'; 1925; aspen, sagebrush; 18' X 18'; cattle; V.

27. Mosby Canyon Study Plot: SE1/4, sec. 31, T. 2 S., R. 19 E.; Uintah; 8,200'; 1922; sagebrush; 16' X 16'; cattle; V.

28. Mosby Face Reseed Plot (Lake Mtn. Game)(UF&G): SW1/4, sec. 32, T. 2 S., R. 19 E.; Uintah; 9,000'; 1961; aspen; in 3 parts:
    a. 2-1/2 acres; cattle; V; P;
    b. 2-1/2 acres; cattle, elk, and deer; V; P;
    c. 6/10 acre; cattle; P; (established in 1968).

29. Mosby Mountain Game (UF&G): SW1/4, sec. 11, T. 3 S., R. 18 E.; Uintah; 8,000'; 1959; mixed shrub; in 2 parts:
    a. 2-1/2 acres; cattle; V; P;
    b. 2-1/2 acres; cattle, elk, and deer; V; P.

30. Mosby Mountain Study Plot: SW1/4, sec. 24, T. 3 S., R. 18 E.; Uintah, 7,500'; 1923; sagebrush; 16' X 16'; cattle, sheep.

Roosevelt District

31. Pole Creek Study Plot: SE1/4, sec. 34, T. 3 N., R. 2 W.; Duchesne; 1923; sagebrush; 16' X 16'; cattle, sheep; V.

32. Summit Park Study Plot: SW1/4, sec. 1, T. 3 N., R. 1 W.; Uintah; 10,500'; 1923; grass; 16' X 16'; cattle, sheep.

Vernal District

33. Brush Creek Mountain: Sec. 12, T. 2 S., R. 21 E.; Uintah; 8,100'; 1939; sagebrush; cattle; V; P.

34. Diamond Mountain: Sec. 4, T. 2 S., R. 22 E.; Uintah; 8,000'; 1952; aspen; in 2 parts:
    a. 1 acre; cattle; V; P;
    b. 1 acre; cattle, deer, elk; V; P.

35. East Brush Creek (UF&G): NW1/4, sec. 9, T. 2 S., R. 22 E.; Uintah; 7,800'; 1962; sagebrush, mountain mahogany; in 2 parts:
    a. 2-1/2 acres; cattle; V; P;
    b. 2-1/2 acres; cattle, deer, elk; V; P.

36. East McKee (Bowden Draw): Sec. 29, T. 1 N., R. 22 E.; Daggett; 8,300'; 1939; sagebrush; 1 acre; sheep; V.

37. Leidy Peak: SW1/4, sec. 31, T. 1 N., R. 19 E.; Uintah; 10,800'; 1957; alpine grass; 5 acres; sheep; V.

38. Pine Hollow Administrative Study: Sec. 3, T. 2 S., R. 21 E.; Uintah; 8,300'; 1965; scrub aspen (sprayed), sagebrush; in 2 parts:
    a. 2 acres; cattle; V; P;
    b. 2 acres; cattle, deer, elk; V; P.

39. Taylor Mountain (UF&G): SW1/4, sec. 20, T. 2 S., R. 21 E.; Uintah; 7,700'; 1962; sagebrush, mountain mahogany; in 2 parts:
    a. 2-1/2 acres; cattle; V; P;
    b. 2-1/2 acres; cattle, elk, deer; V; P.

40. West Brush Creek (UF&G): SE1/4, sec. 2, T. 2 S., R. 21 E.; Uintah; 8,100'; 1962; aspen, sagebrush; in 2 parts:
    a. 2-1/2 acres; cattle; V; P;
    b. 2-1/2 acres; cattle, deer, elk; V; P.

Intermountain Forest and Range Experiment Station

Diamond Mountain Cattle Allotment (Vernal District): Secs. 15, 20, 21, 22, 23, 27, 34; T. 1 S., R. 22 E.; Secs. 1, 2, 3, 4, 11; T. 2 S., R. 22 E.; Uintah; 8,000'; 1959;

41-45. 5 exclosures in seeded grass (crested wheatgrass, smooth brome); 33' X 33'; cattle; V; P;

46-48. 3 exclosures in aspen; 33' X 33'; cattle; V; P;

49-55. 7 exclosures in sagebrush; 33' X 33'; cattle; V; P;

56. 1 exclosure in mountain brush; 33' X 33'; cattle; V; P.

CACHE NATIONAL FOREST

Logan District

57. Mud Flat: NE1/4, sec. 9, T. 12 N., R. 3 E.; Cache; 1955; grass, forb; 6 acres; cattle..

58. Card Canyon (UF&G): SW1/4, sec. 19, T. 12 N., R. 3 E.; Cache; 5,300'; 1946; sagebrush; 1/2 acre; game, livestock; P.

59. Hansen's Draw (UF&G): NE1/4, sec. 29, T. 12 N., R. 2 E.; Cache; 5,000'; 1936; mountain brush; 1/5 acre; game, livestock; P.

60. Pleasant Valley: NE1/4, sec. 34, T. 11 N., R. 3 E.; Cache; 1954; sagebrush (plowed), seeded grass; 2 acres; cattle.

Randolph District

61. Arb's Basin: NW1/4, sec. 15, T. 9 N., R. 4 E.; Rich; 8,500'; 1955; sagebrush (sprayed), seeded grass; 396' X 396'; sheep; V.

62. Elk Valley: NW1/4, sec. 27, T. 12 N., R. 4 E.; Cache; 6,900'; 1955; sagebrush (sprayed), seeded grass; 462' X 462'; cattle; V.

63. Wasatch Ridge: NE1/4, sec. 28, T. 8 N., R. 4 E.; Weber; 8,700'; 1960; sagebrush (sprayed), seeded grass; sheep; V; P.

DIXIE NATIONAL FOREST

Cedar City District

64. Asay Bench (UF&G): SE1/4, sec. 31, T. 37 S., R. 6 W.; Garfield; 7,800'; 1960; bitterbrush, mixed shrub; in 2 parts:
    a. 2 acres; livestock; P;
    b. 1 acre; livestock and game; P.

65. Blowhard: NW1/4, sec. 14, T. 37 S., R. 9 W.; Iron; 10,000'; 1925' grass meadow; 34' X 34'; sheep; V.

66. Bowers Flat: SW1/4, sec. 27, T. 37 S., R. 7 W.; Garfield; 8,100'; 1938; open grass in ponderosa pine; 1 acre; sheep.

67. Bowery: SW1/4, sec. 9, T. 35 S., R. 8 W.; Iron; 7,800'; 1952; sagebrush; 1 acre; cattle; V; P.

68. Burrows Flat: NW1/4, sec. 26, T. 37 S., R. 7 W.; Garfield; 8,000'; 1909; ponderosa pine; grass; 5 acres; sheep; V; P.

69. Long Valley: SW1/4, sec. 12, T. 37 S., R. 8 W.; Iron; 10,000'; 1960; seeded grass (smooth brome, wheatgrasses, Kentucky bluegrass); 6.5 acres; sheep; V; P.

70. Midway: NW1/4, sec. 25, T. 37 S., R. 9 W.; Iron; 9,300'; 1925; grass meadow; 34' X 34'; sheep; V; P.

71. Sage Valley: NW1/4, sec. 30, T. 29 S., R. 8 W.; Iron; 9,600'; 1962; silver sagebrush, seeded grass; 5 acres; sheep.

72. Six Lakes: SE1/4, sec. 8, T. 36 S., R. 9 W.; Iron; 9,700'; 1925; aspen; 12 X 16 rods, increased to 1.2 acres in 1962; sheep and cattle; V; P.

Cedar City District

73. Tippetts Valley: SW1/4, sec. 23, T. 37 S., R. 8 W.; Iron; 9,000'; 1952; aspen; 1 acre; cattle; P.

74. Strawberry Valley: NE1/4, sec. 31, T. 38 S., R. 7 W.; Kane; 8,000'; 1952; grass; 1 acre; cattle; V; P.

75. Uinta Flat: NW1/4, sec. 1, T. 38 S., R. 7 W.; Garfield; 7,900'; 1960; ponderosa pine, seeded grass; 5 acres; sheep; V; P.

76. Webster Flat (UF&G): SE1/4, sec. 30, T. 37 S., R. 9 W.; Iron; 9,200'; 1965; aspen; in 2 parts:
   a. 400' X 700'; sheep and cattle; V; P;
   b. 600' X 900'; sheep, cattle, and deer; V; P.

Circleville District

77. Coyote Hollow: SW1/4, sec. 21, T. 32 S., R. 1 E.; Garfield; 9,500'; seeded grass (crested wheatgrass); 10 acres; cattle; V; P.

78. Riddle Swale (UF&G): NW1/4, sec. 19, T. 33 S., R. 1 W.; Garfield; 7,800'; 1962; black sagebrush, mixed shrub, partially reseeded to intermediate wheatgrass; in 2 parts:
   a. 1 acre; cattle; V; P;
   b. 2 acres; cattle and deer; V; P.

79. Woodchuck (UF&G): SW1/4, sec. 28, T. 31 S., R. 2-1/2 W.; Garfield; 9,000'; 1947; sagebrush, mixed shrub with scattered aspen; in 2 parts:
   a. 1 acre; cattle; V; P;
   b. 1 acre; cattle and deer; V; P.

Enterprise District

80. Cave: NW1/4, sec. 10, T. 38 S., R. 18 W.; Washington; 6,500'; 1920; mixed shrub; livestock; V; P.

81. Colie Flat (UF&G): SW1/4, sec. 2, T. 38 S., R. 19 W.; Washington; 6,700'; 1950; mountain brush; in 2 parts:
   a. 1 acre; cattle; V; P;
   b. 1 acre; cattle and deer; V; P.

82. General Stream Road (UF&G): Sec. 22, T. 39 S., R. 17 W.; Washington; 4,900'; pinyon-juniper, blackbrush; 5 acres; cattle.

83. Iron Peg (UF&G): Sec. 36, T. 37 S., R. 15 W.; Iron; 6,000'; 1954; mixed shrub; in 2 parts:
   a. 1 acre; livestock;
   b. 1 acre; livestock and deer; V; P.

84. Jessie Tie Wash: SE1/4, sec. 30, T. 36 S., R. 19 W.; Washington; 5,500'; 1946; sagebrush, seeded grass; 5 acres; cattle (some portions rabbit tight); V; P. (See Cox 1965).

85. Pine Creek: NE1/4, sec. 1, T. 38 S., R. 19 W.; Washington; 1920's or early 1930's; seeded grass (crested wheatgrass, smooth brome); 5 acres; cattle.

Enterprise District

86. Racer (Pilot Mountain) (UF&G): NW1/4, sec. 24, T. 38 S., R. 18 W.; Washington; 5,900'; 1933; mountain brush; in 2 parts:
    a. 1/6 acre; cattle; V; P;
    b. 1/6 acre; cattle and deer; V; P.

87. Richie Flat (UF&G): SW1/4, sec. 30, T. 37 S., R. 14 W.; Iron; 6,000'; 1956; seeded grass; in 2 parts:
    a. 1 acre; cattle; V; P;
    b. 1 acre; cattle, deer, and rodents; V; P.

88. Rock Hole: NE1/4, sec. 9, T. 37 S., R. 19 W.; Washington; 6,000'; 1946; sagebrush (sprayed), seeded grass; 5 acres; cattle and rabbits; V; P.

89. Roundup Flat: SW1/4, sec. 18, T. 37 S., R. 19 W.; Washington; 5,980'; 1930; pinyon-juniper, sagebrush; 300 sq. ft.; cattle; V; P.

90. Water Canyon: NE1/4, sec. 2, T. 38 S., R. 19 W.; Washington; 7,500'; 1932; mixed shrub; 10 X 20 rods; cattle.

Escalante District

91. Allen Canyon: NE1/4, sec. 30, T. 35 S., R. 1 E.; Garfield; 7,600'; 1962; oak, mixed shrub; 1 acre; livestock and deer; V; P.

92. Davis Flat: SE1/4, sec. 19, T. 32 S., R. 2 E.; Garfield; 10,000'; 1952; seeded grass; 151' X 120'; livestock.

93. Griffin Top Pilot Plot: NW1/4, sec. 2, T. 34 S., R. 1 W.; Garfield; 10,500'; 1962; seeded grass (orchardgrass, smooth brome); 6.3 acres; livestock; V; P.

94. Middle Deer Creek: SW1/4, sec. 19, T. 32 S., R. 5 E.; Garfield; 9,000'; 1944; grass (seeded wheatgrasses on half); 1/2 acre; livestock.

95. North Creek: Sec. 19, T. 33, R. 1 E.; Garfield; 1940; seeded grass (smooth brome) 1 acre; livestock.

Panguitch Lake District

96. Black Lava (Blackrock) (UF&G): NE1/4, sec. 29, T. 36 S., R. 7 W.; Garfield; 7,000'; 1961; ponderosa pine, bitterbrush; 120' X 180'; livestock and deer.

97. Blowup Deer (UF&G): NE1/4, sec. 19, T. 34 S., R. 7 W.; Iron; 7,500'; 1930 (enlarged in 1961); ponderosa pine, oak, mountain brush; in 2 parts:
    a. 100' X 100'; cattle; P;
    b. 90' X 90'; cattle and deer; P.

98. Little Valleys (Corral Hollow) (UF&G): SE1/4, sec. 26, T. 34 S., R. 7 W.; Iron; 8,000'; 1930-1935; sagebrush, bitterbrush; 120' X 120'; cattle and sheep; P.

99. Lower West Pass (Pass Exclosure #2) (UF&G): NW1/4, sec. 7, T. 36 S., R. 6 W.; Garfield; 7,000'; 1952; sagebrush, seeded grass (crested wheatgrass); 120' X 320'; sheep and cattle; V; P.

Panguitch Lake District

100. Panguitch Lake (Haycock Creek) (UF&G): SW1/4, sec. 27, T. 35 S., R. 7 W.; Garfield; 8,200'; 1950; sagebrush, seeded grass (crested wheatgrass); 360' X 360'; cattle and sheep.

101. Upper West Pass (Pass Exclosure #1) (UF&G): NW1/4, sec. 1, T. 36 S., R. 7 W.; Garfield; 7,200'; 1952; sagebrush, seeded grass (crested wheatgrass); 200' X 200'; sheep and cattle; V; P.

Pine Valley District

102. Browse: NE1/4, sec. 19, T. 39 S., R. 13 W.; Washington; 6,100'; 1921, 1933; oak, mountain brush; 179 acres and three 1/3-acre plots within (not in good repair); livestock and deer.

103. Grass Valley (UF&G): NE1/4, sec. 25, T. 38 S., R. 15 W.; Washington; 7,100'; 1942; pinyon-juniper, sagebrush, mountain brush; in 2 parts:
    a. 1-1/6 acres, livestock;
    b. 1-1/6 acres, livestock and deer.

104. Pine Valley (UF&G): SW1/4, sec. 20, T. 39 S., R. 14 W.; Washington; 6,700'; 1935; sagebrush, mountain brush; in 2 parts:
    a. 1/2 acre, livestock; V; P;
    b. 1/2 acre, livestock and big game; V; P.

105. Truman Bench (UF&G): NE1/4, sec. 12, T. 40 S., R. 16 W.; Washington; 5,900'; 1939; pinyon-juniper, sagebrush, mountain brush; 1-1/3 acres; big game.

Powell District

106. Center Creek (Hunt Creek) (UF&G): NE1/4, sec. 21, T. 34 S., R. 3 W.; Garfield; 8,000'; 1961; sagebrush (big and low), blue grama; in 2 parts:
    a. 1 acre; cattle; V; P;
    b. 1 acre; cattle and deer; V; P.

107. Cougar Hollow (UF&G): SW1/4, sec. 5, T. 39 S., R. 4 W.; Kane; 8,500'; 1961; aspen; in 2 parts:
    a. 1 acre; cattle; V; P;
    b. 1 acre; cattle and deer; V; P.

108. Sheep Creek (UF&G): SE1/4, sec. 30, T. 37 S., R. 3 W.; Garfield; 7,000'; 1960; seeded grasses and shrubs in pinyon-juniper (railed); in 3 parts:
    a. 1 acre; cattle;
    b. 1 acre; cattle and deer;
    c. 1 acre; cattle, deer, and rabbits.

Teasdale District

109. Antelope Springs: Sec. 22, T. 31 S., R. 1 E.; Garfield; 9,000'; 1929; sagebrush; 24' X 24'; sheep; V.

110. Bluebell Knoll: Sec. 31, T. 30 S., R. 4 E.; Wayne; 11,120'; 1950; sheep fescue and seeded grass; 5-1/2 acres; sheep; V.

DIXIE NATIONAL FOREST

Teasdale District

111. Boulder Crossing: Sec. 4, T. 30 S., R. 4 E.; Wayne; 8,500'; 1923, sagebrush; 24' X 24' enlarged to 1 acre in 1957; cattle; V; P

112. Pelham Draw: Sec. 17, T. 31 S., R. 2 E.; Garfield; 9,000'; 1927; sagebrush; 1 acre; cattle; V; P.

113. Pot Holes: Sec. 22, T. 30 S., R. 3 E.; Wayne; 8,000'; 1929; sagebrush; 1 acre; livestock; V.

114. Raft Lake: Sec. 32, T. 30 S., R. 4 E.; Wayne; 11,000'; 1924; grass; 16' X 16'; sheep; V.

115. Salt Lake: Sec. 36, T. 31 S., R. 5 E.; Garfield; 8,300'; 1925; grass; 16' X 16'; cattle; V.

116. Steep Creek: Sec. 16, T. 32 S., R. 5 E., Garfield; 8,800'; 1925; mixed shrub, grass; 16' X 16' enlarged to 1 acre in 1967; cattle; V; P.

FISHLAKE NATIONAL FOREST

Beaver District

117. Baker Canyon (UF&G): Sec. 16, T. 29 S., R. 6 W.; Beaver; 7,200'; 1932 (enlarged in 1963); rabbitbrush, sagebrush, seeded grass (crested wheatgrass); 2-1/2 X 1 chain; cattle; P.

118. Bentenson Flat: Sec. 1, T. 30 S., R. 5 W.; Beaver; 9,500'; 1954 and 1958; seeded grass (smooth and mountain brome); 2-1/2 chains X 2-1/2 chains (2 plots); cattle; V; P.

119. Bentenson Flat Burn Aspen Study (UF&G, USU): SW1/4, sec. 30, T. 29 S., R. 4 W.; Beaver; 10,000'; 1961; conifer, aspen (burned in 1957); 42 acres; cattle; V.

120. Big Flat (UF&G): Sec. 19, T. 29 S., R. 4 W.; Beaver; 10,000'; 1950; seeded grass (smooth and mountain brome); in 2 parts:
   a. 2-1/2 X 2-1/2 chains; cattle; V; P;
   b. 2-1/2 X 2-1/2 chains; cattle and deer; P.

121. Birch Creek (Pole Mountain) (UF&G): Sec. 25, T. 30 S., R. 5 W.; Piute; 7,800'; 1952; sagebrush, bitterbrush, mountain mahogany; in 2 parts:
   a. 2-1/2 X 2-1/2 chains; cattle; P;
   b. 2-1/2 X 2-1/2 chains; cattle and deer; P.

122. Grindstone (UF&G) (See front cover); Sec. 29, T. 29 S., R. 4 W.; Piute; 9,000'; 1934; aspen (partly cut); in 2 parts:
   a. 100 X 200 ft.; cattle; V; P;
   b. 100 X 200 ft.; cattle and deer; V; P.

123. Merchant Valley (UF&G): Sec. 3, T. 29 S., R. 5 W.; Beaver; 8,700'; 1932; aspen; in 2 parts:
   a. 1/5 acre; deer;
   b. 1/5 acre; livestock and deer.

Beaver District

124. Timid Springs: Sec. 18, T. 29 S., R. 4 W.; Piute; 10,000'; 1964; spruce-fir (cut over), aspen; in 2 parts:
    a. 1-1/4 X 2-1/2 chains; cattle; P;
    b. 1-1/4 X 2-1/2 chains; deer and cattle; P.

Fillmore District

125. Oak Creek Canyon (UF&G): Sec. 8, T. 17 S., R. 3 W.; Millard; 6,800'; 1952; sagebrush, mountain brush; in 2 parts:
    a. 1-1/2 acres; deer;
    b. 1-1/2 acres; cattle and deer.

126. North Spring: Sec. 18, T. 20 S., R. 2-1/2 W.; Millard; no records.

127. Robins Valley: Sec. 25, T. 20 S., R. 3-1/2 W.; Millard; no records.

Fishlake District

128. Cedarless Flat: SW1/4, sec. 28, T. 26 S., R. 3 E.; Sevier; 8,400'; 1946; seeded grass (crested wheatgrass); 1 acre; cattle; V. (Probably will be discontinued.)

129. Crevice Spring: NE1/4, sec. 25, T. 26 S., R. 2 E.; Sevier; 8,500'; 1946; seeded grass (crested wheatgrass); 1 acre; cattle; V.

130. Hancock Flat - Game Livestock: SE1/4, sec. 11, T. 26 S., R. 1 E.; Sevier; 10,000'; 1962; aspen, conifer; 5 acres; sheep, deer, and elk.

131. Hightop Plateau (Tasha Spring): NW1/4, sec. 30, T. 25 S., R. 2 E.; Sevier; 11,200'; 1959; seeded grass (crested wheatgrass); 5 acres; sheep, deer, and elk.

132. Mt. Terrel: NW1/4, sec. 22, T. 24 S., R. 2 E.; Sevier; 10,000'; Silver sagebrush; 5 acres; cattle. (Probably will be discontinued.)

Kanosh District

133. Big Bench: SE1/4, sec. 9, T. 24 S., R. 4-1/2 W.; Sevier; 8,600'; 1963; sagebrush (sprayed); 10 chains square (10 acres); cattle; V; P.

134. Corn Creek (Kanosh) (IF&RES): NW1/4, sec. 34, T. 23 S., R. 5 W.; Millard; 5,500'; 1931; oak, sagebrush, juniper; 10 acres; cattle; V.

135. Corn Creek Grass Plot: NE1/4, sec. 4, T. 24 S., R. 4-1/2 W.; Millard; 6,200'; 1938; seeded grass (smooth brome); cattle; V; P.

136. Dameron: NW1/4, sec. 5, T. 24 S., R. 5 W.; Millard; 5,500'; 1936; juniper, cliffrose; in 2 parts:
    a. 3/4 acre; cattle;
    b. 3/4 acre; cattle and big game.

Kanosh District

137. Misery Creek: NW1/4, sec. 19, T. 23 S., R. 4 W.; Millard; 8,800'; 1963; aspen, chokecherry; 1 acre; cattle; P.

138. North Cedars (Mud Flat) (UF&G): SW1/4, sec. 12, T. 26 S., R. 5 W.; Sevier; 7,000'; 1963; pinyon-juniper (chained), seeded grass; in 2 parts:
   a. 9 acres; cattle; V; P;
   b. 1 acre; cattle and deer; V; P;
      (30' X 30' rodent exclosure in each part).

139. Rockwood: NE1/4, sec. 34, T. 24 S., R. 4-1/2 W.; Sevier; 8,850'; 1935; aspen; 1 acre; deer and cattle. (Probably will be discontinued.)

140. West Corn Creek: NE1/4, sec. 7, T. 23 S., R. 4 W.; Millard; 9,000'; 1958; aspen, seeded grass; 1 acre; cattle; P.

Loa District

141. Jahu Flat: NW1/4, sec. 17, T. 27 S.; R. 4 E.; Wayne; 9,300'; 1947; seeded grass; 1 acre; cattle.

142. Sheep Valley Study Plot: NE1/4, sec. 22, T. 24 S.; R. 3 E.; Sevier; 10,000'; 1958; seeded grass; 10 acres; cattle; V.

143. Tidwell Revegetation Pilot Plot: NW1/4, sec. 4, T. 26 S., R. 4 E.; Sevier; 8,800'; 1962; sagebrush (sprayed) seeded grass; 25 acres; cattle; V; P.

Monroe District

144. Big Flat: NE1/4, sec. 19, T. 27 S., R. 2 W.; Piute; 9,400'; 1950; sagebrush, seeded grass; 100' X 60'; cattle and sheep.

145. Glenwood Mountain: NE1/4, sec. 30, T. 24 S., R. 1 W.; Sevier; 7,600'; 1957; sagebrush (sprayed), grass; 150' X 150'; cattle and sheep; V; P.

146. John Willis: NW1/4, sec. 33, T. 27 S., R. 2 W.; Piute; 9,250'; 1948; sage-200' X 100'; sheep and cattle; P.

147. Smith Canyon (Willow Creek Game): SW1/4, sec. 17, T. 27 S., R. 2-1/2 W.; Piute; 7,750'; sagebrush, bluebunch wheatgrass; 2 acres; sheep and cattle.

148. South Forshea Mountain: NE1/4, sec. 25, T. 29 S., R. 2-1/2 W.; Piute; 8,900'; 1949; sagebrush (burned and plowed), seeded grass; 2 exclosures, 40' X 60' each; cattle; P. (Probably will be discontinued.)

149. Washburn Reservoir: NW1/4, sec. 28, T. 25 S., R. 2 W.; Sevier; 9,000'; 1966; aspen, seeded grass; 3 to 4 acres; sheep; V; P.

Salina District

150. Black Mountain (UF&G): Sec. 20, T. 22 S., R. 1 E.; Sevier; 7,500'; 1939; pinyon-juniper; in 2 parts:
   a. 1 acre; cattle;
   b. 1 acre; cattle and deer.

FISHLAKE NATIONAL FOREST

Salina District

151. Duncan Mountain Experimental Plot (UF&G): NE1/4, sec. 6, T. 22 S., R. 5 E.; Sevier; 8,300'; 1962; seeded grass (crested wheatgrass); 70 acres; cattle; V; P.

152. Mud Spring (UF&G): Sec. 27, T. 22 S., R. 1 E.; Sevier; 7,200'; 1940; seeded grass (crested wheatgrass); in 2 parts:
    a. 1 acre; cattle;
    b. 1 acre; deer and cattle.

153. Prowse Spring Ripping Study: SW1/4, sec. 29, T. 22 S., R. 1 E.; Sevier; 7,200'; 1964; seeded grass (crested wheatgrass); 10 acres; cattle; V; P.

154. South Water Hollow Elk (UF&G): SW1/4, sec. 2, T. 23 S., R. 4 E.; Sevier; 8,300'; 1961; sagebrush, mahogany, bitterbrush, oak; 200' X 200'; cattle, deer, elk, rabbit; V; P.

155. Willow Creek Plot (Truman's Pasture) (UF&G): NE1/4, sec. 12, T. 21 S., R. 2 E.; Sevier; 9,200'; 1965; seeded grass (intermediate wheatgrass); 112' X 170'; cattle; V; P.

MANTI-LA SAL NATIONAL FOREST

Castle Dale District

156. East Mountain Gap (Pine Spring) (UF&G): SW1/4, sec. 6, T. 17 S., R. 7 E.; Emery; 10,000'; 1962; grass; 1 acre; cattle; V.

157. Grimes Wash (UF&G): NW1/4, sec. 22, T. 17 S., R. 7 E.; Emery; 8,500'; 1962; seeded grass (smooth brome, intermediate wheatgrass); 1 acre; cattle; V; P.

158. Little's Creek Wildlife (UF&G): NW1/4, sec. 31, T. 17 S., R. 6 E.; Emery; 1949; sagebrush, mahogany, bitterbrush, pinyon-juniper; in 2 parts:
    a. 1 acre; livestock; V; P;
    b. 1 acre; livestock and deer; V; P.

159. McCadden Flats: SE1/4, sec. 1, T. 16 S., R. 7 E.; Emery; 8,700'; 1963; seeded grass (sagebrush sprayed); 1 acre; cattle.

160. McCadden Hollow: NW1/4, sec. 1, T. 16 S., R. 7 E.; Emery; 8,500'; 1963; seeded grass (smooth brome, wheatgrasses); 1 acre; cattle.

161. South Trail Mountain (UF&G): NW1/4, sec. 27, T. 17 S., R. 6 E.; Emery; 8,200'; 1962; seeded grass (smooth brome, wheatgrasses); 1 acre; cattle; V; P.

162. South Trail Mountain Wildlife (UF&G): NW1/4, sec. 34, T. 17 S., R. 6 E., Emery; 8,000'; 1962; sagebrush, mountain brush; in 2 parts:
    a. 1 acre; cattle; V;
    b. 1 acre; cattle, deer, and elk; V.

Ephraim District

163. Dry Pole: SE1/4, sec. 11, T. 15 S., R. 5 E.; Sanpete; 10,500'; 1964; seeded grass (Timothy, smooth brome, orchardgrass); 1/4 acre; sheep; V.

Ephraim District

164. Pigeon Creek: Sec. 31, T. 16 S., R. 4 E.; Sanpete; 6,100'; 1962; sagebrush, mountain brush; 2 acres; sheep, cattle, deer, horses, and rabbits; V; P.

165. Reeder Canyon: Sec. 32, T. 16 S., R. 5 E.; Sanpete; 11,000'; 1954; grass, forb; 1 acre; sheep and horses; V.

Ferron District

166. Dairy Creek (Ferron Mountain) (UF&G): NW1/4, sec. 34, T. 19-1/2 S., R. 5 E.; Sanpete; 9,800'; 1954; seeded grass; 100' X 100'; cattle; V; P.

167. East Rim Horn Mountain (North Horn Mountain) (UF&G): Sec. 29, T. 18 S., R. 7 E.; Emery; 8,500'; 1954; sagebrush, seeded grass (crested wheatgrass); in 2 parts:
    a. 1 acre; cattle; V; P;
    b. 1 acre; cattle and deer; V; P.

168. Flagstaff Peak (UF&G): SE1/4, sec. 13, T. 20 S., R. 5 E.; Sanpete; 9,600'; 1952; aspen, seeded grass (smooth brome); 2 acres; cattle; P.

169. South Horn Mountain Big Game Study (UF&G): Sec. 23, T. 19 S., R. 6 E.; Emery; 8,200'; 1963; sagebrush; mahogany, pinyon-juniper; in 2 parts:
    a. 6 acres; cattle; V; P;
    b. 6 acres; cattle and deer; V; P.

170. Wrigley Flat (UF&G): SW1/4, sec. 26, T. 19 S., R. 5 E.; Sanpete; 9,000'; 1957; sagebrush; 2 acres; cattle and sheep; P.

Manti District

171. Clear Creek Flat Tarweed Study: NW1/4, sec. 29, T. 20 S., R. 3 E.; Sanpete; 9,200'; 1958; seeded grass, tarweed; 3 chains square; livestock.

172. Cottonwood Exclosure: SW1/4, sec. 11, T. 18 S., R. 3 E.; Sanpete; 7,200'; 1927; 20' X 15'; livestock.

173. Green's Hollow Elk (UF&G): NW1/4, sec. 29, T. 20 S., R. 5 E.; Sanpete; 8,100'; 1960; sagebrush, seeded grass (crested wheatgrass); in 2 parts:
    a. 1 acre; livestock; V; P;
    b. 1 acre; livestock and deer; V; P.

174. Lowery Cove: Sec. 10, T. 18 S., R. 4 E.; Sanpete; 10,000'; 1932; forb, grass; 18' X 24'; livestock.

175. Manti Canyon, Middle Fork: SE1/4, sec. 16, T. 18 S., R. 4 E.; Sanpete; 10,200'; 1930; grass; 20' X 20'; livestock.

176. Manti Canyon, South Fork: NW1/4, sec. 29, T. 18 S., R. 4 E.; Sanpete; 9,000'; 1930; grass, forb; 18' X 23'; livestock.

177. North Fork, Twelve Mile: SE1/4, sec. 24, T. 19 S., R. 3 E.; Sanpete; 9,100'; 1927; thistle, forb, grass; 20' X 35'; livestock.

Manti District

178. North Fork, Twelve Mile: NE1/4, sec. 26, T. 19 S., R. 3 E.; Sanpete; 8,900'; 1927; tarweed, annuals; 20' X 35'; livestock.

179. Sand Ridge, Six Mile Canyon: NE1/4, sec. 35, T. 18 S., R. 3 E.; Sanpete; 8,400'; 1928; annual and perennial forbs; 20' X 35'; livestock.

180. Twelve Mile Deer (UF&G): SW1/4, sec. 32, T. 19 S., R. 3 E.; Sanpete; 6,600'; 1937 and 1945; sagebrush; in 2 parts:
   a. 3-1/2 X 10 chains; livestock; V; P;
   b. 2-1/2 X 2-1/2 chains; livestock and deer; V; P.

Moab District

181. Amasa's Back (UF&G): SW1/4, sec. 25, T. 27 S., R. 23 E.; San Juan; 7,000'; 1954; serviceberry, mountain mahogany, black sagebrush; in 2 parts:
   a. 1 acre; cattle; V; P;
   b. 1 acre; cattle and deer; V; P.

182. Brumley Ridge Plot (Lower): SE1/4, sec. 4, T. 27 S., R. 24 E.; San Juan; 9,000'; 1961; aspen; 1 acre; cattle.

183. Brumley Ridge Plot (Upper): SE1/4, sec. 4, T. 27 S., R. 24 E.; San Juan; 9,500'; 1957; aspen; 1 acre; cattle.

184. North Beaver Mesa (UF&G): NE1/4, sec. 9, T. 25 S., R. 25 E.; Grand; 7,600'; 1961; oak, mixed shrub, pinyon-juniper; in 2 parts:
   a. 1 acre; cattle; V;
   b. 1 acre; cattle and deer; V.

Monticello District

185. Dry Mesa (UF&G): SE1/4, sec. 16, T. 34 S., R. 18 E.; San Juan; 8,160'; 1947; sagebrush, mixed shrub; in 2 parts:
   a. 1 acre; cattle; V; P;
   b. 1 acre; cattle and deer; V; P.

186. Harts Draw (Lower) (UF&G): NW1/4, sec. 34, T. 32 S., R. 22 E.; San Juan; 6,500'; 1955; sagebrush, pinyon-juniper; in 2 parts:
   a. 1 acre; cattle; V; P;
   b. 1 acre; cattle and deer; V; P.

187. Joshua Flat: SE1/4, sec. 17, T. 36 S., R. 19 E.; San Juan; 8,500'; 1947; aspen, mixed shrubs, seeded grass; 1 acre; cattle and horses; V; P.

188. Little Notch: NW1/4, sec. 35, T. 35 S., R. 19 E.; San Juan; 8,500'; 1947; ponderosa pine, oak, seeded grass; 1 acre; cattle and horses; V.

189. North Long Point (UF&G): NW1/4, sec. 4, T. 34 S., R. 19 E.; San Juan; 8,400'; 1960; aspen, oak, sagebrush; in 2 parts:
   a. 1 acre; cattle; V; P;
   b. 1 acre; cattle and deer; V; P.

190. North Sego Flat: SW1/4, sec. 1, T. 34 S., R. 19 E.; San Juan; 8,500'; 1947; oak, snowberry, seeded grass; 1 acre; cattle and horses; V.

Monticello District

191. Peter's Point (UF&G): NE1/4, sec. 1, T. 37 S., R. 22 E.; San Juan, 7,900'; 1960; sagebrush, oak, mixed shrub (seeded grass and shrubs on part); in 2 parts:
   a. 2 acres; cattle, V; P;
   b. 1 acre; cattle and deer; V; P.

192. Sego Flat: NE1/4, sec. 12, T. 34 S., R. 19 E.; San Juan; 8,500'; 1947; aspen, oak, snowberry, seeded grass; 1 acre; cattle and horses; V; P.

Mount Pleasant District

193. Dairy Fork, Big Game (UF&G): SE1/4, sec. 21, T. 10 S., R. 5 E.; Utah; 6,600'; 1963; sagebrush, oak, and mixed shrub; in 2 parts:
   a. 1 acre; cattle; P;
   b. 1 acre; cattle and deer (1/4 acre rodent proof); V; P.

194. Lasson Draw Big Game: NW1/4 and SW1/4, sec. 28, T. 11 S., R. 4 E.; Utah; 6,400'; 1960; sagebrush, mixed shrub; 2 acres; livestock and big game; V; P.

Intermountain Forest and Range Experiment Station - Great Basin Experimental Area[1] (on Ephraim District except as noted otherwise)

195. Aldous White Knoll Log and Block (Ferron District): SW1/4, sec. 10, T. 18 S., R. 5 E.; Sanpete; 8,600'; 1922; grass, forb; 1/4 acre; sheep; V; P.

196. Alpine Cattle Pasture: NW1/4, sec. 35, T. 17 S., R. 4 E.; Sanpete; 9,900'; 1922; grass, forb; 60 acres; sheep; V; P.

197. Aspen Area: NW1/4, sec. 17, T. 17 S., R. 4 E.; Sanpete; 7,990'; 1928; oak, sagebrush, snowberry, and aspen; 11 acres; sheep.

198. Bear Creek (bottom-slope, below ditch) (Ferron District): NE1/4 sec. 2; T. 18 S., R. 4 E.; Sanpete; 10,000'; 1913; grass, forb; 1/4 acre; sheep; V; P.

199. Bear Creek (high-slope) (ARS), above road (Ferron District): NE1/4, sec. 2, T. 18 S., R. 4 E.; Sanpete; 9,000'; 1951; grass, forb; 1/4 acre; sheep; V.

200. Bear Creek (low-slope) (ARS), below road (Ferron District): NE1/4, sec. 2, T. 18 S., R. 4 E.; Sanpete; 9,000'; 1951; grass, forb; 1/4 acre; sheep; V.

201. Bear Creek (mid-slope, below road) (Ferron District): NE1/4, sec. 2, T. 18 S., R. 4 E.; Sanpete; 10,000'; 1913; grass, forb; 1/4 acre; sheep; V; P.

202. Bear Creek (mid-slope) (ARS), above road (Ferron District): NE1/4, sec. 2, T. 18 S., R. 4 E.; Sanpete; 9,000'; 1951; grass, forb; 1/4 acre; sheep; V.

203. Bear Creek Old Smooth Brome, (bottom-slope) (Ferron District), below Madsen ditch: NE1/4, sec. 2, T. 18 S., R. 4 E.; Sanpete; 9,000'; 1914; seeded grass, forb; 1/4 acre; sheep; V.

204. Bedground: SE1/4, sec. 20, T. 17 S., R. 4 E.; Sanpete; 8,800'; 1940; grass, forb; 1 acre; cattle; V.

[1]For a description of the area and some of the exclosures, see Ellison 1954.

Intermountain Forest and Range Experiment Station - Great Basin Experimental Area
(on Ephraim District except as noted otherwise)

205. Birchleaf Mahogany: NE1/4, sec. 18, T. 17 S., R. 4 E.; Sanpete; 7,480'; 1922; oak, mountain mahogany, pinyon-juniper, sagebrush; 1/4 acre; sheep and deer; V; P.

206. Bitterbrush: NW1/4, sec. 18, T. 17 S., R. 4 E.; Sanpete; 7,160'; 1919; oak, sagebrush, pinyon-juniper; 1/4 acre; sheep and deer; V; P.

207. Bluebell: SE1/4, sec. 21, T. 17 S., R. 4 E.; Sanpete; 8,975'; 1922; grass, forb; 1/4 acre; cattle; V; P.

208. Bluebell Runoff: SE1/4, sec. 21, T. 17 S., R. 4 E.; Sanpete; 9,000'; 1935; mixed shrub, grass, forb; 2 acres; sheep; V.

209. Carrying Capacity Pasture: SW1/4, sec. 26, T. 17 S., R. 4 E.; Sanpete; 10,000'; 1912; grass, forb; sheep; V; P.

210. Cattle Pasture (log and block) (inside Alpine Cattle Pasture): NE1/4, sec. 34, T. 17 S., R. 4 E.; Sanpete; 9,900'; 1922; grass, forb; V.

211. Dahl's (north of road): NW1/4, sec. 18, T. 17 S., R. 4 E.; Sanpete; 7,300'; 1957; oak, pinyon-juniper, sagebrush; 2 acres; sheep; V.

212. Dahl's (south of road): NW1/4, sec. 18, T. 17 S., R. 4 E.; Sanpete; 7,300'; 1955; oak, pinyon-juniper, sagebrush; 1-1/2 acres; deer and sheep; V.

213. Dungeon exclosure: NW1/4, sec. 27, T. 17 S., R. 4 E.; Sanpete; 9,410'; 1940; grass, forb; 1/2 acre; sheep; V.

214. Dusterburg Ridge Burn: NW1/4, sec. 8, T. 17 S., R. 4 E.; Sanpete; 8,000'; 1945; mixed shrubs, oak, seeded grasses; 1 acre; sheep and cattle; V; P.

*215. Elk Knoll Natural Area (Manti District): Secs. 9 and 10, T. 18 S., R. 4 E.; Sanpete; 10,000'; designated as a natural area in 1957--longtime protection from grazing; grass, forb; 40 acres; cattle; V; P. (see Ellison 1954).

216. Erosion Area A: SW1/4, sec. 26; T. 17 S., R. 4 E.; Sanpete; 10,010'; 1912; grass, forb; 11.24 acres; sheep; V; P.

217. Erosion Area B: SW1/4, sec. 26, T. 17 S., R. 4 E.; Sanpete; 10,160'; 1912; seeded grass; 8.97 acres; sheep; V; P.

218. Gopher Study Exclosure: SW1/4, sec. 23, T. 17 S., R. 4 E.; Sanpete; 10,120'; 1941; grass, forb; 4 acres; sheep (pocket gophers controlled on half); V; (see Ellison and Aldous 1952).

*219. Graveyard Natural Area: NW1/4, sec. 17, T. 17 S., R. 4 E.; Sanpete; 7,900'; oak and juniper; 50 acres; sheep; V.

220. Great Basin Headquarters Station: SE1/4, sec. 20, T. 17 S., R. 4 E.; Sanpete; 8,850'; 1912; aspen, conifer; 80 acres; sheep; V.

221. Left Fork Gully Channel: SE1/4, sec. 22, T. 17 S., R. 4 E.; Sanpete; 10,000'; 1959; grass, forb; 1 acre; sheep; V.

Intermountain Forest and Range Experiment Station - Great Basin Experimental Area
(on Ephraim District except as noted otherwise)

222. Left Fork Summit (ARS): SW1/4, sec. 23, T. 17 S., R. 4 E.; Sanpete; 10,120'; 1936, enlarged 1946; seeded grass; 4 acres; sheep; V.

223. Lower Horseshoe: SE1/4, sec. 14, T. 17 S., R. 4 E.; Sanpete; 9,875'; 1912; yellow brush, grass, forb; 1/4 acre; sheep; V; P; (see Johnson 1964)

224. Lower Joes Valley (Ferron District) (UF&G): Sec. 31, T. 17 S., R. 6 E.; Emery; 7,150'; 1930; sagebrush, mountain brush; in 2 parts:
   a. 4 acres; sheep and cattle; V; P; (this part estab. 1945);
   b. 4 acres; sheep, cattle, and deer; V; P.

225. Lower Seely Creek (north side): NW1/4, sec. 32, T. 17 S., R. 5 E.; Sanpete, 8,900'; 1916; aspen; 1/2 acre; sheep; V; P.

226. Lower Seely Creek (south side): NE1/4, sec. 31, T. 17 S., R. 5 E.; Sanpete; 8,900'; 1916; aspen; 1/4 acre; sheep.

227. Lower Thistle Flat (east): SE1/4, sec. 32, T. 17 S., R. 5 E.; Sanpete; 8,600'; 1922; aspen; 1/4 acre; sheep; V; P.

228. Lower Willow Creek (near willow patch on private land): NE1/4, sec. 36, T. 17 S., R. 3 E.; Sanpete; 7,700'; 1933; sagebrush, oak; 1/4 acre; sheep and cattle; V; P.

229. Lyon's (inside Maple Creek exclosure): NE1/4, sec. 18, T. 17 S., R. 4 E.; Sanpete; 7,890'; 1922; oak, snowberry, mahogany, sagebrush; 1/4 acre; sheep and deer; V; P.

230. Major's Flat Deerproof (ARS): NW1/4, sec. 18, T. 17 S., R. 4 E.; Sanpete; 7,100'; 1928; oak, sagebrush, pinyon-juniper; 10 acres; sheep and deer; V.

231. Major's Flat Stockproof (ARS): NW1/4, sec. 18, T. 17 S., R. 4 E.; Sanpete; 7,100'; 1947; oak, sagebrush, pinyon-juniper; 20 acres; sheep; V.

232. Maple Creek: SE1/4, sec. 18, T. 17 S., R. 4 E.; Sanpete; 7,890'; 1928; oak, snowberry, sagebrush; 32 acres; sheep; V; P.

233. Meadows: NE1/4, sec. 34, T. 17 S., R. 4 E.; Sanpete; 9,860'; 1922; grass meadow; 1/4 acre; sheep; V.

234. North Bluebell (above road): SE1/4, sec. 21, T. 17 S., R. 4 E.; Sanpete; 9,000'; 1950; aspen, fir; 1 acre; sheep; V.

235. North Bluebell (below road) ARS: SE1/4, sec. 21, T. 17 S., R. 4 E.; Sanpete; 8,990'; 1950; grass, forb; 1 acre; sheep; V.

236. North Bluebell (moist meadow, below road) ARS: SE1/4, sec. 21, T. 17 S., R. 4 E.; Sanpete; 8,990'; 1950; grass, forb; 1 acre; sheep; V.

237. Oak-sage Runoff: NW1/4, sec. 17, T. 17 S., R. 4 E.; Sanpete; 7,900'; 1934; oak, sagebrush, snowberry; 1-1/2 acres; sheep; V.

Intermountain Forest and Range Experiment Station - Great Basin Experimental Area
(On Ephraim District except as noted otherwise)

238. Philadelphia Flat (ARS): SE1/4, sec. 27, T. 17 S., R. 4 E.; Sanpete; 9,940'; 1954; grass, forb; 1 acre; sheep; V.

239. Philadelphia Flat (log and block): NE1/4, sec. 34, T. 17 S., R. 4 E.; Sanpete; 9,940'; 1913; grass, forb; 1/4 acre; sheep; V; P.

240. Philadelphia Flat (wire) (ARS): NE1/4, sec. 34, T. 17 S., R. 4 E.; Sanpete; 9,940'; 1922; grass, forb; 1 acre; sheep; V.

241. Pigpen Springs: NW1/4, sec. 17, T. 17 S., R. 4 E.; Sanpete; 7,990'; 1948; aspen; 2 acres; sheep; V.

242. Sampson's Left Fork: SE1/4, sec. 15, T. 17 S., R. 4 E.; Sanpete; 10,400'; 1922; seeded grass, forb; 1/4 acre; sheep; V.

243. Seeley Creek Cove (fences now deteriorated): SW1/4, sec. 25, T. 17 S., R. 4 E.; Sanpete; 9,800'; 1914; grass, forb; sheep; V.

244. Seely Creek Dipping Vat (fence in need of repair): NE1/4, sec. 26, T. 17 S., R. 4 E.; Sanpete; 9,000'; 1920; grass, forb; 1/4 acre; sheep; V.

245. Seely Creek (east): NE1/4, sec. 26, T. 17 S., R. 4 E.; Sanpete; 9,000'; 1914; seeded grass (smooth brome); 1/4 acre; sheep; V.

246. Seely Creek (west): NE1/4, sec. 26, T. 17 S., R. 4 E.; Sanpete; 9,000'; 1914; seeded grass (Kentucky bluegrass); 1/4 acre; sheep; V.

247. Snowberry: NW1/4, sec. 17, T. 17 S., R. 4 E.; Sanpete; 8,450'; 1928; aspen, snowberry, sagebrush; 5 acres; sheep and deer; V; P.

248. Tom's Ridge (log and block): NW1/4, sec. 36, T. 17 S., R. 4 E.; Sanpete; 9,600'; 1918; grass, forb; 1/10 acre; sheep; V.

249. Tom's Ridge (wire): NW1/4, sec. 25, T. 17 S., R. 4 E.; Sanpete; 9,600'; 1940; grass, forb; 1/2 acre; sheep; V.

250. Thursby, Dusterburg Ridge: SW1/4, sec. 8, T. 17 S., R. 4 E.; Sanpete; 7,900'; 1921; sagebrush, snowberry; 1/10 acre; sheep and cattle; V.

251. Upper Horseshoe: NE1/4, sec. 14, T. 17 S., R. 4 E.; Sanpete; 9,900'; 1912; grass, forb; 1/4 acre; sheep; V; P; (see Johnson 1964).

252. Upper Seely Creek: NE1/4, sec. 26, T. 17 S., R. 4 E.; Sanpete; 9,800'; 1916; grass, forb; 1/4 acre; sheep; V; P.

253. Upper Willow Creek: SW1/4, sec. 30, T. 17 S., R. 4 E.; Sanpete; 8,100'; 1933; oak, sagebrush, seeded grass; 1/4 acre; sheep and cattle; V.

254. Wagon Road (Ferron District): SW1/4, sec. 9, T. 18 S. R. 5 E.; Sanpete; 8,700'; 1913; aspen, fir; 1/4 acre; sheep; V.

255. West Haystack (log and block): SE1/4, sec. 20, T. 17 S., R. 4 E.; Sanpete; 8,800'; 1950; aspen, fir; 1/4 acre; in 2 parts:
    a. 1/8 acre; cattle; V;
    b. 1/8 acre; cattle and deer; V.

MANTI-LA SAL NATIONAL FOREST

Intermountain Forest and Range Experiment Station - Great Basin Experimental Area (On Ephraim District except as noted otherwise)

256. Willow Creek: SW1/4, sec. 19, T. 17 S., R. 4 E.; Sanpete; 7,850'; 1940; aspen; 2 acres; sheep; V.

257. Wiregrass or Oaks: NE1/4, sec. 18, T. 17 S., R. 4 E.; Sanpete; 7,500'; 1928; oak, sagebrush, juniper, ponderosa pine; 5 acres; sheep and deer; V; P.

UINTA NATIONAL FOREST

Heber District

258. Mill Hollow Snow Bank: SE1/4, sec. 28, T. 4 S., R. 7 E.; Wasatch; 9,500'; 1938; depleted grass, forb, annuals; 3 acres; sheep, cattle, horses; V; P.

259. Soapstone Pass: Sec. 28, T. 35, R. 8 E.; Wasatch; 9,000'; 1946; wyethia, forb, tarweed; 1 acre; sheep, cattle, and horses; V; P.

260. Wolf Creek Summit: Sec. 17, T. 4 S., R. 8 E.; Wasatch; 10,000'; 1946; grass, forb; 1 acre; sheep, cattle, horses, V; P.

Nephi District

261. Birch Creek (IF&RES): NW1/4, sec. 21, T. 12 S., R. 1 E.; Juab; 5,240'; 1946; sagebrush, seeded grass and shrubs; 2-1/2 acres; cattle, sheep.

262. Footes Canyon: Sec. 19, T. 12 S., R. 2 E.; Juab; 8,400'; 1962; aspen; 1/12 acre; livestock, elk, and deer; V; P.

263. Four Mile Canyon: NW1/4, sec. 8, T. 14 S., R. 2 E.; Juab; 8,600'; 1965; aspen, seeded grass; 1/10 acre; cattle, deer, and elk.

264. Gardner Canyon: SW1/4, sec. 22, T. 12 S., R. 1 E.; Juab; 6,100'; 1930; mountain mahogany; in 2 parts:
   a. 1/2 acre; cattle, and sheep;
   b. 1/2 acre; cattle, sheep, deer.

265. Holman Test Plot (UF&G): SE1/4, sec. 34, T. 10 S., R. 2 E.; Utah; 8,400'; 1951; seeded grass; 1 acre; cattle; V.

266. Mud Springs: SW1/4, sec. 15, T. 11 S., R. 2 E.; Utah; 8,900'; 1951; seeded grass; 3 acres; cattle; V; P.

267. Quaking Aspen Unit: Sec. 22, T. 15 S., R. 2 E.; Sanpete; 8,040'; 1950-52; sagebrush, snowberry, seeded grasses; 1 acre; cattle, rabbits; V.

268. Red Creek Flat (UF&G): SE1/4, sec. 10, T. 12 S., R. 2 E.; Juab; 7,280'; 1925 (altered in 1950 and 1954); aspen; in 2 parts:
   a. 1 acre; cattle; V; P;
   b. 1 acre; cattle and deer; V; P.

269. Swett Shanty Flat (UF&G): SE1/4, sec. 13, T. 10 S., R. 2 E.; Utah; 7,500'; 1952 (1936?); aspen, maple, seeded grass; 1/2 acre; cattle; V; P.

270. Wales Top Spray: SE1/4, sec. 32, T. 15 S., R. 2 E.; Juab; 7,800'; 1959; grass (sagebrush sprayed); 3 acres; cattle; V; P.

Pleasant Grove District

271. Timpanogas (Battle Creek) (UF&G): SW1/4, sec. 26, T. 5 S., R. 2 E.; Utah; 5,400'; 1955; sagebrush, oak; in 2 parts:
   a. 1 acre; cattle; V; P;
   b. 1 acre; cattle and deer; V; P.

Spanish Fork District

272. Crooked Creek: SW1/4, sec. 24, T. 4 S., R. 12 W.; Wasatch; 7,800'; 1956; sagebrush; 1 acre; cattle, sheep.

273. Diamond Fork (IF&RES): Sec. 31, T. 7 S., R. 6 E.; Utah; 7,500'; 1931; oakbrush; 10 acres; cattle; V.

274. Hobble Creek: NW1/4, sec. 17, T. 8 S., R. 6 E.; Utah; 7,000'; 1949; tall forb; 10 rods square; cattle; V; P.

275. Little Sheep Creek: NE1/4, sec. 26, T. 7 S., R. 5 E.; Utah; 6,800'; 1938; aspen, seeded grass; 5 rods square; cattle; V; P.

276. Lower Tank Hollow (UF&G): NE1/2, sec. 35, T. 9 S., R. 5 E.; Utah; 6,500'; 1949; sagebrush, seeded grass (crested wheatgrass); in 2 parts:
   a. 10 X 15 rods; cattle; V; P;
   b. 10 X 15 rods; cattle and big game; V; P.

277. Millers Flat: SW1/4, sec. 19, T. 9 S., R. 6 E.; Utah; 7,500'; 1950; sagebrush, seeded grass; 1 acre; cattle.

278. Pump Ridge: SE1/4, sec. 22, T. 7 S., R. 5 E.; Utah; 6,800'; 1952; seeded grass (crested wheatgrass); 15 rods square; cattle; V; P.

279. Tank Hollow, Big Game and Livestock: SE1/4, sec. 26, T. 9 S., R. 5 E.; Utah; 7,000'; 1961; sagebrush, mountain brush, oak; 125 acres; big game, cattle, rabbits; V; P.

280. Tank Hollow Experimental Grass Pilot Study: SW1/4, sec. 35, T. 9 S., R. 5 E.; Utah; 6,000'; 1959; seeded grass; 1/2 acre; cattle; V; P.

281. Upper Tank Hollow Experimental Exclosure (UF&G): NW1/4, sec. 25, T. 9 S., R. 5 E.; Utah; 7,500'; 1951; mountain brush; in 2 parts:
   a. 3 acres; cattle; V; P;
   b. 2 acres; cattle and deer; V; P.

282. Rays Valley: NW1/4, sec. 17, T. 8 S., R. 6 E.; Utah; 7,000'; 1949; tall forb; 10 rods square; cattle; V; P.

Strawberry District

283. Cummings Flat (UF&G): SE1/4, sec. 17, T. 5 S., R. 6 E.; Wasatch; 7,000'; 1945; sagebrush, mountain brush; in 2 parts:
   a. 1/4 acre; cattle; V; P;
   b. 1/4 acre; cattle and deer; V; P.

284. Hogsback: SE1/4, sec. 4, T. 5 S., R. 6 E.; Wasatch; 9,500'; 1945; grass, forb; 1 acre; sheep; V; P.

UINTA NATIONAL FOREST

Strawberry District

285. Mud Creek: Sec. 24, T. 3 S., R. 12 W.; Wasatch; 7,500'; 1951; silver sagebrush; 1 acre; cattle; V; P.

Intermountain Forest & Range Experiment Station

286-298. Mud Creek Sheep Allotment (Strawberry District) 13 study plots, (Nos. 1-8, 10-14): Secs. 21, 22, 27, 34, T. 35, R. 12 W.; Wasatch; 7,800'-8,200'; 1959; 66' X 66' each; forb, grass; sheep; V; P.

299. One study plot (No. 9): SE1/4, sec. 22, T. 3 S., R. 12 W.; Wasatch; 7,600'; 1959; 5 acres; aspen; sheep; V.

WASATCH NATIONAL FOREST

Bountiful District

300. City Creek Watershed: T. 1 N., R. 1 E. (total watershed); Salt Lake; 5,400'-8,000'; 1914; maple, alder, birch, oak, conifer, cottonwood; 8 miles long, 2-1/2 miles wide; all domestic animals.

301. Davis County Experimental Watershed (IF&RES): T. 2 and 3 N., R. 1 E.; Davis; 4,400'-9,259'; 1930-1935; sagebrush, oak, maple, conifer, aspen, grass, forb; 35 square miles; all domestic animals.

302. Red Butte Watershed: T. 1 N., R. 1 E. (total watershed); Salt Lake; 4,800'-8,900'; 1888; mountain brush; 5 miles long by 2-1/2 miles wide; all domestic animals.

Evanston District

303. East Fork Bear River: SW1/4, sec. 26, T. 2 N., R. 10 E.; Summit; 8,800'; 1961; sagebrush; 1 acre; cattle, sheep; V; P.

304. Gold Hill: SE1/4, sec. 14, T. 1 N., R. 9 E.; Summit; 9,500'; 1960; sagebrush; 1 acre; sheep.

305. Humpy: SE1/4, sec. 6, T. 1 N., R. 9 E.; Summit; 9,400'; 1962; sagebrush; 1 acre; sheep; V; P.

306. Lyman Lake: NW1/4, sec. 4, T. 2 N., R. 12 E.; Summit; 9,100'; 1961; sagebrush; 1 acre; sheep, cattle; V; P.

307. Whitney: SW1/4, sec. 4, T. 1 N., R. 9 E.; Summit; 9,200'; 1960; grass; 1 acre; sheep; V; P.

Kamas District

308. Moon Canyon: NW1/4, sec. 6, T. 3 S., R. 7 E.; Summit; 7,700'; 1950; seeded grass; 1 acre; cattle; P.

309. Paulsin Basin: SE1/4, sec. 6, T. 2 S., R. 7 E.; Summit; 9,500'; 1957; seeded grass (Kentucky bluegrass); 1 acre; cattle; P.

Kamas District

310. Paulsin Basin Pilot Reseeding: NW1/4, sec. 12, T. 2 S., R. 6 E.; Summit; 8,800'; 1964; seeded grass; 1.2 acres; cattle; V.

311. Slate Creek: NE1/4, sec. 19, T. 2 S., R. 7 E.; Summit; 6,850'; 1959; sagebrush; 1 acre; cattle; P.

Mountain View District

312. Suicide Park: NE1/4, sec. 20, NW1/4, sec. 21, T. 3 N., R. 13 E.; Summit; 8,900'; 1960; dry meadow; 1 acre; cattle; V; P; (fence may be taken down in 1969)

Tooele District

313. Davenport Summer: NW1/4, sec. 22, T. 3 S., R. 7 W.; Tooele; 7,600'; 1963; aspen; in 2 parts:
   a. 1 acre; cattle; V;
   b. 1 acre, cattle and deer; V.

314. Harker Summer (UF&G): NW1/4, sec. 11, T. 10 S., R. 6 W.; Tooele; 7,200'; 1956; aspen, sagebrush; in 2 parts:
   a. 1 acre; cattle; V; P;
   b. 1 acre, cattle and deer; V; P.

315. Rock Canyon - Log Hollow (UF&G): SW1/4, sec. 10, T. 9 S., R. 7 W.; Tooele; 6,450'; 1938; sagebrush, mountain brush; in 2 parts:
   a. 1/3 acre; livestock; P;
   b. 1/3 acre; livestock and deer; P.

316. Round Canyon Deer, Cow (Winter) (in need of repair): SW1/4, sec. 5, T. 3 S., R. 7 W.; Tooele; 6,200'; 1948; juniper, sagebrush; in 2 parts:
   a. 1 acre; cattle;
   b. 1 acre; cattle and deer.

Intermountain Forest and Range Experiment Station - Benmore Experimental Range (Tooele District): T. 9 S., R. 5 W.; Tooele; 5,600'-5,800'; 1948; seeded grass:

317-332. 16 exclosures (mainly *Agropyron desertorum*): 2 X 4 rods each; cattle; V; P.

333-340. 8 exclosures (mainly *Agropyron cristatum*); 2 X 4 rods each; cattle; V; P.

BUREAU OF LAND MANAGEMENT

Cedar City District

341. Buckhorn: Sec. 34, T. 31 S., R. 8 W.; Iron; 5,900'; 1953; sagebrush; 10 acres; cattle and sheep; P.

342. Castle Cliff (Experimental Plot #1) (UF&G): NE1/4, sec. 7, T. 43 S., R. 18 W.; Washington; 3,600'; 1958; blackbrush; 1 acre; sheep and cattle.

343. Cottonwood (UF&G): Sec. 30, T. 32 S., R. 72; Iron; 5,900'; 1961; sagebrush, galleta, and Indian ricegrass (juniper cut); 660' X 330'; livestock, rabbits, and deer; V; P.

Cedar City District

344. Gould: NE1/4, sec. 30, T. 42 S., R. 12 W.; Washington; 4,300'; 1959; salt desert shrub (fourwing saltbush, Indian ricegrass, galleta); 10 acres; cattle; P.

345. Green's Lake (UF&G): NE1/4, sec. 25, T. 36 S., R. 11 W.; Iron; 6,800'; 1960; sagebrush; in 2 parts:
   a. 1 acre; livestock;
   b. 1 acre; livestock and deer.

346. Hamblin Valley #1 (UF&G): NE1/4, sec. 4, T. 32 S., R. 18 W.; Iron; 6,600'; 1940; sagebrush, seeded grass (crested wheatgrass); 200' X 200'; cattle.

347. Hamblin Valley #2 (UF&G): SW1/4, sec. 9, T. 32 S., R. 1 W.; Iron; 6,600'; 1940; sagebrush, seeded grass (crested wheatgrass); 200' X 200'; cattle.

348. Little Mountain Reseeding Plot: SW1/4 and SE1/4, secs. 16 and 14, T. 35 S., R. 18 W.; Iron; 5,400'; 1940; sagebrush, seeded grass; 200' X 200'; sheep.

349. Manganese Wash: NE1/4 and SE1/4, sec. 25, T. 40 S., R. 18 W.; Washington; 3,800'; 1936; salt desert shrub (galleta); 2-1/2 acres; cattle and rabbits.

350. Middle Ridge (UF&G): NE1/4, sec. 32, T. 38 S., R. 19 W.; Washington; 5,500'; 1958; mountain brush (serviceberry, oak, skunkbrush, bitterbrush); 10 acres; cattle; P.

351. Motoqua (UF&G): SW1/4, sec. 11, T. 40 S., R. 19 W.; Washington; 1938; seeded grass (tall, crested, and pubescent wheatgrasses); 2-1/2 acres; cattle and rabbits.

352. Muley Point Tree Planting: NW1/4, sec. 31, T. 31 S., R. 7 W.; Iron; 5,900'; 1962; Russian olive and chinese elm, grass and weed understory; 40 acres; cattle and rabbits.

353. Negro Lizza Wash #1 (UF&G): SW1/4, sec. 9, T. 33 S., R. 17 W.; Iron; 5,600'; 1940; sagebrush; 200' X 200'; livestock.

354. Negro Lizza Wash #2 (UF&G): NE1/4, sec. 10, T. 33 S., R. 17 W.; Iron; 5,600'; 1940; sagebrush; 200' X 200'; livestock.

355. Old Minersville Road: NW1/4, sec. 7, T. 33 S., R. 10 W.; Iron; 5,700'; 1940; sagebrush, rabbitbrush; 200' X 200'; livestock.

356. Parowan Gap (Rush Lake) (UF&G): NW1/4, sec. 31, T. 33 S., R. 10 W.; Iron; 5,400'; 1940; rabbitbrush; 200' X 200'; livestock.

*357. Sagebrush Flat Natural Area: Secs. 18 and 19, T. 31 S., R. 6 W.; Iron; 7,400'; pinyon-juniper, sagebrush, bitterbrush, bluebunch wheatgrass, Indian ricegrass, galleta; 400 acres; all livestock.

Fillmore District

358. Big Cedar Cove (UF&G): NW1/4 and SE1/4, sec. 14, T. 27 S., R. 9 W.; Beaver; 6,800'; 1959; pinyon-juniper (chained), seeded grass; in 2 parts:
   a. 1 acre; cattle; P;
   b. 1 acre; cattle and deer; P.

Fillmore District

359. Death Canyon: SW1/4, sec. 10, T. 17 S., R. 13 W.; Millard; 6,300'; 1938; sagebrush, shadscale, seeded grass (crested wheatgrass); 260' X 200'; cattle.

360. Narrow Neck Cove (UF&G): SW1/4, sec. 8, T. 26 S., R. 8 W.; Beaver; 6,800'; 1960; sagebrush, pinyon-juniper; in 2 parts (rabbits excluded from 1/2 acre of each):
    a. 1 acre; deer and cattle; V; P;
    b. 2 acres; cattle; V; P.

361. Negro Mag (UF&G): SW1/4, sec. 6, T. 27 S., R. 8 W.; Beaver; 6,800'; 1959; pinyon-juniper; in 2 parts:
    a. 1 acre; cattle; P;
    b. 1 acre; deer; P.

Kanab District

*362. Cockscomb (Natural Area): Secs. 19, 29, 30, T. 41 S., R. 1 W.; Kane; 4,792'-5,682'; sparse pinyon-juniper, sagebrush; 880 acres; all livestock.

363. Elbow: SE1/4, sec. 27, T. 40 S., R. 5 W.; Kane; 6,200'; 1967; sagebrush, pinyon-juniper; in 4 parts:
    a. 2-1/2 acres; livestock;
    b. 2/3 acre; livestock and rabbits;
    c. 2/3 acre; livestock, deer, and rabbits;
    d. 2/3 acre; livestock and deer.

*364. Elephant Butte (Natural Area): Secs. 14, 15, T. 43 S., R. 9 W.; Kane; 6,200'-6,795'; pinyon-juniper, sagebrush; 400 acres; all livestock.

365. Elephant Gap (UF&G): SE1/4, sec. 26, T. 42 S., R. 9 W.; Kane; 5,600'; 1961; pinyon-juniper, sagebrush; in 4 parts:
    a. 1-1/2 acres; livestock;
    b. 1/2 acre; livestock and rabbits;
    c. 1/2 acre; livestock, deer, and rabbits;
    d. 1/2 acre; livestock and deer.

*366. Indian Canyon (Natural Area): Secs. 20, 21, T. 43 S., R. 7 W.; Kane; 5,640'; canyon and streamside flora; 70 acres; all livestock.

367. Nephi Pasture: NW1/4, sec. 1, T. 42 S., R. 4 W.; Kane; 6,400'; 1967; sagebrush; in 4 parts:
    a. 2-1/2 acres; livestock;
    b. 2/3 acre; livestock and rabbits;
    c. 2/3 acre; livestock, deer, and rabbits;
    d. 2/3 acre; livestock and deer.

*368. No Man's Land Mesa (Natural Area) (SCS): Secs. 9, 10, 14, 15, 16, 22, 23, 25, 26, T. 40 S., R. 3 W.; Kane; 6,600'-7,200'; pinyon-juniper, sagebrush, oak; livestock; V; P; (see Mason et al. 1967).

369. Sunset Flat: Sec. 11, T. 38 S., R. 5 E.; Kane; 4,600'; 1960; salt desert shrub (fourwing saltbush); 100' X 200'; cattle.

Kanab District

370. Swapp Allotment Game Range Study Plot: NE1/4, sec. 3, T. 42 S., R. 6 W., Kane; 5,500'; 1961; sagebrush; in 4 parts:
   a. 1-1/2 acres; livestock;
   b. 1/2 acre; livestock and rabbits;
   c. 1/2 acre; livestock, deer, and rabbits;
   d. 1/2 acre; livestock and deer.

*371. Water Canyon (Natural Area): Secs. 29, 30, 32, T. 43 S., R. 7 W.; Kane; 5,400'; canyon and streamside flora; 165 acres; all livestock.

Monticello District

372. Agate: SE1/4, sec. 19, T. 20 S., R. 25 E.; Grand; 4,500'; 1961; sagebrush, galleta; 1 acre; sheep.

373. Alkali (UF&G): SE1/4 and NE1/4, sec. 23, T. 36 S., R. 23 E.; San Juan; 6,200'; 1962; seeded grass (crested wheatgrass); in 2 parts:
   a. 1 acre; cattle;
   b. 1 acre; cattle and deer.

374. Baullies (UF&G): NW1/4, sec. 5, T. 38 S., R. 20 E.; San Juan; 6,200'; 1958; seeded grass (crested wheatgrass); in 2 parts:
   a. 1 acre; cattle; V;
   b. 1 acre; cattle and deer; V.

375. Beef Basin (UF&G): SW1/4, sec. 21, T. 32 S., R. 19 E.; San Juan; 6,300'; 1958; sagebrush, galleta; in 2 parts:
   a. 1 acre; livestock;
   b. 1 acre; livestock and deer.

376. Blue Chief: SE1/4, sec. 35, T. 23 S., R. 24 E.; Grand; 5,080'; 1961; blackbrush, galleta; 1 acre; cattle.

*377. Book Cliff Natural Area (Cunningham) (SCS): Sec. 34, T. 19 S., R. 21 E.; Grand; 7,000'; pinyon-juniper; 100 acres; livestock; P.

*378. Book Cliff Natural Area (Cunningham burn) (SCS): Sec. 27, T. 19 S., R. 21 E.; Grand; 7,000'; grass (bluebunch wheatgrass); 40 acres; livestock; V; P.

379. Buckhorn: NE1/4, sec. 33, T. 22 S., R. 25 E.; Grand; 4,920'; 1961; sagebrush, galleta; 208' square; cattle and sheep.

380. Cisco Mesa: Sec. 22, T. 20 S., R. 23 E.; Grand; 4,840'; 1960; salt desert shrub (shadscale, galleta); 1 acre; sheep and cattle.

381. Cisco Wash: SE1/4, sec. 6, T. 21 S., R. 23 E.; Grand; 4,500'; 1961; salt desert shrub (galleta, shadscale); 208' square; cattle and sheep.

382. Cottonwood: Sec. 28, T. 20 S., R. 24 E.; Grand; 4,600'; 1960; salt desert shrub (Nuttall's saltbush, galleta); 1 acre; sheep and cattle.

383. Cottonwood: NE1/4, sec. 35, T. 19, R. 24 E.; Grand; 4,500'; 1961; salt desert shrub (shadscale, Nuttall's saltbush); 208' square; sheep.

Monticello District

384. Cottonwood (UF&G): SW1/4, sec. 22, T. 32 S., R. 21 E.; San Juan; 6,000'; 1958; sagebrush, galleta; in 2 parts:
   a. 1 acre; livestock; V; P;
   b. 1 acre; livestock and deer; V; P.

385. Cowskin: SE1/4, sec. 28, T. 23 S., R. 24 E.; Grand; 5,040'; 1961; salt desert shrub (fourwing saltbush, galleta); 1 acre; cattle.

386. Deer Flat (UF&G): NW1/4 and SE1/4, sec. 12, T. 36 S., R. 17 E.; San Juan; 7,600'; 1951; seeded grass (crested wheatgrass); in 2 parts:
   a. 300' X 400'; cattle;
   b. 300' X 400'; cattle and deer.

387. Hart Point (UF&G): NE1/4 and SW1/4, sec. 3, T. 32 S., R. 22 E.; San Juan; 6,400'; 1960; sagebrush, blue grama; in 2 parts:
   a. 1 acre; cattle;
   b. 1 acre; cattle and deer.

388. Horse Pasture (UF&G): NE1/4, sec. 14, T. 20 S., R. 21 E.; Grand; 5,100'; 1965; sagebrush, galleta, fourwing saltbush; 5 acres (small deer exclosure inside); cattle and sheep.

389. Hotel Mesa: SE1/4, sec. 34, T. 22 S., R. 24 E.; Grand; 4,400'; 1961; salt desert shrub (shadscale, galleta); cattle and sheep.

390. Lost Spring: SE1/4, sec. 8, T. 23 S., R. 22 E.; Grand; 4,800'; 1960; galleta, Indian ricegrass; 1 acre; sheep and cattle.

391. Lower Lost Park (UF&G): SE1/4, sec. 19, T. 36 S., R. 18 E.; San Juan; 1958; sagebrush, blue grama, galleta; in 2 parts:
   a. 1 acre; cattle;
   b. 1 acre; cattle and deer.

392. Harley Dome (McIntire) (UF&G): NE1/4, sec. 22, T. 18 S., R. 25 E.; Grand; 4,900'; 1960; salt desert shrub (shadscale, cheatgrass); 1 acre; sheep and cattle.

393. Pumphouse: SE1/4, sec. 28, T. 21 S., R. 24 E.; Grand; 4,320'; 1961; salt desert shrub (galleta, shadscale); 208' square; sheep.

394. Sager's Flat (UF&G): SW1/4, sec. 27, T. 21 S., R. 21 E.; Grand; 4,720'; 1960; salt desert shrub (galleta, mat saltbush); 1 acre; cattle and sheep.

395. Sand Flat: SW1/4, sec. 6, T. 22 S., R. 25 E.; Grand; 4,400'; 1961; salt desert shrub (shadscale, galleta); 208' square; cattle and sheep.

396. Shay Mesa (UF&G): NE1/4 and SW1/4, sec. 20, T. 32 S., R. 22 E.; San Juan; 7,000'; 1958; sagebrush, seeded grass (crested wheatgrass); in 2 parts:
   a. 1 acre; livestock;
   b. 1 acre; livestock and deer; V; P.

397. Texas Flat (UF&G): NW1/4, sec. 7, T. 37 S., R. 20 E.; San Juan; 7,200'; 1958; seeded grass (crested wheatgrass); in 2 parts:
   a. 1 acre; cattle; V; P;
   b. 1 acre; cattle and deer; V; P.

Monticello District

398. Thompson (UF&G): SW1/4, sec. 31, T. 21 S., R. 20 E.; Grand; 4,925'; 1938; salt desert shrub (sand dropseed, galleta, shadscale); 1 acre; sheep and cattle.

399. Westwater (Elizondo) (UF&G): SW1/4, sec. 31, T. 18 S., R. 25 E.; Grand; 4,800'; 1961; salt desert shrub (shadscale, galleta, Nuttall's saltbush); 1 acre; sheep.

400. Wild Cow Point (UF&G): SE1/4 and SW1/4, sec. 9, T. 33 S., R. 18 E.; San Juan; 7,300'; 1958; seeded grass (crested wheatgrass); in 2 parts:
   a. 1 acre; cattle; V;
   b. 1 acre; cattle and deer; V.

Price District

401. Blackbrush: Sec. 18, T. 23 S., R. 14 E.; Emery; 4,600'; 1941; blackbrush, Indian ricegrass; 4 acres; cattle, sheep, and rabbits.

402. Buckhorn (UF&G): SE1/4 and NW1/4, sec. 15, T. 19 S., R. 10 E.; Emery; 5,500'; 1937; salt desert shrub (fourwing saltbush, Indian ricegrass, galleta); 4 acres; cattle and rabbits; P.

403. Cedar Mountain: NW1/4, sec. 28, T. 18 S., R. 11 E.; Emery; 6,800'; 1938; sagebrush; 4 acres; cattle, sheep, and rabbits; P.

404. Clarks Valley: SE1/4, sec. 28, T. 14 S., R. 12 E.; Carbon; 5,800'; 1963; greasewood; 4 acres; cattle (rabbits from 3 acres).

*405. Dunes Natural Area: NW1/4 and NE1/4, sec. 14, T. 26 S., R. 13 E.; Emery; 5,200'; oak (Quercus undulata); 320 acres; all livestock.

406. Dutch Flat: NW1/4, sec. 31, T. 20 S., R. 8 E.; Emery; 5,900'; 1940; salt desert shrub (Nuttall's saltbush, Indian ricegrass, galleta); 4 acres; cattle and rabbits; P.

*407. Ireland Mesa Natural Area: Secs. 29, 32, 33, T. 24 S., R. 8 E.; Emery; 6,100'; galleta, ephedra, Bigelow sagebrush, Indian ricegrass; 1,000 acres; livestock.

*408. Link Flat Natural Area: Secs. 28, 29, 30, 31, 32, T. 23 S., R. 9 E.; Emery; 6,600'; salt desert shrub (fourwing saltbush); 1,310 acres; some livestock grazing; P.

409. Little Park Deer (UF&G): SE1/4 and NW1/4, sec. 25, T. 16 S., R. 14 E.; Carbon; 7,000'; 1962; sagebrush; in 2 parts:
   a. 2 acres; cattle and rabbits; P;
   b. 1 acre; cattle and deer; P.

*410. Mesa Butte Natural Area: Secs. 22, 23, 26, 27, 34, 35, T. 23 S., R. 6 E.; Emery; 6,500'; pinyon-juniper, Bigelow sagebrush, Indian ricegrass, galleta; 580 acres; livestock; P.

411. Porphory Bench Deer (Gordon Creek) (UF&G): Sec. 15, T. 14 S., R. 9 E.; Carbon; 5,900'; 1958; sagebrush, wheatgrass, Indian ricegrass, blue grama; in 2 parts:
   a. 1/2 acre; cattle and rabbits; P;
   b. 1/2 acre; cattle and deer; P.

Price District

412. Sinbad: NW1/4, sec. 20, T. 22 S., R. 12 E.; Emery; 6,600'; 1937; fourwing saltbush, blue grama, black sagebrush; 4 acres; cattle and rabbits; P.

413. Walker Flat Experimental Plot: NW1/4, sec. 1, T. 23 S., R. 5 E.; Sevier; 6,200'; 1941; salt desert shrub (shadscale, galleta); in 2 parts:
    a. 2 acres; cattle; P;
    b. 2 acres; cattle and rabbits; P.

Richfield District

414. Airplane Springs (UF&G): NW1/4, sec. 28, T. 32 S., R. 10 E.; Garfield; 7,700'; 1961; seeded grass (crested wheatgrass); in 2 parts:
    a. 1 acre; cattle, sheep, and buffalo; V; P;
    b. 1 acre; deer, rabbits, cattle, sheep, and buffalo; V; P.

415. Bitter Creek Divide: SW1/4, sec. 5, T. 33 S., R. 8 E.; Garfield; 5,600'; 1952; salt desert shrub (shadscale, Nuttall's saltbush, Indian ricegrass, galleta); 1/10 acre; cattle and sheep; V; P.

416. Cove: NW1/4, sec. 23, T. 31 S., R. 4 W.; Garfield; 5,700'; 1960; sagebrush, seeded grass; 21 acres; cattle; P.

417. Halfway Bench: NE1/4, sec. 13, T. 29 S., R. 11 E.; Wayne; 4,600'; 1930; salt desert shrub (shadscale, Indian ricegrass, galleta); 160' X 160'; sheep and cattle; V; P.

418. Horn (UF&G): SW1/4, sec. 22, T. 32 S., R. 10 E.; Garfield; 8,000'; 1956; sagebrush, mixed shrub; 2 acres; cattle and sheep; V; P.

419. Martel's Study Plot: SE1/4, sec. 19, T. 29 S., R. 3 W.; Piute; 6,250'; 1964; sagebrush (seeded grass on half); 20 acres, 80 X 40 rods; cattle and rabbits; P.

*420. North Cainsville Mesa Natural Area: Secs. 5, 7, 8, 18, T. 28 S., R. 9 E.; Wayne; 6,000'; salt desert shrub (fourwing saltbush, shadscale, Indian ricegrass, galleta); all livestock.

421. Sage Flat Experimental Deer (UF&G): NW1/4, sec. 35, T. 22 S., R. 1 W.; Sevier; 6,000'; 1955; sagebrush; in 3 parts:
    a. 1 acre; sheep; P;
    b. 1/2 acre; sheep and deer; P;
    c. 1/2 acre; sheep, deer, and rabbits; P.

422. Sidehill Spring (UF&G): SW1/4, sec. 24, T. 33 S., R. 10 E.; Garfield; 8,200'; 1959; sagebrush; in 2 parts:
    a. 1 acre; sheep and cattle; V;
    b. 1 acre; sheep, cattle, and deer; V.

*423. South Cainsville Mesa Natural Area: Secs. 5, 6, 7, 8, 18, T. 29 S., R. 9 E.; Wayne; 5,850'; sagebrush, shadscale, pinyon-juniper, Indian ricegrass, galleta; 3,791 acres; sheep and cattle; V.

424. South Creek Exclosure (UF&G): SW1/4, sec. 9, T. 32 S., R. 10 E.; Garfield; 1963; sagebrush, mixed shrub; in 2 parts:
    a. 1 acre; cattle and sheep; V; P;
    b. 1 acre; deer, cattle, and sheep; V; P.

Salt Lake District

425. Bovine Deer Study plot (UF&G): NE1/4, sec. 18, T. 9 N., R. 16 W.; Box Elder; 6,000'; 1955; sagebrush, bitterbrush, black sagebrush; in 2 parts:
   a. sheep and cattle;
   b. sheep, cattle, and deer.

426. Red Butte Deer (UF&G): SW1/4, sec. 10, T. 11 N., R. 17 W.; Box Elder; 6,000'; 1964; sagebrush; 240' X 401'; cattle, deer, rabbits.

427. Rush Valley: NW1/4, sec. 34, T. 6 S., R. 4 W.; Tooele; 5,100'; 1940; salt desert shrub (Nuttall's saltbush, shadscale); 500' X 500'; sheep.

428. Woodruff Pastures (UF&G): NW1/4, sec. 11, T. 9 N., R. 6 E.; Rich; 7,000'; 1963; sagebrush, bitterbrush, black sagebrush; in 2 parts:
   a. cattle; 200 X 300'; P;
   b. cattle and deer; 200' X 300'; P.

429. (No name) NW1/4, sec. 31, T. 14 S., R. 16 W.; Juab; 6,000'; 1963; black sagebrush, rabbitbrush, galleta; 2 acres; cattle and sheep; P.

430. (No name) NE1/4, sec. 4, T. 13 S., R. 9 W.; Juab; 5,300'; 1963; shadscale, rabbitbrush, galleta; 2 acres; sheep and cattle; P.

431. (No name) NW1/4, sec. 10, T. 11 S., R. 6 W.; Juab; 6,000'; 1963; juniper, black sagebrush, rabbitbrush, shadscale; 2 acres; cattle and sheep; P.

Vernal District

432. Atchee Ridge (UF&G): NE1/4, sec. 4, T. 13 S., R. 25 E.; Uintah; 6,500'; 1964; mountain mahogany, serviceberry; in 2 parts:
   a. 4 acres; cattle; P;
   b. 1 acre; deer; P.

433. Big Park (UF&G): SE1/4 and NE1/4, sec. 4, T. 13 S., R. 24 E.; Uintah; 6,500'; 1964; sagebrush, fourwing saltbush; in 2 parts:
   a. 4 acres; cattle;
   b. 1 acre; deer.

434. Blue Mountain Big Game (UF&G): NW1/4, sec. 15, T. 5 S., R. 25 E.; Uintah; 8,000'; 1965; sagebrush; in 2 parts:
   a. 3 acres; cattle;
   b. 2 acres; cattle and deer.

435. Browns Park: NW1/4, sec. 33, T. 2 N., R. 25 E.; Daggett; 5,720'; 1958; sagebrush, shadscale (partially seeded to crested wheatgrass); 10 acres; cattle; P.

436. Brush Creek (UF&G): NE1/4, sec. 35, T. 2 S., R. 22 E.; Uintah; 6,000'; 1964; sagebrush, shadscale, seeded grass (crested wheatgrass); in 3 parts:
   a. 3 acres; cattle;
   b. 2 acres; cattle and big game;
   c. 35' X 35'; cattle, big game, and rodents.

437. Burns Bench: NW1/4, sec. 22, T. 4 S., R. 22 E.; Uintah; 5,210'; 1964; salt desert shrub (Nuttall's saltbush, shadscale); 185' X 185'; sheep.

Vernal District

438. Clay Basin Big Game (UF&G): NE1/4, sec. 28, T. 3 N., R. 24 E.; Daggett; 6,420'; 1958; sagebrush, shadscale, fourwing saltbush; 400' X 400'; sheep and cattle; P.

439. Crows Roost (UF&G): Sec. 35, T. 14 S., R. 22 E.; Uintah; 6,500'; 1967; fourwing saltbush, sagebrush; in 2 parts:
   a. 1 acre; deer, cattle, and sheep;
   b. 4 acres; cattle and sheep.

440. Deadman Bench: SW1/4, sec. 13, T. 7 S., R. 24 E.; Uintah; seeded grass (crested wheatgrass); 40 acres; 1320' X 1320'; sheep; V; P.

441. Gyp Plant Hill: NW1/4, sec. 16, T. 4 S., R. 22 E.; Uintah; 5,340'; 1964; salt desert shrub (shadscale, winterfat, galleta, Indian ricegrass); 3 acres; sheep.

442. Lower McCook Ridge Game Study Plot (UF&G): SW1/4, sec. 31, T. 13 S., R. 24 E.; Uintah; 6,500'; 1964; salt desert shrub (fourwing saltbush, sagebrush); in 2 parts:
   a. 4 acres; cattle;
   b. 1 acre; cattle and deer.

443. McCook Ridge Deer Plot (UF&G): NW1/4, sec. 7, T. 15 S., R. 25 E.; Uintah; 7,000'; 1956; mahogany, serviceberry; in 2 parts:
   a. 1 acre; cattle;
   b. 1 acre; cattle and deer.

*444. Nine Mile Butte (Natural Area): Sec. 35, T. 11 S., R. 17 E.; Uintah; 5,000'; salt desert shrub (shadscale, galleta); 1/4 mi. X 1/5 mi.; livestock; V; P.

445. Red Creek Flat (UF&G): SW1/4, sec. 21, T. 2 N., R. 24 E.; Daggett; 5,800'; 1963; sagebrush, seeded grass (crested wheatgrass); in 2 parts:
   a. 2.5 acres; livestock; P;
   b. 2.5 acres; livestock and big game; P.

446. Taylor Flat (UF&G): NW1/4, sec. 35, T. 2 N., R. 24 E.; Daggett; 5,720'; 1963; sagebrush, shadscale (partially seeded to grass); in 2 parts:
   a. 2.5 acres; cattle;
   b. 2.5 acres; big game and cattle.

447. Twelve Mile: NE1/4, sec. 3, T. 6 S., R. 20 E.; Uintah; sagebrush, shadscale; 5 acres; sheep.

*448. White Face Butte Natural Area: Sec. 25, T. 12 S., R. 25 E.; Uintah; 7,000'; pinyon-juniper; 3/4 mi. X 1/3 mi.; livestock (heavy deer use in winter); V; P.

449. Winter Ridge Game (UF&G): NW1/4, sec. 26, T. 15 S., R. 21 E.; Uintah; 7,200'; 1964; sagebrush; 330' X 660'; cattle and deer.

NATIONAL PARKS

*450. Bryce Canyon National Park: Garfield and Kane; 6,700'-9,100'; 1923; pinyon-juniper at lower elevations, ponderosa pine and Douglas-fir at higher elevations; 36,010 acres; all domestic livestock excluded.

NATIONAL PARKS

451. Bryce Canyon National Park - Bryce Canyon Deer Exclosure (UF&G): Sec. 22, T. 4 W., R. 37 S.; Garfield; 8,580'; 1957; ponderosa pine and Douglas-fir; 1 acre; deer (livestock excluded from entire Park).

*452. Canyonlands National Park - Virginia Park Natural Area (U of U): Sec. 8, T. 31 S., R. 19 E.; San Juan; 5,600'; grassland (galleta, needleandthread); 240 acres; all livestock; V; P.

453. Dinosaur National Monument Livestock and Deer Exclosure: SE1/4, sec. 25, T. 3 S., R. 24 E.; Uintah; 5,400'; 1965; juniper-sagebrush; in 2 parts:
 a. 5 acres; livestock; V;
 b. 5 acres; livestock and deer; V.

*454. Zion National Park: Washington; 3,950'-8,740'; 1919; Sonoran desert, pinyon-juniper; oakbrush, ponderosa pine, Douglas-fir (at higher elevations); 230 sq. mi.; all domestic livestock excluded.

*455. Zion National Park - Timber Top Mountain Natural Area (SCS): Washington; 7,500'; ponderosa pine, Douglas-fir, oak, manzanita; 300 acres; deer and all domestic animals; P.

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION

Benmore Experimental Range (See Wasatch National Forest)

456-505. Desert Experimental Range: T. 24 and 25, R. 17 and 18 W.; Millard; 5,200'-8,400'; 1933; various salt desert shrub types; approx. 50 exclosures 1 to 10 acres in size on Experimental Range and Fillmore District (BLM); sheep and cattle; V; P.

Diamond Mountain Cattle Allotment (See Ashley National Forest)

Great Basin Experimental Area (See Manti-La Sal National Forest)

Mud Creek Sheep Allotment (See Uinta National Forest)

UTAH DIVISION OF FISH AND GAME

506. Byron Howard (IF&RES): Sec. 36, T. 16 S., R. 7 E.; Emery; 7,000'; 1963; seeded grass and shrubs; in 2 parts:
 a. 2 acres; livestock; V;
 b. 2 acres; livestock and deer; V.

507. Delle Ranch: SW1/4, sec. 5, T. 3 S., R. 7 W.; Tooele; 5,600'; 1948; sagebrush, mountain brush; in 2 parts:
 a. 1 acre; livestock; P;
 b. 1 acre; livestock and deer; P.

508. Four Mile Canyon: T. 13 S., R. 1 E.; Juab; 1959; 50 acres; livestock.

509. Hardware Ranch: SE1/4, sec. 11, T. 10 N., R. 3 E.; Cache; 5,850'; 1946; sagebrush, and mountain brush; 1 acre; game and livestock; P.

510. Indian Peaks: Sec. 21, T. 29 S., R. 18 W.; Wayne; 1960; in 2 parts:
 a. 1 acre; livestock;
 b. 1 acre; livestock and game;
 (7 smaller exclosures; some rabbit-tight)

511. Kanab Creek: Sec. 3, T. 42 S., R. 6 W.; Kane; 1961; in 2 parts:
   a. 1 acre; livestock;
   b. 2 acres; livestock and game.

512. Pole Canyon: Sec. 9, T. 20 S., R. 2 E.; Sanpete; 6,000'; 1960; oak, mountain brush, and seeded grasses; in 2 parts:
   a. 1 acre; livestock; V; P;
   b. 1 acre; livestock and deer; V; P.

513. Yankee Reservoir: Sec. 20, T. 35 S., R. 8 W.; Iron; 1961; 1/2 acre; livestock and big game.

UTAH STATE UNIVERSITY

The following exclosures are constructed on a Bureau of Reclamation withdrawal from Public Domain lands in Grand County (see West and Ibrahim 1968):

514. Atriplex confertifolia - Hilaria jamesii habitat type: Sec. 5, T. 22 S., R. 23 E.; Grand; 4,430'; 1966; salt desert shrub (shadscale, galleta); 80 acres (half furrowed and seeded); sheep and cattle; V; P.

515. Atriplex corrugata habitat type: Sec. 20, T. 21 S., R. 23 E.; Grand; 4,000'; 1962; salt desert shrub; 40 acres; sheep and cattle; V; P.

516. Atriplex corrugata habitat type: Sec. 13, T. 22 S., R. 23 E.; Grand; 4,300'; 1962; salt desert shrub; 40 acres (half furrowed and seeded); sheep and cattle; V; P.

517. Atriplex corrugata habitat type: Sec. 34, T. 22 S., R. 23 E.; Grand; 4,000'; 1965, salt desert shrub; 80 acres (half furrowed andseeded); sheep and cattle; V; P.

518. Atriplex nuttallii var. nuttallii - Hilaria jamesii habitat type: Sec. 33, T. 22 S., R. 23 E.; Grand; 4,000'; 1965; salt desert shrub (Nuttall's saltbush, galleta); 80 acres (half furrowed and seeded); sheep and cattle; V; P.

519. Atriplex nuttallii var. nuttallii - Hilaria jamesii habitat type: Sec. 8, T. 22 S., R. 23 E.; Grand; 4,000'; 1965; salt desert shrub (Nuttall's saltbush, galleta); 40 acres (half furrowed and seeded); sheep and cattle; V; P.

The following exclosures are constructed on Bureau of Land Management lands (Salt Lake District) in Box Elder County; elevation 4,100'-4,600'; salt desert shrub type; sheep and cattle excluded; V.: (Information on size and date of establishment not available.)

520. Sec. 24, T. 11 N., R. 12 W.; 1 exclosure;
521. Sec. 31, T. 12 N., R. 11 W.; 1 exclosure;
522. Sec. 14, T. 13 N., R. 11 W.; 1 exclosure;
523-524. Sec. 15, T. 13 N., R. 11 W.; 2 exclosures;
525-526. Sec. 16, T. 13 N., R. 11 W.; 2 exclosures;
527. Sec. 17, T. 13 N., R. 11 W.; 1 exclosure;
528. Sec. 14, T. 14 N., R. 11 W.; 1 exclosure;

BRIGHAM YOUNG UNIVERSITY

529. Pole Canyon (Uinta National Forest, Spanish Fork District): Sec. 9, T. 6 S., R. 3 E.; Utah; 6,500'; 1949; mountain brush (oak, maple); livestock; V; P; (Allman 1953; Nixon 1967).

INDEXES

INDEX BY DATE OF ESTABLISHMENT

INDEX BY ELEVATION

INDEX BY TYPE OF ANIMAL EXCLUDED

INDEX BY VEGETATION TYPE AND MAJOR SPECIES

REFERENCES

Allman, Verl Phillips. 1953. A preliminary study of vegetation in an exclosure in the chaparral of the Wasatch Mountains, Utah. Utah Acad. Sci., Arts and Letters Proc. 30:63-73.

Anderson, E. William. 1966. Natural areas. J. Range Manage. 19:239-242.

Cox, Ted E. 1965. Rabbit impact on reseeded grass establishment. U.S. Forest Service, Intermountain Region, Range Improvement Notes 10(1):7-10.

Ellison, Lincoln. 1954. Subalpine vegetation of the Wasatch Plateau, Utah. Ecol. Monogr. 24:89-184.

_______ and C. M. Aldous. 1954. Influence of pocket gophers on vegetation of subalpine grassland in central Utah. Ecology 33:177-186.

Johnson, Hyrum B. 1964. Changes in the vegetation of two restricted areas of the Wasatch Plateau as related to reduced grazing and complete protection. Unpub. M.S. Thesis, Brigham Young Univ.

Mason, LaMar R., Horace M. Andrews, James A. Carley, and E. Dwain Haacke. 1967. Vegetation and soils of No Man's Land Mesa relict area, Utah. J. Range Manage. 20:45-49.

Nixon, Elray S. 1967. A comparative study of the mountain brush vegetation in Utah. The Great Basin Naturalist 27:59-66.

West, Neil E., and Kamal I. Ibrahim. 1968. Soil-vegetation relationships in the shadscale zone of southeastern Utah. Ecology 49:445-456.

Williams, Clayton. 1962. The exclosure--a tool of range management. Wyoming Range Manage., Issue 165, 2 pp.

_______. 1963. Range exclosure within the state of Wyoming. Wyoming Range Manage., Issue 170, 18 pp.

Young, Stanford. 1958. Exclosures in big game management in Utah. J. Range Manage. 11:186-193.

AFLC/HAFB, Ogden

Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field Research Work Units are maintained in:

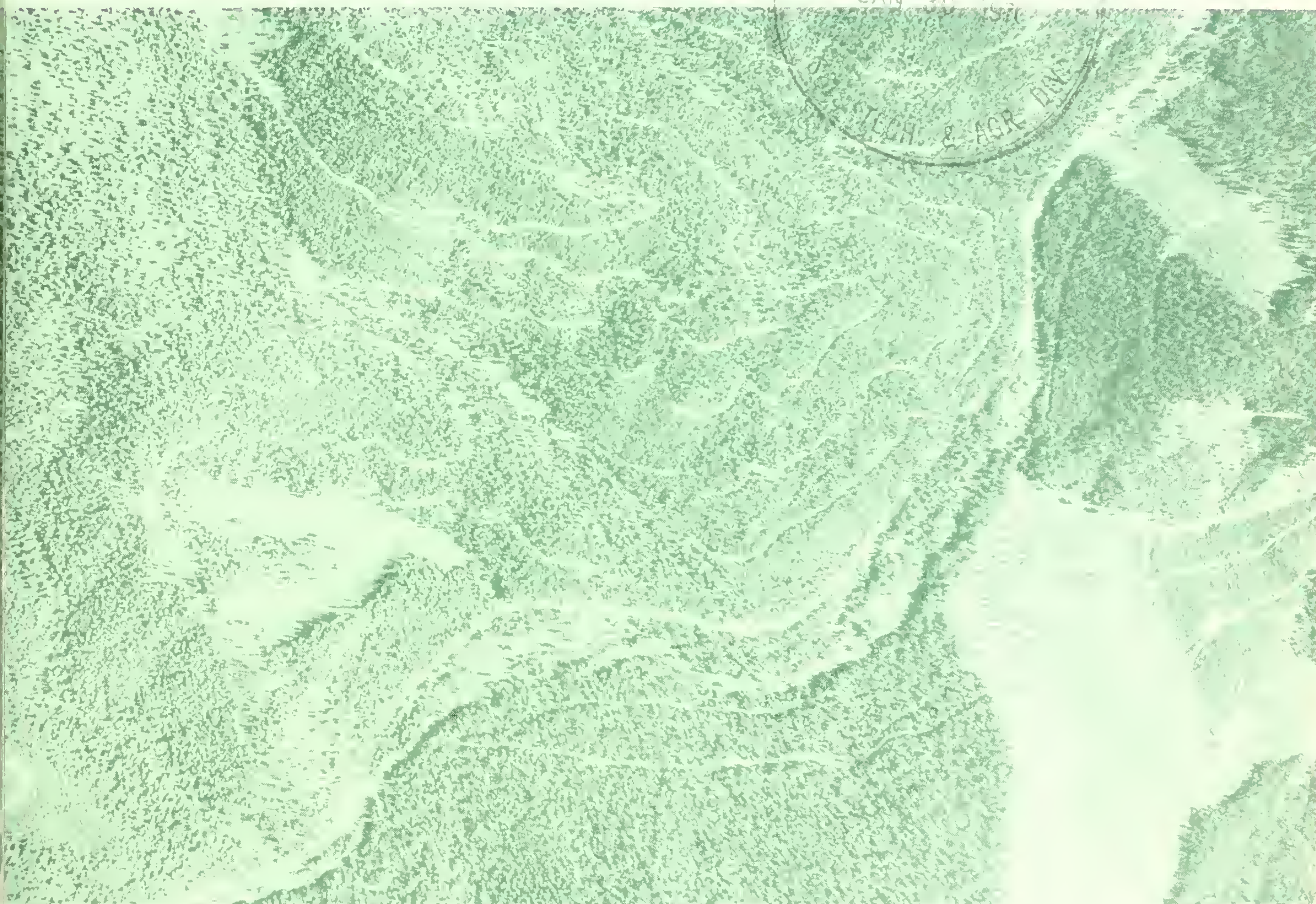
- Boise, Idaho
- Bozeman, Montana (in cooperation with Montana State University)
- Logan, Utah (in cooperation with Utah State University)
- Missoula, Montana (in cooperation with University of Montana)
- Moscow, Idaho (in cooperation with the University of Idaho)
- Provo, Utah (in cooperation with Brigham Young University)

FOREST SERVICE CREED

The Forest Service of the U. S. Department of Agriculture is dedicated to the principle of multiple use management of the Nation's forest resources for sustained yields of wood, water, forage, wildlife, and recreation. Through forestry research, cooperation with the States and private forest owners, and management of the National Forests and National Grasslands, it strives — as directed by Congress — to provide increasingly greater service to a growing nation.

SOME CASE HISTORIES OF NATURAL REGENERATION IN THE WESTERN WHITE PINE TYPE

R. J. Boyd



USDA FOREST SERVICE
RESEARCH PAPER INT-63, 1969

INTERMOUNTAIN FOREST & RANGE EXPERIMENT STATION
Ogden, Utah

USDA Forest Service
Research Paper INT-63
1969

SOME CASE HISTORIES OF NATURAL REGENERATION IN THE WESTERN WHITE PINE TYPE

R. J. Boyd

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401
Joseph F. Pechanec, Director

THE AUTHOR

RAY BOYD received his B.S. in general sciences from Colorado State University in 1949 and his master of forestry degree in 1951. From 1949 to 1953 he did silvicultural research for the Rocky Mountain Forest and Range Experiment Station. Since 1953 he has been an Associate Silviculturist, assigned to the Station's silviculture of western white pine work unit now at Moscow, Idaho.

INTRODUCTION

Natural regeneration of conifers in the "Western White Pine Type" is generally quite prompt on favorable sites under any of the even-aged silvicultural systems when an adequate seed source is reserved. Seedtree, shelterwood, and strip or block clearcutting have all met with considerable success (Haig et al. 1941). The coming of blister rust (Cronartium ribicola J. C. Fisch. ex Rabenh.) to the western white pine (Pinus monticola Dougl.) type made these methods less desirable and shifted the emphasis to clearcutting, prescribed broadcast burning, and planting. Under this system, Ribes (the currant genus and alternate host for blister rust) could be more economically eradicated and greater western white pine potentials established.

Recent developments have shown the futility of practical rust control by known Ribes eradication or chemical treatments (Ketcham, Wellner, and Evans 1968). Western white pine breeding programs should provide stock with an adequate degree of rust immunity for field planting in about 15 years. But until a chemical treatment which is applicable to seedling stands is developed, purposeful natural regeneration of white pine seems to be completely impractical except under those rare circumstances where Ribes are practically nonexistent or where climatic conditions limit the amount of pine infection.

The current emphasis in management of these forests, then, is on the regeneration of other suitable species common to the type. These may include grand fir (Abies grandis Lindl.), Douglas-fir (Pseudotsuga menziesii (Mirb.) Franc.), western hemlock (Tsuga heterophylla (Raf.) Sarg.), western redcedar (Thuja plicata D. Don.), western larch (Larix occidentalis Nutt.), ponderosa pine (Pinus ponderosa Laws.), lodgepole pine (Pinus contorta Dougl. var. murrayana (Grev. & Balf.) Engelm.), Engelmann spruce (Picea engelmannii Parry) and subalpine fir (Abies lasiocarpa (Hook.) Nutt.). These species constitute the major coniferous component of the ecological plant associations in which the Western White Pine cover type occurs. The principal "habitat types" include: Abies grandis/Pachistima myrsinites; Thuja plicata-Tsuga heterophylla/Pachistima myrsinites; Thuja plicata/Pachistima myrsinites; and Picea engelmannii-Abies lasiocarpa/Pachistima myrsinites (Daubenmire 1952).

While planting and seeding will be employed within these forest types when necessary or justifiable, reliance must be placed on natural regeneration for most of the reforestation job. But what natural regeneration can the timber manager expect in these types under various silvicultural systems? How fast will restocking occur? Can the composition and density of the new stand be controlled in the regeneration process, reducing the need for future silvicultural measures? Twenty years of natural reproduction records from stands on the Deception Creek Experimental Forest in northern Idaho provide some answers to these questions. The studies were established to supplement and give more definitive answers to some of the recommendations of Haig et al. (1941).[1] Although designed to feature western white pine in the future stand, they provide some valuable information on other species which should be useful in formulating alternative management guidelines.

---

[1]Most of the studies reported were established by Kenneth P. Davis and Charles A. Wellner.

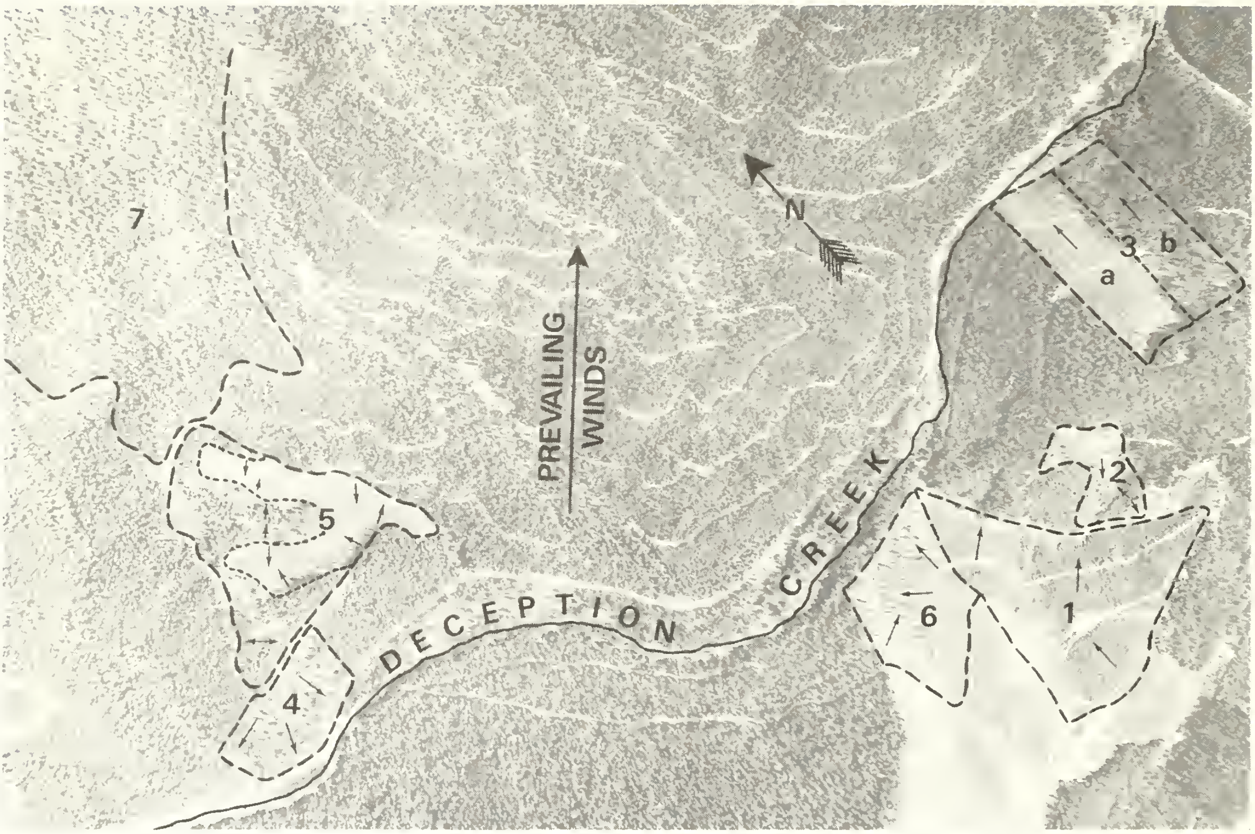


Figure 1.--1959 aerial view (approximate scale 1:15,000) of a portion of the Deception Creek Experimental Forest showing the location of regeneration studies described in this report. (Small arrows show aspect.)

Area 1.--Ames Creek: alternate shelterwood and clearcut strips.
Area 2.--Ames Creek seedtree block.
Area 3.--Tamarack Hill shelterwood block: a. low-value overwood felled; b. low-value overwood felled or girdled.
Area 4.--Haynes Creek shelterwood block.
Area 5.--Finger Gulch: alternate shelterwood and clearcut strips.
Area 6.--Synder Creek seedtree block.
Area 7.--Echo Peak selection cutting.

METHODS

The studies consist of five reproduction cuttings made between 1935 and 1937, and two that were made about 1951 (fig. 1). Treatments tested were strip clearcutting, shelterwood cutting, seedtree cutting, and selection cutting, each within the Abies grandis/Pachistima and Thuja-Tsuga/Pachistima habitat types, roughly equivalent, in the study area, to southerly and northerly aspects, respectively. Reproduction was inventoried on permanent transects at intervals ranging from 2 to 7 years after the initial regeneration cutting. Surveys generally consisted of an examination of species' occurrence on 4-milacre (1/250-acre) quadrats located along the transect lines, and a complete tally of seedlings on a 1-milacre (1/1000-acre) subsample of each 4-milacre unit. The percentage of 4-milacre units containing one or more trees (the "4-milacre stocking") provides an estimate of seedling distribution while the 1-milacre seedling count gives an estimate of the total number of seedlings per acre. When considered together, these values characterize the distribution and density of the regeneration stand. Only "established" seedlings, 3 years old or older, were recorded.

A 4-milacre stocking of 65 percent has, for many years, been the criterion of adequate stocking in the western white pine type (Wellner 1940). This is the standard used in this report and is equivalent, in the average seedling stand, to about 1,000 trees per acre or to a 1-milacre stocking of 40 percent.[2]

INDIVIDUAL STUDY AREAS

Ames Creek: Alternate Shelterwood and Clearcut Strips

Description

Following the leads from examples of successful strip-clearcutting dating back to 1910, this 36-acre area on a northeasterly exposure in the *Thuja-Tsuga/Pachistima* habitat type was horse-logged in 1935. Two clearcut strips, 4 to 7 chains wide, alternated with three shelterwood strips 4 to 5 chains in width (fig. 2). Unmerchantable timber on the clearcut strips was felled in 1935 and 1936 following logging; slash on these strips was control-broadcast burned in 1936.

The shelterwood cutting removed 60 percent of the 53,000 board feet per acre and left a stand averaging 31 trees per acre. Of these trees, about 27 were western white pine. This residual stand admitted 70 percent of full sunlight to the forest floor. Unmerchantable trees were felled and the slash progressively burned in the spring of 1936. By 1951 the area was adequately regenerated and the remainder of the shelterwood stand was "jammer" logged.[3]

Regeneration on this tract was influenced somewhat by a stand of mature timber that was on the western border of the upper portion. Undoubtedly, seed from this stand, which was not cut until 1952, was cast into the clearcut and shelterwood strips along with seed from the shelterwood residual.

Results

Shelterwood strips.--Regeneration within the shelterwood strips was very prompt and the distribution quite uniform (fig. 3). Four years after logging the 4-milacre stocking to all species was over 60 percent with 548 seedlings per acre. Eight years after logging the stocking had increased to 97 percent with 6,126 seedlings per acre.

Although the shelterwood stand contained no hemlock, this species was by far the most abundant in the reproduction. Some trees were advance growth, but the majority were seedlings originating from seed dispersed into the area from adjacent uncut stands. Western white pine was second in seedling representation with a 4-milacre stocking

---

[2]Present regeneration examinations of the Northern Region of the Forest Service are based on 1/300-acre sample plots. By their standard a "minimum acceptable stand" would have at least 100 trees of crop-tree quality per acre, and a "desirable stand" would require at least 250 crop trees. Assuming only one crop tree per stocked plot and applying conversions developed by Lynch and Schumacher (1941), the "minimum acceptable stand" would be equivalent to 38 percent 4-milacre stocking or about 210 trees per acre. The "desirable stand" would be equivalent to a 4-milacre stocking of 85 percent or about 3,000 trees per acre.

[3]"Jammer" logging is a portable cable system utilizing a mobile boom 25-30 feet long. Maximum skidding distances are 400 to 600 feet. The system is operated with or without a haul-back line.

Figure 2.--Ames Creek alternate shelterwood and clearcut strips 3 years after logging.

of 70 percent 8 years after logging. Grand fir was the third most abundant species, followed by western larch and Douglas-fir. Redcedar and spruce appeared as minor components on limited portions of the area.

There was no stocking survey immediately after removal of the shelterwood residual in 1951; therefore, the logging damage to reproduction already established could not be estimated. Four years after logging, however, these losses had been more than replaced by new germinants and by seedlings that were less than 3 years old in 1950.

With the exception of hemlock and larch, there was a continued increase in number of trees per acre throughout the 20-year period, but generally at a lesser rate after the initial 8 years. While the greatest increase in number of established grand fir seedlings occurred during the final 5 years of the 20-year period, this caused virtually no increase in stocking.

Clearcut strips.--Though quite adequate, regeneration on the clearcut strips has not been as prompt nor as complete as on the intervening shelterwood strips (fig. 4). A good seed year preceded logging on this area, and the broadcast burning of slash on the clearcuts apparently destroyed or reduced the reproduction from the prelogging seed supply. Four years after cutting, all-species' stocking was 15 percent as compared to 61 percent under shelterwood. From the eighth year on, stocking on the clearcut and shelterwood areas was nearly the same.

Seedling-abundance rankings for the species were essentially the same on the clearcut as on the shelterwood strips, but the number of seedlings and stocking percent for all species except western hemlock were generally reduced. Grand fir reproduction was only about one-fourth as abundant on the clearcut areas. Larch and Douglas-fir stocking and seedlings per acre were also less than under the shelterwood.

Hemlock, at the end of 20 years, constituted nearly 90 percent of the stand on the clearcut area. However, the more intolerant species on the clearcut area were in a somewhat better competitive position than on the shelterwood area. Overwood shade had for many years favored the growth of tolerant species in the shelterwood areas.

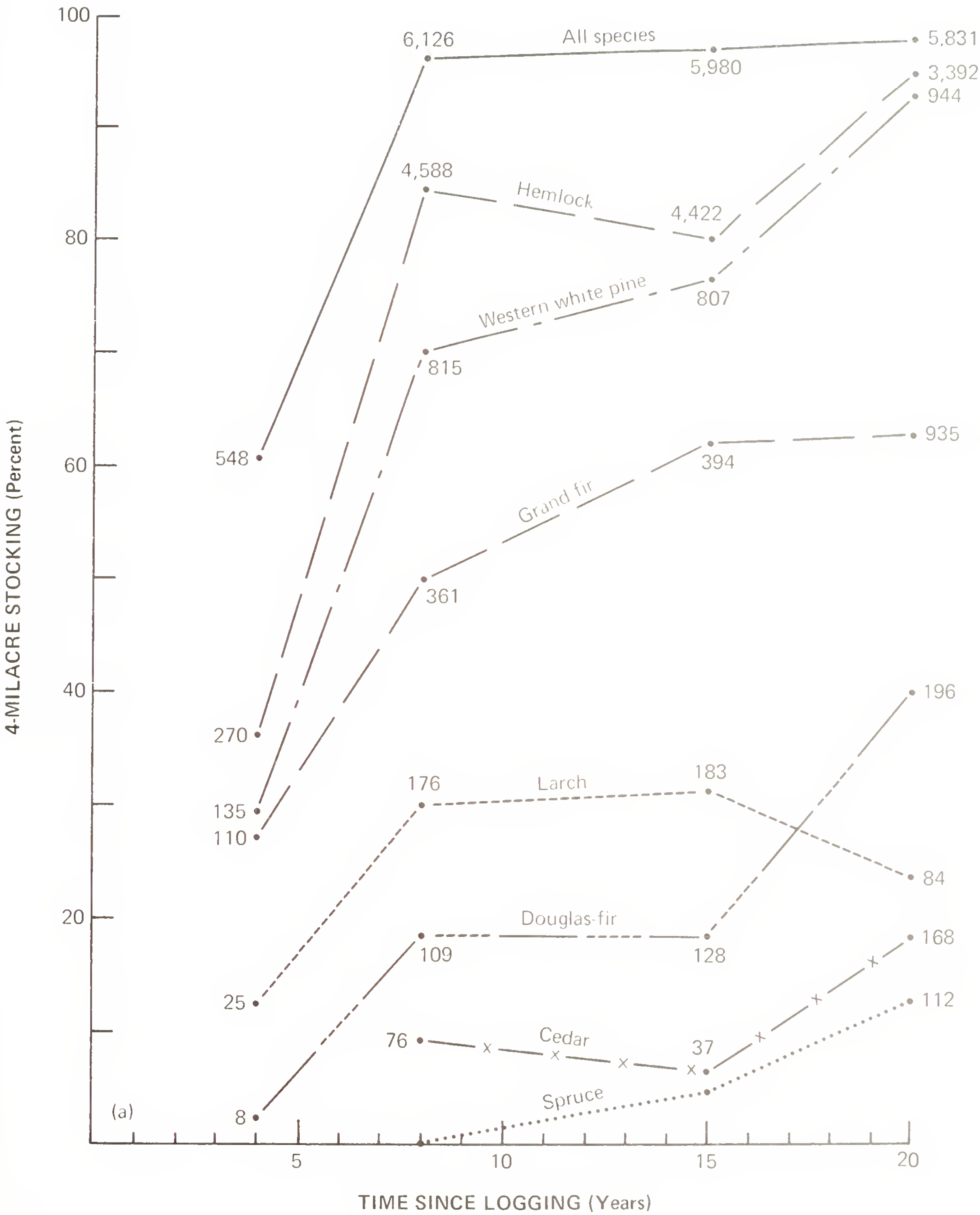


Figure [illegible].--Regeneration trends for shelterwood strips in the [illegible]. Numbers on the points of the curves designate numbers of [illegible] per [illegible].

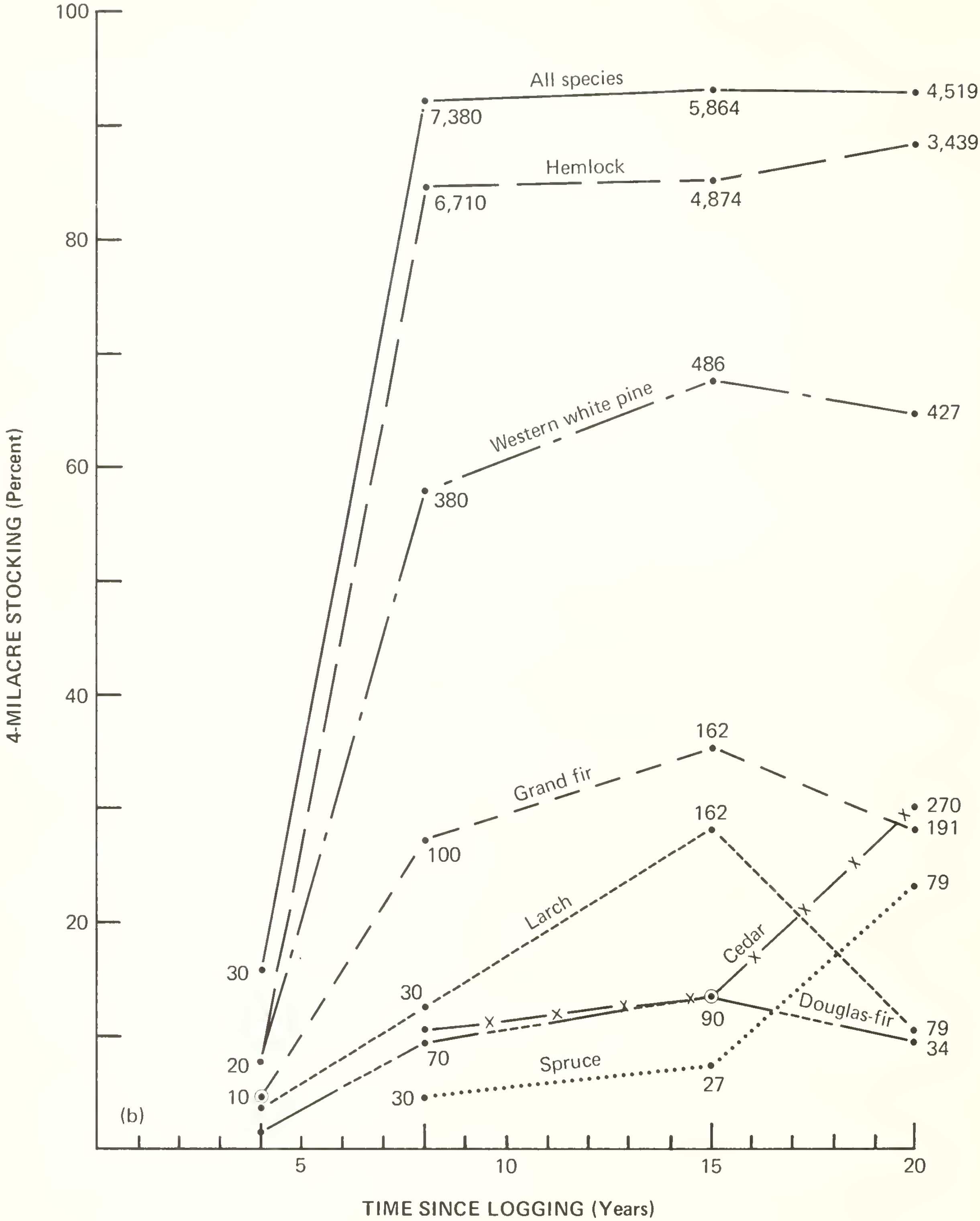


Figure 4.--Regeneration trends for clearcut strips in the Ames Creek Alternate. Numbers on the points of the curves designate numbers of seedlings per acre.

Ames Creek: Seedtree Block

Description

This area was originally horse-logged as a shelterwood in 1935, then accidentally burned over in the fall of 1936. The subsequent salvage of fire-killed trees left a seed-tree stand of four to six western white pine trees per acre. The area is 11.5 acres in size, and the exposure is generally southwesterly (*Abies grandis/Pachistima* habitat type) with some northwesterly (*Thuja-Tsuga/Pachistima* habitat type) aspects. Mature stands border the upper edge of the area on the north and east.

Results

The Ames Creek area regenerated rather slowly for the first 15 years after logging (fig. 5). At the end of this period, 60 percent of the area was stocked with "any-species." From 1950 to 1955, stocking increased to 96 percent and the number of seedlings per acre increased by threefold. Grand fir, the most abundant species in the adjacent stands, comprised 60 percent of the stand 20 years after logging. Hemlock and white pine seedlings were second and third in abundance. A small component of redcedar, Douglas-fir and larch completed the stand.

The rapid increase in regeneration establishment from 1950 to 1955 probably resulted from favorable summer weather in 1948. Precipitation that year was well above normal for July, and temperatures averaged 2 to 3 degrees below normal for July and August. Seedlings which germinated during this favorable year were probably not recorded in 1950 as "established" seedlings.

Hemlock and redcedar reproduction was restricted to the northwesterly aspect of a spur ridge which extends through the area. The predominant southwesterly slopes became covered by a dense growth of *Ceanothus*; under this competition, western white pine seedlings were spindly and of poor vigor compared to the grand fir.

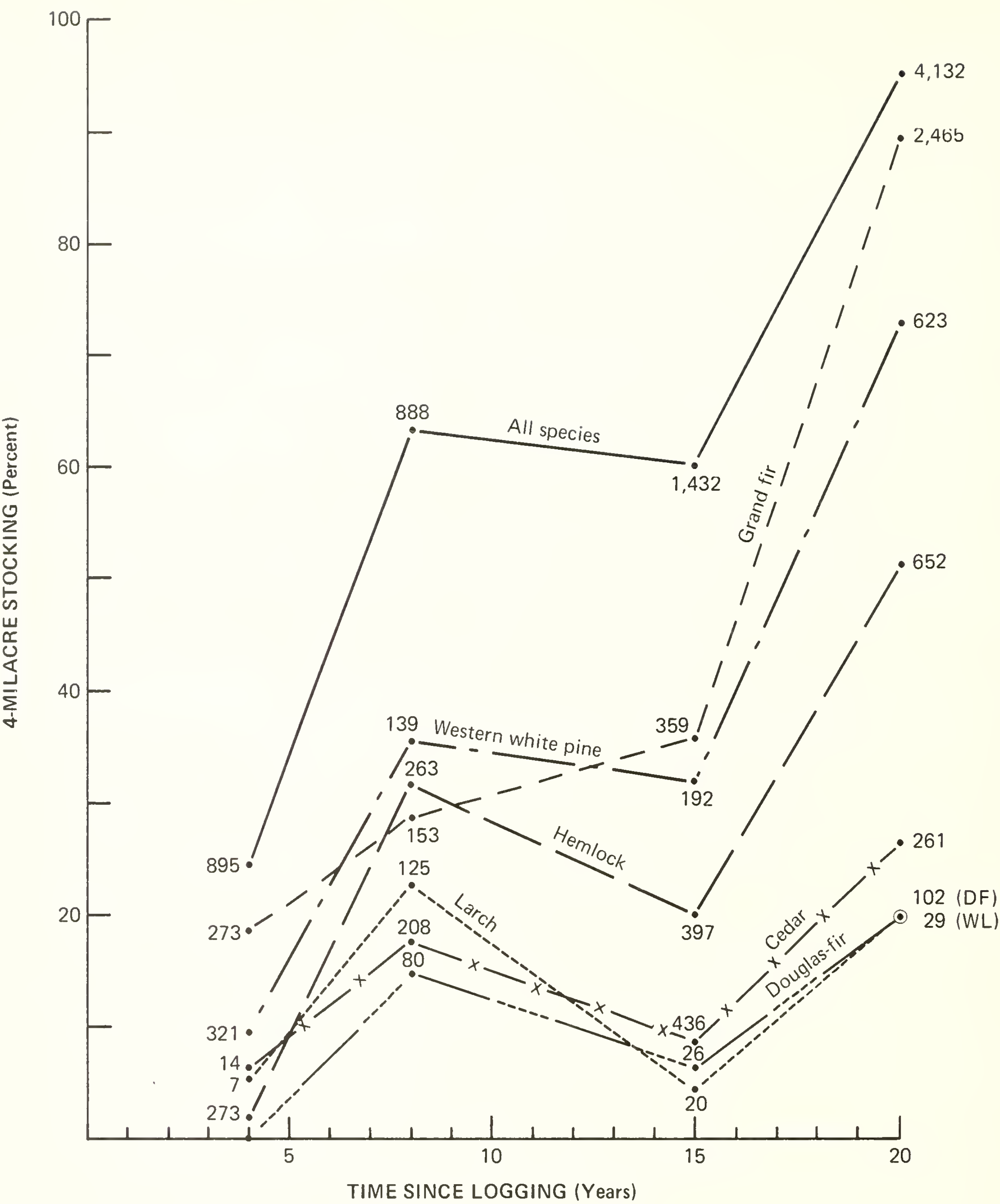


Figure 5.--Regeneration trends in the Ames Creek seedtree block. Numbers on the points of the curves designate numbers of seedlings per acre.

Figure 6.--Heavy shading by the Tamarack Hill shelterwood stand favored growth of western hemlock and suppression of less tolerant species.

Tamarack Hill: Shelterwood Block

Description

This 27-acre tract is located on a steep north slope. The entire area is Thuja-Tsuga/Pachistima habitat type. In 1935 and 1936, two overstory treatments were applied, both of which resulted in nearly pure western white pine shelterwood stands. One half of the tract (area 3a in fig. 1) contains hemlock and grand fir trees that were all highly defective or otherwise unmerchantable; these were felled and the slash was piled and burned. On the other half (area 3B), fir and hemlock larger than 8 inches d.b.h. were girdled, smaller stems were felled, and the slash was piled and burned. The reserve stand permitted only an estimated 50 percent of full sunlight (fig. 6), beneath the canopy on the area where all of the low-value stems were felled. Under the canopy where girdling had been done, the light probably was even less for several years, but it approached the same intensity after the girdled trees died and began to deteriorate.

Results

Four years after logging, stocking of the combined species on this area was above 80 percent, and by the eighth year stocking exceeded 90 percent (figs. 7, 8) with 13,000 seedlings per acre. Regeneration was most rapid on the portion of the area where all of the low-value trees were felled, but it seems likely that this was due more to a favorable location with respect to adjoining seed sources and the prevailing wind than to the nature of the treatment of unmerchantable overstory.

At the end of the period of record, hemlock and grand fir, though virtually eliminated from the shelterwood stand, far outnumbered western white pine in the regeneration.

The disturbance caused by logging the residual overstory on half of the area in 1952 reduced stocking of all-species from 100 percent to 86 percent. Losses were greatest among the western white pine, grand fir, and larch reproduction.

Haynes Creek: Shelterwood Block

Description

Horse-logging on this 15-acre block in 1936 removed most of the associated species, leaving a nearly pure western white pine shelterwood. Slash was piled and burned in 1936 and 1937. The light intensity in this shelterwood was probably less than 50 percent. The establishment report states that the canopy was denser than in either of the previously mentioned shelterwood stands. The area lies on a very steep lower slope with south- to west-facing aspects. Mature stands border the area on all sides. The survey transects were located so as to sample reproduction separately on the westerly (*Thuja-Tsuga/Pachistima* habitat type), southwesterly, and southerly (both *Abies grandis/Pachistima* habitat type) exposures (figs. 9, 10, 11).

Results

Regeneration of the Haynes Creek shelterwood block has been slow. Stocking of all species combined reached a satisfactory level within 10 to 15 years on the more favorable westerly aspect and within 19 years on the more severe southerly exposure; however, stocking was not yet adequate after 19 years on the very unfavorable southwest exposure (fig. 10). Individual-species regeneration followed a similar pattern. Both grand fir and Douglas-fir were generally more abundant and had better stocking than western white pine, although seed for these species had to come primarily from adjacent stands. Hemlock reproduction was restricted to the moist lower slopes.

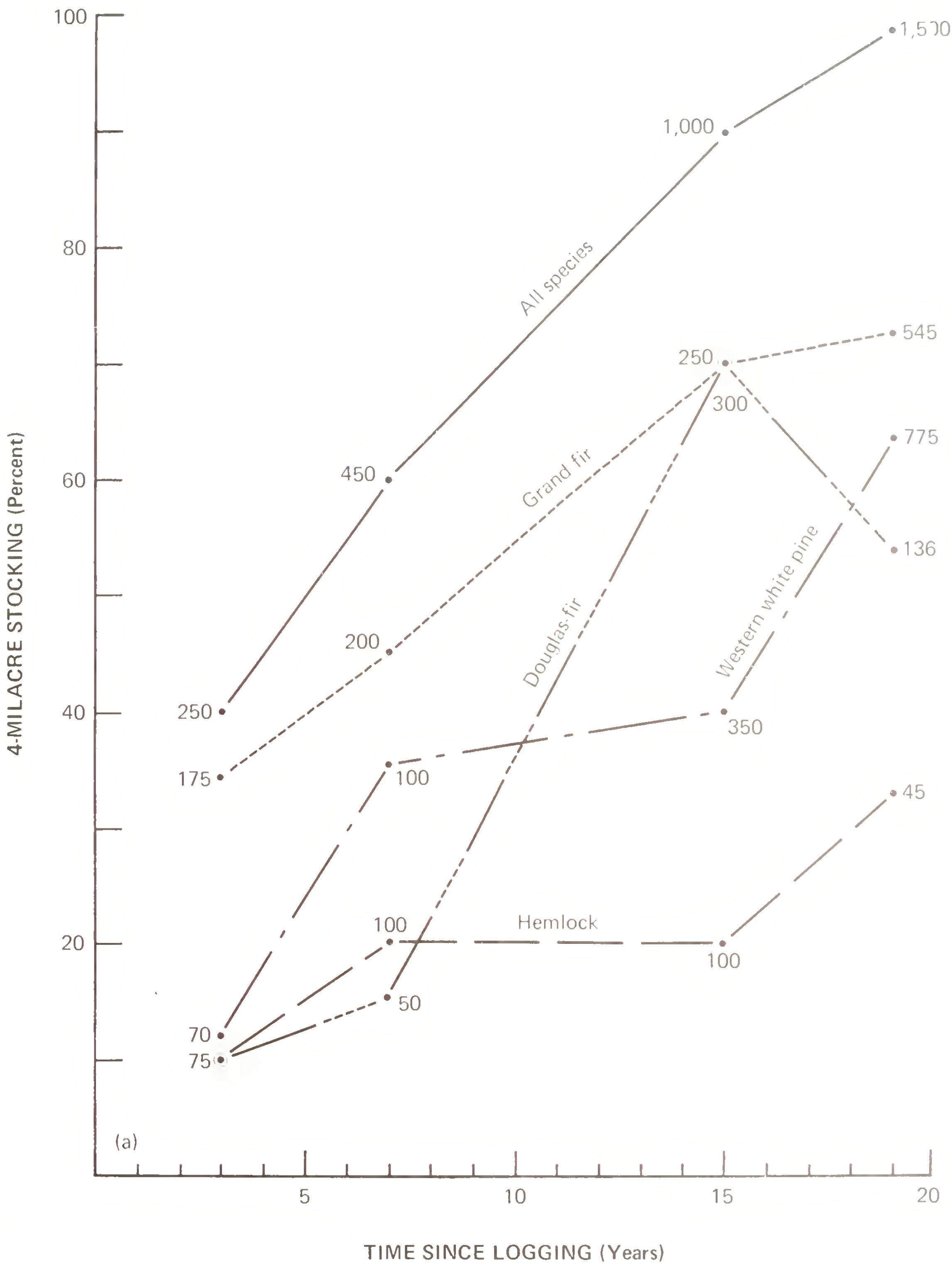


Figure 9.--Regeneration trends on the Haynes Creek shelterwood block [illegible]. Numbers on the points of the curves designate numbers of [illegible].

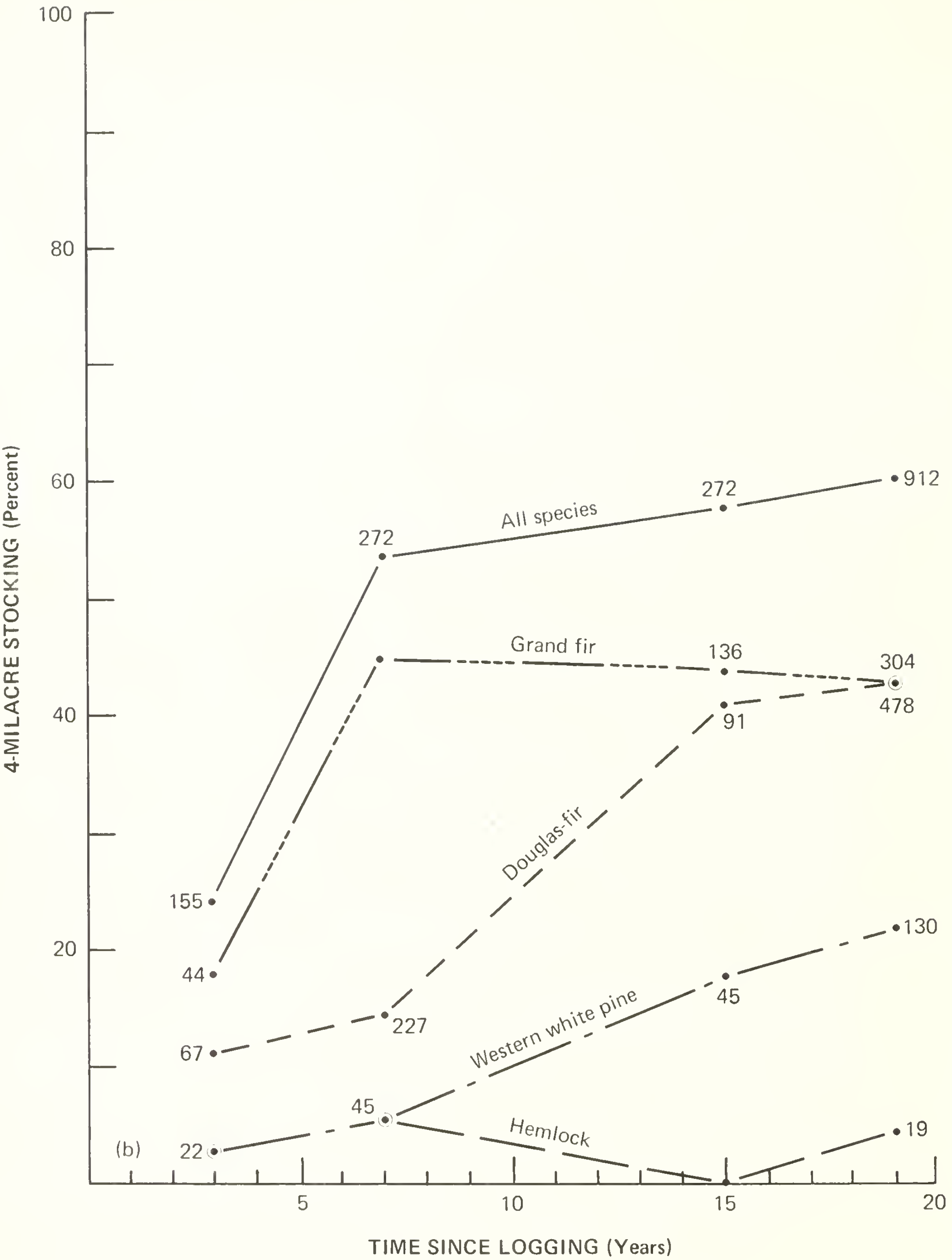


Figure 10.--Regeneration trends on the Haynes Creek shelterwood block (southwest aspect). Numbers on the points of the curves designate numbers of seedlings per acre.

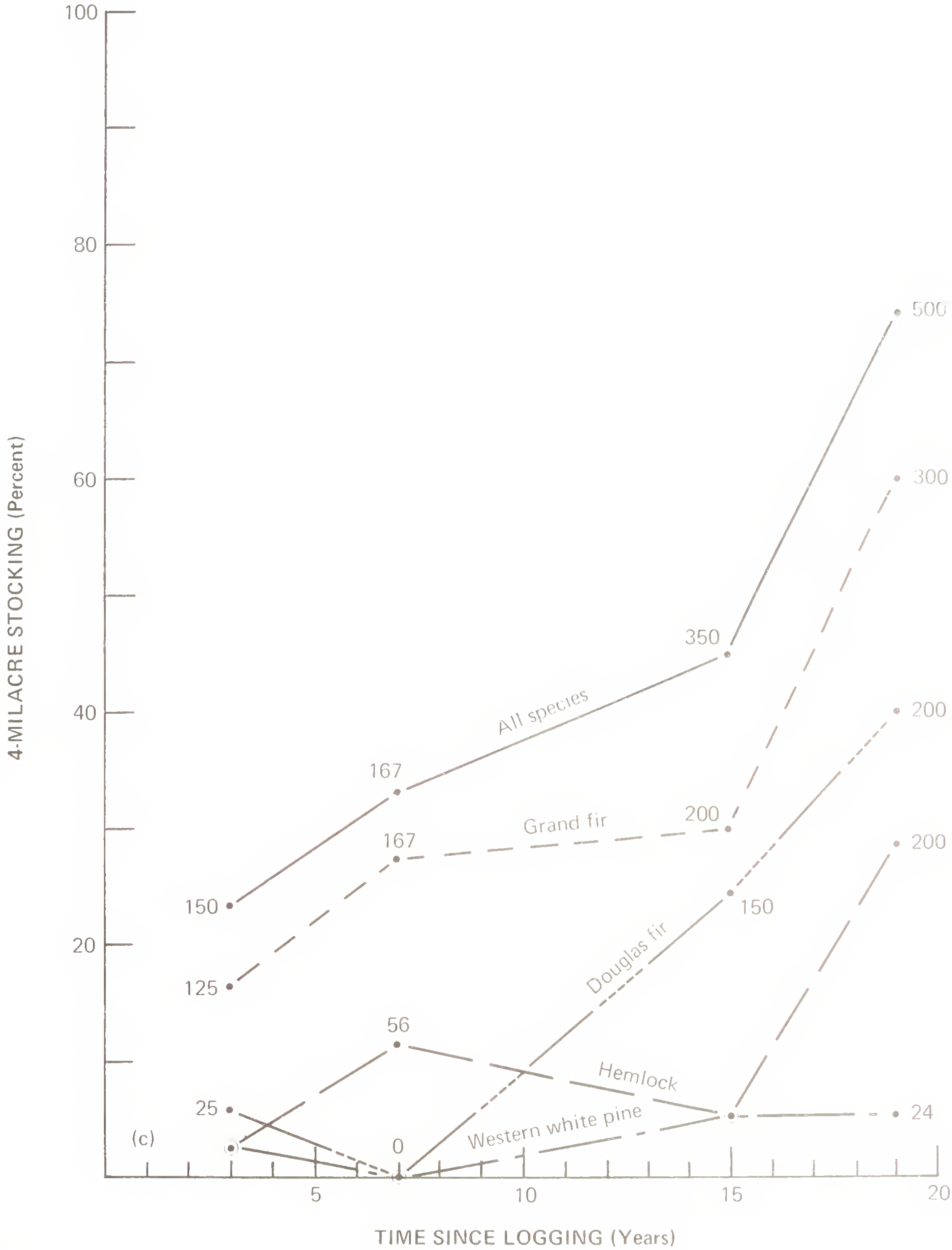


Figure 11.--Regeneration trends on the Haynes Creek shelterwood [illegible]
Numbers on the points of the curves designate numbers of seedlings per acre.

Finger Gulch: Shelterwood-Strip-Clearcutting

Description

This area contains two clearcut strips, 4 to 9 chains wide, and adjacent shelterwood cuttings. The clearcut portions total 17 acres and straddle the main stream and a tributary while 21 acres of shelterwood occupy the upper slopes and ridgetops. Ecologically, the area is a mosaic of *Thuja-Tsuga/Pachistima* and *Abies grandis/Pachistima* habitat types with northeasterly-through-southerly-to-southwesterly aspects. The timber was horse-logged in 1937. Slash on the clearcut strips was broadcast-burned in 1938 and 1939. The shelterwood cutting left 50 percent of the western white pine volume and an average of 15 trees per acre exceeding 14 inches d.b.h. The defective residual trees in the shelterwood were slashed, piled, and burned.

Results

Stocking of all species combined on the shelterwood portion of the Finger Gulch area was over 80 percent at the time of the first survey, 14 years after logging (fig. 12). It seems likely that stocking reached an adequate level prior to the tenth year. Grand fir occupies the most prominent position, followed by hemlock and western white pine.

On the clearcut strips, 13 years passed before the all-species' stocking level was adequate (fig. 13). As on the shelterwood area, grand fir was the best distributed species, but hemlock was superior numerically because of its high density in small areas where topography and moisture favored its establishment.

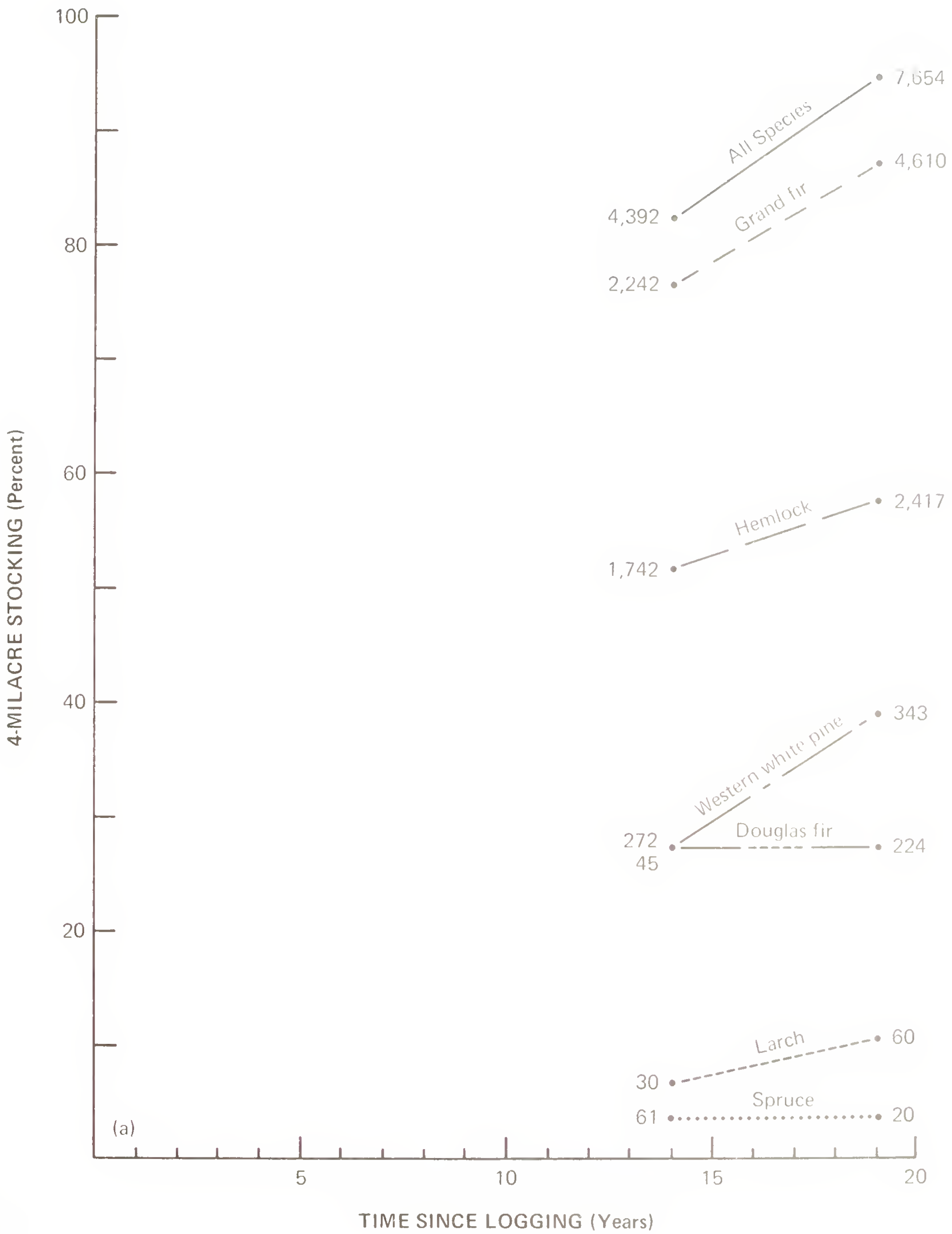


Figure 12.--Regeneration trends in shelterwood strips in Finger [illegible]. [illegible] the points of the curves designate numbers of see[illegible].

Finger Gulch: Shelterwood-Strip-Clearcutting

Description

This area contains two clearcut strips, 4 to 9 chains wide, and adjacent shelterwood cuttings. The clearcut portions total 17 acres and straddle the main stream and a tributary while 21 acres of shelterwood occupy the upper slopes and ridgetops. Ecologically, the area is a mosaic of *Thuja-Tsuga/Pachistima* and *Abies grandis/Pachistima* habitat types with northeasterly-through-southerly-to-southwesterly aspects. The timber was horse-logged in 1937. Slash on the clearcut strips was broadcast-burned in 1938 and 1939. The shelterwood cutting left 50 percent of the western white pine volume and an average of 15 trees per acre exceeding 14 inches d.b.h. The defective residual trees in the shelterwood were slashed, piled, and burned.

Results

Stocking of all species combined on the shelterwood portion of the Finger Gulch area was over 80 percent at the time of the first survey, 14 years after logging (fig. 12). It seems likely that stocking reached an adequate level prior to the tenth year. Grand fir occupies the most prominent position, followed by hemlock and western white pine.

On the clearcut strips, 13 years passed before the all-species' stocking level was adequate (fig. 13). As on the shelterwood area, grand fir was the best distributed species, but hemlock was superior numerically because of its high density in small areas where topography and moisture favored its establishment.

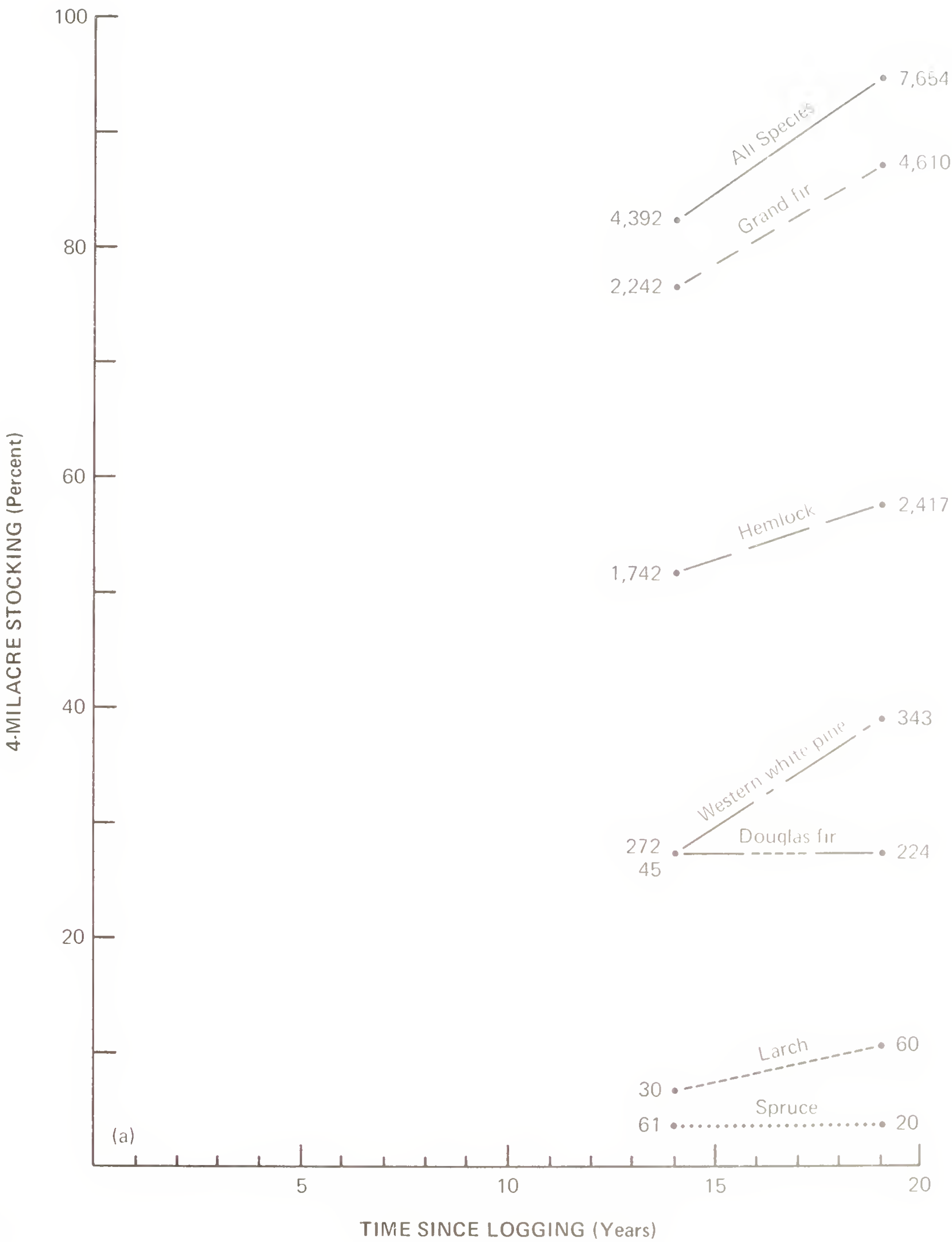


Figure 12.--Regeneration trends in shelterwood strips in Finger [illegible] the points of the curves designate numbers of se[illegible]

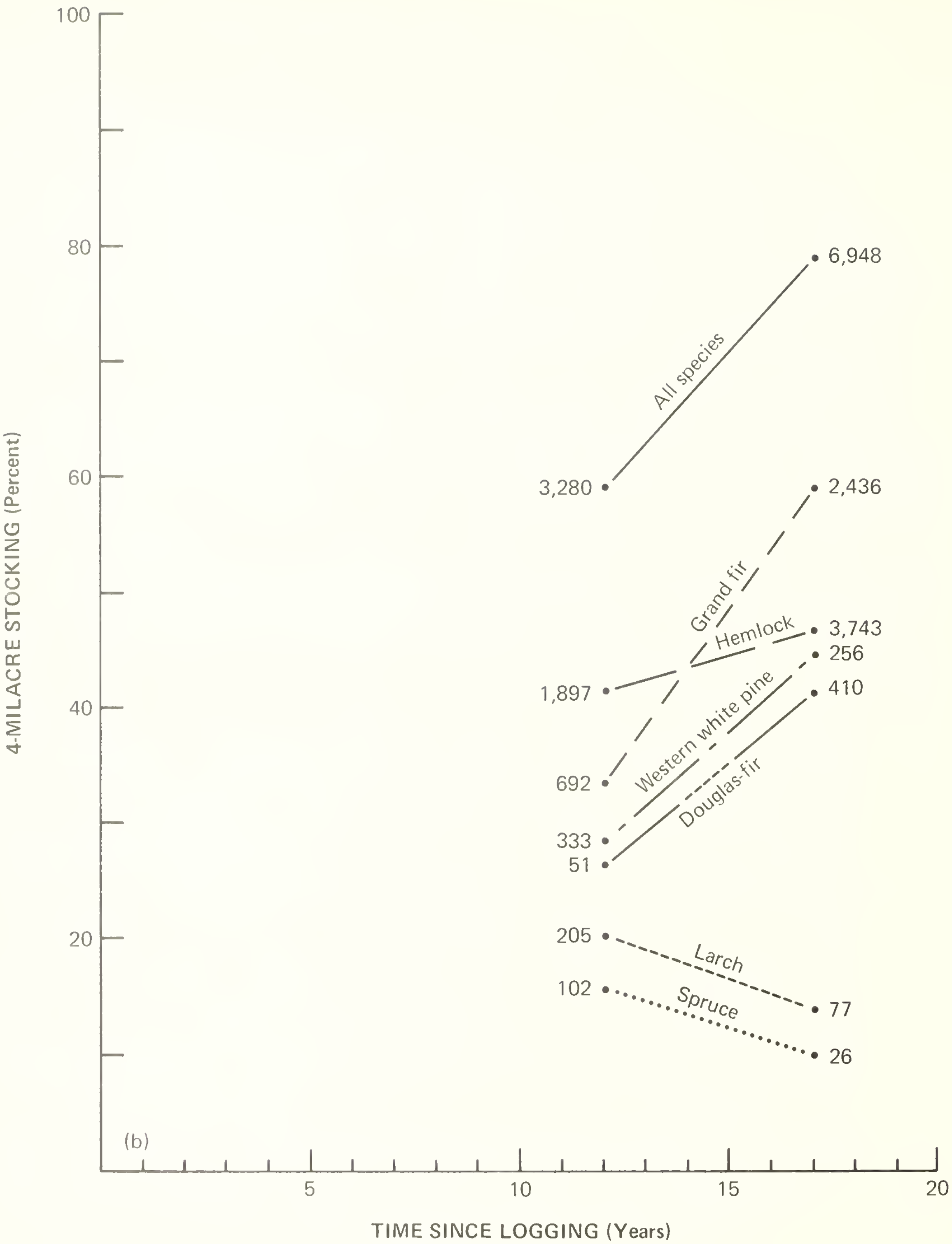


Figure 13.--Regeneration trends in clearcut strips in Finger Gulch. Numbers on the points of the curves designate numbers of seedlings per acre.

Figure 14.--Regeneration entered promptly under the western white pine seedtree stand on this lower north slope in Snyder Creek.

Snyder Creek: Seedtree Cutting

Description

This 11-acre, north-slope tract was jammer-logged in 1952 leaving about [illegible] western white pine seed trees per acre and some unmerchantable hemlock and grand fir. Slash from the logging was piled and burned in 1953. The unmerchantable trees were felled in 1954 and the slash from these was also piled and burned. Mature timber bordered this area on the north and west (fig. 14).

Results

Annual observations during the post-logging years showed that this area regenerated rapidly to a variety of species with hemlock and western white pine the most abundant. Most of the early western white pine reproduction was infected with blister rust. By 1956 Ribes eradication had reduced the infection source enough to permit good establishment of relatively rust-free pine (fig. 15), but other species had gained in dominance. For instance, reproduction measurements during 1959 showed that while 88 percent of the area was stocked with western white pine, other species were dominant on 65 percent of the plots.

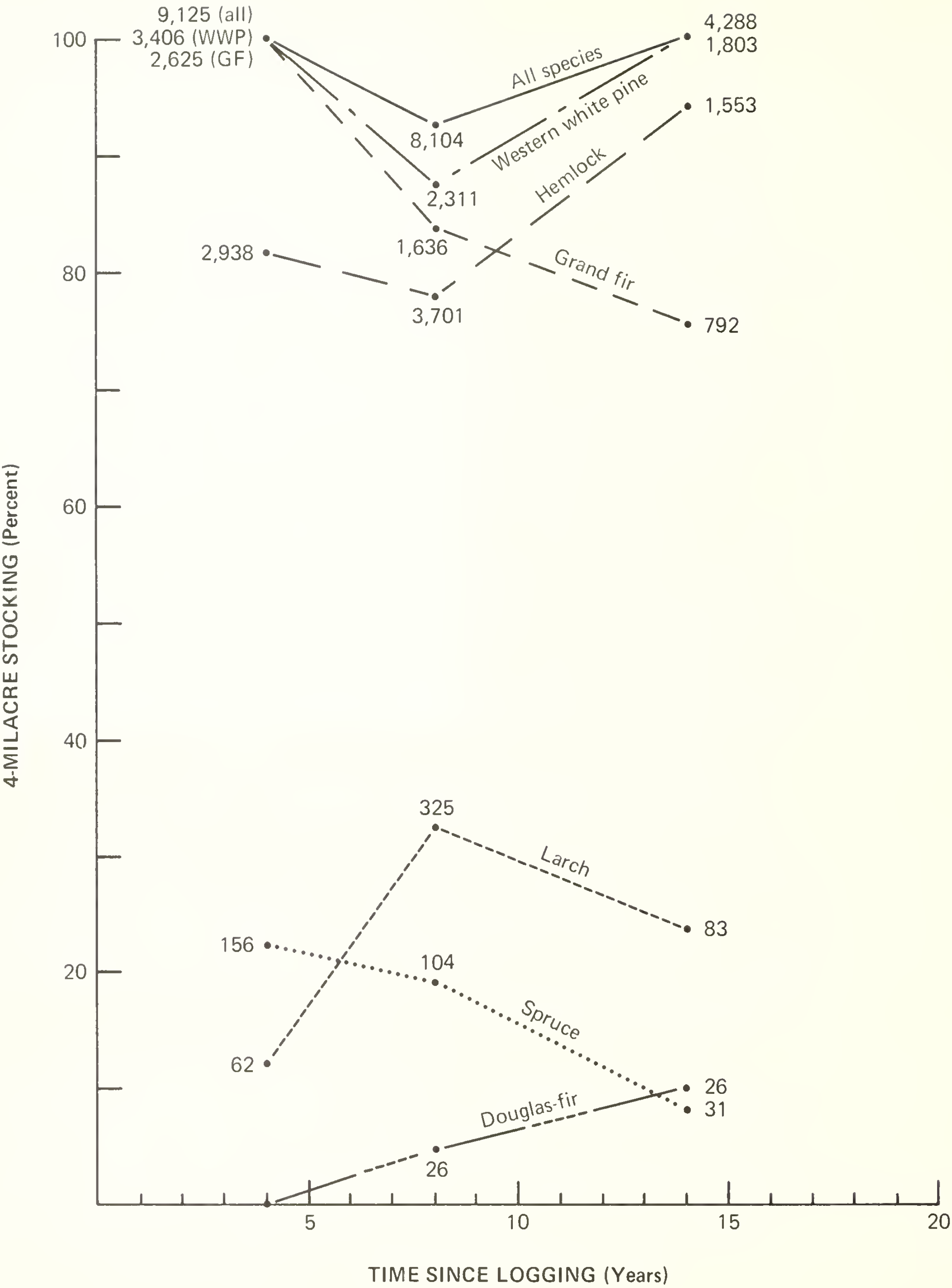


Figure 15.--Regeneration trends on the Snyder Creek seedtree block. Numbers on the points of the curves designate numbers of seedlings per acre.

Echo Peak. Selection Cuttings

Description and Methods

This study was established on a 700-acre tract of uneven-aged timber to test the effects of repeated light cuttings on regeneration and on the growth of the remaining stand. Cuttings of this type have been proposed, and used to a limited extent, as the best way to manage the drier and warmer south-facing slopes within the "western white pine type." Gradual harvest, permitting a gradual entry of reproduction, helps to protect the characteristically thin soils from serious losses which might result from more drastic conversion methods.

The Echo Peak area is situated on rather dry upper slopes, with east, south, and west aspects represented. Portions of the stand were partially logged in 1939-41 and the entire area was again selectively logged in 1950-51 to remove dead, defective, and poor-vigor trees. In 1952 ten randomly located strips, each containing five circular 1/5-acre plots, were established. On these plots, trees larger than 6 inches d.b.h. were tagged for growth measurements and counts were made of all smaller trees by 1-inch diameter classes. Trees less than 3 years old were not recorded. In 1957 a smaller reproduction sample was taken within five 1/20-acre plots that were concentric with the five original 1/5-acre plots. About one-third of the study plots were in areas classified as *Thuja-Tsuga/Pachistima* and the remainder were on *Abies grandis/Pachistima* sites. Composition of the "seed-producing" overwood (trees 10 inches d.b.h. or larger) in 1952 was 44 percent grand fir, 26 percent Douglas-fir, 26 percent western white pine, 2 percent larch, and 2 percent hemlock. The former harvest cuttings and natural mortality had removed approximately 50 percent of the merchantable volume.

Results

Until 1952 the cuttings in the Echo Peak tract had not resulted in any appreciable regeneration. At that time, the stand 1-inch d.b.h. and under averaged only 46 trees per acre. By 1957, reproduction was considerably more abundant with an average of 338 trees per acre that were less than 0.6 inch in diameter. Western white pine and Douglas-fir reproduction increased during the 5-year period but not nearly as rapidly as grand fir.

Regeneration on plots classified as *Thuja-Tsuga/Pachistima* habitat type had an average of over 400 seedlings per acre in 1957. Plots within areas of the *Abies grandis/Pachistima* habitat type had an average of under 300 seedlings per acre. Species composition on these two habitat types was similar. More than 75 percent of the seedlings were grand fir on each habitat type. Of the 18 plots in the *Thuja-Tsuga/Pachistima* habitat type, none were without seedlings whereas four of the 32 plots in the *Abies grandis/Pachistima* habitat type had no seedlings.

DISCUSSION AND CONCLUSIONS

The results of these studies confirm much of what has already been reported concerning the natural regeneration of western white pine (Haig et al. 1941). Also, these results provide additional information concerning the regenerative behavior of other species and help to refine our knowledge of the variables associated with natural regeneration in two of the major habitat types of Northern Rocky Mountain forests.

Thuja-Tsuga/Pachistima Habitat Type

On favorable aspects, represented at Deception Creek by the *Thuja-Tsuga/Pachistima* habitat type, the forester can use any of the even-aged silvicultural systems and be quite sure of adequate diverse natural regeneration within 5 to 10 years after the regeneration cut. Western hemlock is apt to be the most abundant species in the new stand if a seed source is left nearby. Hemlock regeneration was generally as abundant in clearcut areas as it was under shelterwood stands. Where the shelterwood stand was not removed early in the regeneration process, hemlock reproduction now almost completely dominates the new stand. On clearcuts or shelterwood regenerated stands where the overwood was removed promptly after regeneration was obtained, the full-sunlight environment has generally resulted in reproduction with a greater variety of species in the potential crop-tree stand.

Natural regeneration of grand fir on these moist sites seems to have been best under a shelterwood stand, but was suppressed by hemlock when the shelterwood was retained too long.

Western white pine regeneration has been prompt and adequate, but protection from blister rust has been a continuous and costly job. Like grand fir, but to a greater extent, western white pine was dominated by hemlock reproduction under the prolonged shade of shelterwood stands.

Although western larch is of minor numerical importance in the reproduction stands on these areas, it usually becomes dominant on any quadrat on which it occurs, due to its rapid early growth. A rather curious decline in the stocking percentage of larch appears to have occurred, even under clearcut conditions, after an initial period of continuous build-up.

Douglas-fir was a minor component of the reproduction stand on all study areas of the Thuja-Tsuga/Pachistima habitat type. In older, unmanaged stands of this habitat type, Douglas-fir is nearly always a minor and short-lived stand component. Until its performance in stands characterized as Thuja-Tsuga/Pachistima habitat type has been proven, it should probably not be relied upon as an important element of the crop-tree stands.

Abies grandis/Pachistima Habitat Type

Dry sites, represented at the Deception Creek Experimental Forest by the Abies grandis/Pachistima habitat type, are characterized by a prolonged forest regeneration period which may exceed 20 years. With such long regenerative periods, additional time and growth will be lost through subsequent years of severe competition from other vegetation, mainly shrubs.

None of the species restocked these areas as rapidly as they did those areas of the Thuja-Tsuga/Pachistima habitat type, and their importance differed considerably. Grand fir was the most abundant species in the new stands, followed closely by western white pine and Douglas-fir. Under selection cuttings, grand fir promises to dominate future stands to the almost complete exclusion of other, less shade-tolerant species. Clearcut and shelterwood conditions have resulted in regeneration of the greatest variety of species.

Douglas-fir has a much more important role in these south-slope reproduction stands than on the moist sites. It is more abundant under these south-slope conditions and it maintains better vigor through to maturity.

Some important factors that determine what regeneration prescription is best for a given area include:

1. Species desired in the future stand. With the demonstrated uncertainty of the comparative economic values as well as unforeseen species' susceptibility to certain disease or insect epidemics, it would seem that "mixtures" should usually be favored in regeneration planning--conditioned by the use of available and pertinent information on suitability of species to the site and to each other.

2. Nature of the parent stand. Natural regeneration measures should not be attempted in overmature stands where there is an inadequate seed source of desirable species. Furthermore, natural regeneration should not be the sole measure where the seed source consists of only one species on a site that is capable of supporting a more diverse stand. Careful consideration should also be given to the composition of the adjacent stands in relation to the size of the area to be regenerated and the probable abundance and dissemination of the seed of various species.

3. Other-use considerations. Maintenance of a timber cover for soil or down-stream watershed protection may be a prime consideration. Forests can be regenerated under these limitations by selection cutting, but species' diversity may have to be sacrificed. On south slopes, where this is most apt to be a problem, such cuttings will hasten the production of a climax forest of grand fir. Another consideration might be the need to provide a better winter range for big game. Maintenance of present big game herds depends upon the preservation of shrub cover on much of the lower south slopes characterized as *Abies grandis/Pachistima* habitat type. This need could reduce, or even eliminate, the need for tree regeneration on these areas.

4. Topography and slash disposal. Slash disposal in a residual seed-tree or shelterwood stand located on steep slopes requires costly piling and burning. Prescribed burning of clearcut blocks or strips seems to be the only practical alternative at present. On gentle slopes or level ground, machine methods of slash disposal and other site preparation become economically possible and this provides wider choice of silvicultural techniques.

5. Advance growth. New reproduction may receive severe competition from brush and older understory trees at the outset. Abundance and condition of this advance growth, together with the anticipated logging mortality and injury, should be considered in deciding whether to feature it in the next crop or not. Most of this is apt to be hemlock, grand fir, and redcedar. The hemlock and grand fir are often badly infected with brown stringy rot (*Echinodontium tinctorium* Ell. & Ev.). Furthermore, a marked increase in root-rot infection (*Armillaria mellea* (Vahl. ex Fr.) Quel.), with accompanying decline in vigor, has been observed after the abrupt release and thinning of western redcedar (Koenigs 1969).

While prompt regeneration is desirable, a gradual entry of natural regeneration may have certain advantages. In the first place it may provide for a greater diversity of species in the new stand. Species seldom seed equally well in any given year, so a sequence of years could provide a greater number of species and more varied management opportunities in the future. A gradual stocking build-up also provides for better initial stocking control through periodic checks that give the manager an opportunity to remove the seed source in time to prevent, or at least reduce, overstocking problems. The hazards of overstocking might also be reduced by adjusting the amount of initial seed source to match the probability of obtaining prompt and abundant regeneration.

Foresters dealing with the problem of how to treat an area in order to establish a new stand for future harvest must consider a complex set of economic and biological factors; these circumstances seldom lead to an easy solution. There is certainly no panacea, no cut-and-dried procedure, which can be used with equal success everywhere and every time. Planting on prepared sites gives the best assurance of prompt regeneration of the desired species properly spaced for best future stand development; but this practice is limited by high site preparation and planting costs, plus the difficulties of obtaining planting stock or a suitable seed source at the right time. Natural regeneration will probably be our main source of new stands for many years. Studies such as those reported here can help to provide guidelines to be used in meeting our regeneration goals.

LITERATURE CITED

Haig, Irvin T., Kenneth P. Davis, and Robert Weidman.
1941. Natural regeneration in the western white pine type. U.S. Dep. Agr. Tech. Bull. 767, 99 pp., illus.

Daubenmire, R.
1952. Forest vegetation of northern Idaho and adjacent Washington and its bearing on concepts of vegetation classification. Ecol. Monogr. 22: 301-330, illus.

Ketcham, David E., Charles A. Wellner, and Samuel S. Evans, Jr.
1968. Western white pine management programs realigned on Northern Rocky Mountain National Forests. J. Forest. 66(4): 329-332, illus.

Koenigs, J. W.
1969. Root rot and chlorosis in released and thinned western redcedar. J. Forest. 67(5): 312-315, illus.

Lynch, D. W., and F. X. Schumacher.
1941. Concerning dispersion of natural regeneration. J. Forest. 39(1): 49-51, illus.

Wellner, C. A.
1940. Relationships between three measures of stocking in natural reproduction of the western white pine type. J. Forest. 38: 636-638, illus.

Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field Research Work Units are maintained in:

- Boise, Idaho
- Bozeman, Montana (in cooperation with Montana State University)
- Logan, Utah (in cooperation with Utah State University)
- Missoula, Montana (in cooperation with University of Montana)
- Moscow, Idaho (in cooperation with the University of Idaho)
- Provo, Utah (in cooperation with Brigham Young University)

FOREST SERVICE CREED

The Forest Service of the U. S. Department of Agriculture is dedicated to the principle of multiple use management of the Nation's forest resources for sustained yields of wood, water, forage, wildlife, and recreation. Through forestry research, cooperation with the States and private forest owners, and management of the National Forests and National Grasslands, it strives — as directed by Congress — to provide increasingly greater service to a growing nation.

SITE PREPARATION AIDS NATURAL REGENERATION

IN WESTERN LARCH-ENGELMANN SPRUCE STRIP CLEARCUTTINGS

R. J. Boyd and G. H. Deitschman

USDA FOREST SERVICE
RESEARCH PAPER INT-64, 1969

INTERMOUNTAIN FOREST & RANGE EXPERIMENT STATION
Ogden, Utah

USDA Forest Service
Research Paper INT-64
1969

SITE PREPARATION AIDS NATURAL REGENERATION IN WESTERN LARCH-ENGELMANN SPRUCE STRIP CLEARCUTTINGS

R. J. Boyd and G. H. Deitschman

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401
Joseph F. Pechanec, Director

THE AUTHORS

RAY BOYD received his B.S. in general sciences from Colorado State University in 1949 and his master of forestry degree in 1951. From 1949 to 1953 he did silvicultural research for the Rocky Mountain Forest and Range Experiment Station. Since 1953 he has been an Associate Silviculturist, assigned to the Station's silviculture of western white pine work unit now at Moscow, Idaho.

GLENN H. DEITSCHMAN, a native of Minnesota, earned his B.S. degree in forestry at the University of Minnesota, and his master's degree at Penn State. His Forest Service career began at the Central States Station's branch at Carbondale, Illinois, in 1948, where he was a Research Forester in silviculture and regeneration. From 1955 to 1961 he was Research Center Leader at Ames, Iowa. Since 1961 he has been Leader of Intermountain Station's silviculture of western white pine work unit at Moscow, Idaho.

INTRODUCTION

Much has been written concerning the seedbed requirements for efficient natural regeneration of Engelmann spruce (Picea engelmannii Parry), western larch (Larix occidentalis Nutt.) and their associated species (Lowdermilk 1925, Barr 1930, Smith 1955, Day 1964, Roe 1952, Roe and DeJarnette 1965, and Alexander 1966). Seedling establishment is favored by the exposure of mineral soil through scarification and, to a lesser extent, by burning. It is generally agreed that some sort of seedbed preparation is necessary for prompt and adequate reproduction. But what is the best way to create the optimum environmental conditions? Is the scarification that results from logging sufficient--or should additional mechanical scarification be used? Is prescribed broadcast burning more efficient? Can the composition of the future stand be controlled by modifications of the site-preparation measures? These were the objectives of a cooperative study started in a northern Idaho larch-spruce stand in 1954.[1]

STUDY AREA

The study area is located on Roundtop Mountain in the St. Joe National Forest in northern Idaho. The entire study area is on a northerly aspect at an elevation of 5,200 to 5,800 feet and is representative of the Picea-Abies/Menziesia habitat type (Daubenmire 1952).[2]

The existing mature stand was over 200 years old and averaged approximately 15 MBF per acre. Composition of the main merchantable stand, based on the number of trees per acre, was as follows:

Species	Occurrence in total stand
Western larch (Larix occidentalis Nutt.)	56%
Engelmann spruce (Picea engelmannii Parry)	22%
Mountain hemlock (Tsuga mertensiana (Bong.) Carr.)	15%
Subalpine fir (Abies lasiocarpa (Hook.) Nutt.)	7%

Minor amounts of Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco), western white pine (Pinus monticola Dougl.) and grand fir (Abies grandis (Dougl.) Lindl.) were also present. Stands were rather open with an almost continuous undergrowth of false huckleberry (Menziesia ferrugina Sm.).

Approximately one-half of the volume on the area was harvested in 1951-53 by the strip-clearcutting method. The cut strips averaged 640 feet in width and 2,200 feet in length, with the long axis extending up and down the slope and in a north-south direction (fig. 1). The intervening uncut strips were approximately the same size.

---

[1]Cooperators included: Potlatch Forests, Inc.; the St. Joe National Forest; the University of Idaho College of Forestry; and the Northern Pacific Railway Company.
The study was designed by C. A. Wellner. Initial measurements were made by R. F. Watt.

[2]The area would be reclassified as Tsuga mertensiana/Menziesia according to revisions in classification planned by Dr. Daubenmire (personal communication).

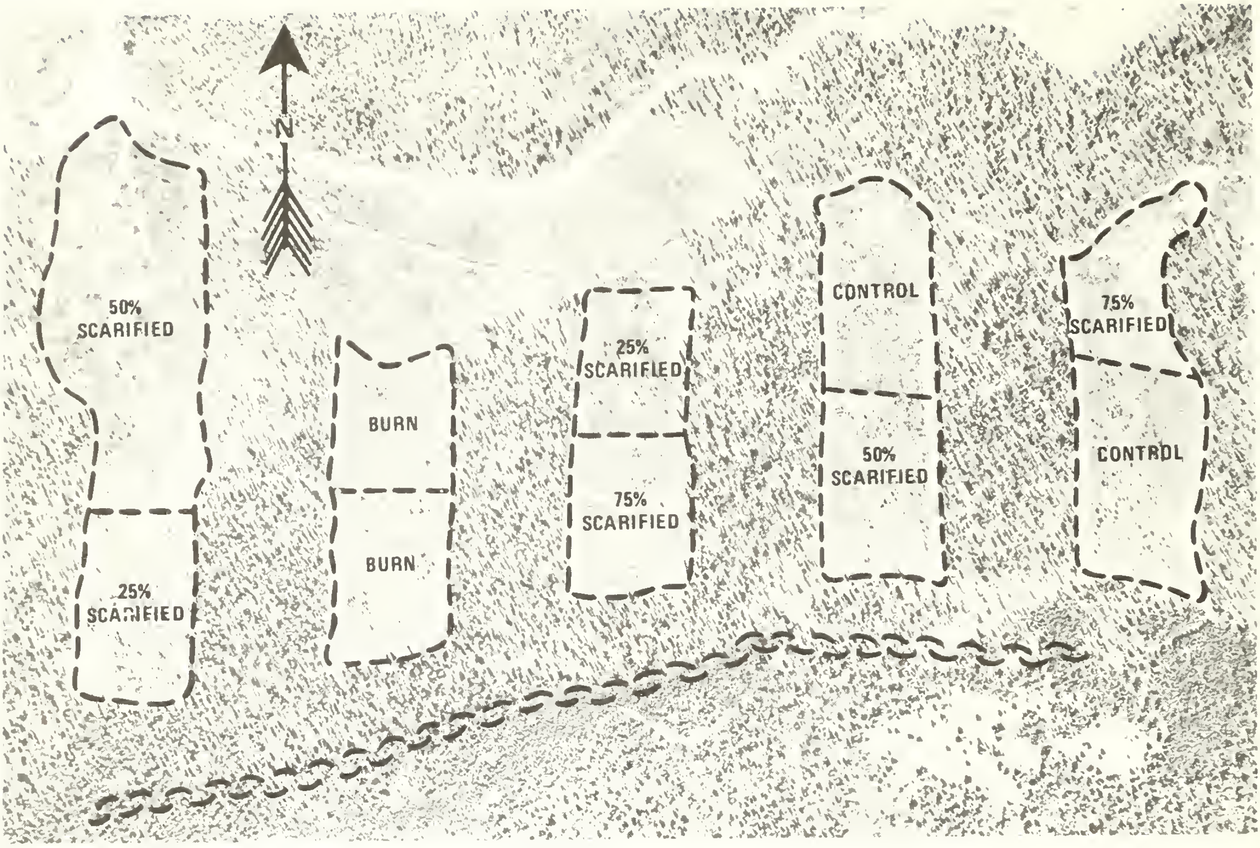


Figure 1.--Aerial photograph of study area showing clearcut strips and treatment areas. (Courtesy Potlatch Forests, Inc.)

Cutting did not extend to the crest of the ridge, so the top of each cut strip was bordered by uncut timber. Timber from the study area was cat-skidded in tree-lengths to landings at the foot of the strips. During the fall of 1954, several site preparation treatments were carried out to test their effectiveness in promoting subsequent natural regeneration on the clearcut strips.

STUDY METHODS

Site-preparation treatments assigned to the clearcut strips were as follows:

1. Control--no further disturbance.
2. Prescribed broadcast burning.
3. Light scarification--25% of the area bulldozer-scarified.
4. Moderate scarification--50% of the area bulldozer-scarified.
5. Heavy scarification--75% of the area bulldozer-scarified.

Some seed had been already dispersed by trees in the uncut strips before site preparation began. Broadcast burning was done on September 10, early in the seed dissemination season. Scarification was accomplished during the period of September 10 to September 18, 1954 with a D-7 crawler tractor equipped with a brush blade. Heavy slash accumulations from the bulldozer work were burned in late September and early October, probably after seed dissemination was nearly complete.

We have no seedfall records on the study area itself, but records were kept from 1952 to 1960 on a 15-acre clearcut block located about 1/2 mile north and at a slightly lower elevation. These records indicate that spruce, subalpine fir and western larch seed production in 1954 was exceptionally good (table 1). Just how much of this may have been destroyed on the study areas by site preparation treatments is unknown.

Each of the five strips was divided at mid-slope into two different treatment areas, providing upper- and lower-slope replications for each treatment. Treatments were assigned at random within upper- and lower-slope replications with the restriction that both burn treatments would occupy the same strip. Before and after treatment, surveys were made to determine how well each treatment modified the seedling environment. Point-samples were taken every 5 links along transects located diagonally across each treatment area. Vegetation types (tall shrubs, low shrubs, and herbaceous) and seedbed conditions (mineral, burned-mineral, and undisturbed) were recorded at each point.

To determine how effectively the treatments aided natural regeneration, reproduction surveys were made during the summer of 1960 using two random transects in each of the treatment areas. Transects were oriented east-west, perpendicular to the cutting line. Reproduction was recorded within concentric, circular 1- and 4-milacre plots spaced 1/2-chain apart along the transect lines. Only 3-year-old and older seedlings were tallied as established reproduction. The advance reproduction and subsequent reproduction were recorded separately, by species. No attempt was made to evaluate the production potential of the advance regeneration. Four-milacre stocking was determined on the basis of presence and dominance of species. A complete reproduction record was made on the 1-milacre unit to provide per-acre estimates of the potential stand. Visual estimates of vegetation cover and soil-surface conditions were also made on the 1-milacre units.

Statistical analysis was made where results were not obvious. Results of these analyses are reported in the text as "significant" or "nonsignificant" based on a 95 percent confidence level.

Table 1.--Seed production during a 9-year period near the Roundtop Mountain study area[1]

Year	Western larch	Douglas-fir	Engelmann spruce	Subalpine fir[2]
	----	Thousands of seed per acre	----	
1952	1.7	10.2	11.1	1.2
1953	--	0.4	2.6	0.6
1954	17.6	10.4	232.6	6.3
1955-56 (2-year total)	19.6	20.4	27.2	9.0
1957	4.7	3.0	1.1	0.2
1958-60 (3-year total)	2.8	10.6	66.2	1.5

[1]Data provided by Potlatch Forests, Inc.
[2]Includes some grand fir.

RESULTS

Environmental Modifications

Although the study treatments called for 25, 50, and 75 percent scarifications, actual levels of 22, 39, and 52 percent were obtained, as measured by mineral soil exposure. Fifty-three percent of the broadcast-burned area had mineral soil exposed after burning (fig. 2).

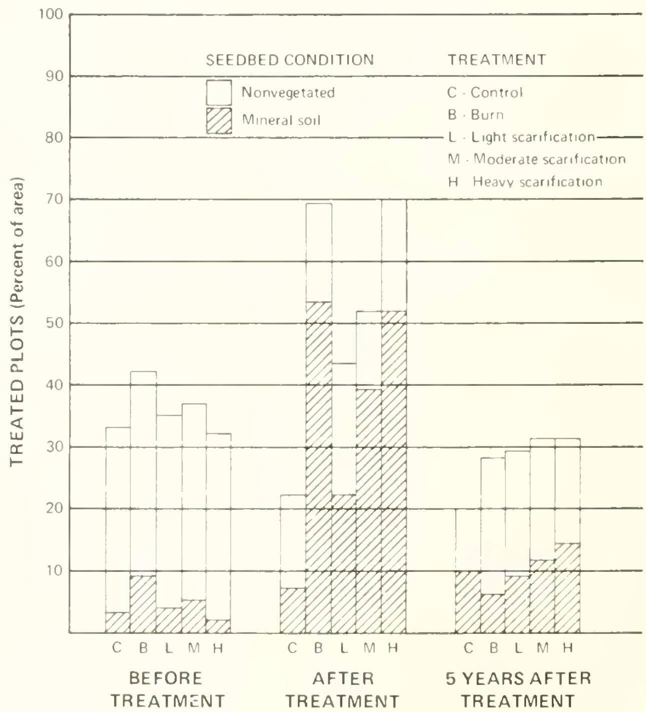
Site preparation, either by burning or scarification, slowed the recovery of tall shrub cover but had little effect on low shrubs and herbs. The overall effect, however, was a general decrease in competition between tree reproduction and other vegetative growth on the treated plots. Burning and heavy scarification were the most effective in reducing this competition.

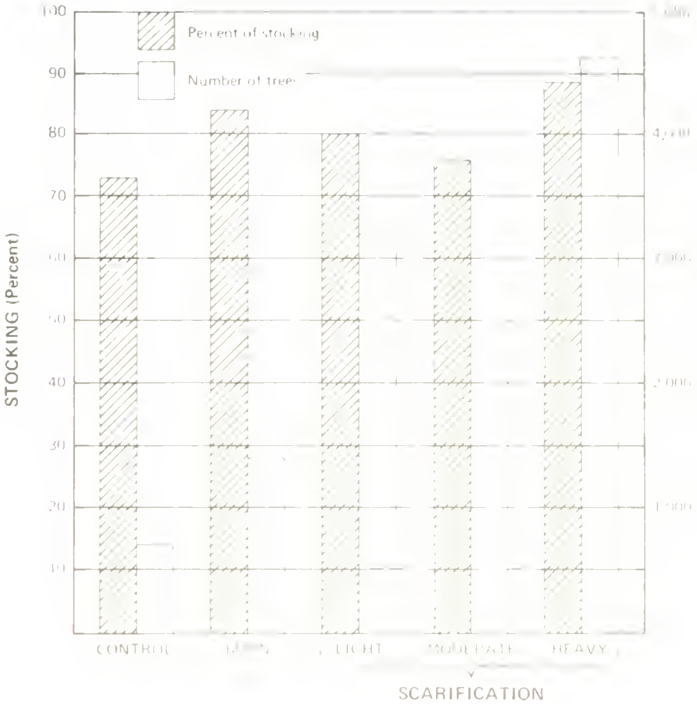
Five years later, invasion of vegetation had nearly obliterated all early post-treatment differences in seedbed conditions. The proportion of non-vegetated area on the treated plots was reduced to approximately 30 percent regardless of treatment as compared to 20 percent on the control area (fig. 2). Most of the regrowth was in the tall-shrub category which increased from an average of 26 percent coverage in 1955 to 44 percent coverage in 1960.

Reproduction

The five different treatments produced no significant differences in stocking on the 4-milacre plots, if all tree species were considered and no distinction was made between advance and subsequent reproduction. On this basis, stocking varied from 73

Figure 2.--Seedbed conditions before and after treatment, and 5 years later.





[illegible]

percent on the control plots to 89 percent on the area most heavily scarified (fig. [illegible]). Since a 4-milacre stocking of 6[illegible] percent has customarily been considered adequate in this region, the gross stocking of reproduction reached satisfactory levels on all treatments. On the other hand, the number of trees per acre were quite markedly affected by treatment. Both the control plots and the burned area were well stocked with surprisingly few total trees per acre; this indicates good distribution with a minimum of clumping.

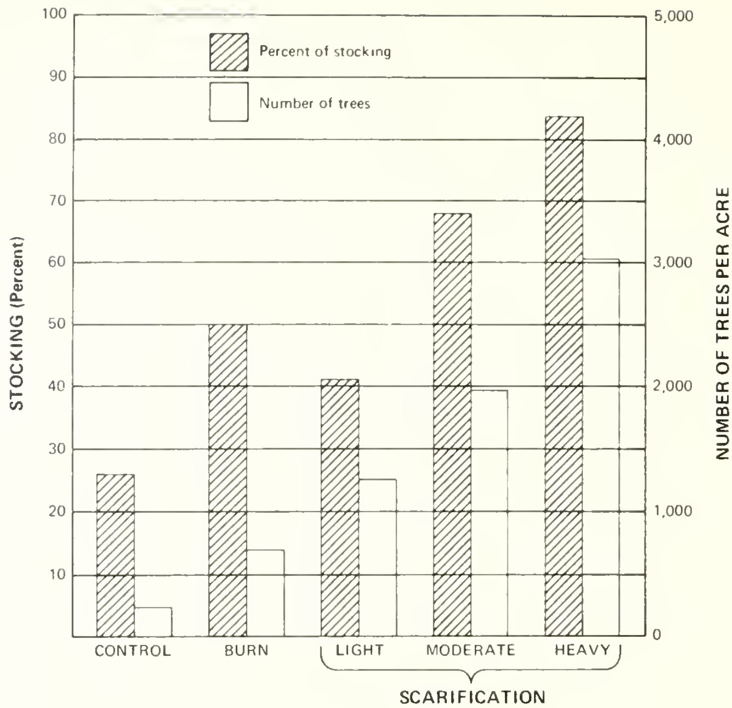
From the standpoint of future merchantability, advance reproduction of subalpine fir, mountain hemlock, and even Engelmann spruce may have questionable merit because of poor form and susceptibility to rot. There is some question as to what extent these trees can contribute to establishment of a productive new stand; however, such contribution would certainly be highly variable. Widespread injury to advance growth frequently accompanies logging and supplemental site preparation measures. This injury provides many opportunities for rot infection among susceptible species. Day and Duffy (1963), for instance, estimated that only 7 percent of the advance subalpine fir and spruce reproduction had "good potential" in southwestern Alberta cutover stands. On the other hand, Roe and Schmidt[3] in a survey of logged areas in southern Idaho, western Wyoming, and Utah, found that an average of 57 percent of advance subalpine fir and 60 percent of advance Engelmann spruce had "good management potential."

There is some doubt also as to the future economic value of subalpine fir and mountain hemlock, even when tree from early suppression and injury. Because of their susceptibility to heart rot and because of the low values attached to these [illegible]

---

[3]Roe, Arthur L. and Wyman C. Schmidt. Factors affecting natural regeneration of spruce in the Intermountain Region. Unpublished manuscript, Intermountain Forest and Range Exp. Sta.

Figure 4.--Stocking percent and number of trees per acre ("most desirable" species only) 6 years after treatment.

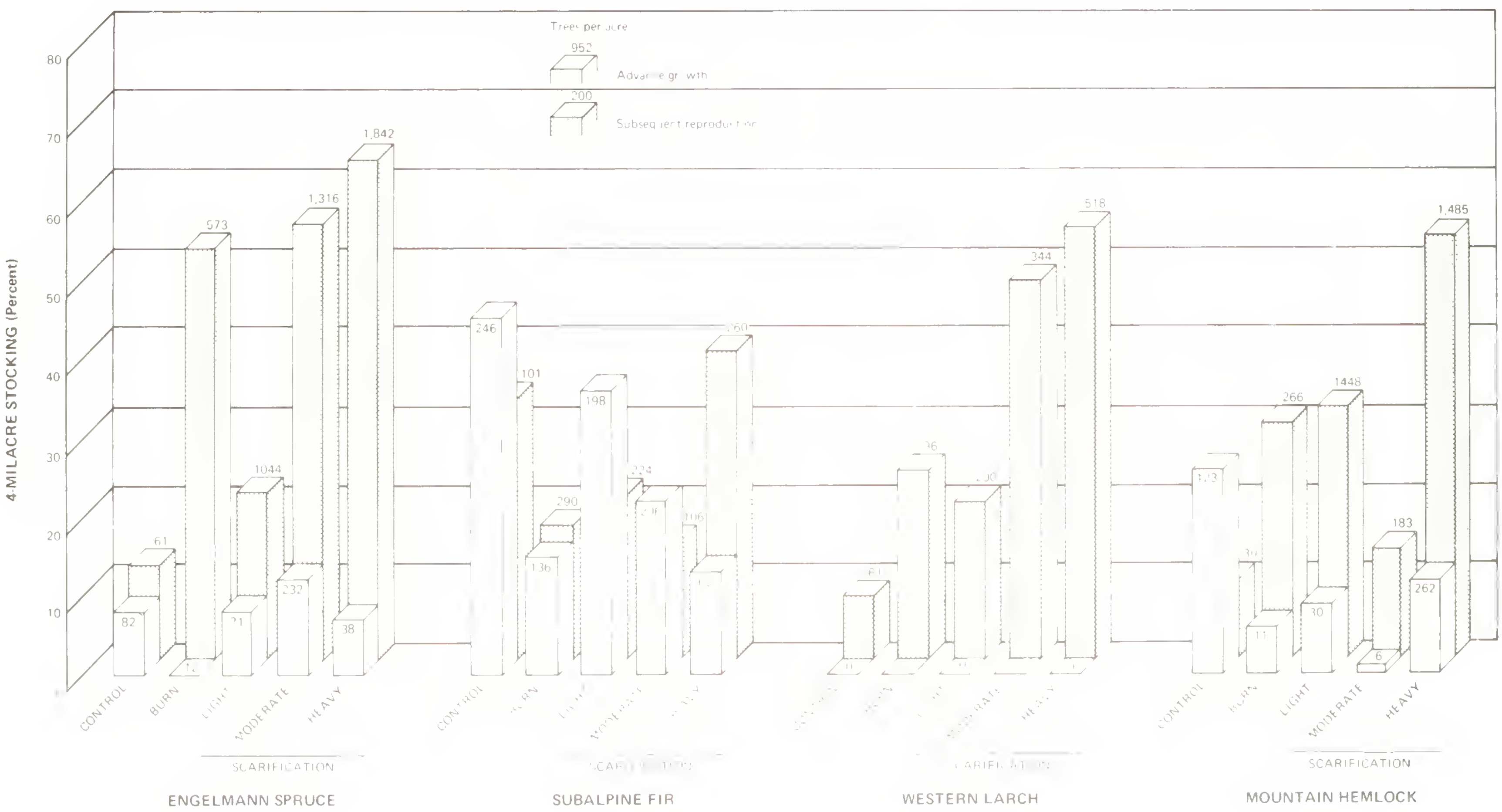


comparison to others, most timber managers prefer to use regeneration measures that tend to discourage them as major components, but accept them as minor components of new stands (LeBarron and Jemison 1953, Smith 1955, Day and Duffy 1963). With these two considerations in mind, an analysis was made in which the spruce, larch, Douglas-fir and grand fir were selected as the "most desirable" species. This approach eliminated most of the advance reproduction since it was predominantly subalpine fir and mountain hemlock.

Stocking computed on this basis shows significant differences in stocking obtained by the five site preparation treatments (fig. 4). Burning resulted in 50-percent stocking in terms of the "most desirable" stand component; the untreated control produced only 26 percent stocking. On the three sites that received bulldozer scarifications, stocking varied directly with the degree of scarification--from a low of 41 percent where lightly scarified to 82 percent on areas that were heavily scarified.

Number of trees per acre of the "most desirable" components of the reproduction stand varied from 224 trees per acre on the untreated area to 3,000 trees per acre on the sites that received heavy scarification (fig. 4). On the burned area, a relatively small total number of seedlings (690 per acre) resulted in a rather high 4-milacre stocking of 50 percent. On the bulldozer-scarified plots the distribution of reproduction is definitely patchy--a mosaic of heavily overstocked areas and some understocked portions.

An appraisal of the contribution of each species and class of reproduction is presented in figure 5 which depicts by species and site preparation the 4-milacre stocking and the number of trees per acre of advance and subsequent reproduction. These results are discussed by individual species in the following paragraphs. Since no survey was made to determine the amount and distribution of advance reproduction on the study area prior to treatment, differences in the occurrence of these trees afterwards may not accurately reflect treatment effects.



4-MILACRE STOCKING (Percent)
80
70
60
50
40
30
20
10
Trees per acre
952
200
1,842
1,316
573
1044
61
82
232
38
246
101
198
290
224
136
518
344
1,485
1448
266
183
262
30
11
6
CONTROL
BURN
LIGHT
MODERATE
HEAVY
SCARIFICATION
ENGELMANN SPRUCE
SUBALPINE FIR
WESTERN LARCH
MOUNTAIN HEMLOCK

Engelmann Spruce

Subsequent regeneration of spruce was strongly influenced by site-preparation treatments. Stocking to new spruce seedlings was greater than 50 percent on plots that were burned and also on those given moderate to heavy scarification. Scarified plots averaged over 1,000 seedlings per acre, distributed fairly well except on the lightly scarified plots. The best distribution of spruce reproduction was obtained on the burned areas where a stocking of over 50 percent was obtained with an average of 573 seedlings per acre.

The ratio of spruce to subalpine fir reproduction was increased by site preparation. Scarification was especially discriminative, producing from 5 to 12 times more spruce seedlings per acre than subalpine fir. Spruce/fir ratios for control and burned areas were 0.6 and 2.0, respectively.

Subalpine fir

On the control areas, subalpine fir was the most abundant and widely distributed species in terms of both advance and subsequent reproduction. Advance seedlings of subalpine fir outnumbered those of spruce by about 3 to 1. Subsequent subalpine fir seedlings held nearly a 2 to 1 advantage. Site preparation generally resulted in additional subalpine fir regeneration, but increases were smaller than with other species and stocking levels were either reduced or remained constant.

Western Larch

As the intolerant nature of western larch would suggest, there was no advance regeneration of this species. Following clearcutting, only 8 percent of the control area became stocked with larch. Burning and light scarification resulted in larch stocking of 20 percent, or more; moderate and heavy scarification gave further improvement amounting to an additional 20 percent. This amount of larch regeneration, particularly on the burned area, was surprisingly small in comparison to that obtained on similarly prepared areas in the western larch--Douglas-fir type in western Montana (Roe 1952). However, the good distribution and rapid growth of the larch seedlings have added much to its importance. For instance, on the heavily scarified sites, larch was the dominant tree on 37 percent of the stocked plots while constituting only 11 percent of the total reproduction stand.

Although burning did not result in as much larch reproduction as was produced by other treatments, the larch seedlings were better distributed in relation to their number. Four-milacre stocking on burned areas equaled that on light scarification areas, but with about half as many seedlings per acre.

Mountain Hemlock

The mountain hemlock seed source was "patchy" and this caused considerable variation in restocking results; however, it is evident that hemlock seedling establishment was benefited by site preparation. Subsequent regeneration of this species was second only to spruce except on the moderately scarified plots. Hemlock and subalpine fir together constitute approximately 82 percent of the advance growth and 53 percent of the new stand on the control plots.

DISCUSSION AND CONCLUSIONS

It seems evident that both prescribed broadcast burning and mechanical scarification have their place as aids to the establishment of natural regeneration in the larch-fir type. Burning has the advantage of being usable over a wider range of topographic conditions. It also seems to create conditions more favorable for obtaining acceptable stocking with fewer seedlings, thus reducing future expenditures for cleaning and thinning. If advance growth is considered undesirable, burning will more effectively eliminate it from the future stand. While valid direct comparisons of site preparation costs are difficult to make, USDA Forest Service Region 1 cost analyses currently show that site preparation by machine-piling, scarification and pile-burning is, on the average, 25 percent more costly than slashing and prescribed burning.[4]

Machine scarification has the advantages of being flexible enough to: (1) permit preservation of much of the advance growth as part of the future stand while creating favorable conditions elsewhere for subsequent reproduction; and (2) permit better timing of the site preparation to take full advantage of natural seed dispersal without fear of destroying part of the important first seed crop. Risks to men and adjacent timber are likely to be less with bulldozer scarification than with prescribed broadcast burning.

Probably the most difficult decision facing the timber manager occurs when suitable advance growth is present. Then, it is not a choice between burning or scarification, but whether to rely on the advance growth at no additional establishment cost, or to prepare the site for new reproduction. Should the advance stand have a reasonably good future after logging, it may be unwise to spend money to destroy it in favor of new reproduction. It would seem that additional research is needed to help develop standards for appraising the production potential and management requirements of stands with a large component of advance growth.

Although the site preparation in this study did not appreciably improve the stocking levels, it certainly increased the diversity of stand components and, consequently, the diversity of management opportunities. Where no special site preparation was applied, the reproduction stand was composed predominantly of advance subalpine fir and mountain hemlock; such a stand tends to become highly defective and provides rather limited alternatives for future management. Burning or scarification have increased these management alternatives by providing stands composed mainly of subsequent reproduction of the same three species plus an important addition of western larch and a small amount of Douglas-fir and grand fir. Furthermore, the broader species' mixture may permit more efficient utilization of the site and provide a stand which is less susceptible to serious damage.

[4]Personal communication, USDA Forest Service Region 1 Division of Timber Management.

LITERATURE CITED

Alexander, Robert R.
1966. Stocking of reproduction on spruce-fir clearcuttings in Colorado. U.S. Forest Serv. Res. Note RM-72, 8 pp., illus.

Barr, Percy Munson
1930. The effect of soil moisture on the establishment of spruce reproduction in British Columbia. Yale Univ. School Forest. Bull. 26, 77 pp., illus.

Daubenmire, R.
1952. Forest vegetation of northern Idaho and adjacent Washington and its bearings on concepts of vegetation classification. Ecol. Monogr. 22: 301-330, illus.

Day, R. J.
1964. The microenvironments occupied by spruce and fir regeneration in the Rocky Mountains. Can. Dep. Forest. Pub. 1037, 25 pp., illus.

Day, R. J. and P. J. B. Duffy
1963. Regeneration after logging in the Crowsnest Forest. Can. Dep. Forest. Pub. 1007, 32 pp., illus.

LeBarron, R. K. and G. M. Jemison
1953. Ecology and silviculture of the Engelmann spruce-alpine fir type. J. Forest. 51: 349-355.

Lowdermilk, W. C.
1925. Factors affecting reproduction of Engelmann spruce. J. Agr. Res. 30(11): 995-1009, illus.

Roe, Arthur L.
1952. Larch-Douglas-fir regeneration studies in Montana. Northwest Sci. 26(3): 95-102.

Roe, A. L., and G. M. DeJarnette
1965. Results of regeneration cutting in a spruce-subalpine fir stand. U.S. Forest Serv. Res. Pap. INT-17, 14 pp., illus.

Smith, J. H. G.
1955. Some factors affecting reproduction of Engelmann spruce and alpine fir. British Columbia Forest Serv. Tech. Pub. T43, 43 pp., illus.

AFLC/HAFB, Ogden

Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Project headquarters are also at:

Boise, Idaho

Bozeman, Montana (in cooperation with Montana State University)

Logan, Utah (in cooperation with Utah State University)

Missoula, Montana (in cooperation with University of Montana)

Moscow, Idaho (in cooperation with the University of Idaho)

Provo, Utah (in cooperation with Brigham Young University)

FOREST SERVICE CREED

The Forest Service of the U.S. Department of Agriculture is dedicated to the principle of multiple use management of the Nation's Forest Resources for sustained yields of wood, water, forage, wildlife, and recreation. Through forestry research, cooperation with the States and private owners, and management of the National Forests and National Grasslands, it strives — as directed by Congress — to provide increasingly greater service to a growing Nation.

EFFECT OF ROADS ON GROWTH OF WESTERN WHITE PINE PLANTATIONS IN NORTHERN IDAHO

ROBERT D. PFISTER

USDA FOREST SERVICE
RESEARCH PAPER INT-65, 1969

INTERMOUNTAIN FOREST & RANGE
EXPERIMENT STATION
Ogden, Utah

USDA Forest Service
Research Paper INT-65
1969

EFFECT OF ROADS ON GROWTH OF WESTERN WHITE PINE PLANTATIONS IN NORTHERN IDAHO

Robert D. Pfister

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401
Joseph F. Pechanec, Director

ROBERT D. PFISTER, Associate Silviculturist and leader of the silviculture of western larch and Engelmann spruce work unit at Missoula, Montana, joined the Intermountain Station staff in 1961. He holds the B.S. and M.S. degrees in forest management from Iowa State University and Oregon State University, respectively. During this study the author was stationed at the Forestry Sciences Laboratory in Moscow, Idaho.

INTRODUCTION

The system of "jammer" logging commonly used for harvesting timber on steep slopes in northern Idaho requires a network of roads spaced 300 to 500 feet apart. A well-designed and maintained road layout gives the land manager ready access for fire protection and application of cultural treatments. On the other hand, such a permanent road system requires preemption of timber-producing land for roadbeds, cuts, and fills. Estimates of land area used for roads have ranged from 5 to 21 percent of the total land area according to varying criteria and different sources (Moessner 1960; Olson 1952; Roffler[1]). Thus, some land managers assume a 10- to 15-percent loss of timber-production area when establishing and maintaining this type of road system. Furthermore, watershed managers have been concerned about a possible disruption of water movement through the soil mantle caused by roadcuts, with a consequent effect on adjacent and downslope stand development.[2]

A pertinent question facing the land manager is whether the open area actually occupied by the road is a legitimate estimate of the percentage loss in total area productivity. Is 10 to 15 percent an accurate estimate of timber-production area loss, or do roads affect production in the adjacent stands? In Germany, Kramer (1958) studied 108 temporary sample strips along roads that were 4 meters to greater than 20 meters in width in pure beech (Fagus sylvatica L.) and pure Norway spruce (Picea abies (L.) Karst.) stands from 30 to 150 years old. Roadside trees had greater growth in both height and diameter than those located farther within the stand. Volume effects were calculated by expanding the width of the 10-meter roadside strip to include half of the road width. For Norway spruce, the volume per hectare of these "expanded" roadside strips did not decrease until the unstocked area exceeded 5 meters (16.4 feet). For beech, the critical width of the unstocked area was 12 meters (39.4 feet). The capacity of beech to utilize larger openings than spruce was attributed to the large difference in crown expansion potential between the two species.

Landbeck (1965), conducting his studies in East Germany, followed the methods of Kramer (1958) and established 95 temporary plots along roads 3 to 6.5 meters (9.8 to 21.3 feet) wide in pure Scotch pine (Pinus sylvestris L.) stands aged 60 to 120 years. Here, too, the diameter of roadside trees was greater than that of interior trees, but height was slightly less and quality was lower. The volume per hectare of the "expanded" roadside strips (strip plus half of road width) was less than 2 percent lower than the volume per hectare within the stand. No critical width for the unstocked area could be established because the range of road widths was so narrow.

If roads seriously affect timber production in northern Idaho, land managers need a quantitative estimate of production losses to aid in management planning and evaluation of logging systems. The objective of this study was to estimate the potential timber production loss caused by a permanent road system. A projection of such loss was established by determining the magnitude of "edge effect" in managed stands in northern Idaho and comparing it with the width of road opening.

---

[1]Roffler, H. C. Lost Block Road Study. USDA Forest Serv., Northern Region, Coeur d'Alene Forest, Unpub. Rep., 4 pp. 1950.

[2]Coile, T. S. Forest and range soil problem analysis for the Northern Rocky Mountain Region. USDA Forest Serv., Intermountain Forest and Range Exp. Sta., Unpub. Rep., 33 pp. 1950.

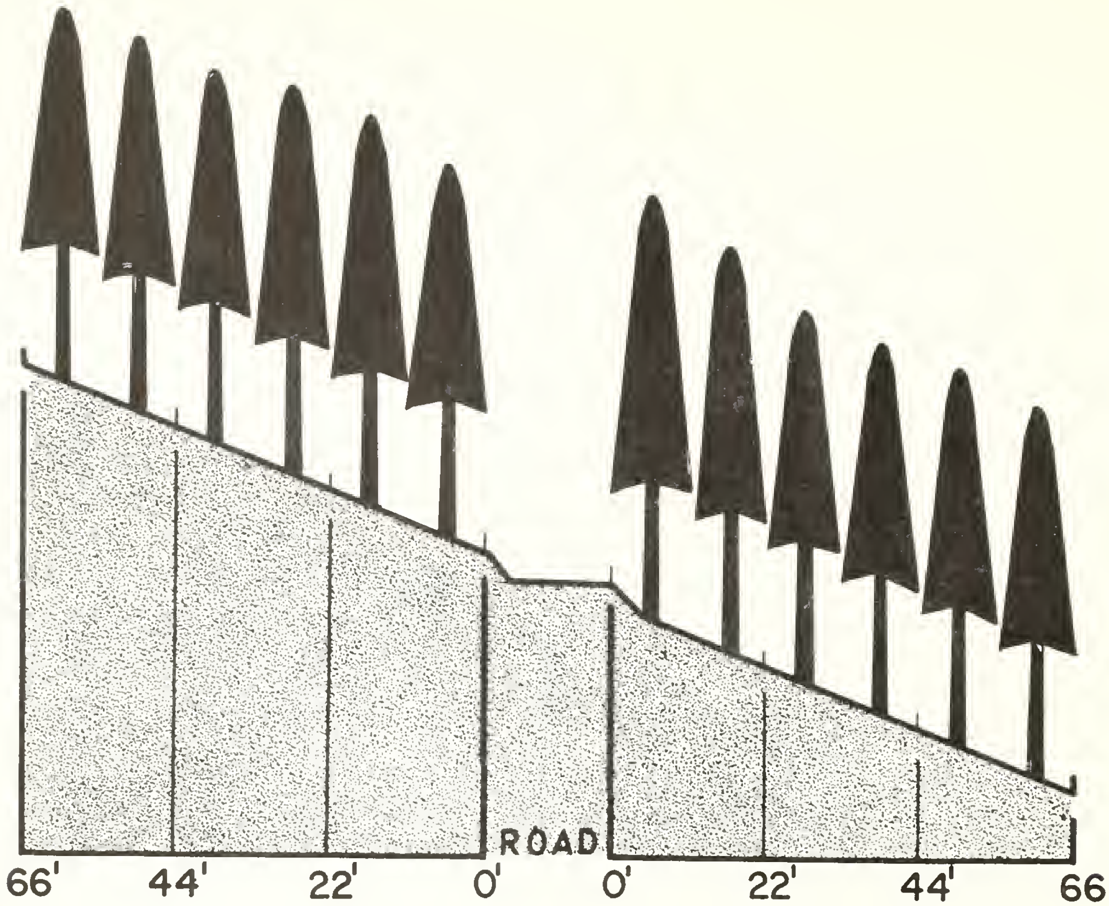


Figure 1.--Diagrammatic layout of plantation plots in relation to road.

METHODS

Since the long-range need is for information on managed stands, study areas were in western white pine plantations between 25 and 50 years old containing permanent roads constructed about the time of stand establishment. Plantations with obvious stocking irregularity or low survival were not selected. (Some irregularities were not obvious until data had been collected.) At each selected location, paired 1/20-acre plots were established above and below the roads. Plots were 33 feet wide and extended 66 feet into the stand from the top of the cut bank or from the top edge of the road shoulder (figure 1). The 24 plots were measured and grouped for subsequent analysis as shown in table 1. Soils in the Coeur d'Alene National Forest study areas were Brown Podzolics developed from volcanic ash overlying and intermixed with argillites and quartzites of the "Belt" formation; the Kaniksu National Forest study area soils were developed mainly from coarse-textured glacial outwash.

Roads were predominantly single-lane and outsloped at the time of measurement. Judging by location and present condition, it is reasonable to assume that they were maintained in an outsloped condition during most of the stand history. Road width, as well as cut-and-fill dimensions were measured at each plot location.

Table 1.--Distribution and description of sample plots

Number of plots	Location	Age of stands (yr.)	Slope Average %	Slope (Range) %	Aspects
12	Cathedral Peak (Coeur d'Alene N.F.)	40	44	(20-80)	NW,N,NE,[illegible]
6	Brett Creek (Coeur d'Alene N.F.)	29	42	(25-55)	N, NE
3	Miscellaneous (Coeur d'Alene N.F.)	23-46	12	(7-25)	NE, SW
3	Miscellaneous (Kaniksu N.F.)	30-33	20	(16-26)	NE

Height, diameter, crown class, and distance from the road edge were recorded for all trees larger than 2.5 inches d.b.h. Height increment (for the first 5 years above breast height) was measured on all dominant and codominant trees to assess road effects on height during early stand development.

Scatter diagrams were prepared for each plot relating tree diameter and height to distance from the road. The diagrams were used to evaluate stocking uniformity and to estimate how far the road effects extended into the stand. Analysis of variance, with individual degree-of-freedom tests, was used to test the hypothesis that roads had no effect on growth of adjacent trees.

RESULTS

The Cathedral Peak plantation plots were selected for detailed analyses of road effects because they had uniform stocking, were all of the same age, and there was a well-located road through an area large enough for several replications on varying aspects and topography. Applicability of data from Brett Creek and elsewhere was diminished by variation in stocking due to heavy blister rust mortality, nonutilization of roadside space, inadequate area to obtain suitable replications within each plantation, and different ages of the plantations. The results reported below are therefore based primarily on these 12 Cathedral Peak plots; the information from the other 12 plots is used only to supplement the Cathedral Peak analysis.

For the Cathedral Peak plots, scatter diagrams revealed an obvious roadside effect on height and diameter of trees in the plots below the road; this effect appeared to extend an average of 24 feet into the stand. No roadside effects were observed in the plots above the road.

Heights and diameters of dominant and codominant trees were adjusted to remove between-plot site variation and were pooled within six 11-foot zones as shown in figure 2. The average height of border trees in the plots below the road was 113 percent of that within the stand, or approximately 7 feet greater. The average diameter of border trees in plots below the road was 131 percent of that within the stand, or approximately 2.5 inches greater. In neither case were effects evident above the road. (Distance from road edge did not appear to influence early height increment for the 5 years above breast height on any of the 12 plots.)

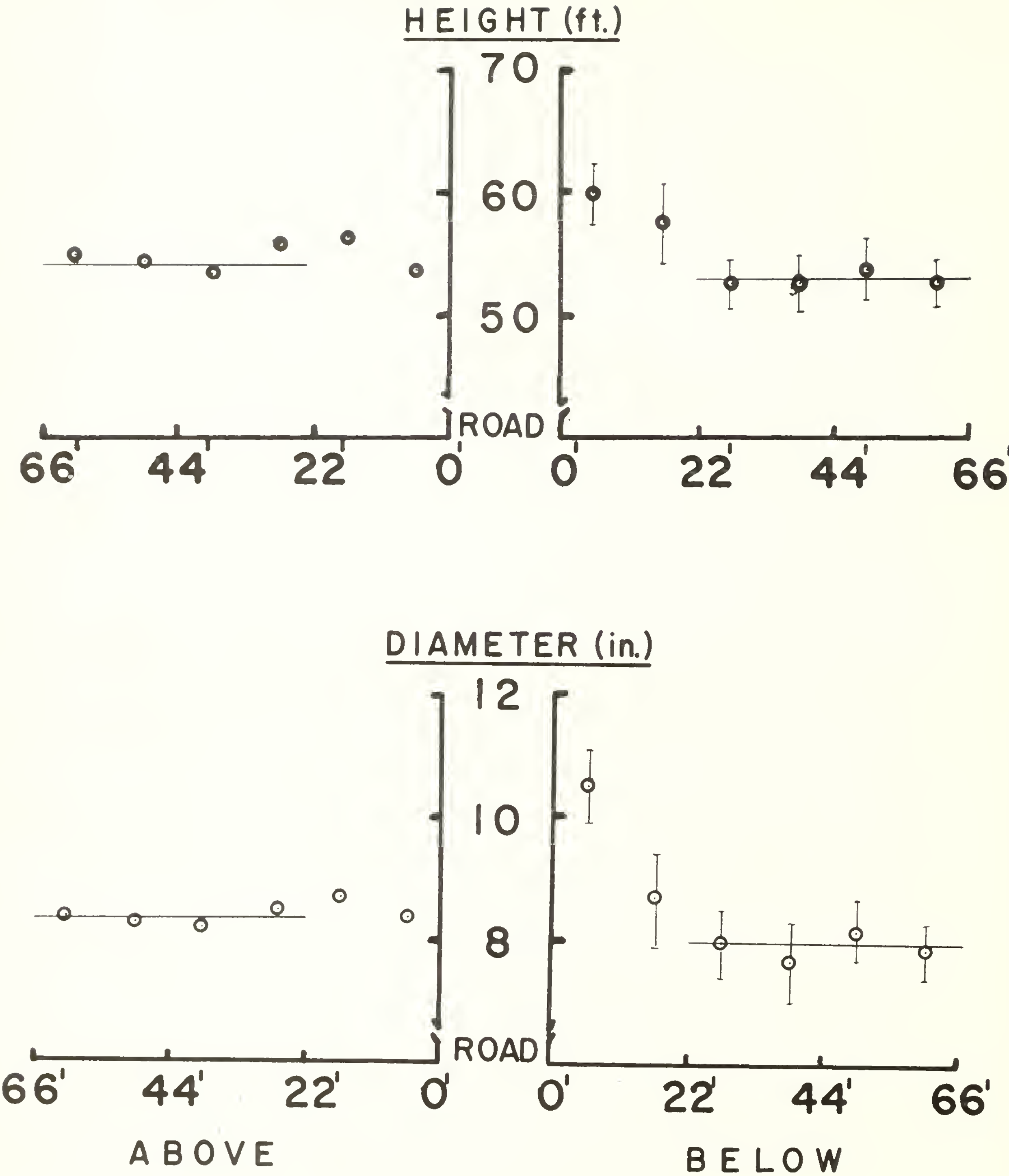


Figure 2.--Effect of road on heights and diameters of dominant and codominant trees. (Each point is the average value for pooled data from 6 plots. Vertical lines represent the 95 percent confidence interval.)

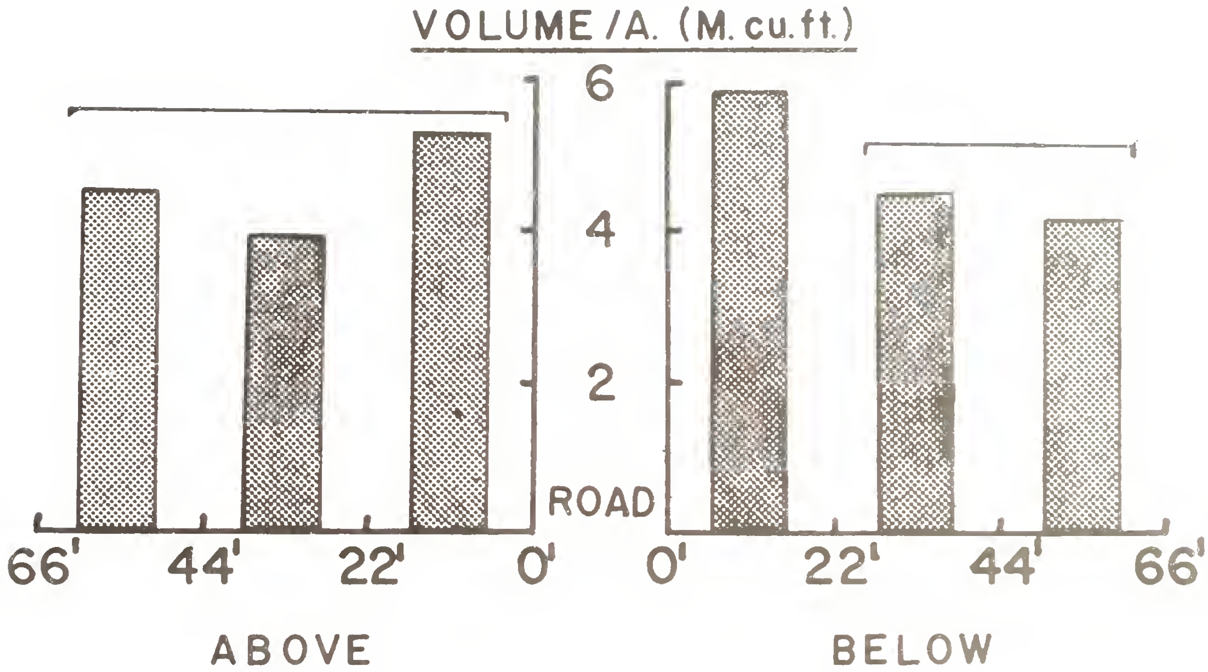


Figure 3.--Total stand volume by zones in relation to distance from the road. (Zones connected by brackets are not significantly different, $P < 0.05$.)

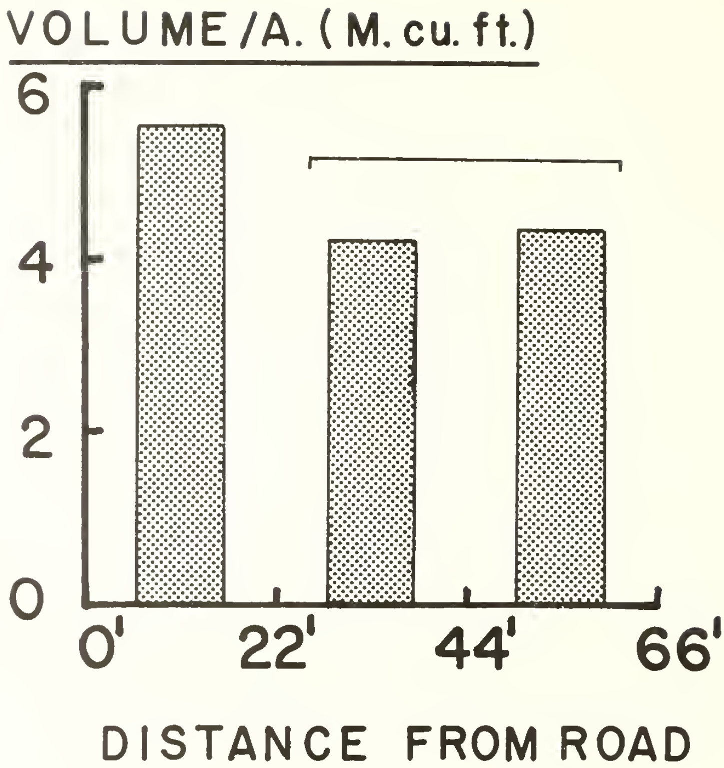
Because the "edge effect" appeared negligible beyond 22 feet from the road, the plots were divided into three equal 22-foot zones for analysis of volume. Above- and below-road plots were analyzed separately using 6 plots and 3 zones for each test. An orthogonal individual degree-of-freedom test was employed to test for significant differences between zones.

Volume in the roadside zone of below-road plots was significantly greater than in the two zones within the stand (figure 3). Roadside volume appeared greater in above-road plots, but was not significant. By pooling the data for above- and below-the-road plots, the total effect on utilization of road area can be determined and the significant additional volume growth (130 percent of that within the stand) is apparent (figure 4).

The average distance (road width plus cut width) was 18.5 feet. The increased volume in roadside zones was sufficient to compensate for 13.1 feet of this distance, leaving 5.4 feet of unproductive road area. With an average space of 400 feet between roads, the unproductive road area would convert to only about 1.4 percent of the total area.

The miscellaneous plots on the Coeur d'Alene and Kaniksu National Forests showed the same trend of increased growth adjacent to the road with a magnitude of response very comparable to Cathedral Peak. Data from the Brett Creek plots were highly variable because of heavy blister rust mortality. Volume above the road appeared unaffected, but in contrast to the other plots, growth of below-road border trees was slightly diminished. However, this stand was established after the road was built and the trees were not planted to fully utilize the road opening in much of the area. On 2 of the 3 below-road plots the closest border tree was 10 feet from the edge of the road. This 10-foot space was occupied by dense shrubbery evidently negating a potential growth response of border trees.

Figure 4.--The net effect of roads on total stand volume production by pooling data from above and below the road. (Zones connected by the bracket are not significantly different, P <0.05.)



DISCUSSION

The obvious additional growth of below-road trees indicates improved site productivity due to additional water availability. Precipitation falling on an outsloped road is redistributed below the road and the unvegetated fill should provide a reservoir of available water for adjacent trees during part of the summer drought period.

A normal growth increase in border trees in response to additional growing space is apparently masked by water distribution effects. Below-road trees would have this effect included as part of the total response. Conversely, ~~a significant~~ growth response in above-the-road trees may indicate that the expected additional growth due to space is reduced by the loss of moisture from the cut bank. These roadside effects indicate that disruption of water movement through the soil mantle because of roads (see footnote 2) is not a serious consideration for soils similar to those in this study.

The common method of multiplying clearing width times road length to obtain estimates of area in roads does not take into account the capacity of trees to utilize at least part of the opening. Silen and Gratkowski (1953) presented an enlightened view on use of road measurements in their analysis of a staggered-setting system of clear-cutting on the H. J. Andrews Experimental Forest in Oregon. The total area disturbed by roads and landings amounted to 9.8 percent, but the estimated loss in productive area was only 4.1 percent when reasonable assumptions on crown expansion and productivity were included in the calculations.

A similar approach can be demonstrated for our conditions by a simple exercise. On an average slope of 50 percent, a 12-foot road would require an additional 9 feet for cut and fill. Planting at the toe of the fill and 3 feet above the cut bank would result in a nonstocked width of 24 feet. Assuming 400 feet between roads and a 12-by-12 spacing we would lose only one row out of 33 for each road, or only 3 percent. Additional growth below the road would further reduce the loss of productive area. Thus, the loss becomes insignificant in relation to the improved accessibility for protection and management.

The small loss in total stand production (1.4 percent) shown by this study is comparable with that found in Germany for roads of similar width. Kramer (1958) reported no volume reduction in Norway spruce roadside strips for roads less than 16.4 feet wide and only about 7 percent reduction in volume of roadside strips for roads from 16.4 to 29.5 feet wide. Assuming a road spacing of 400 feet, this 7 percent would convert to a net loss of production area over the entire stand of about 1.6 percent. Applying the same assumptions and calculations to Landbeck's (1965) data, the Scotch pine stands sustained an overall production loss of only 0.4 percent. Kramer's report (1958) also demonstrated that edge effect was much greater in stands 50 to 80 years old than in younger stands. Therefore, as the stands approach maturity we may expect a greater edge effect and less production loss than the 1.4 percent estimated in this study.

This study was based on western white pine stands, but this close agreement with the above noted studies indicates that a similar response could be expected with other species. In fact, those species with a greater crown expansion potential than western white pine should utilize road openings more fully.

CONCLUSIONS

On soils comparable to those studied (relatively stable with good drainage characteristics) near maximum production can be maintained concurrently with continued maintenance of a permanent road system. To do so, it is necessary to keep roads reasonably narrow (less than 14 feet). Furthermore, trees must occupy the site up to the toe of the fill and near the top of the cut for maximum utilization of space.

The potential loss of timber-producing land is minor and can be reduced to practically zero if road widths are kept to the minimum actually needed. With large, modern equipment one of our perennial problems in road building is keeping width to the minimum needed for access and safety. The arguments for narrow roads (except for main roads) need to be reemphasized and enforced in current practices. Narrow roads are cheaper to build, less maintenance is required, they are more stable from a watershed protection standpoint, and they are less offensive from a recreational (esthetic) view, especially if the new stand is established to make maximum utilization of the space.

LITERATURE CITED

Kramer, Von Horst
1958. Wegebreite und Zuwachs im angrenzenden Bestand. (The effect of width of forest roads on increment in adjacent stands.) Allg. Forst- u. Jagdztg. 129(6):121-134.

Landbeck, Herbert.
1965. Wegebreite und Randwirkung bei der Kiefer. (Road width and edge effect in Scotch pine.) Arch. Forstw. 14(1): 41-59.

Moessner, Karl E.
1960. Estimating the area in logging roads by dot sampling on aerial photos. U.S. Forest Serv., Intermountain Forest and Range Exp. Sta. Res. Note 77, 4 pp.

Olson, D. S.
1952. Underground damage from logging in the western white pine type. J. Forest. 50(6): 460-462.

Silen, Roy R., and H. S. Gratkowski.
1953. An estimate of the amount of road in the staggered-setting system of clearcutting. U.S. Forest Serv., Pacific Northwest Forest and Range Exp. Sta. Res. Note 92, 4 pp.

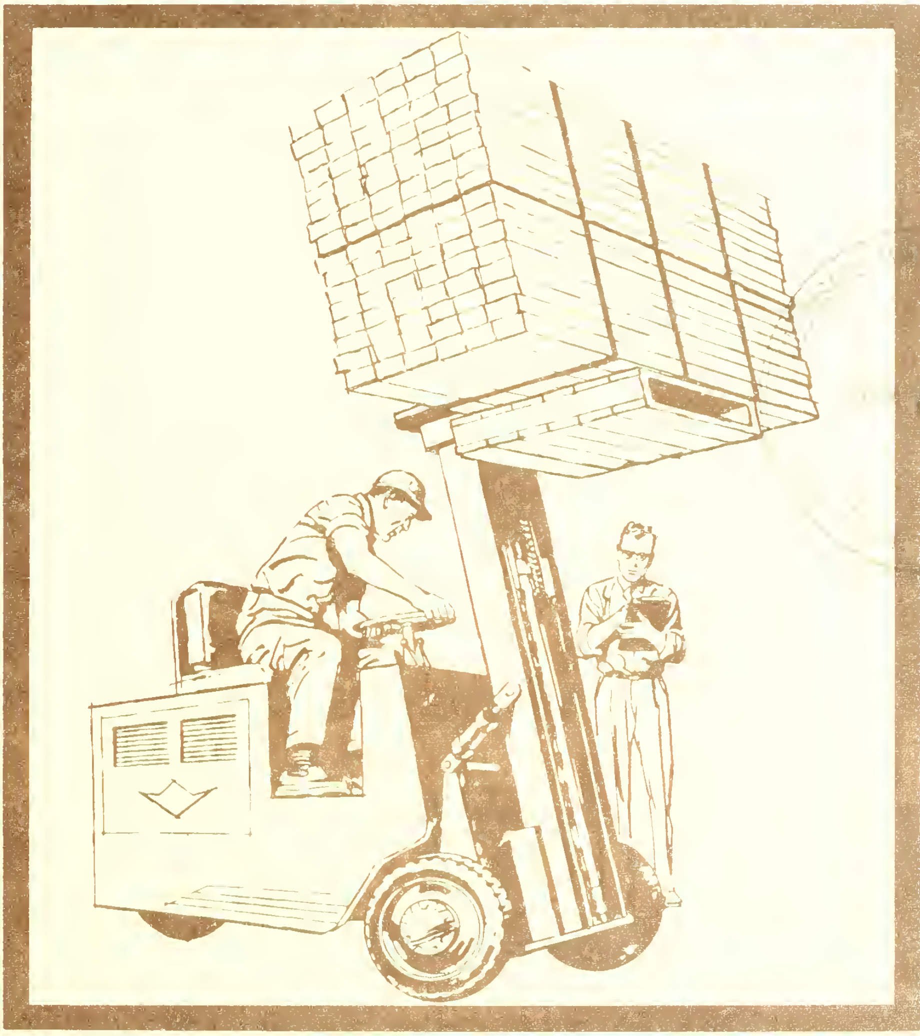
AFLC/HAFB, Ogden

FOREST SERVICE CREED

The Forest Service of the U. S. Department of Agriculture is dedicated to the principle of multiple use management of the Nation's forest resources for sustained yields of wood, water, forage, wildlife, and recreation. Through forestry research, cooperation with the States and private forest owners, and management of the National Forests and National Grasslands, it strives — as directed by Congress — to provide increasingly greater service to a growing nation.

ECONOMICS OF PRODUCING AND HANDLING PACKAGED LUMBER

JOHN R. HOST



USDA FOREST SERVICE
RESEARCH PAPER INT-66, 1969

INTERMOUNTAIN FOREST & RANGE EXPERIMENT STATION
Ogden, Utah

USDA Forest Service
Research Paper INT-66
1969

ECONOMICS OF PRODUCING AND HANDLING PACKAGED LUMBER

John R. Host

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401
Joseph F. Pechanec, Director

THE AUTHOR

JOHN R. HOST is a marketing analyst, stationed in Missoula, Montana, at the Forestry Sciences Laboratory. He joined the Station's staff in 1967; prior to that time, he was employed in forest engineering, teaching, and sawmill management.

CONTENTS

INTRODUCTION

Distribution is a major cost in manufacturing industries. Inventory handling, order assembly, and merchandising costs can amount to as much as 35 percent of retail prices in the lumber industry.

In an attempt to reduce total distribution costs, an increasing number of sawmills are packaging lumber. The first unitized flatcar of lumber was shipped in 1958. In 1968 over 40,000 unitized flatcars were shipped. Economies realized by the customer in unloading and storage have forced the rapid growth of lumber packaging. This trend will be sustained by the increasing role that distribution centers are assuming in lumber marketing.

Although it costs more for sawmills to ship packaged lumber than loose lumber, there is evidence that packaging of lumber is a profitable activity for the sawmill when such factors as improved marketability, reduced recordkeeping, and somewhat improved prices are considered.

This report presents an economic analysis of lumber packaging that may be useful to manufacturers in evaluating the process for their own operations. It is based on cost information obtained from six lumber mills in western Montana whose production ranges from 30 to 150 million board feet per year. Cost data include equipment installation and operating costs for packaging and handling lumber. Taxes, insurance, and overhead are not included because they are considered as plantwide or departmental operating expenses and are not allocated specifically to the operational procedures under study.

PACKAGING LUMBER

The general process of lumber packaging is shown in figure 1. Packages are assembled at the planer sorting chain after the material has been graded and sorted. Pieces of lumber are stacked into homogeneous units. The width of each unit is standardized at a nominal 4 feet. Height is usually 2 feet but varies. Length varies in standard 2-foot multiples from 8 to 26 feet. In this study, a unit 4 feet wide by 2 feet high by 16 feet long with a volume of 1,920 board feet is used for illustration.

Once assembled, the unit is transported to the inventory storage area or to the banding station. The banding operation consists of squaring the unit ends (even-ending), compressing the load, applying the banding under tension, and sealing it while the unit is still under compression. If the unit is to be wrapped, a laminated kraft paper wrapping is stapled over it. The unit is then loaded onto a flatcar or put into inventory for loading out at a later time.

MECHANICAL BANDING

The banding operation starts when the forklift operator places loads onto the infeed conveyor. The banding machine operator controls the infeed conveyor, even-ends the load, operates the compression machine, applies and seals the banding, and operates the conveyor to move the banded unit to the wrapping station or to the outfeed end for pickup by the forklift (fig. 2).

The rate of production is controlled by the flow of lumber onto the infeed conveyor and off the outfeed conveyor. The forklift phase of the operation is most efficient if the packages can be doubled up at the planer chain; e.g., two 2- by 4-foot packages stacked together with a bolster between each package. The packages are separated and placed on the infeed conveyor to the banding machine separately.

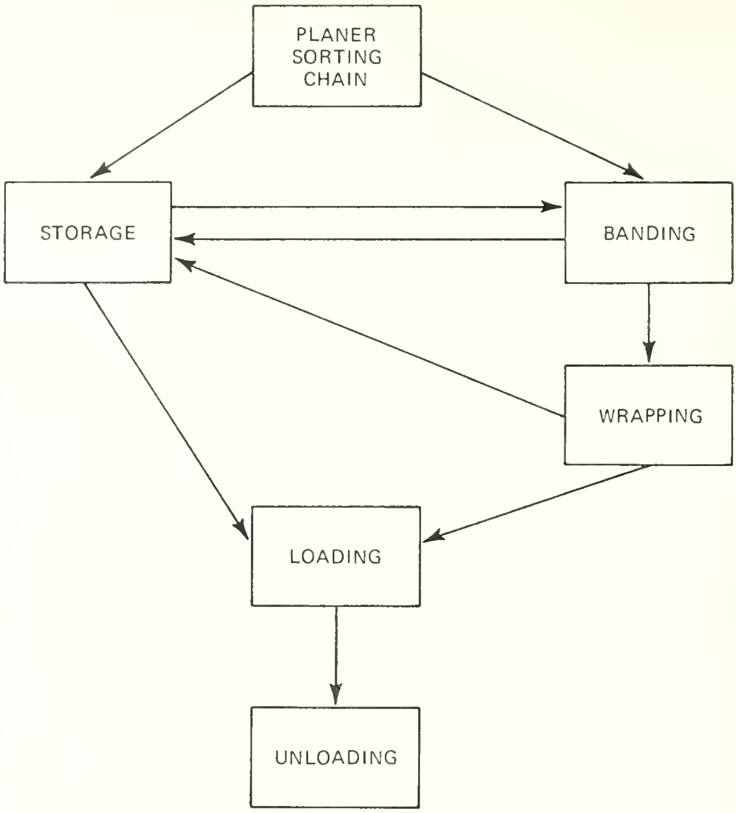


Figure 1.--Banding and wrapping process flow.

By timing mechanical banding operations at the different mills through 1-hour intervals, we derived an average time of 4 minutes 12 seconds per unit. Thus 12 units per hour, or 5 minutes per unit, which is a realistic rate, will be used throughout this study. Twelve units per hour, at 1,920 board feet per unit, is a productivity rate of 11,520 board feet per man-hour for the two-man crew.

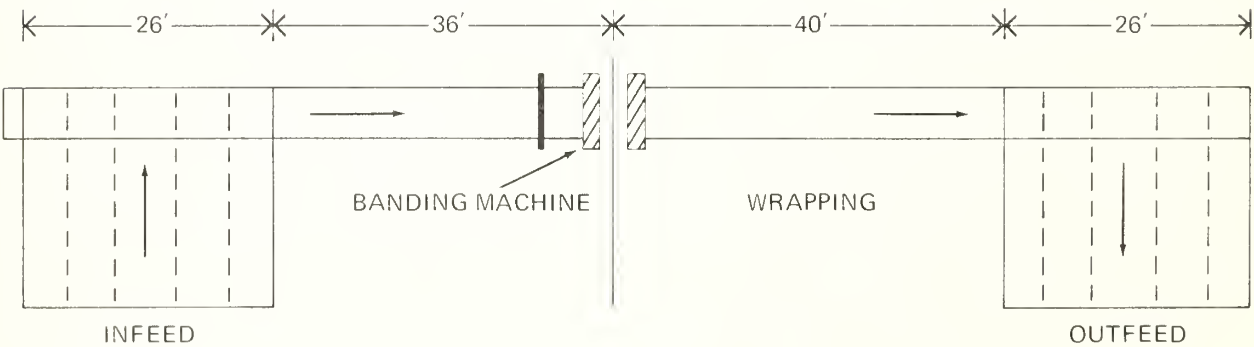


Figure 2.--Banding and wrapping layout.

The costs per M board feet for mechanical banding are

Labor	$0.347
Amortization	.256
Materials	.165
Forklift operation	.041
	$0.809

Labor is $0.347 per M board feet.--At 4.00 per man-hour, this productivity rate represents a gross labor cost of 0.347 per M board feet. The wages assumed in this example may be applicable for some operations and unrealistic for others.

Amortization of banding machine is $0.256 per M board feet.--The average cost of a banding machine, installed, is $12,500. Assuming straight-line depreciation for a 5-year period, the annual amortization charge is $2,500. This cost includes conveyors, band and wrapping station, shed roof, and wiring. The annual banding production ranges from 7.5 to 12.0 million board feet. A median of 9.75 million board feet is used, which results in an amortization cost of $0.256 per M board feet. We recognize that the volume banded is limited by sales and not by the production capacity of the installation.

Materials cost $0.165 per M board feet.--Materials costs have been obtained from current price lists. Strapping material used is 3/4 X 0.025 inch, which costs $0.01203 per lineal foot. A 2- by 4-foot unit requires two 12.3-foot bands. These cost $0.296. Two seals are required per unit at $0.020. Thus, the total cost for materials is $0.316 per unit, or $0.165 per M board feet.

Forklift operation cost is $0.041 per M board feet.--Operating costs for a forklift are $0.950 per hour. This does not include depreciation. Generally, the forklift used in this part of the operation has been fully depreciated because it is a spare machine. At 23 M board feet per hour, this provides a cost of $0.041 per M board feet.

MECHANICAL WRAPPING

The wrapping station consists of a working space on the outfeed conveyor from the banding machine. The wrapping material is unspooled downward onto the banded unit from an overhead storage rack and stapled around the bottom of the sides and ends.

The wrapping operation requires two men. The banding machine operator can be one of these two men depending upon the production rate desired. Because there is a variable in manpower requirements that affects productivity and costs, this study shall consider both situations (Alternative 1) where the banding machine operator is not used in the wrapping operation, and (Alternative 2) where the banding machine operator is used in the wrapping operation.

Alternative 1

Where the banding machine operator is not used in the wrapping operation, the banding operation sets the production rate for wrapping. This has been substantiated by limited time studies.

Using this method to wrap lumber units, the cost per M board feet is

Labor	$0.347
Materials	0.990
Machine	--
	$1.337

Labor cost.--Productivity and labor cost are the same as for the banding operation.

Wrapping materials cost.--The cost of wrapping materials is a function of unit length and is not dependent upon production volume. A 2- by 4- by 16-foot unit requires 160 square feet of wrapping material. Using a price of $11.46 per M square feet, the wrapping material costs $0.955 per M board feet for a 16-foot unit. The cost of staples is estimated at $0.035 per M board feet. Total materials cost for wrapping is $0.990 per M board feet.

Machine cost.--The installation cost of the wrapping facility has been included in the banding machine installation. Hence, amortization charges for wrapping have been included in the banding cost. Such an allocation is permissible because the wrapping storage rack is built as part of the banding installation. In practice, the wrapping materials storage rack is a minor expense since it is usually made of scrap materials.

The cost of the forklift operation has also been charged against the banding operation. We did this because a forklift is needed for the banding operation whether or not the package is to be wrapped.

Alternative 2

Where the banding machine operator is used in the wrapping operation, overall productivity is reduced from 12 units per hour to 7 units or 13 M board feet per hour. This is because the banding operator has a break in continuity and he must move back and forth between the banding and wrapping stations.[1]

Using this method to wrap lumber units, the cost per M board feet is

Labor	$0.576
Materials	0.990
Machine	--
	$1.566

Labor cost.--The labor charge of $0.576 per M board feet is derived by using an opportunity cost analysis as follows: Using four men for the combined banding and wrapping operation (Alternative 1), the total labor cost is $0.694 per M board feet. Where three men are used (Alternative 2), the combined total labor charge is $0.923 per M board feet. The charge of $0.576 per M board feet to wrapping assumes the difference in total labor costs for the two different methods is attributed to the wrapping method that results from reduced productivity for the combined operation.

Materials cost.--The cost of wrapping materials is the same as in Alternative 1.

Machine cost.--There is no charge for machine amortization or operation as in Alternative 1.

[1]In this instance, three men are used instead of four for combined transport, banding, and wrapping. Productivity is reduced to 4.48 M board feet per man-hour for three men as compared to 5.76 M board feet per man-hour for four men.

HAND BANDING

The cost per M board feet of hand banding lumber packages is

Labor	$0.900
Materials	.165
Machine	.021
	$1.086

Two men require 4 hours to band 40 M board feet by hand. Parttime use of a forklift is also needed. This is estimated at 1 hour. A total of 9 man-hours for 40 M board feet or 4,444 board feet per man-hour is the productivity rate.

The labor cost is $36.00 and the forklift machine operation costs an additional $0.950. The materials cost is the same as for machine banding, $0.165 per M board feet, even though there is the likelihood that some wastage will occur. The total cost for hand banding is $1.086 per M board feet.

HAND WRAPPING

The cost of hand wrapping is

Labor	$0.800
Materials	.990
	$1.790

Two men are required to hand wrap the units. Their productivity is 5 M board feet per man-hour. The total wage charge is $0.800 per M board feet. No forklift charges are made because forklift handling has been done in the banding process. The cost of materials is the same as for machine wrapping.

COST COMPARISON

The preceding section has presented costs for banding and wrapping lumber by different methods. These costs are summarized in table 1, which shows that on a cost per M board feet, machine banding and machine wrapping using Alternative 1 is the least costly.

Table 1.--Summary of banding and wrapping costs

Item	Machine: Band	Machine: Band and wrap, Alt. 1	Machine: Band and wrap, Alt. 2	Hand: Band	Hand: Band and wrap
Number of men	2	4	3	2.25	2.25
Productivity (MBF/man-hour)	11.5	5.8	4.5	4.4	5.0
Cost ($/MBF)					
Labor	0.347	0.694	0.923	0.900	1.700
Materials	.165	1.155	1.155	.165	1.155
Machine[1]	.297	.297	.297	.021	.021
Total	0.809	2.146	2.375	1.086	2.876

[1]Includes amortization of banding and wrapping facility and forklift operating expense where applicable.

However, a break-even analysis is required to determine the feasibility of installing machine banding and wrapping equipment because the amortization costs in table 1 are based on a fixed annual production volume of 9.75 million board feet (see page 3). If a different production volume is used, then these amortization costs will be different. Figure 3 shows that amortization costs per M board feet for the banding machine vary inversely with production volume.

Under the conditions observed in this study, the break-even point between hand and machine banding occurs at 4.7 million board feet annual production. Where annual banding production is not expected to equal 4.7 million board feet, it is not feasible to install a semiautomatic banding machine. When further consideration is given to the combined banding and wrapping process, a different situation occurs. The break-even point for annual production volume shifts to 2.6 million board feet because machine wrapping costs less than hand wrapping, as shown in figure 4. When the wrapping cost is added to its respective banding cost, the break-even point shifts to a lower annual production volume.

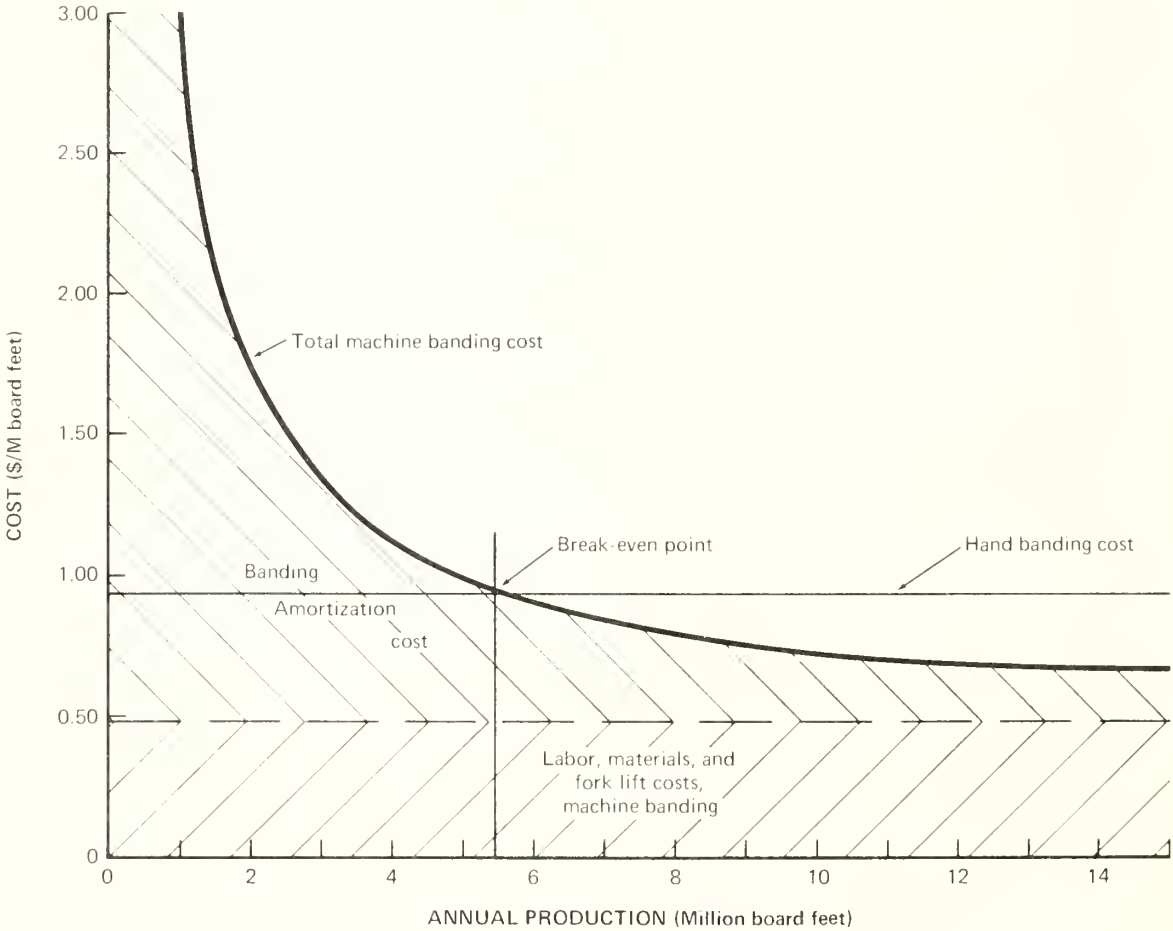


Figure 3.--Break-even comparison, hand vs. machine banding.

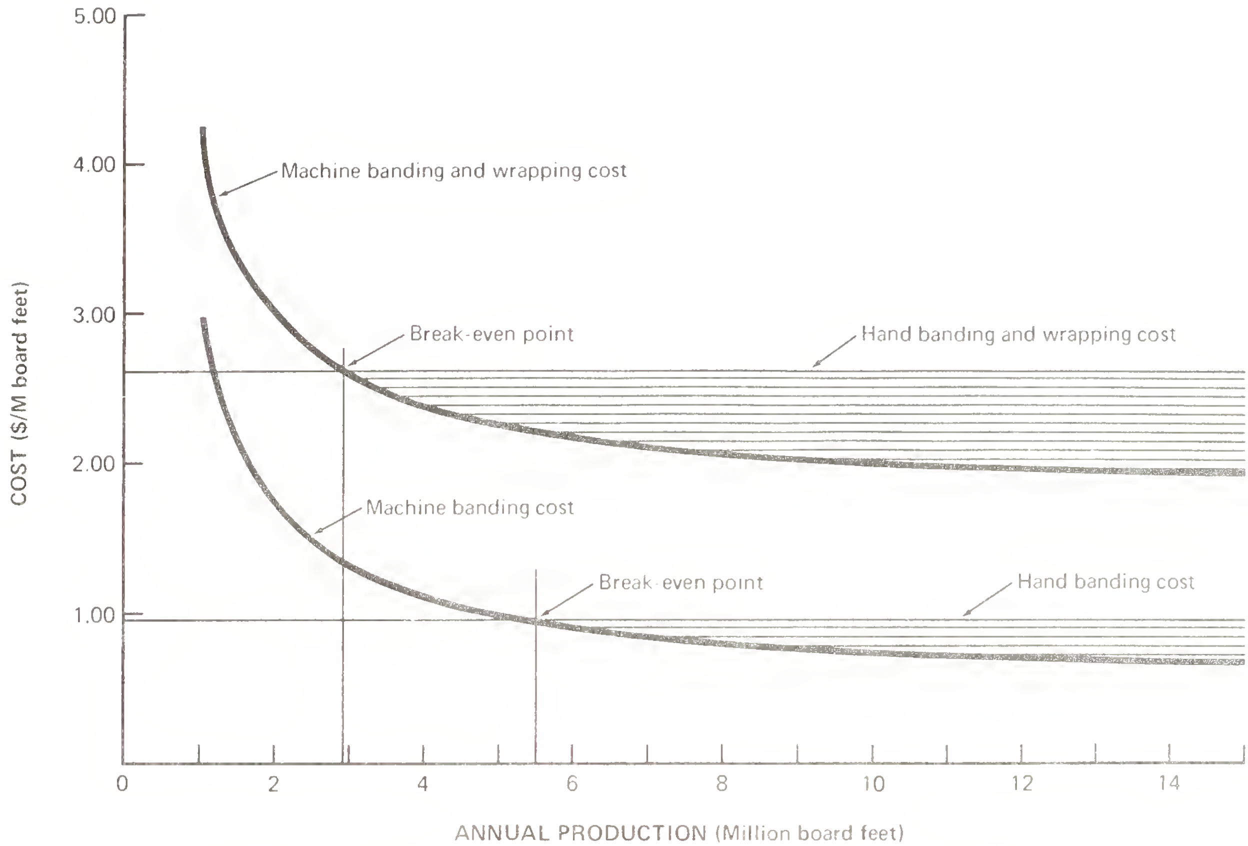


Figure 4.--[illegible] *comparison,* [illegible].

LOADING AND UNLOADING LUMBER

Most western lumber is shipped by railroad to eastern markets. This part of the study compares the cost of loading and unloading flatcars with packaged lumber vs. loading and unloading boxcars with "loose" (unpackaged) lumber. Some packaged lumber is shipped on trucks, in wide-door boxcars, and in special "Tomco" flatcars but cost data on these are not included in this study.

LOADING FLATCARS

Loading packaged lumber onto flatcars requires planning because package placement is carefully prescribed by the American Association of Railroads (Section No. 5 of the Rules Governing the Loading of Forest Products on Open Top Cars). A diagram is used to show the placement of different length units to ensure proper overlap of unit ends to make a solid load.

A forklift with operator and one additional man are needed to load and strap the packages on the car. This can be done with little or no supervision after the crew has the experience of loading out a few cars. Assuming a 40-M-board-foot order to be loaded on the car, a two-man crew can complete the job in 2 hours. A productivity rate of 10 M board feet per man-hour is attained.

The cost per M board feet for flatcar loading of unitized lumber is

Labor	$0.40
Materials (banding)	.27
Materials (dunnage)	.44
Forklift	.05
	$1.16

Labor cost is $0.40 per M board feet.--At $4.00 per man-hour, the total labor cost is $16.00 per 40 M board feet, or $0.40 per M board feet.

Banding materials cost $0.269 per M board feet.--Strapping material amounts to 430 lineal feet per car. Layer unitizing straps are 250 lineal feet per car.[2] Load unitizing straps are estimated at 180 lineal feet per car. A study of 50 cars from a West Coast mill showed an average of 428 lineal feet was loaded on each car. Using 430 lineal feet per car, the banding cost is $10.16 per car. Seals for the banding cost $0.60 per car. Total banding materials for the 40-M-board-feet car cost $10.76 or $0.269 per M board feet.

Dunnage costs $0.44 per M board feet.--To properly brace the load requires about 500 board feet of dunnage. The AAR specifications demand the absence of strength impairing knots and decay, and recommend using rough lumber. The market value of this material is about $27.50 if a price of $55.00 per M board feet is assumed. Generally, 2,000 pounds weight is charged for this dunnage. This is about 800 pounds more than the actual weight so the net cost will amount to $17.50 if a $1.25 cwt. freight rate is used. This will then be a cost of $0.438 per M board feet.

Machine cost is $0.05 per M board feet.--A forklift is used for 2 hours to load a flatcar at $0.834 per hour; it costs $1.90 per 40 M board feet, or $0.04 per M board feet.

LOADING BOXCARS

Because of the variation in organizing loading personnel, it is difficult to determine productivity for hand loading loose lumber. Personnel used for boxcar loading can include some or all of the following: two car loaders, checker, yard pickup or tallyman, part-time forklift and carrier operators, and part-time shipping clerk. Cars loaded per two-man loading team will range from one car per day using hourly wage help up to three cars per day using contract loaders. For instance, the loading costs ranged from $1.70 to $3.03 per M board feet in this study. A large part of the difference results from contract loading vs. hourly rate loading. The incentive method is by far the cheaper. The average cost, weighted by volume shipped from each mill, is $2.30 per M board feet.

UNLOADING FLATCARS

To unload a flatcar containing packaged lumber is a relatively simple operation. Assuming the car can be unloaded from both sides and adequate preparation has been made for storing the packages, the job can be done in 45 minutes time. This requires the use of a forklift operator and a helper to remove strapping.

---

[2] Layer unitizing straps are used to encircle adjacent units and bind them tightly against the load stabilizing framework. Load stabilizing straps are used to bind different layers together to tie the units into one solid load. Bearing pieces are 2 inches, or thicker, lumber nailed to the floor of the flatcar approximately crosswise.

For the sake of consistency, the same assumptions made in loading operations will be used for unloading where applicable; that is, car volume is 40 M board feet; wage cost is $4.00 per hour; and forklift operating cost is $0.950 per hour.

At 1-1/2 man-hours to unload 40 M board feet, the productivity rate is 26.7 M board feet per man-hour.

The total wage cost for unloading is $6.00 and the machine operating cost is $0.71 for a combined total of $6.71 for 40 M board feet, or $0.168 per M board feet.

UNLOADING BOXCARS

The cost of unloading a boxcar of loose lumber is difficult to determine because of the variation in orders. A highly mixed load can require two men as much as 3 days. On the other hand, a straight car shipment can be unloaded in 12 hours by two men. It will be assumed that 15 hours are needed to unload a boxcar.

At this rate, productivity is 1.33 M board feet per man-hour. Usually the yard will use pickup labor procured at the local employment agency. The wage cost for this is estimated at $2.75 per hour. Thirty man-hours at $2.75 results in a wage cost of $82.50 per 40 M board feet, or $2.062 per M board feet. The costs of supervision and of moving lumber from the car siding are not included.

COST SUMMARY AND COMPARISON

The total marketing impact of packaged lumber involves both the producer and his customer. This section summarizes the costs and benefits that accrue to the lumber mill and to the yard.

LUMBER MILL

The lumber producer is directly concerned with costs up to and including the loading of lumber. The total costs per M board feet to the producer for packaged lumber are

	Hand	Machine
Band	$1.09	$0.81
Wrap	1.79	1.34
Load	1.16	1.16
Total	$4.04	$3.31

The total cost for unpackaged lumber is $2.30, which is $1.01 less than machine packaged lumber and $1.74 less than hand packaged lumber.

By offering this service, the mill operator is providing some degree of product differentiation as compared to the mill that doesn't offer packaged lumber.

Aside from this, the mill operator is obtaining a service charge over the current selling price. In most instances, this service charge is enough to cover the additional cost.

CUSTOMER

An examination of benefits to the customer will point out why the market is paying for this service and why the impetus for this service has come from the marketplace.

There is an appreciable cost difference between unloading packaged and unpackaged lumber--$0.17 per M board feet as compared to $2.06 per M board feet.

The customer saves $1.89 per M board feet. Furthermore, it is estimated that the yard operator realizes an additional $1.30 per M board feet savings in storage and handling costs resulting from: less storage space to handle a given inventory volume through higher stacking; outside storage reducing the need for sheds; no need to band units for delivery. Hence, the yard operator accrues a total savings of around $3.20 per M board feet.

OTHER ADVANTAGES

Over and above cost considerations, there are the following benefits derived by both the producer and the customer from packaged lumber. These also have cost implications.

Speed and flexibility of loading.--Shipping personnel at the six sawmills in Montana mentioned that loading with packaged lumber permits convenient shipping of order surges when the stock is already in inventory.

Diamond Lumber Company of Tillamook, Oregon, uses four men to do the work formerly done by 14 men.[3] Efficiencies can be gained where lesser daily volumes are handled.

Breakage loss reduction.--When lumber is handled as a solid package, there is less chance for breakage or loss of individual pieces throughout the materials handling process.

Inventory procedure.--Each lumber unit has a prescribed volume for a given length. This greatly simplifies the inventory process. Also, while permitting a systematic storage method, it allows a degree of flexibility in that units can be stored where convenient with the assurance that the volume will remain constant.

A yard operator can maintain his inventory more easily because the units are marked with number of pieces, grade, and species. When a unit is opened up or loaded out, the operator is reminded how that particular item is stocked in relation to his desired volume; e.g., he is reminded as to whether or not he should order more stock.

Order assembly.--Order assembly is simplified in that pieces of lumber do not have to be tallied individually. This is particularly advantageous when sales are made using unit volumes for lot sizes.

Protection in storage -The primary demand for wrapped lumber stems from the need to preserve quality during storage through inclement weather. One study shows that the percent of studs falling out of grade during storage because of bow and crook can be as low as 4.2 percent in packaged units as compared to 12.5 percent uncovered.[4]

---

[3] Forest Industries. 3 man packaging unit--1 MM a day. Portland, Oregon, July 1964

[4] Crow's Digest. Exposure tests evaluate lumber wraps. Portland, Oregon. October 1967.

Partially wrapped piles had as much as 20.8 percent grade fallout. This study showed that the moisture content increased 0.16 percent during the same 6-month period. Thus, it appears as though proper wrapping material can help a great deal in reducing the perishability of lumber in storage.

The ability to ship banded or wrapped lumber is also a significant sales factor--particularly during late fall and through the winter--to customers who store stocks outside. It has been reported that the ability to ship wrapped lumber is the main factor in maintaining production at high levels in three plants: all felt that this also helped to obtain orders not requiring banding or wrapping.

Yard material handling.--Improved material handling has become well recognized not only for the distribution yard but for the retail yard as well. Clark Row reported practically all retail yards sampled in the Southeastern States that had forklift trucks preferred strapped shipments.[5]

Yard area reduction.--Strapped lumber packages can be stacked safely as high as a forklift can reach. This higher stacking reduces the amount of ground area required for a given inventory volume. Too, sheds are not necessary. Consequently, property taxes are lower. It is estimated that storage costs are reduced by two-thirds because of these factors.

Pricing aid.--Keeping the units intact until it is opportune to open them prevents the dealer's customers from picking through the pile to take out the best pieces. Where this picking over is done, the leftovers usually consist of poorer material for the specified grade, which is difficult to sell. Oftentimes this little dab is put into a lower grade at a reduced price or put into a "bargain pile" also at a lower price.

Delivery.--The loads can be dumped with less chance of breakage and will remain intact; thus, it is simpler for the customer to check the volume delivered. There is no scattering of pieces or individual pieces to count. Also, keeping the packages banded until time to be used in construction prevents the removal of pieces beforehand. There is less chance for pilferage at the job site. Practical Builder reports that this is an increasingly important consideration for the builder where pilferage can amount to $125 per unit being constructed.[6] Not only the dollar loss but the complicating of schedules can be costly.

---

[5]Row, Clark. Changing role of retail dealers in lumber marketing. USDA Forest Serv. Res. Pap. SO-7. 1964.

[6]Practical Builder. Theft, vandalism, and pilferage. Bristol, Conn. July 1967.

LIMITATIONS

It might appear as though unit banding is the panacea for material handling. Like anything else it has its limitations or disadvantages.

Pattern stock.--Although some pattern stock has been banded, it generally has been done on a limited or experimental basis. Where edges have been run to a pattern, damage can occur from the side compression in the banding process. This occurs from the difficulty in accurately matching all the layers in the unit. Also, there is a tendency for these layers to become better alined as the load is vibrated in transit. As this alinement occurs under pressure, the pattern work tears and the pieces come together. This reduces the tension of the strapping and increases the possibility of coring in the unit.

Lot volume.--Another limitation in unit packaging becomes apparent when the customer demands lot volumes not suited for unitized loads. Not only does this prohibit unit handling but it relegates the difficult highly specified orders to hand loading. This will probably raise hand loading costs as the proportion of flatcar loaded orders increases.

Most Montana sawmills ship highly mixed stock. In fact, some of them feel this is the most important part of their sales. At times, market conditions are such that this is a very strong factor in keeping the order file at a reasonable level both volumewise and pricewise.

Claim adjustment.--It was mentioned previously that banding lumber can possibly reduce claims due to breakage. On the other hand, when claims are justified, a serious delay can occur when the unit is wrapped. The basis for claim will not be noticed until the wrapping is removed; this can be at delivery time or some months later.

Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field Research Work Units are maintained in:

- Boise, Idaho
- Bozeman, Montana (in cooperation with Montana State University)
- Logan, Utah (in cooperation with Utah State University)
- Missoula, Montana (in cooperation with University of Montana)
- Moscow, Idaho (in cooperation with the University of Idaho)
- Provo, Utah (in cooperation with Brigham Young University)

FOREST SERVICE CREED

The Forest Service of the U. S. Department of Agriculture is dedicated to the principle of multiple use management of the Nation's forest resources for sustained yields of wood, water, forage, wildlife, and recreation. Through forestry research, cooperation with the States and private forest owners, and management of the National Forests and National Grasslands, it strives — as directed by Congress — to provide increasingly greater service to a growing nation.

USDA FOREST SERVICE
RESEARCH PAPER INT-67
1969

SOIL MOISTURE DEPLETION AND ESTIMATED EVAPOTRANSPIRATION ON UTAH MOUNTAIN WATERSHEDS

ROBERT S. JOHNSTON, RONALD K. TEW, and
ROBERT D. DOTY

INTERMOUNTAIN FOREST & RANGE EXPERIMENT STATION
Ogden, Utah

USDA Forest Service
Research Paper INT-67
1969

SOIL MOISTURE DEPLETION AND ESTIMATED EVAPOTRANSPIRATION ON UTAH MOUNTAIN WATERSHEDS

Robert S. Johnston, Ronald K. Tew, and Robert D. Doty

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401
Joseph F. Pechanec, Director

THE AUTHORS

R. S. JOHNSTON, Associate Forest Hydrologist, joined the staff of the Intermountain Station in 1964. He holds a B.S. degree in forestry from Rutgers, and currently is completing requirements for a Ph.D. degree in watershed management from Colorado State University.

R. K. TEW, now a soil scientist with the Soil Conservation Service at Manti, served as Associate Plant Physiologist at the Intermountain Station from 1963 to 1968. He received his B.S. degree in agronomy from Brigham Young University and his M.S. and Ph.D. degrees from Utah State University.

R. D. DOTY, Associate Research Forester, has been employed by the Intermountain Station since 1964. He holds a B.S. degree in forestry from the University of Idaho and currently is fulfilling Utah State University requirements for an M.S. degree in watershed management.

Throughout this study, all three scientists were stationed in Logan at the Forestry Sciences Laboratory, where they were assigned to the water yield improvement work unit.

INTRODUCTION

This paper summarizes recently completed studies on water use of several important plant communities in the Intermountain Region. These studies were designed to inventory water use and to evaluate the effects of several vegetation conversion and stand manipulation practices on potential water yield.

Data were collected from 219 moisture sampling locations representing 14 sites and 10 vegetation types. Soil moisture depletion and evapotranspiration data from some of these sites have been or are in the process of being published elsewhere (see list of references in table 1, page 7). However, data on six vegetation types from five of the sites probably will not be reported in other publications.

The format is designed to provide the administrator, the researcher, and the student with soil moisture depletion and estimated evapotranspiration data taken from a wide variety of vegetation types, soils, and elevations. Obviously, all sites and vegetation types have not been studied in this short period. A summary of these data in a single publication may prevent unnecessary duplication of this work by others and point up gaps in our knowledge of water consumption.

SITE DESCRIPTIONS

All study sites are within three general areas of Utah (fig. 1). Sites 1, 2, and 3 are in northern Utah within the Logan River drainage (upper right). Sites 4 through 8 are in north-central Utah on the Davis County Experimental Watershed northeast of Bountiful (lower right). Sites 9 through 14 are in central Utah on the Great Basin experimental area east of Ephraim (lower left).

Each study was planned and conducted independently; consequently, supplementary soil and vegetation descriptions are not uniform. Brief site descriptions are presented in table 1; more detailed considerations of the soils and vegetation for most sites are available in the literature citations (last column). Their location within the site is referenced by plot designations, such as 5a, 5b, 5c (tables 1 and 2, pages 7 and 10, respectively). Natural understory vegetation on all sites was maintained throughout each study; vegetation-type designations indicate only the overstory or dominant species.

METHODS AND RESULTS

Studies were to determine comparative water losses from two or more vegetation covers on paired or adjacent plots (e.g., mature versus clearcut aspen or aspen versus grass). Soil moisture on the study plots was measured several times each season with neutron moisture probes. All measurements on the Davis County Experimental Watershed (sites 4 through 8, tables 1 and 2) were made with a Nuclear Chicago probe; all others were made with a Troxler probe.[1] Measurements were taken in the top 6 inches and at 1-foot intervals thereafter to the bottom of each hole.

The number of holes drilled at each site and their depths are presented in table 2. Most were drilled by a hand-held pneumatic jackhammer, except those on sites 7 and 8, where a track-mounted pneumatic drill was used. The latter method results in more uniform soil moisture access holes and more accurate readings.[2]

---

[1]Trade names are used for identification only; they do not imply endorsement by USDA Forest Service.

[2]Richardson, B. Z. Installation of soil moisture access tubes in rocky soils. J. Soil and Water Conserv. 21(4): 143-145. 1966.

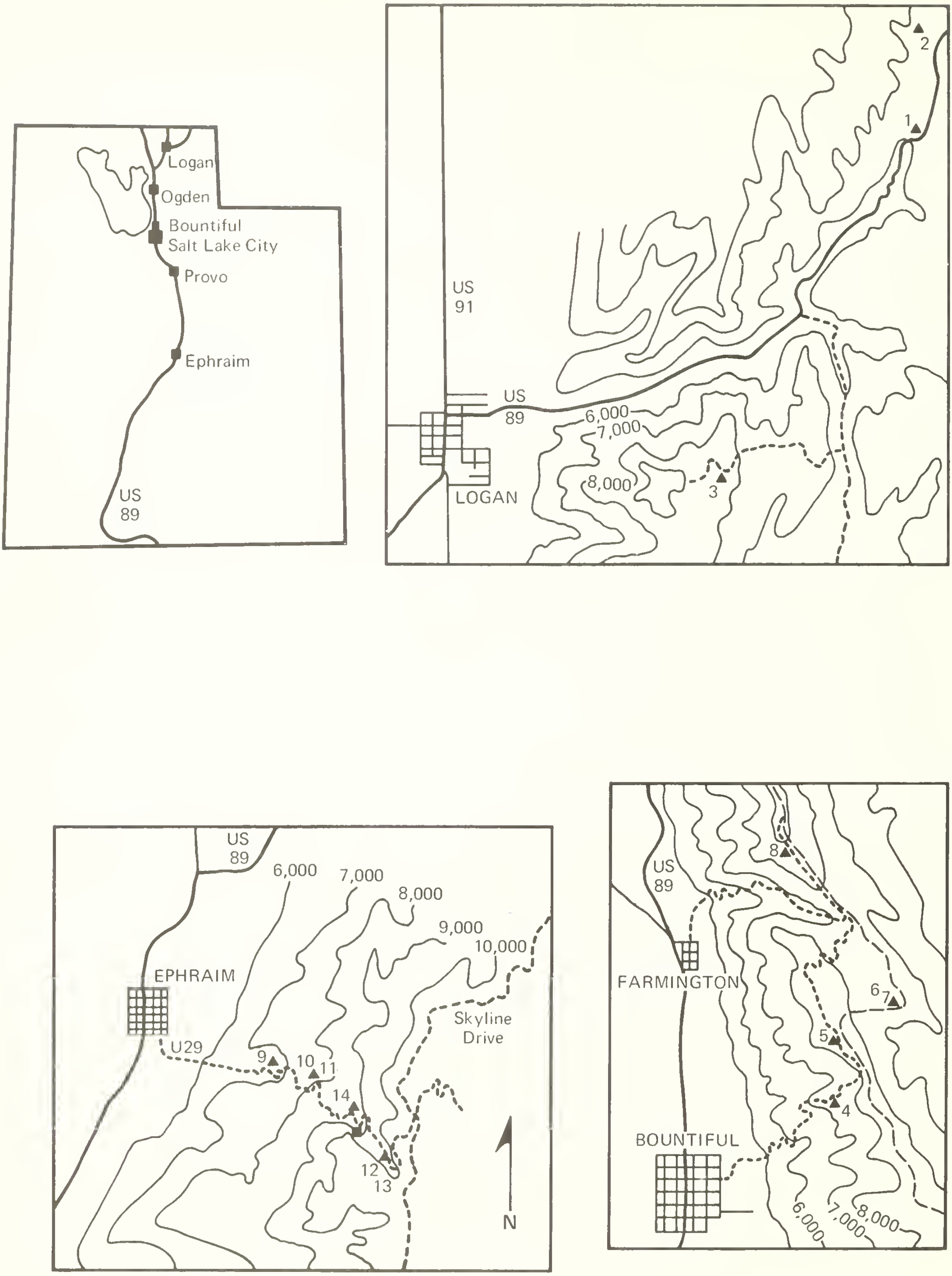


Figure 1.--Map of Utah with three enlarged areas showing locations and elevations of study sites.

The average maximum and minimum water contents and evapotranspiration estimates for all sampling points are given in table 2. The maximum water content shown is the amount measured on the initial sampling date, which varied from year to year depending upon phenology and accessibility. Minimum water content is the amount measured on the final sampling date, usually the minimum reached during the growing season. The difference between maximum and minimum measurements represents soil moisture depletion. Because the amount and distribution of summer rainfall profoundly affected these final moisture measurements, precipitation was measured on or near each study area. Precipitation during the growing season was added to soil moisture depletion to obtain an estimate of evapotranspiration.

DISCUSSION

Treatment effects can be evaluated by considering the treatment area as a system in which various inflow and outflow parameters can be measured and balanced. The general and somewhat oversimplified water balance equation

$$Q = P - ET - I - \Delta GW - \Delta S \qquad (1)$$

is used frequently in forest hydrology problems of this type. In the equation, Q is streamflow, P is precipitation, ET is evapotranspiration, I is interception, ΔGW is change in groundwater aquifer storage, and ΔS is change in soil moisture storage.

If treatments are confined to small plots, some estimate of effects can be obtained by modifying the water balance equation and making some necessary assumptions. On a small plot, streamflow and changes in the groundwater aquifer storage no longer are considered because they cannot be measured readily. Treatment benefits are restricted to measurable site parameters, and interception losses and reduced evapotranspiration become a measure of treatment effects. Interception losses are difficult to evaluate and are not characterized adequately for most vegetation types; therefore, interception usually is pooled with the evapotranspiration term. The water balance equation now can be written

$$ET = P - R - D - \Delta S. \qquad (2)$$

In equation (1), deep seepage of soil moisture (D) and surface runoff (R) are not considered as separate terms. Deep seepage is assumed to be part of the soil moisture storage term (S), until such time as it is incorporated in the groundwater and reappears as streamflow (Q), or contributes to aquifer storage (GW). In plot studies, however, deep seepage is defined as the soil water that moves below the depth of rooting or below the depth of soil moisture measurements and, as such, must be considered a loss to the site. Because deep seepage is difficult to measure, it is assumed to be negligible or, when paired plots are compared, to be uniform; then, in either case, results are not unduly biased. Surface runoff also is a potential loss to the site and must be considered in equation (2). Surface runoff can be collected and measured, but usually is negligible on well-vegetated sites in the watersheds of the Intermountain Region. On the single bare plot (5c), precipitation has been corrected by estimated runoff (table 2). Precipitation and soil moisture measurements can be made with relative ease and accuracy on small study areas.

Slatyer[3] suggests that the water balance equation be reduced to ET = ΔS during dry weather, because surface runoff and downward drainage are closely linked to soil water recharge. Throughout much of the West, including Utah, summer precipitation on well-vegetated land seldom exceeds the immediate storage capacity of the surface few inches of soil. Therefore, it is readily available to loss by evapotranspiration. For this reason, the water balance equation becomes ET = $\Delta S + P$ during the summer months.

Results presented in table 2 were taken from several independent studies and reflect water loss estimates from a large variety of vegetation covers and sites. Both soil moisture depletion and evapotranspiration are influenced by a large number of factors, including aspect, elevation, and several variables (e.g., climate, vegetation, and soil). Therefore, comparisons of water losses from dissimilar sites are suspect (table 2). However, this is not to say that all trends and observations are invalid. We simply want to caution against indiscriminate use of the data and to point out that comparisons of water withdrawal by various cover types are most valid when based on results obtained from paired plots.

For example, certain trends in water consumption associated with single variables were noted and reported in the independent studies mentioned above. These observations were perfectly valid within the context of a particular study. However, as the scope of available information broadens with increased sampling, these trends are confounded and masked by the influence of other variables. To cite an instance, when aspen sites 11 and 12 were considered separately, data indicated a definite trend in water use at two elevations. But, when evapotranspiration losses for all aspen sites during a single season are considered, no trends attributable to elevation are apparent as shown below.

Elevation (Ft.)	Soil moisture depletion (In.)	Precipitation (In.)	Evapotranspiration (In.)
6,100	8.31	4.29	12.60
7,000	11.55	4.30	15.85
7,640	9.29	1.01	10.30
7,800	9.51	1.01	10.52
7,900	5.67	4.80	10.47
8,400	17.39	1.13	18.52
9,200	7.62	5.55	13.17

Our estimated losses probably are conservative, because the moisture that moved laterally into the plots subsequently is lost by evaporation or transpiration. It should also be noted that depletion figures represent only the soil moisture changes within the depth of measurement (4 to 9 feet). This depth does not necessarily represent the maximum depth of root penetration on a given site. Because moisture withdrawal by roots below the depth of measurement is not included in the depletion figures, we may have underestimated depletion and evapotranspiration losses.

Maximum moisture contents are constant on a given site, rarely varying more than 1 or 2 inches for the entire measured profile. Seldom, if ever, in the mountain watersheds of this region does winter precipitation fail to fully recharge the soil profile. Hence, differences in maximum moisture contents merely reflect the difficulty in measuring field moisture capacity. Slight differences in moisture storage recorded for the particular day that initial measurements were made each year are due to gravitational water still present in the profile or to previous water withdrawal by evapotranspiration.

[3]Slatyer, R. D. Plant water relations. New York: Academic Press. 366 pp. 1967.

Minimum moisture contents and resulting soil moisture depletion values varied considerably both between sites supporting a given vegetation type and between years for any given site. These data reflect both moisture withdrawal and precipitation characteristics prior to final measurement. In some years, summer storms repeatedly replenish moisture deficiencies in the surface few feet of soil, but this water usually is lost through evapotranspiration within a few days. Most of the late-season rainfall contributes to the replenishment of soil moisture deficits.

Growing season rainfall fluctuated greatly between the study years of 1963 and 1967. For example, summer rainfall on site 5 averaged 4.61 inches, but ranged from 1.13 to 10.43 inches. This type of variation is advantageous because it provides a good estimate of the extremes that can be expected in soil moisture deficiencies and evapotranspiration values. Measurements from site 5a during 1963 and 1965 illustrate how rainfall can influence soil moisture measurements and contribute to interpretation problems. Maximum water content in the 9-foot profile was essentially the same (37.75 and 37.55 inches) during each year. Minimum moisture contents were [illegible] inches in 1963 and 25.72 inches in 1965. Rainfall in 1965 was nearly twice as great as in 1963. When precipitation was added to the soil moisture depletion figures, evapotranspiration was estimated to be 1.89 inches greater for the 1965 growing season.

To make the results more comparable, total evapotranspiration values cited in table 2 were converted to inches of evapotranspiration per foot of measured soil profile. Then the highest and lowest evapotranspiration value for each vegetation type for all years and sites were used to construct figure 2. The graph illustrates the wide range of evapotranspiration values that might be expected over several years on many mountain sites. These results should not be considered conclusive as data on several of the vegetation types were taken for a limited number of sites and years of measurement.

Tree and shrub types show a generally greater loss than sagebrush-grass, grass-herb, or bare types. Estimates for both sagebrush-grass (site 6) and bare types (site 5c) are based on but one site each and so are not reliable. Certainly, we would not expect the same minimum evapotranspiration value per foot of soil from both bare and well-vegetated sites, and--when legitimate comparisons are made--our expectations are substantiated. Comparative losses from adjacent grass-herb and bare plots (5b and 5c, table 2) show evapotranspiration losses nearly always 0.5 inch or greater per foot of soil on the vegetated plot.

In all instances, sprout vegetation has a narrower range than respective mature types; so sprout ranges are found on the lower side of the evapotranspiration scale, although there is considerable overlapping (fig. 2).

The range of evapotranspiration losses from Douglas-fir (Pseudotsuga menziesii) appears to be too small, but the information available is meager, representing data recorded for 2 years from site 16 and for a single year from site 3b.

Most of the information assembled is for aspen, Gambel oak, and grass-herb types, consequently, the range of evapotranspiration losses per foot of soil is widest for these types. The higher evapotranspiration losses from the grass-herb type overlap all the other tree and shrub types, especially in the 1.75- to 2.75-inch range. Maximum rates of evapotranspiration are 3.26 and 3.10 inches per foot of soil from the mature aspen and oak types, respectively.

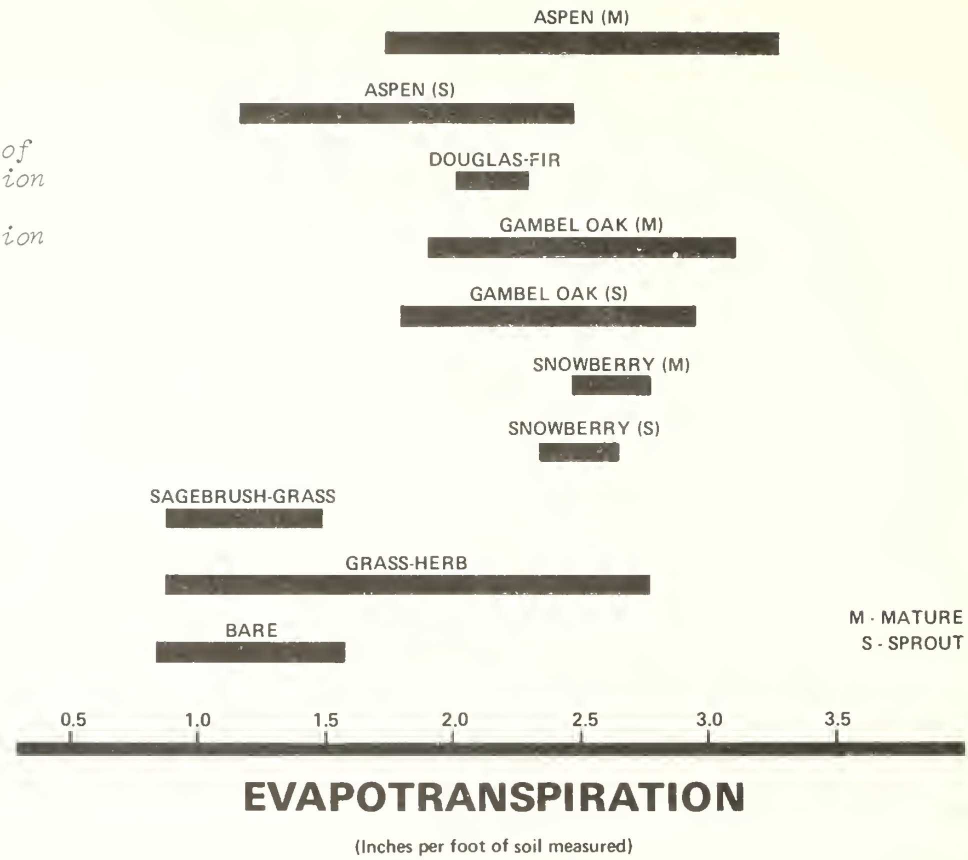


Figure 2.--Range of evapotranspiration estimates for several vegetation types.

CONCLUSIONS

Results of all studies indicate that moisture depletion is greatest early in the growing season (May to July) and that late-season losses generally are confined to withdrawal from deeper parts of the soil profile. By the end of each summer, most of the available soil moisture throughout the rooting depth is depleted.

On paired plots, mature aspen stands utilized 0.48 to 4.50 inches more soil moisture from the upper 6 feet of profile than sprout stands. These differences diminish rapidly after the first year as sprout stands mature and evapotranspiration accelerates. Comparisons of evapotranspiration losses on Gambel oak plots show mature oak utilizes only 0.25 to 1.15 inches more moisture from the upper 6-foot soil profile than 1-year-old sprout stands. In two instances, 3-year-old oak sprouts had greater evapotranspiration losses than mature stands. Removal of oak and aspen can prolong water savings only if sprouting is prevented.

An indication of prospective water savings following conversion of aspen to grass can be obtained from moisture measurements on sites 1, 2, 5, and 6. Reduced evapotranspiration losses ranged from 1.08 to 5.18 inches from 6-foot sampling depths and 2.76 to 7.59 inches from a 9-foot soil profile. The average reduced water consumption on plot 5 was 5.75 inches for the 4-year period. Conversion of Gambel oak to grass (site 4) reduced evapotranspiration losses by 4.55 and 3.83 inches from an 8-foot-deep soil.

Shallow-rooted plants extract less water from depth than deep-rooted vegetation; this is the premise upon which all vegetation conversion practices for increased water yields are based. The difference in evapotranspiration losses before and after treatment is water saved. Eventually, such water will emerge as streamflow or will be stored in the groundwater aquifer. Obviously, treatments will be most beneficial on sites showing the greatest decrease in rooting depths.

Table 1.--Site locations and information on associated soils and vegetation

Site no.	Location	Soils	Vegetation	References
1, 2, 3	At three elevations in Logan Canyon drainage.	At least 6 ft. of relatively rock-free, clay-loam soil; calcareous parent material.	All located within three adjacent vegetative types--Douglas-fir (Pseudotsuga menziesii), aspen (Populus tremuloides), and grass-forb; vigorous grass-forb vegetation, 3 to 5 ft. tall by late summer.	
4	Three adjacent plots in Stone Creek drainage, Davis County Experimental Watershed.	Coarse-textured soil; mica-schist parent material; solum, approximately 20 in. deep, underlain by fractured rock containing small amounts of silt and clay.	Plot 4a.--Gambel oak (Quercus gambelii), mature stand; trees, 8 to 14 ft. tall; basal area, 65 sq.ft./acre; luxurious herbaceous understory. Plot 4b.- Mature oak cut, allowed to resprout; understory vegetation same as 4a. Plot 4c.--Mature oak cut, sprouts killed by spraying in 1965; several grasses introduced.	Tew, R. K. 1966. Soil moisture depletion by Gambel oak in northern Utah. U.S. Forest Serv. Res. Note INT-54. 7 pp.
5	Three adjacent 0.1-acre plots near headwaters of Parrish Canyon, Davis County Experimental Watershed.	Dark-brown, sandy-loam; gneiss-schist parent material; depth variable; large boulders and rocks prevalent.	Plot 5a.--Scrubby aspen overstory. Lush herbaceous understory; average tree height, 17 ft.; basal area, 100 sq.ft./acre; ground cover, 73% vegetation, 12% litter, and 15% bare. Plot 5b.--Aspen overstory removed in 1947; original understory, grasses and herbaceous species, has deteriorated since treatment; in 1967, ground cover, 21% litter, 30% bare, and 49% vegetation, of which 11% was tar weed (Madia glomerata). Plot 5c.--All vegetation removed in 1947; plot kept bare until 1968.	Johnston, Robert S. Evapotranspiration from bare, herbaceous, and aspen plots: a check on a former study. Water Resources Res. (In press.)

Table 1. (con.)

Site no.	Location	Soils	Vegetation	References
6	Two plots on lower Chicken Creek watershed, Davis County Experimental Watershed.	Reddish-brown, loamy soil, well-drained, deep; parent material, shale and conglomerate rock.	Plot 6a.--Aspen overstory; lush grass-forb understory. Most abundant grass, mountain brome (Bromus carinatus); ground cover, 56% vegetation, 29% litter, and 15% bare. Plot 6b.--Important grass species: mountain brome, cheatgrass (Bromus tectorum), tar weed, and catchweed (Galium aparine); ground cover, 48% vegetation, 11% litter, and 41% bare.	
7	Six subplots on upper Chicken Creek watershed, Davis County Experimental Watershed.	Deep, loamy soil developed in colluvium; mixed sandstone, gneiss, and schist parent materials.	Plot 7a.--Mature, two-storied aspen on three subplots; average tree heights, 48 and 17 ft.; basal area, 90 sq.ft./acre; ground cover, 67% vegetation, 27% litter, and 6% rock. (See accompanying reference for information on other plots.) Plot 7b.--Aspen removed in 1964 from three subplots, allowed to resprout; ground cover, 75% vegetation, 18% litter, and 7% bare; understory species similar on both sites. (See accompanying reference for information on other plots.)	Johnston, R. S. 1969. Aspen sprout production and water use. USDA Forest Serv. Res. Note INT-89. 6 pp.
8	Near head of Halfway Creek watershed, Davis County Experimental Watershed.	Extremely immature, rocky, sandy loams, 4 to 5 ft. deep; gneiss-schist parent material, granitic intrusions.	Site, a single plot. Major species: big sagebrush (Artemisia tridentata), various grasses (Poa sp., Agropyron sp., Festuca sp.), and forbs (Lupinus sp., Erigonium sp., and Aster sp.); ground cover, 32% shrubs, 23% grass and forbs, 7% litter, and 38% bare and rock.	

Table 1. (con.)

Site no.	Location	Soils	Vegetation	References
9, 10	At various elevations in Ephraim Canyon drainage.	Clays and silty clays from either Flagstaff Limestone Formation or North Horn Formation; profiles at lower elevation oakbrush sites poorly developed, compared with those at higher elevation sites.	Gambel oak, 7 to 10 ft. tall at 6,600 ft. elevation, 10 to 14 ft. tall at 7,900-ft. elevation. In 1963, mature oak clearcut on selected plots; vigorous sprout stand followed cutting.	Tew, R. K. 1967. Soil moisture depletion by Gambel oak in central Utah. U.S. Forest Serv. Res. Note INT-74. 8 pp.
11, 12	do.	do.	Mature aspen, 120 to 272 stems/acre; basal area, 162 sq.ft/acre on lower elevation sites, 202 sq.ft./acre on higher elevation sites; clearcut in 1963; subsequent sprouting provided two age groups at each site for purpose of comparison.	Tew, R. K. 1967. Soil moisture depletion by aspen in central Utah. U.S. Forest Serv. Res. Note INT-73. 8 pp.
13	do.	do.	Mostly penstemon (<u>Penstemon rydbergii</u>); some native grass species.	
14	do.	do.	Snowberry (<u>Symphoricarpos oreophilus</u>): two age groups; mature plants, approximately 3 ft. tall and young sprouts.	

Table 2.--Soil moisture depletion and evapotranspiration losses from 10 vegetation types in Utah

Site no.	Elevation	No. of holes	Depth	Year	Maximum	Minimum	Soil moisture depletion	Precipi- tation	Evapo- transpiration
	Ft.		Ft.		- - - - -	- - - - -	Inches of water	- - - - -	- - - - -
					ASPEN (Mature)				
1a	6,100	6	6	1965	22.56	17.48	5.08	--	--
				1966	23.07	14.76	8.31	4.29	12.60
				1967	22.70	14.30	8.40	5.00	13.40
2a	7,000	6	6	1965	23.20	19.90	3.30	--	--
				1966	25.47	13.92	11.55	4.30	15.85
				1967	28.44	13.83	14.61	5.00	19.61
3a	8,500	5	6	1966	26.21	12.51	13.70	3.90	17.60
5a	8,400	3	9	1963	37.73	18.61	19.12	5.06	24.18
				1964	36.02	18.77	17.25	1.83	19.08
				1965	37.55	25.72	11.83	10.43	22.26
				1966	34.54	17.15	17.39	1.13	18.52
				1967	38.62	18.24	20.38	--	--
6a	7,640	6	6	1966	21.46	12.17	9.29	1.01	10.30
				1967	24.01	14.52	9.49	2.47	11.96
7a	7,800	6	6	1965	20.92	15.67	5.25	5.87	11.12
				1966	20.72	11.21	9.51	1.01	10.52
				1967	21.52	10.86	10.66	2.47	13.13
11a	7,900	12	6	1964	29.65	21.57	8.08	3.98	12.06
				1965	28.96	23.62	5.34	10.65	15.99
				1966	30.00	24.33	5.67	4.80	10.47
12a	9,200	12	6	1964	23.74	15.33	8.41	3.78	12.19
				1965	24.07	18.69	5.38	9.28	14.66
				1966	23.86	16.24	7.62	5.55	13.17

Table 2. (con.)

Site no.	Elevation	No. of holes	Depth	Year	Maximum	Minimum	Soil moisture depletion	Precipitation	Evapotranspiration
	Ft.		Ft.		- - - - - -	- - - - - -	Inches of water	- - - - - -	- - - - - -
					ASPEN (Sprout)				
7b	7,800	6	6	1965	21.63	19.60	2.03	5.87	7.90
				1966	20.61	14.65	5.96	1.01	6.97
				1967	21.55	13.91	7.64	2.47	10.11
11b	7,900	12	6	1964	30.24	23.36	6.88	3.98	10.86
				1965	29.74	25.63	4.11	10.65	14.76
				1966	30.32	25.13	5.19	4.80	9.99
12b	9,200	12	6	1964	22.94	17.59	5.35	3.78	9.13
				1965	22.97	22.09	0.88	9.28	10.16
				1966	23.28	18.07	5.21	5.55	10.76
					DOUGLAS-FIR				
1b	6,100	6	6	1965	22.69	17.47	5.22	-	
				1966	22.61	14.89	7.72	4.29	12.01
				1967	22.71	14.39	8.32	5.00	13.32
3b	8,500	5	6	1966	16.93	7.13	9.80	3.90	13.70
					GAMBEL OAK (Mature)				
4a	7,130	9	8	1963	26.00	13.47	12.53	5.99	18.52
				1964	24.84	--	-	2.90	-
				1965	24.16	17.78	6.38	10.68	17.06
				1966	24.93	14.20	10.73	4.08	14.81
				1967	25.54	14.46	11.08	7.15	18.23
9a	6,600	12	6	1964	24.79	15.29	9.50	3.31	12.81
				1965	23.21	17.20	6.01	9.07	15.08
				1966	22.13	14.75	7.38	4.01	11.39
10a	7,900	12	6	1964	30.05	18.46	11.59	3.98	15.57
				1965	29.17	21.18	7.99	10.65	18.64
				1966	26.76	17.81	8.95	4.80	13.75

Table 2. (con.)

Site no.	Elevation	No. of holes	Depth	Year	Maximum	Minimum	Soil moisture depletion	Precipi-tation	Evapo-transpiration
	Ft.		Ft.		Inches of water				
					GAMBEL OAK (Sprouts)				
4b	7,130	9	8	1966	23.78	13.47	10.31	4.08	14.39
				1967	23.92	13.07	10.85	7.51	18.36
9b	6,600	12	6	1964	25.59	16.34	9.25	3.31	12.56
				1965	24.77	18.72	6.05	9.07	15.12
				1966	23.38	15.11	8.27	4.01	12.28
10b	7,900	12	6	1964	30.36	19.92	10.44	3.98	14.42
				1965	29.63	22.64	6.99	10.65	17.64
				1966	27.93	18.48	9.45	4.80	14.25
					SNOWBERRY (Mature)				
14a	8,850	4	5	1964	24.19	15.65	8.54	3.78	12.32
				1965	24.69	20.58	4.11	9.28	13.39
				1966	23.68	15.48	8.20	5.55	13.75
					SNOWBERRY (Sprouts)				
14b	8,850	4	5	1964	25.41	17.60	7.81	3.78	11.59
				1965	26.12	23.05	3.07	9.28	12.35
				1966	24.70	17.10	7.60	5.55	13.15
					SAGEBRUSH - GRASS				
8	8,800	5	6	1966	9.58	5.22	4.36	0.76	5.12
				1967	9.96	5.42	4.54	4.43	8.97
					GRASS - HERBACEOUS				
1c	6,100	6	6	1965	21.87	16.70	5.17	--	--
				1966	22.23	11.34	10.89	4.29	15.18
				1967	21.92	12.44	9.48	5.00	14.48

Table 2. (con.)

Site no.	Elevation	No. of holes	Depth	Year	Maximum	Minimum	Soil moisture depletion	Precipi-tation	Evapo-transpiration
	Ft.		Ft.		- - - - -	- - - - -	Inches of water	- - - - -	- - - - -
				GRASS - HERBACEOUS (con.)					
2b	7,000	6	6	1965	21.82	19.03	2.79	--	--
				1966	23.97	14.20	9.77	4.30	14.07
				1967	24.66	14.66	10.00	5.00	15.00
4c	7,130	9	8	1966	20.39	14.21	6.18	4.08	10.26
				1967	20.81	13.56	7.25	7.15	14.40
5b	8,400	4	9	1963	40.69	27.65	13.04	5.06	18.10
				1964	36.36	26.70	9.66	1.83	11.49
				1965	41.33	32.16	9.17	10.43	19.60
				1966	40.30	29.45	10.85	1.13	11.98
				1967	41.67	26.59	15.08		
6b	7,640	4	6	1966	16.75	12.64	4.11	1.01	5.12
				1967	18.49	13.07	5.42	2.47	7.89
13	9,200	4	4	1964	18.45	11.18	7.27	3.78	11.05
				1965	18.82	17.40	1.42	9.28	10.70
				1966	18.07	12.99	5.08	5.55	10.63
				BARE					
5c	8,400	5	9	1963	38.85	30.13	8.72	4.78	13.50
				1964	37.13	31.35	5.78	1.73	7.51
				1965	40.47	36.13	4.34	9.86	14.20
				1966	41.22	32.38	8.84	1.07	9.91

Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field Research Work Units are maintained in:

- Boise, Idaho
- Bozeman, Montana (in cooperation with Montana State University)
- Logan, Utah (in cooperation with Utah State University)
- Missoula, Montana (in cooperation with University of Montana)
- Moscow, Idaho (in cooperation with the University of Idaho)
- Provo, Utah (in cooperation with Brigham Young University)

FOREST SERVICE CREED

The Forest Service of the U. S. Department of Agriculture is dedicated to the principle of multiple use management of the Nation's forest resources for sustained yields of wood, water, forage, wildlife, and recreation. Through forestry research, cooperation with the States and private forest owners, and management of the National Forests and National Grasslands, it strives — as directed by Congress — to provide increasingly greater service to a growing nation.

USDA FOREST SERVICE
RESEARCH PAPER INT-68
1969

LARCH CASEBEARER AND OTHER FACTORS INVOLVED WITH DETERIORATION OF WESTERN LARCH STANDS IN NORTHERN IDAHO

Scott Tunnock, Robert E. Denton, Clinton E. Carlson,

and Willis W. Janssen

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Ogden, Utah 84401
and
NORTHERN REGION
Missoula, Montana 59801

THE AUTHORS

SCOTT TUNNOCK since 1961 has been an entomologist for the Division of State and Private Forestry, USDA Forest Serviec, Missoula, Montana. Prior to his present position, from 1958 to 1961, he was an entomologist for the Intermountain Forest and Range Experiment Station, stationed at the Forestry Scienees Laboratory at Missoula. He reeeived his B.S. degree in Entomology at the University of New Hampshire (1954) and his M.S. degree in Entomology from Oregon State University (1956).

ROBERT E. DENTON in 1957 began his present employment as a research entomologist assigned to the Intermountain Station's Defoliating Insect Work Unit now located at Moseow, Idaho. Prior to his present position, from 1950 to 1955, he was an entomologist with the former Bureau of Entomology and Plant Quarantine at Coeur d' Alene, Idaho. He received his B.S. degree in Forestry at the New York State College of Forestry, Syraeuse University, and his M.S. degree in Forest Entomology at the School of Natural Resourees, University of Miehigan.

CLINTON E. CARLSON sinee graduation from college has worked as a pathologist for the Division of State and Private Forestry, USDA Forest Service, Missoula, Montana. He obtained his B.S. degree in Forest Seienee (1964) and his M.S. degree in Forest Genetics (1966) from the University of Montana.

WILLIS W. JANSSEN worked as a soil specialist for the USDA Forest Service from 1957 to 1959 and from 1965 to 1969. He is presently employed as an Extension Farm Management field man supported by the State of Colorado and the U.S. Department of Agriculture. He obtained his B.S. and M.S. degrees in 1956 and 1957 from the University of Illinois.

THIS PUBLICATION WAS DONE IN COOPERATION WITH DIVISION OF STATE AND PRIVATE FORESTRY AND DIVISION OF SOILS AND WATERSHED MANAGEMENT, NORTHERN REGION

USDA Forest Service
Research Paper INT-68
1969

LARCH CASEBEARER AND OTHER FACTORS INVOLVED WITH DETERIORATION OF WESTERN LARCH STANDS IN NORTHERN IDAHO

Scott Tunnock, Robert E. Denton, Clinton E. Carlson,

and

Willis W. Janssen

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Joseph F. Pechanec, Director Ogden, Utah 84401

NORTHERN REGION
Neal M. Rahm, Regional Forester Missoula, Montana 59801

U.S. DEPARTMENT OF AGRICULTURE - FOREST SERVICE

CONTENTS

ABSTRACT

In northern Idaho, dead and dying trees were found in stands of western larch that had been defoliated severely by larch casebearer during periods ranging from 4 to 10 years. Annual radial growth had decreased to 0.1 mm. in many trees. Examinations were made to determine the extent that larch casebearer and other factors contributed to this deterioration. Beetles were found in 11 of the 72 trees sampled. Western larch borer was collected from nine trees and scavenger beetles from the other two. The borer was abundant enough in only six trees to be a factor in causing mortality. Root rot was detected in 14 of the 72 trees and could have contributed to the death of several. Tree deterioration showed no correlation with soil series or fertility. This study did not confirm that larch casebearer was the sole cause of tree mortality; however, larch casebearer is definitely responsible for weakening and predisposing western larch stands to mortality.

INTRODUCTION

Many stands of western larch [illegible] Nutt.) in northern Idaho have been severely defoliated by larch casebearer [illegible] (Hübner)) for periods ranging from 4 to 10 years; these stands contain dead and dying trees.

Several entomologists, including Craighead[1] and Dowden[2] consider the larch casebearer a tree killer. However, Webb's[3] studies suggest that although the casebearer may contribute to host tree mortality, it is seldom wholly responsible. These observations were made in the eastern United States on eastern larch ([illegible] (Du Roi) K. Koch).

Denton[4] showed initial results of repeated defoliation on radial increment. Prior to casebearer damage, larch trees near St. Maries, Idaho, added 4.0 mm. radial increment in 1956; severe defoliation has occurred since 1957. When measurements were made in 1962 radial increment had decreased to 1.0 mm., representing a 75 percent reduction in growth for the 5-year period. During this same period, annual growth of nondefoliated larch trees decreased from 4.4 to 3.4 mm., or a reduction of 23 percent.

The hypothesis is that repeated severe larch casebearer defoliation can cause serious deterioration and mortality of larch stands. The objective of this study was to determine the validity of this hypothesis and the extent that other factors in association with larch casebearer contribute to deterioration.

METHODS

Three sites in each of two study areas were sampled. The first study area was located in the headwaters of Marble Creek, St. Joe National Forest, Idaho. This drainage has been severely defoliated by larch casebearer since 1962, and its stands contain the greatest amount of host tree deterioration (figure 1) of any [illegible]; many trees in these stands were already dead. The second study area was about 125 air miles further north, near Falls, Idaho, in the Kaniksu National Forest. Severe casebearer feeding has occurred here since 1965, but only a few trees have died. Tip killing is confined mostly to the outer 25 percent of the branch length.

At each of the six sites, 10 sample trees (total, 60 trees) that showed various degrees of die-back and two "check" trees (with little or no die-back on branch tips) were uprooted by a bulldozer to permit detailed examination. Altogether 36 trees were sampled in each of the two study areas.

The roots, bole, and foliage of each sample tree were examined for factors that could have contributed to its deterioration. Insect and disease specimens present on sample trees were collected for identification. Increment cores were taken near the root collar of each tree and used to prepare cultures of any existing pathogens (figure 2). Diameter, tree height, crown class, and degree of damage were determined for each sample tree. The damage categories were assigned as follows:

Sparse--Die-back just beginning, or up to 25 percent of the branch length dead (majority of branches).

---

[1] F. C. Craighead. Insect enemies of eastern forests. U.S. Dep. Agr. Misc. Pub. 657, 490 p. 1950.

[2] P. B. Dowden. Biological control of forest insects in the United States and Canada. J. Forestry 55:723-726. 1957.

[3] F. E. Webb. An ecological study of the larch casebearer. Diss. Abstr. 13(5). Ann Arbor, Mich. Univ. Microfilm. 1953.

[4] R. E. Denton. The larch casebearer in western larch forests, Northern Rocky Mountain Region; a problem analysis. Unpub. rep. filed at Intermountain Forest & Range Exp. Sta., USDA Forest Service, Ogden, Utah. 1964.

Figure 1.--Stand of deteriorating western larch severely defoliated during a 5-year period by larch casebearer in the Marble Creek drainage. Only the upper third of the crown is alive on the tree in background.

Medium--From 25 to 85 percent of the branch length dead.

Severe--Foliage remaining only on the inner 15 percent of the branch length, or epicormic branchlets apparent, or all branches dead except the upper one-fourth of the crown.

Dead--No foliage.

Soil conditions and type were recorded at each site. Examinations of Marble Creek soils were made during August 21 to 25, and of Falls soils during October 16 to 18, 1967.

Checking Radial Growth Rates

A disc was cut at breast height from each sample tree to measure annual radial growth. Two radii were arbitrarily chosen for measurement on each disc after the surfaces were sanded. Annual radial increments were measured to the nearest 0.1 mm. for the period 1958-1967, using a De Rouen[5] increment measurer.

Increment measurements of 10 trees were averaged to calculate the annual growth rates for each site. It was obvious that little difference existed in growth rates between sites in an area; therefore, data for 30 trees at Falls were combined, and data for 30 trees at Marble Creek were combined to arrive at a single set of curves for each area (figures 3 and 4). The values were plotted on semilogarithmic paper to emphasize any major departures from the established growth rates of the trees prior to infestation by larch casebearer.

[5]Mention of trade names does not imply endorsement by USDA Forest Service.

Figure ?.--Removing increment cores from root collar of western larch to culture pathogens. Note that roots have been exposed for examination.

In each area, two increment cores were taken at breast height from each of 10 western white pines (*Pinus monticola* Dougl.) to determine if their growth rates were affected during the same period (1958-1967).

RESULTS

The diameters at breast height on the 72 sample larch trees ranged from 5.0 to 11.1 inches, and heights ranged from 15 to 45 feet. Only one tree was classed as suppressed. Damage varied from slight die-back on the branch tips to dead trees. Insects other than larch casebearer were found only on dead trees except for one moderately damaged tree (table 1).

Relationship Between Insects and Damage

Larch casebearer was the only defoliator present on the larch trees sampled; however, larch borer and scavenger beetles were found in 11 of the 72 trees (table 1). Western larch borer (*Tetropium velutinum* LeConte) larvae were collected from nine trees; scavenger beetles from the other two. Ross[6] reported that western larch borer may cause death of *Larix* but indicated that it might be more important as a wood borer than as a tree killer. Western larch borer was estimated to be abundant enough in only six of the nine trees to be considered a factor in causing tree mortality.

---

[6] D. A. Ross. The western larch borer, *Tetropium velutinum* Le Conte, in interior British Columbia. J. Entomol. Soc. Brit. Columbia 64:25-28. 1967.

Table 1.--Examination of western larch trees heavily infested with larch casebearer larvae wi

Area	Tree number	Site 1									
		d.b.h.	Tree height	Crown class	Damage class	Insects other than casebearer	Culture results[1]	d.b.h.	Tree height	Cr
		Inches	Feet					Inches	Feet	
Marble Creek	1	5.3	35	Intermediate	Dead	Few T.v.[2]	A.m.	7.2	32	Op
	2	7.1	40	Intermediate	Severe	--	N	6.5	35	Co
	3	6.9	35	Codominant	Severe	--	Y	3.5	22	Co
	4	7.3	40	Codominant	Severe	--	Y	7.4	35	Op
	5	5.0	32	Codominant	Severe	--	Y	4.8	25	Op
	6	7.2	40	Codominant	Medium	--	N	5.5	25	Op
	7	3.7	22	Intermediate	Dead	Few secondaries	A.m.	8.8	32	Op
	8	6.9	33	Intermediate	Severe	--	B	6.0	30	In
	9	3.5	20	Intermediate	Dead	Few secondaries	A.m.	6.9	35	Co
	10	5.1	22	Intermediate	Medium	--	A.m.	4.4	30	Co
	11	8.1	45	Codominant	Sparse	--	B	6.5	40	Op
	12	10.6	45	Dominant	None	--	Y	8.5	42	Do
Falls	1	4.0	17	Dominant	Medium	--	N	5.0	18	Co
	2	3.0	15	Dominant	Sparse	--	N	8.0	30	Do
	3	5.0	35	Dominant	Medium	--	A.m.	4.5	25	Do
	4	8.0	36	Dominant	Sparse	--	N	3.5	22	Do
	5	6.0	35	Dominant	Sparse	--	N	3.0	22	Do
	6	6.0	24	Dominant	Sparse	--	B	5.0	28	Do
	7	3.0	20	Intermediate	Medium	--	B	6.0	28	In
	8	7.0	30	Codominant	Sparse	--	A.m.	9.0	42	Do
	9	6.0	35	Suppressed	Sparse	--	N	3.5	22	In
	10	7.0	38	Intermediate	Medium	--	Y	4.0	20	Do
	11	6.0	30	Dominant	None	--	Y	3.0	20	In
	12	9.0	35	Dominant	None	--	N	4.5	30	D

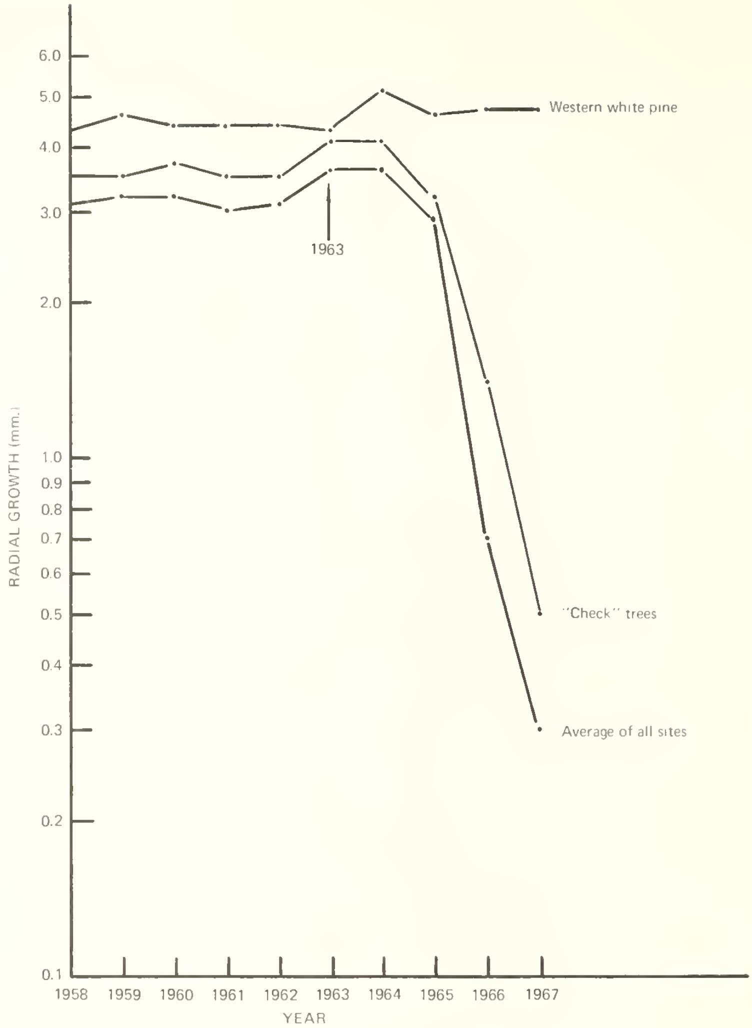
[1]A.m. = *Armillaria mellea*; B = bacteria; Y = yeast; N = no growth.
[2]T.v. = The western larch borer, *Tetropium velutinum* Lec. Specimens were identified by Dr.

headwaters of Marble Creek, and near Falls, Idaho, to determine cause of deterioration.

	Site 2						Site 3		
	Damage class	Insects other than casebearer	Culture results	d.b.h.	Tree height	Crown class	Damage class	Insects other than casebearer	Culture results
				Inches	Feet				
	Sparse	--	N	6.0	22	Open grown	Dead	T.v. in collar	Y
	Medium	--	N	8.0	35	Open grown	Dead	T.v. in collar	Y
	Dead	Few T.v.	A.m.	9.0	35	Open grown	Medium	--	B
	Medium	--	Y	11.1	40	Open grown	Severe	--	Y
	Severe	--	A.m.	8.4	32	Open grown	Medium	--	Y
	Dead	Many T.v.	A.m.	5.5	20	Open grown	Severe	--	A.m.
	Sparse	--	N	6.9	28	Open grown	Severe	--	N
e	Dead	Few T.v.	Y	8.6	35	Open grown	Dead	Many T.v.	N
	Sparse	--	B	5.6	25	Open grown	Severe	--	N
	Dead	T.v. had emerged	A.m.	7.2	35	Dominant	Severe	--	N
	Sparse	--	N	10.0	40	Open grown	None	--	Y
	None	--	N	6.4	27	Open grown	None	--	N
	Medium	--	A.m.	3.5	21	Intermediate	Severe	--	A.m.
	Sparse	--	N	4.0	22	Intermediate	Medium	--	B
	Medium	--	N	4.5	30	Dominant	Sparse	--	B
	Sparse	--	N	4.0	35	Intermediate	Severe	--	N
	Medium	--	N	3.0	16	Dominant	Severe	--	N
	Sparse	--	N	3.5	26	Dominant	Medium	Many T.v.	N
ce	Sparse	--	Y	4.0	25	Codominant	Severe	--	N
	Sparse	--	B	3.0	20	Codominant	Severe	--	N
ce	Sparse	--	N	7.0	40	Dominant	Sparse	--	N
	Severe	--	A.m.	4.0	22	Dominant	Sparse	--	Y
te	None	--	N	3.0	22	Intermediate	None	--	N
	None	--	N	7.0	38	Dominant	None	--	N

s, Forest Entomology Laboratory, Vernon, B.C., Canada.

Figure 3.--Graph comparing radial growth increments of defoliated western larch and western white pine species at Falls, Idaho.

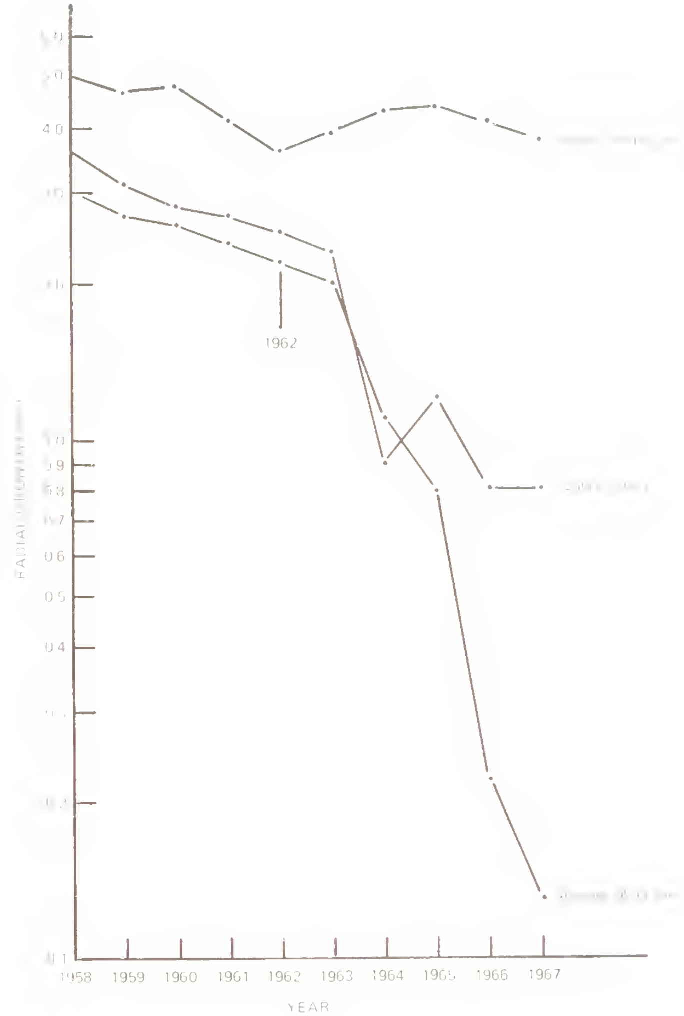


The question arises, "If the larch casebearer had been eliminated from these larch trees when they were weakened to the point where growth practically stopped, would they have recovered in the absence of western larch borer?" If so, the western larch borer might be considered a definite factor in tree mortality. If the trees could not have recovered, *T. velutinum* would be classified only as a secondary causal agent.

Relationship Between Diseases and Damage

Armillaria mellea (Vahl.) Quel. was cultured from each of 12 trees in which root-rot was visible and in two others that were apparently rot free. Four of these 14 trees were infested with *T. velutinum*, which would have probably killed them in the absence of root rot. From a total of 48 cultures, 15 produced a yeast, 9 bacteria, and 34 showed no pathogens (table 1). No attempt was made to identify the yeast and bacteria. *A. mellea* is known to be a parasitic disease and could have been a major factor in the death of the trees on which it was found. The bacteria and yeast probably are normal components within the physiological system of the tree and exist in a beneficial relationship with the tree; they very likely do not cause damage to the larch.

Figure 4.--Graph comparing radial growth increments of defoliated western larch and western white pine species from [illegible] Creek.



Effect of Repeated Defoliation on Radial Growth

Radial increment measurements of 10 trees for each of three sites (total, 30 trees) in the two study areas are summarized in tables 2 and 3. Data for the three sites in each study area were combined, and the resulting curves for each area are plotted graphically in figures 3 and 4.

The two infested trees selected as "check" trees at each site showed practically no evidence of die-back; however, increment measurements revealed that radial growth had been sharply curtailed, even though crown deterioration hadn't progressed to the same degree as the other trees sampled. Thus, because these trees were infested they cannot be considered as true "check" trees.

In the Falls area, growth increments of sample western larch decreased from 3.6 mm. in 1963 to 0.3 mm. in 1967--this amounts to a 92 percent reduction in the 4-year period of severe larch casebearer defoliation. During this same period, western white pine showed an increase in radial increment (figure 3).

Table 2.--Average radial increment per plot--Marble Creek

Site	Radial growth (in mm.)									
	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967
Site 1	2.7	2.3	2.3	2.0	2.0	2.0	1.5	1.5	0.24	0.13
Site 2	2.8	2.4	2.6	2.4	1.9	1.3	1.0	.6	.20	.12
Site 3	3.5	3.3	2.9	2.7	2.8	2.6	.9	.3	.20	.14
Average sites 1, 2, 3	3.0	2.7	2.6	2.4	2.2	2.0	1.1	.8	.22	.13
Average check trees	3.6	3.1	2.8	2.7	2.5	2.3	.9	1.2	.80	.80
Average western white pine	5.1	4.7	4.8	4.1	3.6	3.9	4.3	4.4	4.10	3.80

In Marble Creek, growth increments of living western larch sample trees decreased from 2.2 mm in 1962 to slightly more than 0.1 mm in 1967--a 94 percent reduction in the 5-year period of severe defoliation. As in the Falls area, western white pine showed an overall increase in radial increment during the same period (figure 4).

Relationship Between Soil Types and Damage

Soils at each sampling site were examined, described, and samples collected to determine organic matter, P, K, Ca, Mg, and Ph.

The soils at Marble Creek and Falls have several common characteristics (table 4):

1. They are capped with loess (wind-deposited silt) varying in depth from 9 to 24 inches;
2. The soils are deep--5 feet or more;
3. The soil profiles are relatively free of rock--less than 15 percent throughout;
4. Soil textures of all horizons are a silt loam.

Differences: Soils in the Marble Creek area are developed in meta-sediments associated with the Belt series that are highly weathered and fractured, while the soils at Falls are developed in thick lacustrine deposits, consisting of silt, deposited in varves. Soil test data indicate that the soil at Falls is more fertile than the soil at Marble Creek. This does not necessarily mean that it is more productive, since other factors such as climate, physical properties of the soil, and management practices may offset the fertility advantage. The Falls soil has a very hard or indurated layer at 16 inches that restricts rooting depth and may reduce tree growth. However, this layer also limits leaching of nutrients.

Table 3.--Average radial increment per plot--Falls, Idaho

Site	Radial growth (in mm.)									
	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967
Site 1	4.0	4.1	4.0	3.7	3.7	4.4	3.6	2.5	0.8	0.3
Site 2	3.3	3.2	3.2	2.8	3.0	3.6	4.1	3.5	.7	.5
Site 3	2.0	2.3	2.4	2.4	2.5	2.7	3.0	2.6	.6	.2
Average sites 1, 2, 3	3.1	3.2	3.2	3.0	3.1	3.6	3.6	2.9	.7	.3
Average check trees	3.5	3.5	3.7	3.5	3.5	4.1	4.1	3.2	1.4	.5
Average western white pine	4.3	4.6	4.4	4.4	4.4	4.3	5.1	4.6	4.7	4.7

Table 4.--[illegible]

Sampling depth (inches)	Horizon	pH	[illegible]	Organic matter (percent)	Avail. P	[illegible]	[illegible]	[illegible]	[illegible]
	MARBLE CREEK								
5-10	B2ir	7.0	0	2.20 low	166 high	170 low	[illegible]	[illegible]	[illegible]
15-17	B2	6.4	0	.90 v. low	131 med.	130 low	[illegible]	[illegible]	[illegible]
26	II A2-B2	6.3	0	.20 v. low	18 v. low	170 low	2,000	[illegible]	[illegible]
54	II C	5.9	0	.20 v. low	20 v. low	270 med.	[illegible]	[illegible]	[illegible]
	FALLS Site 1								
0-19	B2ir	--		--	--	--	--	--	--
19-25	II A21	6.9	0	0.50	102 med.	300 med.	[illegible]	[illegible]	[illegible]
25-30	II A22-B21	6.7	0	.30	125 high	250 med.	[illegible]	[illegible]	[illegible]
34	II A23-B22	6.6	0	.40	102 med.	240 low	[illegible]	[illegible]	[illegible]
	FALLS Site 3								
0-9	B2ir	7.0	0	2.30 low	480 high	400 med.	852	112.0	silt
9-16	II A21	6.9	0	.10 v. low	44 v. low	280 med.	[illegible]	299.0	silt
16-21	II A22-B21	6.3	0	.20 v. low	62 low	250 med.	1,784	181.0	silt
21-30	II A23-B22x	6.1	0	.20 v. low	78 low	210 med.	706	256.0	silt
40	II A24-B23x	6.1	0	.20 v. low	80 low	170 low	2,052	173.0	silt

When these two soils are compared to fertility standards established by Wilde[7] for forest soils, the surface horizon receives a rating of Grade A for all elements, except K in the Marble Creek soil, which is Grade B. Subsoil fertility of the Marble Creek soil is Grade C for available P and K, while at Falls it is Grade B. Fertility standards are shown in the following tabulation:

Wilde--Forest soil fertility rating

	pH	Available P (Lbs./acre)	Available K (Lbs./acre)
Grade A	5.5-7.3	100	250
Grade B	5.0-6.0	70	200
Grade C	4.8-5.5	25	100

It was believed earlier that deep, loamy, fertile soils would produce more vigorous trees which would thereby be more tolerant of casebearer damage than trees grown on marginal soils. However, there appears to be no correlation between severity of infestation or tree mortality and soil productivity because infestation and tree damage are nearly the same for both Falls and Marble Creek.

---

[7]S. A. Wilde. Forest Soils. New York, The Ronald Press Co. 360 p. 1958.

DISCUSSION

It is evident that die-back and branch killing in western larch stands are the result of repeated severe defoliation by larch casebearer. These conditions appeared after the third or fourth year of continuous heavy feeding. Whether this defoliation has caused the actual death of trees has not been confirmed. After trees have become weakened or reach the advanced state of deterioration such as the ones shown in figure 1, they are susceptible to invasion by secondary agents. Wood borers and root rots are common killers of weakened trees and evidence of these destructive agents was found in most of the dead trees examined during this study. These data do not show at what stage of deterioration the sample trees were invaded by borers or rots. Most of the moderately to severely damaged trees did not contain these destructive secondaries. Therefore, it is obvious that badly weakened trees may die without the presence of wood borers or rots; if this happens, larch casebearer has to be considered the cause of death.

Tree deterioration could not be correlated with site factors such as soil moisture or soil fertility. While radial increment of larch trees decreased during the last 4- to 5-year period within the two sample areas, increment increased on neighboring western white pine trees. If there was a lack of soil moisture, the white pines would have put on less growth. Soils at Falls and Marble Creek are capable of growing vigorous larch trees; furthermore, there are no obvious physical or chemical soil properties that create unhealthy conditions for larch trees. Again, larch casebearer which is common to both areas seems to be the only factor that could be responsible for this deterioration.

Aerial surveys in May 1968 revealed deterioration within thousands of acres of western larch on the Kaniksu, Coeur d'Alene, and St. Joe National Forests in northern Idaho. Observations indicated that the degree of deterioration had no correlation with growing sites, stand density, aspect, or stand composition. Deterioration was as severe under one set of conditions as another.

Studies are planned to accomplish the following: measure the rate of deterioration from year to year; determine whether stand density is a factor; compare growth rates between defoliated and nondefoliated larch stands; and determine any other factors that might be of importance.

The implication is clear that larch casebearer is responsible for weakening and predisposing western larch stands to mortality. Due to the destructiveness of larch casebearer, plans and finances are justified to determine feasible control methods and to curtail the impending destruction of a valuable timber species.

ABOUT THE FOREST SERVICE . . .

As our Nation grows, people expect and need more from their forests—more wood; more water, fish, and wildlife; more recreation and natural beauty; more special forest products and forage. The Forest Service of the U. S. Department of Agriculture helps to fulfill these expectations and needs through three major activities:

- Conducting forest and range research at over 75 locations ranging from Puerto Rico to Alaska to Hawaii.
- Participating with all State Forestry agencies in cooperative programs to protect, improve, and wisely use our Country's 395 million acres of State, local, and private forest lands.
- Managing and protecting the 187-million acre National Forest System.

The Forest Service does this by encouraging use of the new knowledge that research scientists develop; by setting an example in managing, under sustained yield, the National Forests and Grasslands for multiple use purposes; and by cooperating with all States and with private citizens in their efforts to achieve better management, protection, and use of forest resources.

Traditionally, Forest Service people have been active members of the communities and towns in which they live and work. They strive to secure for all, continuous benefits from the Country's forest resources.

For more than 60 years, the Forest Service has been serving the Nation as a leading natural resource conservation agency.

USDA Forest Service
Research Paper INT-69
1969

HEAT TRANSFER AND FIRE SPREAD

Hal E. Anderson

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Ogden, Utah 84401

USDA Forest Service
Research Paper INT-69
1969

HEAT TRANSFER AND FIRE SPREAD

Hal E. Anderson

Research partially supported by the Advanced Research Projects Agency, Department of Defense, under ARPA Order 818. This report has been cleared for open publication.

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401
Joseph F. Pechanec, Director

THE AUTHOR

HAL E. ANDERSON has been Project Leader of the Fuel Science Research Work Unit since 1966. He joined the staff of Intermountain Station's Northern Forest Fire Laboratory at Missoula, Montana, in 1961 and served as Project Leader of the Fire Physics Project from 1962 to 1966. Prior to employment with the Forest Service he was with the General Electric Company and worked on thermal and nuclear instrumentation from 1952 to 1961. His B.S. degree in physics was obtained at Central Washington State College in 1952.

CONTENTS

GENERAL PROBLEM

Research in fire physics and fuel science at the Northern Forest Fire Laboratory (Missoula, Montana) is directed toward understanding and describing fire propagation through forest fuels and determining how the rate of fire spread is influenced by atmospheric, topographic, and fuel variables. Considerable qualitative information has been collected over the years; but quantitative data have become available only recently. An increase in this information has raised new questions and posed new problems. One fundamental question is: What are the relative roles of the several mechanisms of heat transfer (radiation, convection, conduction, and mass transport) in activating and sustaining the spread of fire?

Test fires in mat-type fuel beds of pine needles burned in still air and with controlled wind conditions demonstrated that radiation significantly influenced fire spread in still air (Rothermel and Anderson 1966). Several mathematical models of fire spread by the various heat transfer mechanisms have been developed and tested to some degree (Fons 1946; Emmons 1963; Hottel et al. 1965; Thomas and Law 1965). From this research and from results of our own experiments, we have developed and tested a mathematical description of fire spread (under no-wind condition) based on radiant heat transfer. This paper presents the development of the mathematical description, and the test procedures and results, and compares data from these tests with those from other fire research.

DEVELOPMENT OF MATHEMATICAL DESCRIPTION

MOISTURE CONTENT

Fuel moisture content has long been recognized as a major influence on ignition and fire spread (Gisborne 1928); therefore, any mathematical description of fire spread must include the influence of moisture. My approach to this task is to estimate the total heat required to remove the moisture and subsequently raise the fuel to ignition temperature. Various earlier researchers (Fons 1950; Martin 1964; Simms 1960, 1961, 1963) indicate a temperature of 300° to 380°C. typifies the pilot ignition point. Research at the Northern Forest Fire Laboratory (Mutch 1964) showed that a temperature of 320°C. (608°F.) would produce pilot ignitions in ground forest fuels. This temperature agrees with results of other research and was selected to represent pilot ignition temperature.

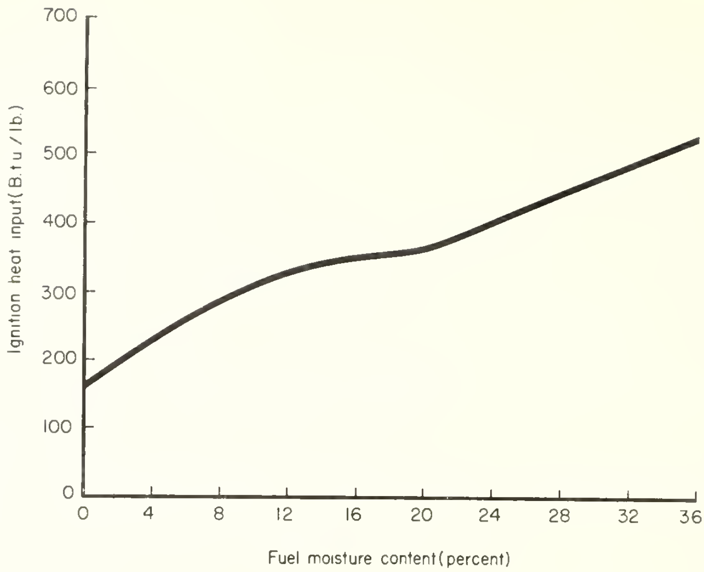
The energy required to remove the water contained in a pound of wet fuel and then to ignite it was determined from data published by Byram et al. (1952). These data were developed into an equation that estimates the energy input per pound of fuel at any moisture content up to 20 percent of ovendry weight. The equation takes into account the heat required to raise the fuel to ignition, the heat required to raise the moisture to boiling temperature, the heat of desorption, the latent heat of vaporization, and the variation in boiling temperature with moisture content. Until now, no consideration had been given to the endothermic heat of pyrolysis that leads to the ignition of fuel.

$$Q_{ig} = C_F(T_i - T_1) + C_W\left[M(T_2 - T_1) + \left[71\left(\frac{M^{0.83}}{0.83}\right)\right]_0^M - M(71M^{-0.169})\right] + L_t\left[\left(\frac{T}{71}\right)^{-5.92}\right]_{T_1}^{T_2} + H(M)_{T_1} \qquad (1)$$

where:

Q_{ig} = B.t.u./lb. (cal./g.)
C_F = 0.327, specific heat of fuel
C_W = 1.0, specific heat of water
T_1 = ambient temperature

Figure 1.--Heat required to bring 1 pound of fuel to ignition as a function of fuel moisture content.



T_2 = boiling temperature

T_i = ignition temperature 608°F. (320°C.)

L_t = latent heat of vaporization

M = moisture content, lb./lb. (g./g.)

$H(M)T_1$ = heat of desorption (16 cal./g.).

Using this equation, we developed a curve (figure 1) to show the relation of energy input to moisture content of the fuel (in percent).

Additional definitions are listed in the Appendix.

RADIANT HEAT

We knew how much heat was required to raise the moist fuel to ignition and the temperature at ignition. Our next step was to develop an equation that would describe the change in rate of spread. Research by Thomas (1963) and Emmons (1963) indicated that the heat flux from the fire to unburned fuel can be related to rate of spread. Assuming that the energy required to cause ignition remains constant and that the emissive power of the fire remains constant--just high enough to cause ignition when the fire reaches the unburned fuel--we can write:

$$Q = \int_0^\infty E\ e^{-ax} dt \qquad (2)$$

where:

Q = heat per vertical cross section of the fuel bed to cause ignition, B.t.u./ft.^{2}
E = emissive power of the fire, B.t.u./ft.^{2} - hr.
a = attenuation constant
x = distance from the fire front to the fuel particle or elemental volume in question, ft.
t = time, hr.

This can be modified by:

$$dt = \frac{dx}{R}$$

where:

R = steady rate of spread, ft./hr.

Substituting and integrating equation (2):

$$R = \frac{E}{aQ} \qquad (3)$$

The quantity, Q = B.t.u./ft.^{2}, must be modified so Q_{ig}, B.t.u./lb., can be used. This is accomplished by:

$$Q = \frac{Q_{ig}\rho_f}{\sigma_a/4} \qquad (4)$$

where:

ρ_f = fuel particle density, lb./ft.^{3} (g./cm.^{3})

$\sigma_a/4$ = fuel particle projected surface area to volume ratio, ft.^{2}/ft.^{3} (cm.^{2}/cm.^{3})

The attenuation factor "a" must be put into some measurable form. It is assumed to be proportional to the total projected area of fuel in a unit volume of space (Committee on Fire Research, 1961, p. 126).

$$a = \frac{1}{4\lambda} \qquad (5)$$

where:

λ = void volume per total surface area

1/4 = projected portion of surface area.

Equations 4 and 5 are substituted in equation 3, which takes the form.

$$R = \frac{\sigma_a \lambda E}{\rho_f Q_{ig}} \qquad (6)$$

This mathematical description states that the rate of spread is dependent on the emissive power of the fire and will be modified by the size of the fuel particles, σ_a, porosity of the fuel bed, λ; density of the fuel particles, ρ_f; and the amount of energy required for ignition (primarily a function of the amount of moisture in the fuel), Q_{ig}. The emissive power of the fire is made up of two components: (1) the combustion zone within the fuel bed; (2) the flame plume above the fuel bed. Both components contribute to radiant heating. However, convective heating takes place only in the fuel bed and in the region of the fuel bed-fire plume interface. In the study reported herein we are concerned with describing rate of spread in absence of wind with the assumption that radiation was the primary source of heat.

The fuel descriptors are independent of the two source components. However, the contributions of heat to the fuel are dependent on the relative weight and influence of each mode of heat transfer. The radiant heat from each component is defined thus:

$E_c = \sigma\varepsilon_c T_c^4$ (combustion zone emissive power)

$E_f = \sigma\varepsilon_f T_f^4$ (flame emissive power).

The impact of the flame's emissive power on the fuel ahead of the fire is a function of distance and shape of the flame; these must be taken into account. This modification describes the irradiance of the element. By integrating the configuration factor, F_{12}, over the distance of influence and dividing by the configuration factor for an infinite plane source integrated over 1 foot for the two components transferring radiant heat, a numerical value, F_{12}', is obtained; it describes the magnitude of the heat impact of each component. The absorptivity of the fuel element is considered equal to unity; however, the radiant heat loss of the element to its surroundings is regarded as negligible.

Equation 6 was modified to show these considerations:

$$R = \frac{\sigma_a \lambda}{\rho_f Q_{ig}} [\sigma \varepsilon_c T_c^4 \; F_{12}' \; + \sigma \varepsilon_f T_f^4 \; F_{12}'] \tag{7}$$

An earlier report (Anderson 1968) showed that the variation in flame irradiance can be important. The configuration factor for the combustion zone was determined prior to testing. However, the flame configuration factor had to be determined later from photographs of the flame shape. A form of equation 7 was tested against data collected from earlier testing (Anderson and Rothermel 1965) and was found to agree with rates of spread previously observed. We designed a study program to investigate unknowns in equation 7 and to determine whether radiant heat could account for rate of spread under the no-wind condition.

CONVECTIVE HEAT

We recognized that radiant heat might not account for all the heat; so we had to determine a convective heat transfer coefficient for the needles. For this, some measure of the gas velocity in the fuel bed had to be derived. Also, the Reynolds and Nusselt numbers were essential for calculating the convective heat transfer coefficient h_c. The research previously reviewed by Hottel (Blinov and Khudiakov 1959) and presented by Thomas (1963) showed two expressions for Reynolds number:

$$N_{RE} = \frac{V_L d}{\nu} \tag{8}$$

$$N_{RE} = \frac{m_1}{\mu d} \tag{9}$$

where:

V_L = regression rate of liquid burning surface

d = characteristic dimension, pan diameter or flame depth

ν = kinematic viscosity = μ/ρ_g

μ = dynamic viscosity

ρ_g = gas density

m_1 = rate of weight loss.

Equation 9 can be put into the same form as equation 8 by rearranging terms:

$m_1 = \rho_b A V_F$, lb./sec.

$A = d^2$

$\mu = \nu \rho_g$

V_F = linear regression rate of fuel surface, ft./sec.

ρ_b = bulk density of fuel bed

$$N_{RE} = \frac{m_1}{\mu d} = \frac{\rho_b d^2 V_F}{\nu \rho_g d} = \frac{V_F d}{\nu} \left(\frac{\rho_b}{\rho_g}\right). \qquad (10)$$

The quantity $V_F\left(\frac{\rho_b}{\rho_g}\right)$ represents the gas velocity, V_g, at the surface of the fuel, and V_F is the same as the V_L used by Hottel. Multiplying the regression rate of the surface by the ratio of fuel density to gas density provides the value of the gas velocity at the surface. This means that liquid-pool fires and solid-fuel fires should correlate.

BULK DENSITY OF FUEL BED

We noted a similarity between equation 6 and the equation published by Thomas and Law (1965). The equations are equivalent in concept except that $\sigma_a\lambda/\rho_f$ is replaced by $1/\rho_b$ (bulk density of the fuel bed). These two quantities are approximately equal; the exact relation can be determined by considering the properties of the fuel particle and fuel bed. The porosity of a fuel bed, λ, is defined as:

$$\lambda = \frac{V_1 - V_2}{\sigma_a V_2} \qquad (11)$$

where: λ = porosity, ft.^{3}/ft.^{2}

σ_a = fuel particle surface area-to-volume ratio, ft.^{2}/ft.^{3}

V_1 = fuel bed volume, ft.^{3}

V_2 = fuel particles volume, ft.^{3}

Rearranging this equation we have:

$$\sigma_a\lambda + 1 = V_1/V_2 \qquad (12)$$

The volumes of the fuel bed, V_1, and the fuel particles, V_2, are proportional to the respective densities:

$V_1 = W_b/\rho_b$ and $V_2 = W_b/\rho_f$

where W_b is the weight of the fuel. Combining these terms and substituting into equation 12, the result is:

$$\sigma_a\lambda + 1 = \rho_f/\rho_b \quad \text{or} \quad 1/\rho_b = \frac{\sigma_a\lambda}{\rho_f} + \frac{1}{\rho_f}. \qquad (13)$$

This relation exists for fuel beds made up of a single size of fuel. In more complex fuel beds, the bulk density provides a gross estimate; whereas appraising by size classes, variation of particle density, and proportion of each size class provides a more accurate estimate. For the present, we are considering only homogeneous beds of a single fuel.

FLAME AND BURNING CHARACTERISTICS

Information that would enable us to predict flame size or burning rates from a given fuel complex is not yet available; hence, it is difficult to estimate rates of fire spread accurately. Factors that affect flame size and burning rate include: (1) physical properties of the fuel bed and of the fuel particles; and (2) chemical properties of the fuel elements (e.g., crude fat content, silica-free ash content, and the amount of cellulose and/or hemicellulose in the fuel. Investigations are being conducted at the Northern Forest Fire Laboratory to determine how much the chemical properties of the fuel influence flammability--discussion of such investigations is outside the scope of this paper.

The physical properties of fuels are also under study at the Laboratory and include fuel particle size, thermal properties, fuel bed porosity and continuity, and several other factors. These are of importance to the spread equation since some enter the fuel descriptor set, $\sigma\lambda/\rho_f Q_{ig}$. Frequently it has been observed that the residence time of flame at a given point in a fuel bed is related to diameter of the fuel particle. A review of fire research literature and unpublished tests here at the Laboratory indicate that residence time is a function of particle diameter (Fons et al. 1962; Byram et al. 1966; McCarter and Broido 1965; Wooliscroft and Law 1967).

TEST PROCEDURES

The measurements necessary to evaluate the rate of spread according to equation 7 were determined from the unknowns in the equation. These are the emissivities of the combustion and flame zones, the temperature of each zone, and the flame shape mean configuration factor for each zone. By comparing the calculated rate of spread to the observed rate we obtain a means of determining the relative importance of the role of radiant heat transfer in the propagation of fire. This does not give us any information about the generation of radiant energy. However, we gain some insight into the generation phase through measurements of weight loss, flame residence time, and radiant heat fluxes to the fuel.

Many of the methods mentioned above except for two have been described in previous publications (Anderson and Rothermel 1965; Anderson 1968). Two measurements not used in previous work are: determination of the configuration factor; and the radiant heat flux passing through a fuel element. Configuration factor determinations were made using the techniques described in "Flame Shape and Fire Spread" (Anderson 1968). A sequence of at least 10 photographs (1 second exposure at f:11 on Plus X film) in an overlay was used to determine average flame shape and length.

Radiant heat fluxes from the flame and the combustion zone were measured with Gardon-type heat rate sensors. These sensors were water cooled and shielded with sapphire windows so that only radiant heat was measured. The recorded millivolt signal from these sensors was corrected for transmissivity, percent radiation below the wavelength cutoff of the window, configuration factor, and view area enclosed. Besides indicating the heat flux passing through a particular point, the resulting values could be compared with the combustion and flame zone temperature measurements for calculation of the emissivity of each zone.

The heat rate sensors in the fuel bed were placed with the sensing element 0.5 inch below the surface of the fuel bed. Each sensor faced the oncoming fire front and was positioned to view all of the fire in the fuel bed. Thermocouples were located at the surface of the fuel bed and 0.5 inch below it to provide data on temperatures as the fire front approached and passed. The peak values represented the fire front's arrival and were used to calculate the blackbody emissive power of the combustion zone's fire front. The emissivity of the zone was determined by dividing the heat rate sensor value of heat flux by the calculated blackbody value.

The heat flux of the flame was measured in nearly the same manner as were the heat rate sensors in the fuel bed except the sensors were positioned so that one edge of their view angle coincided with the surface of the fuel bed. The sensor then viewed the space above the bed. Thermocouples, 5 mil chromel/alumel, were placed 2, 11, and

22 inches above the fuel bed surface to measure flame temperature. Analysis of the flame size for each test set (consisting of 3 or more fires) indicated which thermocouples were in the flame envelope. From these thermocouples an average flame temperature was determined. This was used to determine an average blackbody emissive power. The average emissive power of the flame was also determined by considering the heat rate sensor value at discrete distances from the flame. The emissivity of the flame was determined as described for the combustion zone.

A preliminary series of tests was made with ponderosa pine needle beds to assess the magnitude of the influence of porosity. Fuel beds of 0.5 and 1.0 ft.^{2} load area and constant loadings were burned as stationary fires with surface ignition. The fuel depth was varied to provide various porosities and measurements of weight loss and flame length were made.

The radiant heat fire tests were conducted with three replications in three pine needle fuels--ponderosa pine (Pinus ponderosa Laws.); western white pine (Pinus monticola Dougl.); and lodgepole pine (Pinus contorta Dougl.). The fuels were conditioned to moisture contents varying from 2.5 to 23 percent of ovendry weight. Ambient conditions were maintained at 90° F. with relative humidities of 7 to 92 percent; ambient conditions were matched to fuel moisture contents. Fuel beds were prepared according to established technique (Schuette 1965). A summary of the test conditions and fuel characteristics is given in table 1.

Table 1.--Ambient conditions and fuel characteristics for each test set

(A set constitutes three or more fires)

Fuel type & moisture content	Air temperature	Relative humidity	σ	Particle density ρ_f	[illegible]	[illegible]	[illegible]
%	°F.	% RH	ft.^{2}/ft.^{3}	lb./ft.^{3}	ft./ft.	[illegible]	[illegible]
PP - 2.6	90.5	7.0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
PP - 4.2	90.5	15.2	1,741	[illegible]	[illegible]	[illegible]	[illegible]
PP - 5.3	90.5	22.2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
PP - 5.9	90.7	30.7	1,741	[illegible]	[illegible]	[illegible]	[illegible]
PP - 8.6	90.8	51.3	1,741	[illegible]	[illegible]	[illegible]	[illegible]
PP - 14.0	90.3	75.3	1,741	[illegible]	[illegible]	[illegible]	[illegible]
PP - 20.5	90.5	92.2	1,741	[illegible]	[illegible]	[illegible]	[illegible]
WP - 3.4	90.6	6.1	2,790	[illegible]	[illegible]	[illegible]	[illegible]
WP - 6.7	91.1	21.6	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
WP - 7.4	90.5	30.9	2,790	[illegible]	[illegible]	[illegible]	[illegible]
WP - 10.1	90.8	51.2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
WP - 15.3	90.4	75.8	2,790	[illegible]	[illegible]	[illegible]	[illegible]
WP - 21.6	90.5	91.3	2,790	[illegible]	[illegible]	[illegible]	[illegible]
LPP - 3.6	92.2	6.2	2,188	33.4	[illegible]	[illegible]	[illegible]
LPP - 5.4	90.8	21.9	2,188	33.4	[illegible]	[illegible]	[illegible]
LPP - 6.5	90.8	31.0	2,188	33.4	[illegible]	[illegible]	[illegible]
LPP - 8.8	90.8	51.1	2,188	33.4	[illegible]	[illegible]	[illegible]
LPP - 13.4	90.7	75.8	2,188	33.4	[illegible]	[illegible]	[illegible]
LPP - 23.2	90.1	91.0	2,188	33.4	5.0 × [illegible]	[illegible]	[illegible]

PP is ponderosa pine
WP is western white pine
LPP is lodgepole pine

TEST RESULTS AND DISCUSSION

ROLE OF FUEL DESCRIPTORS

During the development of the equation to describe fire spread in terms of radiant heat transfer, a group of fuel descriptors was established. This group, $\sigma_a\lambda/\rho_f Q_{ig}$, can be determined prior to a test fire; by correlating it to the rate of spread, a best estimate of the heat flux can be obtained. Figure 2 shows the results of 3 or more test fires averaged at each condition. Taking an increment along the linear portion of the curve, the maximum heat flux into the fuel is found to be 40 X 10^3 B.t.u./ft.^{2} - hr.(3.0 cal./cm.^{2} - sec.). Low fuel moisture contents resulted in the high rates of spread and as moisture content increased a point was reached where a departure from a linear relation occurred. Following the departure to zero rate of spread, the intercept represents the point where moisture content prevents fire spread. By determining Q_{ig} and referring to figure 1, the moisture contents for no spread were found:

Ponderosa pine: $\sigma_a\lambda/\rho_f Q_{ig} = 1.13 \text{ X } 10^{-3}$, $Q_{ig} = 412 \frac{\text{B.t.u.}}{\text{lb.}}$

MC = 24.2 percent

Western white pine: $\sigma_a\lambda/\rho_f Q_{ig} = 1.13 \text{ X } 10^{-3}$, $Q_{ig} = 412 \frac{\text{B.t.u.}}{\text{lb.}}$

MC = 24.2 percent

Lodgepole pine: $\sigma_a\lambda/\rho_f Q_{ig} = 0.81 \text{ X } 10^{-3}$, $Q_{ig} = 359 \frac{\text{B.t.u.}}{\text{lb.}}$

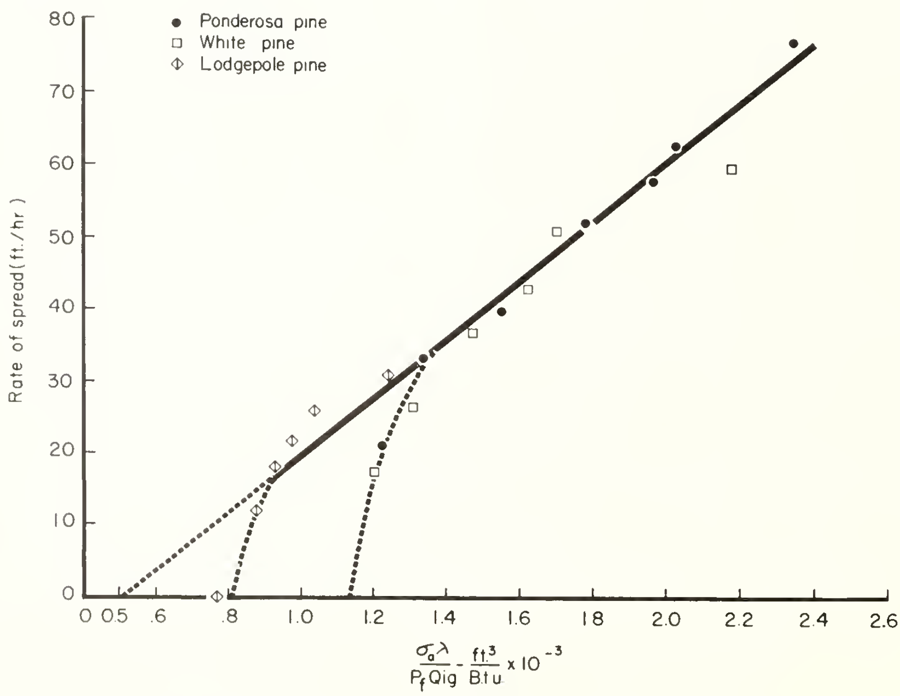


Figure 2.--A near linear relation is exhibited between the experimental rate of spread and the fuel descriptor's set. Note the rolloff at the low end.

Table 2.--Calculated maximum heat fluxes associated with rate of spread and the fuel descriptors

Fuel type & moisture content	$\frac{\sigma_a \lambda}{\rho_f Q_{ig}}$	Experimental rate of spread R_E	Heat flux $q_{T/A}$	
%	ft.^{3}/B.t.u.	ft./hr.	B.t.u./ft.^{2} - hr.	Cal./cm.^{2} - sec.
PP - 2.6	2.34×10^{-3}	76.1	3.26×10^4	2.46
PP - 4.2	2.02×10^{-3}	61.8	3.06×10^4	2.30
PP - 5.3	1.96×10^{-3}	57.0	2.90×10^4	2.18
PP - 5.9	1.78×10^{-3}	51.6	2.90×10^4	2.18
PP - 8.6	1.55×10^{-3}	39.6	2.56×10^4	1.93
PP - 14.0	1.34×10^{-3}	33.0	2.46×10^4	1.85
PP - 20.5	1.22×10^{-3}	21.0	1.74×10^4	1.31
WP - 3.4	2.17×10^{-3}	58.8	2.71×10^4	2.04
WP - 6.7	1.70×10^{-3}	50.4	2.96×10^4	2.23
WP - 7.4	1.62×10^{-3}	42.6	2.63×10^4	1.98
WP - 10.1	1.47×10^{-3}	36.6	2.49×10^4	1.88
WP - 15.3	1.32×10^{-3}	26.4	2.00×10^4	1.51
WP - 21.6	1.20×10^{-3}	17.4	1.45×10^4	1.09
LPP - 3.6	1.24×10^{-3}	30.6	2.47×10^4	1.86
LPP - 5.4	1.14×10^{-3}	25.8	2.26×10^4	1.70
LPP - 6.5	$.98 \times 10^{-3}$	21.6	2.21×10^4	1.66
LPP - 8.8	$.93 \times 10^{-3}$	18.0	1.94×10^4	1.46
LPP - 13.4	$.88 \times 10^{-3}$	12.0	1.36×10^4	1.02
LPP - 23.2	$.77 \times 10^{-3}$			

PP is ponderosa pine
WP is western white pine
LPP is lodgepole pine

The values for ponderosa and western white pine are in agreement with previous laboratory findings. Fires in lodgepole pine needle beds at 23.2 percent MC would not spread even with repeated ignition of the fuel bed leading edge substantiating the above cutoff value. The porosity of this fuel appears to be the factor responsible but additional work with variations in porosity is needed to substantiate this.

RADIANT HEAT

The total heat flux related to fire spread was calculated for each set of test fires. These values are tabulated in table 2. The radiant heat fluxes reported by Thomas and Law (1965) are of the same magnitude where σ and/or λ were varied. This general agreement indicates radiant heat does contribute to rate of spread, but in the present case the energy is the combined sum of the heat transfer components. The next step was to determine how much heat was being supplied by the flame and how much by the combustion zone. Analysis of all the tests showed a nearly constant combustion zone temperature with no significant correlation to fuel moisture content.

Table 3.--Test results for each fuel type and moisture condition

(Values are average of three or more fires in each set.)

Fuel type & moisture content		R	t_R	D	L	B	T_c	T_f	ε_f	F_{12}	F_{12}	Ef*
	%	ft./hr.	min.	ft.	ft.	lb./min.	°F.	°F.		Flame	Comb. zone	B.t.u./ft.- hr.
PP -	2.6	76.1	1.27	1.61	5.5	0.98	1591	1680	0.28	1.18	0.08	6.22 X 10^3
PP -	4.2	61.8	1.27	1.31	5.0	.77	1591	1627	.28	1.19	.08	9.46 X 10^3
PP -	5.3	57.0	1.27	1.20	4.7	.81	1591	1570	.28	1.11	.08	8.70 X 10^3
PP -	5.9	51.6	1.27	1.09	4.3	.70	1591	1509	.28	1.07	.08	8.88 X 10^3
PP -	8.6	39.6	1.27	.84	3.5	.57	1591	1507	.28	.95	.08	6.58 X 10^3
PP -	14.0	33.0	1.27	.70	2.9	.35	1591	1392	.28	.85	.08	6.33 X 10^3
PP -	20.5	21.0	1.27	.44	2.0	.17	1591	1254	.28	.71	.08	1.97 X 10^3
WP -	3.4	58.8	.92	.90	2.2	.35	1434	1321	.16	.60	.08	4.03 X 10^3
WP -	6.7	50.4	.92	.78	2.0	.31	1434	1380	.16	.58	.08	3.31 X 10^3
WP -	7.4	42.6	.92	.65	1.9	.31	1434	1531	.16	.57	.08	4.28 X 10^3
WP -	10.2	36.6	.92	.56	1.5	.27	1434	1450	.16	.46	.08	3.64 X 10^3
WP -	15.3	26.4	.92	.40	1.1	.26	1434	1311	.16	.40	.08	2.88 X 10^3
WP -	21.6	17.4	.92	.27	.9	.20	1434	1229	.16	.35	.08	1.73 X 10^3
LPP-	3.6	30.6	1.06	.54	1.5	.21	1492	1548	.16	.43	.08	3.20 X 10^3
LPP-	5.4	25.8	1.06	.46	1.5	.19	1492	1548	.16	.42	.08	4.50 X 10^3
LPP-	6.5	21.6	1.06	.38	1.1	.13	1492	1303	.16	.36	.08	4.7 X 10^3
LPP-	8.8	18.0	1.06	.32	.9	.14	1492	1358	.16	.33	.08	3.9 X 10^3
LPP-	13.4	12.0	1.06	.21	.7	.12	1492	1135	.16	.20	.08	

*Average of heat flux sensor signal.

PP is ponderosa pine
WP is western white pine
LPP is lodgepole pine

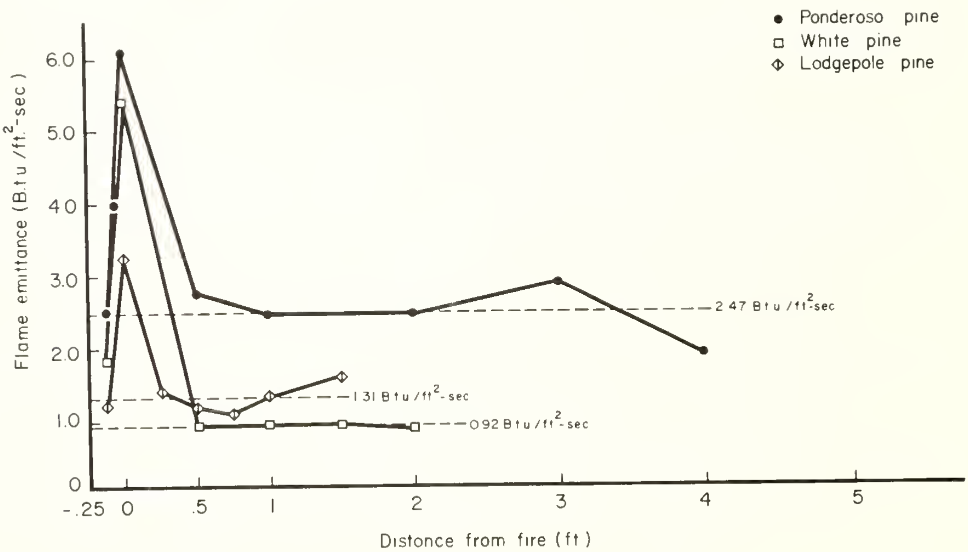


Figure 3.--Flame emittance calculations from heat rate sensors for fires in fuel beds at 6-percent moisture content.

The different fuel types produced a slight difference in the average temperature of the combustion zone, as follows:

Fuel type	Average temperature
Ponderosa pine	1591° F. (867° C.)
Western white pine	1434° F. (779° C.)
Lodgepole pine	1492° F. (811° C.)

These combustion zone temperatures are not unusual if moisture is removed from the fuel before the fire front or combustion zone reaches it. The irradiance of the fuel could change with moisture content changes because emissivity varied or the absorptivity of the intervening gases varied. The heat rate sensors for the combustion zone were placed too close to the surface of the fuel and were not sufficiently collimated. As a result, poor repeatability was obtained. However, these measurements did indicate a rather constant heat flux from the combustion zone. We found no decrease in heat flux with increases in fuel moisture content; this tended to support the thermocouple data but due to the lack of repeatability no reliable estimate of combustion zone emissivity could be made. The equation was evaluated for rate of spread by using a value of 1.0 for the combustion zone.

The thermocouples located above the fuel bed showed that the average flame temperature decreased as fuel moisture content increased:

Fuel type	Temperature range (°F.)	Rate of change (°F./percent MC)
Ponderosa pine	1680 - 1254	24
Western white pine	1531 - 1229	24
Lodgepole pine	1548 - 1135	42

Also, the burning rate, flame length, and flame depth were found to decrease in this same manner,as shown in table 3. These three parameters along with flame temperature govern the emissive power of the flame. The values obtained from the heat rate sensors do show a decrease with moisture increase but not as rapidly as the above variables of burning rate, flame length and depth. The emissive power values derived from the heat rate sensors at various distances from the flame agreed very closely with the values determined after the sensors had entered the flame (figure 3). The average emissive power was obtained from these values and compared with the blackbody emissive power determined by the thermocouple readings to calculate the emissivity of each test set (figure 4). Ponderosa pine fuel beds produced taller and thicker flames than the other fuels which generated flames with smaller dimensions; the calculated emissivities are substantiated by these physical characteristics of the flames.

By using the data of the emissive powers we can estimate the total radiant heat flux that has an impact on the fuel ahead of the fire. The values of heat flux can be calculated according to equation 7 and summed for comparison with the total heat flux found to be necessary to produce the measured rate of spread (see table 2). The results of this analysis are shown in figure 5 with the summed radiant heat flux as a percentage of the total heat flux and plotted against fuel moisture content. The radiant heat fluxes were determined by using a combustion zone emissivity of 1.00 and flame emissivities of 0.28 for ponderosa pine fires and 0.16 for lodgepole and western white pine fires.

This analysis shows that radiant heat can account for 40 percent or less of the total heat flux necessary for the fire spread observed in these fuel beds. The rest of the heat flux must come from some other heat transfer mechanism. Conduction appears to be insignificant; a brief analysis indicated only 1/50 of the necessary energy would be available through this mechanism. This means convective heat transfer must be the primary source through some horizontal transport mechanism.

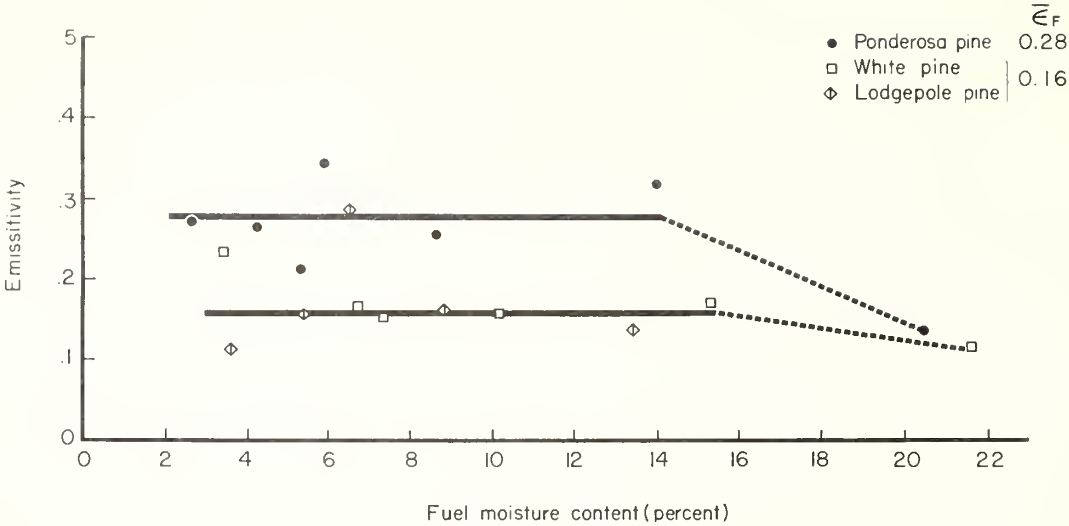


Figure 4.--Flame emissivities for fires in three fuels at the same environmental conditions were determined from heat flux sensor measurements.

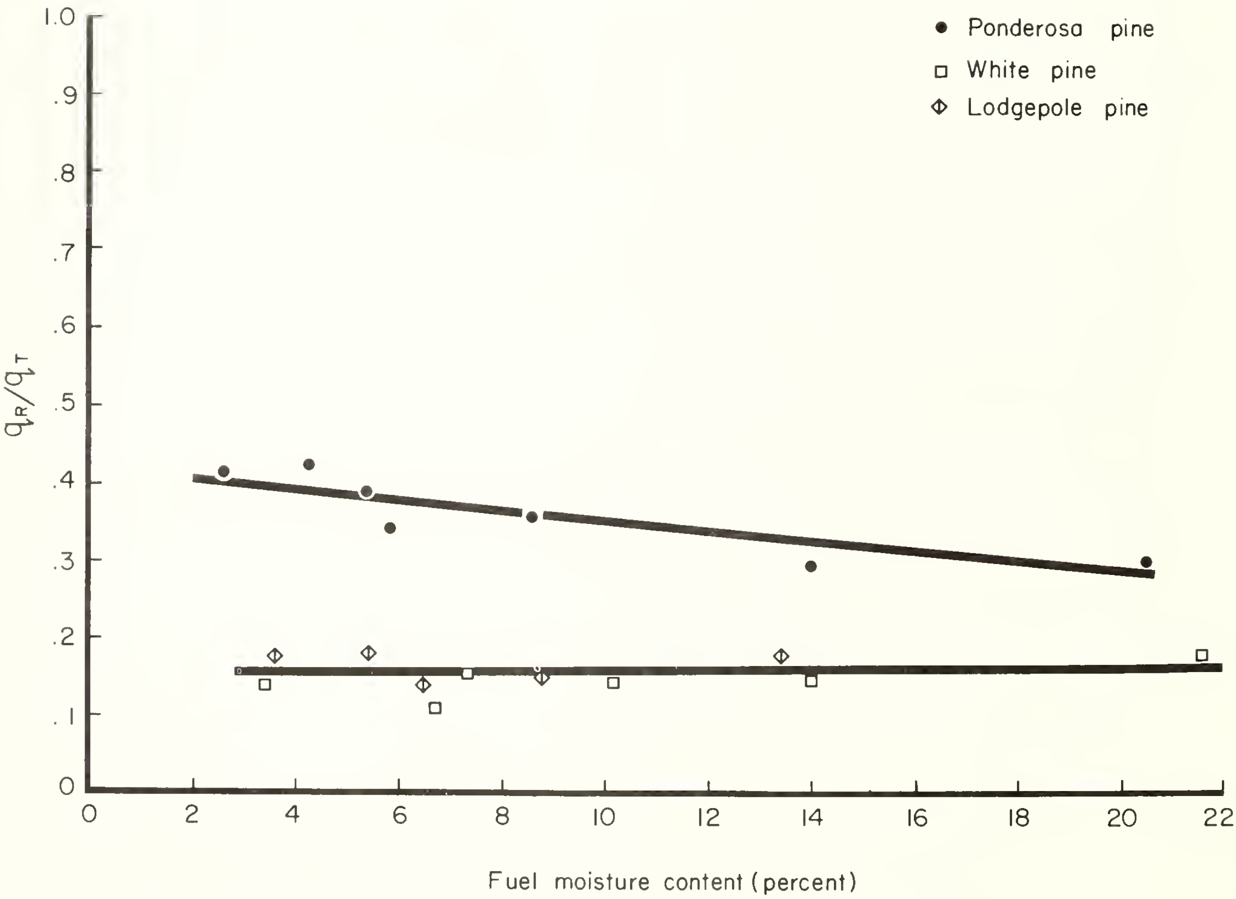


Figure 5.--Portion of total heat flux contributable to radiant heat flux.

CONVECTIVE HEAT

As mentioned earlier, it was necessary to determine a convective heat transfer coefficient. In addition, both the Reynolds and the Nusselt numbers had to be computed. Using the procedures outlined previously, a gas velocity and Reynolds number were calculated for each test set. If solid fuel fires respond in a manner similar to liquid pool fires, then nearly equal values of Reynolds numbers should occur for fires of similar dimensions. Figure 6 shows how the solid fuel fires grouped near the curve for gasoline pool fires. The same forces seem to apply to the various fires resulting in turbulent, transitional, and laminar regimes. Fires in ponderosa pine beds with less than 9 percent moisture content were turbulent and in the transitional regime for moisture contents above 9 percent. All fires in western white pine and lodgepole pine were in the transitional or laminar regimes.

Values for the gas velocity in each test set were determined and were used with the diameter of the fuel particle to determine the Reynolds number. The Nusselt number for cylinders was used to calculate the convective heat transfer coefficient. This combined with the temperature difference between the combustion zone and the ambient air provided a measure of the convective heat transfer component.

In all tests the calculated convective heat flux exceeded the net heat flux which is obtained by subtracting the radiant heat flux from the total heat flux values in table 2. This means that a horizontal transfer efficiency coefficient does exist. This horizontal transfer coefficient was calculated for each fuel:

Ponderosa pine: $\eta = (0.90 - 0.014\ MC^*)$
Western white pine: $\eta = (1.00 - 0.028\ MC)$
Lodgepole pine: $\eta = (1.00 - 0.036\ MC)$

---

*MC is the fuel moisture content in percent.

These coefficients infer less heat transfer in ponderosa fuel of low moisture contents and a more rapid decrease in heat transfer for western white pine and lodgepole pine fuels because their burning regimes are transitional or laminar.

Incorporating the horizontal transfer coefficients into equation 7 the new description of fire spread by heat transfer becomes:

$$R = \frac{\sigma\ \lambda}{\rho_f Q_{ig}} \left[\sigma \varepsilon_c T_c^4 \left(\int_0^\infty F_{12}dx\right) + \sigma \varepsilon_F T_F^4 \left(\int_0^\infty F_{12}dx\right) + \eta h_c (T_c - T_1)\right] \qquad (14)$$

where:

T_c = combustion zone temperature

T_1 = ambient air temperature.

Values for each component of the equation were obtained for the experimental data. The resulting rates of spread are compared to the experimental values in figure 7. The equation was found to describe rate of spread quite accurately but does point out the following areas where additional research is needed:

1. Estimation prior to a fire of how much flame will be generated.

2. Is there a physical limitation to fire spread caused by maximum heat flux into the fuel bed?

3. What is the relation between fuel bed characteristics and convective heat transfer?

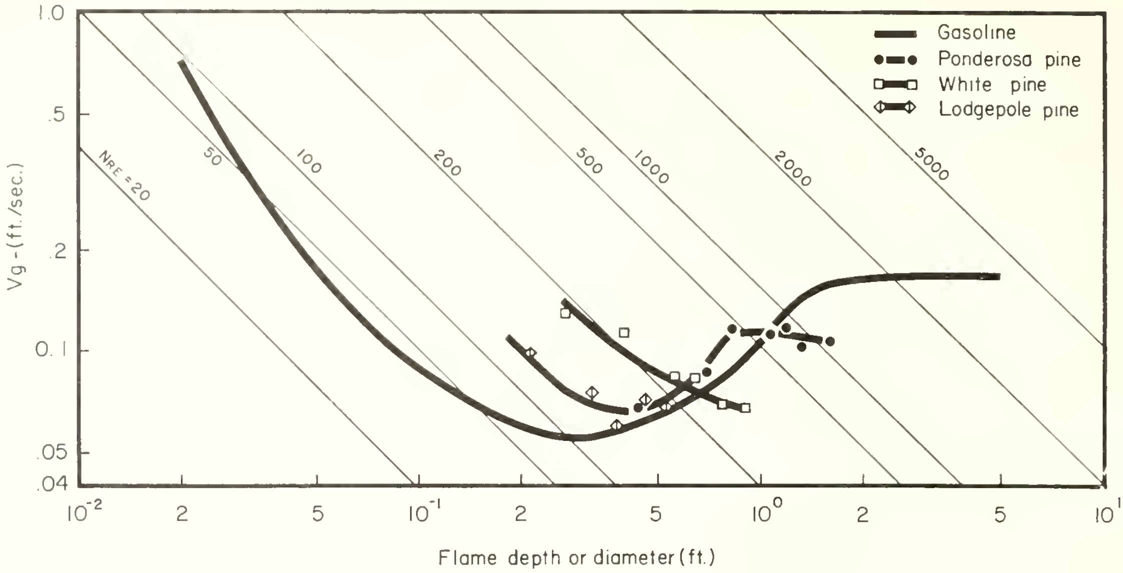


Figure 6.--Burning regimes of various fuels based on cold vapor density and viscosity.

Figure 7.--Comparison of experimental rates of spread to theoretical curve of fire spread showing end points for fuel moisture content.

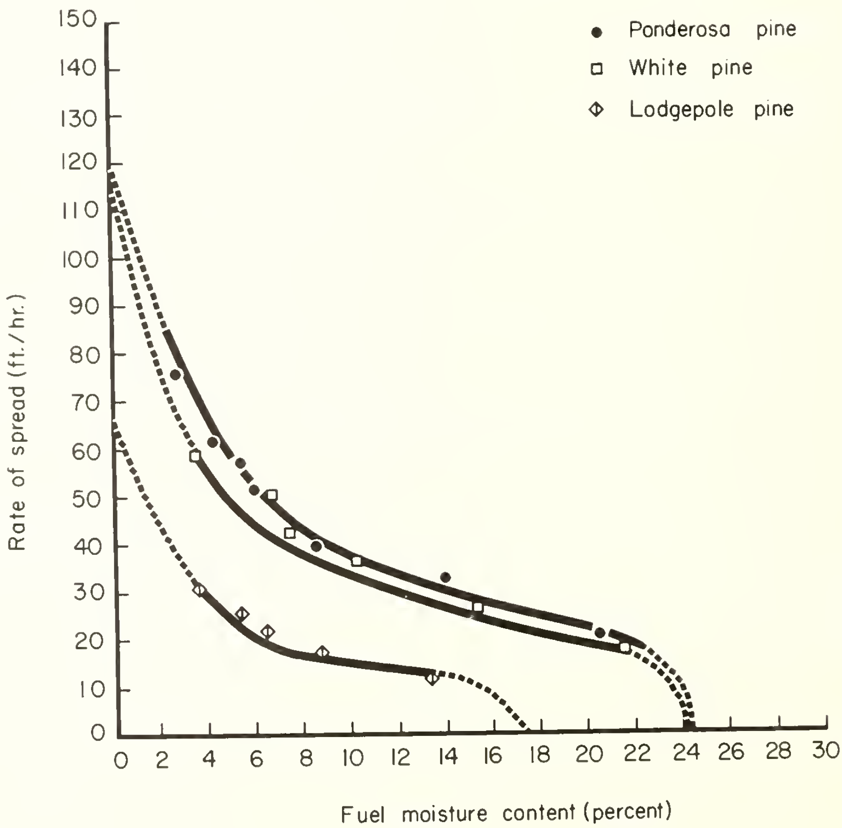
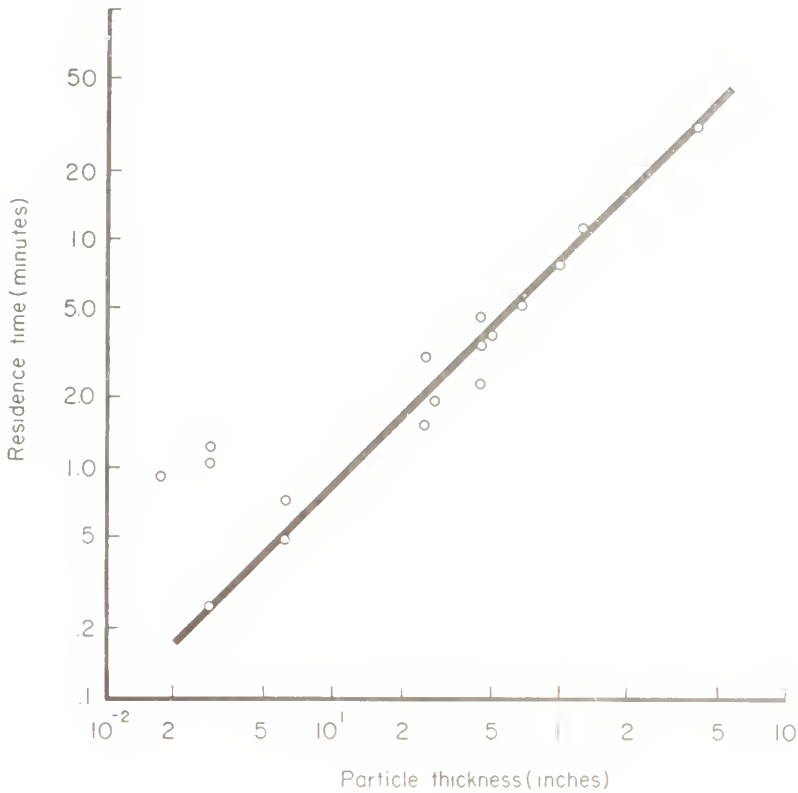


Figure 8.--Relation of residence time to particle thickness determined from measurements made during test fires.



4. Over what range of particle sizes and bed porosities does the fuel descriptor set apply?

Values for the combustion zone and flame temperatures determined experimentally were used to test equation 14 against fires in beds of different widths. This was done for the fires described in "Fire Spread and Flame Shape" (Anderson 1968). The equation yielded a rate of spread that was within: 99 percent of the experimental rate of spread for a 1.5-foot-wide ponderosa pine bed; 77 percent to 89 percent for 5.0-foot beds; 103 percent for a 1.5-foot-wide bed of western white pine; and 89 percent for 5.0-foot-wide beds. Rate of spread was overestimated at 136 percent of the experimental value for 5-foot-wide beds of lodgepole pine primarily because the flame depth measurements differed by a factor of three. In addition, the flame-shielded test (Rothermel and Anderson 1966) was used and the value from the equation was 97 percent of the experimental spread assuming no radiant heat from the flame. These evaluations support the credibility of the equation and further work will determine whether this approach is applicable to a variety of fuels.

FIRE RESPONSE TO σ AND λ

In fuel beds where the particles are loosely arranged, each particle will burn in a manner predominantly controlled by its own thermal properties. The energy feedback to the particle from surrounding fuel elements and their pyrolysis products will influence the burning characteristics but may be a nearly constant value until the particles are very far apart or very close together. This idea was checked by plotting research data for a variety of particle sizes ranging from 1.75×10^{-2} to 4.00 inches against the residence time or duration of active flaming. The results shown in figure 8 suggest that in porous fuel beds, residence time in minutes is equal to 8 times the particle diameter or thickness in inches. At the low end of the curve the residence time for a single needle falls on the line. Those points above the line are residence times for the test fuel beds and have porosities from 4.3 to 9.1 X 10^{-3} ft.^{3}/ft.^{2}. Much of the other data were for fuel beds with porosities between 2.45 and 6.04 X 10^{-2} ft.^{3}/ft.^{2}. It would appear porosity has an important influence on the residence time and the burning rate of a fuel bed and rather small changes can make major changes in a fuel bed's burning characteristics.

The tests of stationary fires in fuel beds of fixed area and loading revealed the influence of porosity on burning rate and flame length. It was found that an optimum porosity exists where the fuel burning rate is maximum (figure 9). This occurs with loading held constant but as loading is increased, the maximum burning rate occurs at a different porosity. It is possible that as loading increases the burning rate will reach a nearly constant level over a large range of porosities. Additional work is in progress to fully evaluate porosity, area of combustion, and loading. The values of $\sigma_a\lambda$ for the three fuel types used in the main test series ranged from 10 for lodgepole to 18.9 for western white pine with ponderosa pine at 16. These values are on the low side of optimum porosity and any variation will have a significant effect on the fire's behavior. Comparing these results to porosities measured in the field, we found even lower porosities for the needle layer under a pure stand of ponderosa pine. Any disturbance to the forest floor litter layer increasing the spacing between needles can cause an increase in burning rate and more flaming activity. It appears the dimensionless group $\sigma_a\lambda$, may be a good indicator of potential fire spread in a fuel.

The influence of fuel particle density seems quite straightforward and follows the results presented by Fons et al. (1962). He shows that as the specific gravity of the fuel decreases the rate of spread increases. The location of ρ_f in the denominator of equation 14 reflects this behavior.

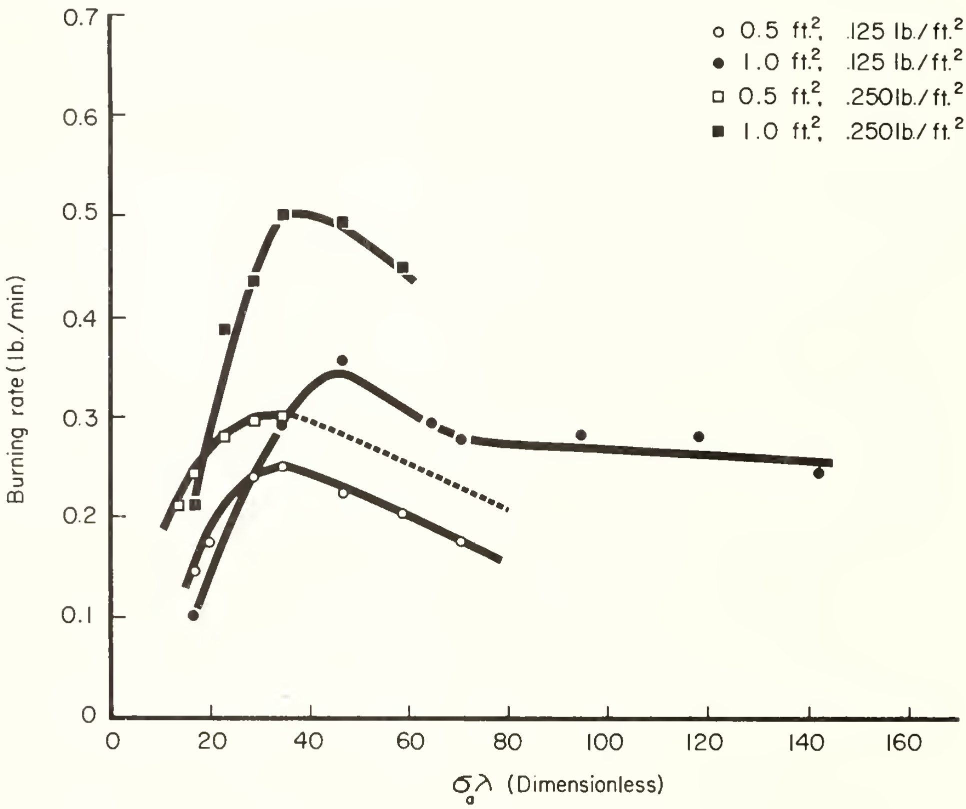


Figure 9.--Influence of porosity, λ, on burning rate for fires in ponderosa pine needles with a σ_a of 1,740 ft.^{2}/ft.^{3}. Each data point is average of three fires.

CONCLUSIONS

The work conducted to date indicates that radiant heat transfer can account for only 40 percent of the total heat flux necessary to sustain a spreading fire. Convective heat transfer at the interface of the combustion zone and the new fuel probably accounts for the rest. Burning characteristics and flame depth are strongly controlled by the fuel particle size and the porosity of the bed. In porous beds the residence time of a fire is controlled by the particle size. A direct relationship seems to exist between residence time and particle size.

Fuel beds of solid fuel elements can be correlated to liquid pool fires by using the ratio of fuel bed density to cold vapor gas density. Three burning regimes, turbulent, transitional, and laminar, exist in solid fuels and may contribute to discrepancies found among various sets of experimental fires.

A group of selected fuel descriptors consolidates the more important parameters into a measure of the bulk heat requirement, B.t.u./ft.^{3}, and, with the experimental rates of spread, indicates the maximum heat flux is near 40×10^3 B.t.u./ft.^{2} - hr. (3 cal./cm.^{2} - sec.).

The tallest flames and highest burning rates occur where an optimum porosity exists. Natural litter fuel beds appear to have low porosities and small changes can cause large shifts in burning rate.

LITERATURE CITED

Anderson, Hal E.
1968. Flame shape and fire spread. Fire Technol. 1968 (Feb.): 51-58, illus.

_______ and R. C. Rothermel.
1965. Influence of moisture and wind upon the characteristics of free-burning fires. Tenth Symp. (Int.) on Combust., pp. 1009-10-19, illus. Pittsburgh: The Combustion Institute.

Blinov, V. I., and G. N. Khudiakov.
1959. Certain laws governing diffusive burning of liquids. Reviewed by H. C. Hottel. Fire Res. Abstr. and Rev. 1(2): 41-44.

Byram, G. M., H. B. Clements, M. E. Bishop, and R. M. Nelson, Jr.
1966. An experimental study of model fires. Project Fire Model final report. U.S. Forest Serv., Southeastern Forest Exp. Sta., 51 pp., illus.

_______, F. M. Sauer, W. L. Fons, and R. K. Arnold.
1952. Thermal properties of forest fuels. U.S. Forest Serv., Fire Research, 34 pp., illus.

Committee on Fire Research.
1961. A study of fire problems. Nat. Acad. Sci., Nat. Res. Counc. Pub. 949, 174 pp., illus.

Emmons, Howard.
1963. Fire in the forest. Fire Res. Abstr. and Rev. 5(3): 163-178, illus.

Fons, Wallace L.
1946. Analysis of fire spread in light forest fuels. J. Agr. Res. 72: 93-121, illus.

Fons, Wallace L.
1950. Heating and ignition of small wood cylinders. Ind. and Eng. Chem. 42(10): 2130-2133, illus.

_______, H. B. Clements, E. R. Elliott, and P. M. George.
1962. Project Fire Model summary progress report II. U.S. Forest Serv., Southeastern Forest Exp. Sta., 55 pp., illus.

Gisborne, H. T.
1928. Measuring forest fire danger in northern Idaho. U.S. Dep. Agr. Misc. Pub. 29, 64 pp., illus.

Hottel, H. C., C. G. Williams, and F. R. Steward.
1965. The modeling of fire spread through a fuel bed. Tenth Symp. (Int.) on Combust., pp. 997-1007, illus. Pittsburgh: The Combustion Institute.

Martin, S.
1964. Ignition of organic materials by radiation. Fire Res. Abstr. and Rev. 6(2): 85-98, illus.

McCarter, R. J., and A. Broido.
1965. Radiative and convective energy from wood crib fires. Pyrodynamics 2: 65-85, illus.

Mutch, R. W.
1964. Ignition delay of ponderosa pine needles and sphagnum moss. J. Appl. Chem. 14: 271-275.

Rothermel, Richard C., and Hal E. Anderson.
1966. Fire spread characteristics determined in the laboratory. U.S. Forest Serv. Res. Pap. INT-30, 34 pp., illus.

Schuette, Robert D.
1965. Preparing reproducible pine needle fuel beds. U.S. Forest Serv. Res. Note INT-36, 7 pp., illus.

Simms, D. L.
1960. Ignition of cellulosic materials by radiation. Combust. and Flame 4(4): 293-300, illus.

_______.
1961. Experiments on the ignition of cellulosic materials by thermal radiation. Combust. and Flame 5(4): 369-375, illus.

_______.
1963. On the pilot ignition of wood by radiation. Combust. and Flame 7(3): 253-261, illus.

Thomas, P. H.
1963. The size of flames from natural fires. Ninth Symp. (Int.) on Combust., pp. 844-859. New York: Academic Press, Inc.

_______ and Margaret Law.
1965. Experiments on the spread of fire. Rep. on Forest Res. 1965: 124-130, illus.

Wooliscroft, M. J., and Margaret Law.
1967. A report on forest fire fieldwork. Joint Fire Res. Organ., Fire Res. Note 647, 14 pp., illus.

APPENDIX

Symbol	Definition	[illegible]
A	= area	ft.
C_f	= specific heat of fuel	0.327
C_w	= specific heat of water	1.000
D	= flame depth	ft.
E	= emissive power of fire	B.t.u./ft.[illegible]
E_c	= combustion zone emissive power	B.t.u./ft.[illegible]
E_f	= flame emissive power	B.t.[illegible]
F_{12}	= configuration factor	--
H	= fuel heat content	[illegible]
$H(M)_{T_1}$	= heat of desorption	B.t.u./[illegible]
L	= flame length	ft.
L_t	= latent heat of vaporization	B.t.u.
M	= moisture content	lb./lb.
MC	= fuel moisture content, ovendry	percent
N_{RE}	= Reynolds number	--
Q	= heat per vertical cross section of bed	B.t.u./ft.
Q_{ig}	= heat to raise 1 lb. fuel to ignition	B.t.u./lb.
R	= rate of spread	ft./hr.
T_1	= ambient temperature	°F.
T_2	= boiling temperature	°F.
T_F	= temperature of flame zone	°F.
T_I	= ignition temperature	608°F. (320°C.)
T_c	= temperature of combustion zone	°F.
V_1	= void volume per unit of load area	ft.^{3}/ft.
V_2	= fuel volume per unit of load area	ft. /ft.
V_F	= fuel bed regression burning rate	ft./sec.
V_L	= liquid burning velocity	ft./sec.

Symbol	Definition	Measure
a	= attenuation constant	ft.$^{-1}$
d	= characteristic dimension	ft.
h_c	= convective heat transfer coefficient	B.t.u./ft.^{2} - hr. - °
m	= weight loss rate	lb./sec.
$q_{T/A}$	= total heat flux	B.t.u./ft. - hr.
t	= time	hr.
t_b	= fuel bed depth	ft.
w_b	= weight of fuel per unit of load area	lb./ft.^{2}
x	= separation distance	ft.
ε_c	= emissivity of combustion zone	--
ε_f	= emissivity of flame zone	--
η	= horizontal convective heat transfer coefficient	--
λ	= bed void volume-to-surface area ratio	ft.^{3}/ft.^{2}
μ	= dynamic viscosity	--
ν	= kinematic viscosity	ft.^{2}/sec.
ρ_b	= bulk density of fuel bed	lb./ft.^{3}
ρ_f	= fuel particle density	lb./ft.^{3}
ρ_g	= gas density	lb./ft.^{3}
σ_a	= particle surface area-to-volume ratio	ft.^{2}/ft.^{3}
σ	= Stefan-Boltzman constant	B.t.u./ft. - hr. - °

Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field Research Work Units are maintained in:

- Boise, Idaho
- Bozeman, Montana (in cooperation with Montana State University)
- Logan, Utah (in cooperation with Utah State University)
- Missoula, Montana (in cooperation with University of Montana)
- Moscow, Idaho (in cooperation with the University of Idaho)
- Provo, Utah (in cooperation with Brigham Young University)

FOREST SERVICE CREED

The Forest Service of the U. S. Department of Agriculture is dedicated to the principle of multiple use management of the Nation's forest resources for sustained yields of wood, water, forage, wildlife, and recreation. Through forestry research, cooperation with the States and private forest owners, and management of the National Forests and National Grasslands, it strives — as directed by Congress — to provide increasingly greater service to a growing nation.

USDA Forest Service
Research Paper INT-70
1969

ESTIMATION OF VISITOR USE FROM SELF-REGISTRATION AT DEVELOPED RECREATION SITES

J. ALAN WAGAR

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Ogden, Utah

Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field Research Work Units are maintained in:

- Boise, Idaho
- Bozeman, Montana (in cooperation with Montana State University)
- Logan, Utah (in cooperation with Utah State University)
- Missoula, Montana (in cooperation with University of Montana)
- Moscow, Idaho (in cooperation with the University of Idaho)
- Provo, Utah (in cooperation with Brigham Young University)

USDA Forest Service
Research Paper INT-70
1969

ESTIMATION OF VISITOR USE FROM SELF-REGISTRATION AT DEVELOPED RECREATION SITES

J. Alan Wagar

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401
Joseph F. Pechanec, Director

THE AUTHOR

J. ALAN WAGAR was leader of the Cooperative Recreation Research Work Unit maintained at Logan by the Intermountain Forest and Range Experiment Station in cooperation with Utah State University at the time this study was conducted--a position he had held from 1962 to 1968. Currently he is leader of a similar work unit maintained at Seattle by the Pacific Northwest Forest and Range Experiment Station in cooperation with the University of Washington. Before he joined the Intermountain Station staff, Dr. Wagar's Forest Service career included assignments at the Northeastern Forest Experiment Station and at the Rocky Mountain Forest and Range Experiment Station. Dr. Wagar received his bachelor of science degree in forestry from the University of Washington and his master's and doctoral degrees from the University of Michigan.

CONTENTS

INTRODUCTION

Double-sampling methods have provided a good start in estimating visitor use of developed recreation sites, and the traffic counter version of double sampling is widely used now by the Forest Service.[1] The basic idea in double sampling is simple. The relationship between visitor use and traffic counts (or some other predictor variable) is established from sample counts made at the same time for both use and traffic. This relationship is then applied to the season-long traffic count record to estimate season-long use.

In double-sampling estimates based on traffic counts, errors seem to come mainly from the fairly loose relationship of traffic counts to recreational use, rather than from inaccuracies in sample counts. Both water consumption and "net counts" of axles from printing traffic counters have been tested and have advantages over conventional traffic counters as predictor variables.[2] [3] However, even better predictor variables would be desirable and may be available.

What we need is a predictor variable that is closely related to visitor use, inexpensively measured, and not affected by mechanical breakdowns of equipment. In addition, if the relationship between the predictor variable and visitor use was fairly consistent from site to site, then approximate but still useful estimates of use could be made on sites for which sample counts of visitors were not available.

Because self-registration cards seemed to provide a predictor variable with these desirable characteristics, a method using such cards was developed and tested. The campgrounds studied had self-registration systems, traffic count data, and sample counts of visitors. Therefore, the new sampling method could be compared to the existing traffic counter method. This paper reports on the test of this method. It also provides procedures for applying the method.

Procedures were designed to estimate visitor use from self-registrations for three different situations:

Situation 1. Estimates for a recreation site during a year when sample counts are made.

Situation 2. Estimates for the same site for several additional years when no sample counts are made.

Situation 3. Estimates for other sites where no sample counts are made at all.

In all three situations, visitor self-registration data are collected. Sample visitor counts are taken only in situation 1. The relationships computed in situation 1 are used to estimate use in both situations 1 and 2. For situation 3, area-wide relationships are computed from sites that were sampled, and these are used to estimate use at similar but unsampled sites.

---

[1]For example, see James, George A. Instructions for using traffic counters to estimate recreation use on developed sites. U.S. Forest Serv., Southeastern Forest Exp. Sta. 12 pp. 1966.

[2]James, George A., and Gary L. Tyre. Use of watermeter records to estimate recreation visits and use on developed sites. U.S. Forest Serv. Res. Note SE-73, 3 pp. 1967.

[3]Wagar, J. Alan, and Joel F. Thalheimer. Trial results of net-count procedures for estimating visitor use at developed recreation sites. USDA Forest Serv. Res. Note INT-105. 1969.

The following printout is provided for situations 1 and 2 by the computer using the program that has been designed for the self-registration method:

```
REGION   4, FOREST 10, DISTRICT   7,  PRINCIPAL SITE    18.0, KIND  41.1

DEVILS CANYON               , SEASON FROM  6-17 TO  9- 9 1967, SERIAL NO. R4-12

     YEARS SINCE VISITOR COUNTS MADE,   34 FACILITY GROUPINGS

     ACTIVITY AND NUMBER                          VISITOR DAYS      PERCENT ERROR  (.90 CONF)

DAYTIME USE

     PICNICKING(43.1)                                      51.                 148.88

     CAMPING(41.1)                                        521.                  29.07

     TEAM SPORTS(21.0)                                     51.                 148.88

     VIEW SCENERY(1.1)                                    156.                  48.59


     TOTAL  (DAY)                                         779.                  34.22

NIGHT TIME USE

     OVERNIGHT CAMPING                                   1809.                  16.02

TOTAL USE  (DAY AND NIGHT)                               2588.                  15.64

                                                  AVE. OCCUPANCY       PERCENT ERROR  (.90 CONF)


FACILITY GROUPINGS OCCUPIED  (DAY)                         3.                   20.48
                                                  (  8.56 PERCENT OCCUPIED)

FACILITY GROUPINGS OCCUPIED  (NIGHT)                       5.                    9.82
                                                  ( 15.73 PERCENT OCCUPIED)


ROUGH ESTIMATE OF VISITORS =          1687.
```

The following printout is provided for situation 3:

```
REGION   6, FOREST 13, DISTRICT  2, PRINCIPAL SITE   146.0, KIND   41.1

HELLS CROSSING              , SEASON FROM  5-25  TO  9- 6 1968, SERIAL NO. 0014046

ESTIMATE BASED ON REGIONAL RELATIONSHIPS,     17 FACILITY GROUPINGS

REGISTERED VISITOR HOURS   (DAY) =   27039., DAYTIME HOURS IN SEASON=    1260.

REGISTERED VISITOR HOURS  (NIGHT) =    28992., NIGHT TIME HOURS IN SEASON=  1260.

                                           VISITOR DAYS  PERCENT ERROR (.90 CONF)

DAYTIME USE                                       2525.              74.38

NIGHT TIME USE                                    3799.              65.81

TOTAL USE                                         6324.              49.45

     ROUGH ESTIMATE OF VISITORS =         2323.
```

A TEST OF THE SELF-REGISTRATION METHOD

During the summer of 1967, self-registration records and visitor-use counts were taken for the 42-unit Panguitch Lake Campground on the Dixie National Forest in southern Utah, the 34-unit Devil's Canyon Campground on the Manti-LaSal National Forest in central Utah, and the 23-unit Green River Lakes Campground on the Bridger National Forest in western Wyoming. The Panguitch Lake and Green River Lakes Campgrounds are both destination sites. Many visitors used these for extended periods. By contrast, Devil's Canyon was used primarily as a transient, one-night-stop campground.

Data Collection and Processing Procedures

At the three recreation sites, the visitor registration record was obtained from self-registration cards, while the visitor-use counts were taken on a random schedule.

Self-registration cards

At the entrance to each recreation site studied, cards were provided in two boxes on a large sign. Instructions on the sign read as follows:

FOR HOLDERS OF $7.00 ENTRANCE PERMIT

1. Select a vacant camp unit.
2. Fill out one of the GOLD CARDS available from the dispenser and deposit it in the DISPLAY BOX at your camp unit.

FOR HOLDERS OF $1.00 DAILY PERMITS

1. Select a vacant camp unit.
2. Deposit your $1.00 DAILY PERMIT in the DISPLAY BOX at your camp unit.

FOR ALL OTHERS

1. Select a vacant camp unit.
2. Obtain an envelope from the envelope dispenser. Fill in the information requested on the ENVELOPE and the enclosed PINK CARD.
3. Place $1.00 in the ENVELOPE, seal, and drop in the DEPOSIT BOX.
4. Place the PINK CARD in the DISPLAY BOX at your camp unit.

Unfortunately, the location of these signs was not the same at all three sites. At Green River Lakes, the sign was on the left-hand side of the road. At Panguitch Lake, it was on the right-hand side of the road. Only at Devil's Canyon, was it on an island in the center of the road so that drivers could take registration cards without leaving their vehicles.

The registration information requested on the cards (fig. 1) included name, unit occupied, number of people in group, annual permit number (gold cards only), vehicle license and state, time and date of arrival, and expected time and date of departure. Cards were collected weekly, were marked and bundled separately for each site, and were forwarded to the Regional Office for coding and keypunching.

Some editing of the cards was necessary before they were coded for keypunching. Each visitor group with a Federal Recreation Permit normally filled out only one gold registration card. Visitors without the permit sometimes filled out several pink cards--one for each day of their visit. Names and dates were compared on these cards and the data were combined on a single card. A few visitors had daily permits, obtained

U. S. DEPT. AGRICULTURE
FOREST SERVICE

NAME ____________

OCCUPYING UNIT # ________ NUMBER OF PEOPLE ________

ANNUAL PERMIT # ____________

VEHICLE LICENSE # ________ STATE ________

ARRIVED ________ (hour, AM or PM) ___M ________ (date)

EXPECT TO LEAVE ________ (hour, AM or PM) ___M ________ (date)

DROP THIS CARD IN TICKET BOX AT CAMP UNIT

AFPS, Ogden, Utah

U. S. DEPT. AGRICULTURE
FOREST SERVICE

$1 DAILY PERMIT PURCHASE

NAME ____________

OCCUPYING UNIT # ________ NUMBER OF PEOPLE ________

VEHICLE LICENSE # ________ STATE ________

ARRIVED ________ (hour, AM or PM) ___M ________ (date)

EXPECT TO LEAVE ________ (hour, AM or PM) ___M ________ (date)

DROP THIS CARD IN TICKET BOX AT CAMP UNIT

AFPS, Ogden, Utah

Figure 1.--Self-registration cards used in 1967 for checking Federal Recreation Area Entrance Permits, Region 4, Forest Service. The card at left (gold) was for groups having the $7.00 permit. The card at right (pink) was for groups not having the annual permit.

directly from National Forest or District Ranger Offices. Registration was not required for holders of daily permits, but daily permits represented only a tiny fraction of total use and were not used as part of the self-registration record..

Of the cards collected on the three study sites, 81 percent were filled in completely enough to be usable. If arrival and departure information on the cards was incomplete, and if groups had stayed more than 2 days, some arrival and departure times were estimated and filled in. (It was assumed that salvaging cards for relatively long-term visitors would enhance the registration record more than it would detract from it by introducing inaccuracies. However, to simplify the instructions and reduce coding time, procedures described on pages 23-26 require use of completed cards only.)

Self-registration cards were coded for keypunching, using the procedures described on pages 23-26. Devil's Canyon Campground had the largest number of usable cards--319. Because data from three cards were punched on one computer card, 107 computer cards were needed. An additional 25 cards were punched to give visitor-count data, sampling times, and site identification. All data for Devil's Canyon Campground required approximately 3 hours of office preparation and 2 hours of keypunching and verifying.

Visitor-use counts

During the summer-use season, 12 day-long visitor-use counts were made for each of the three sites using the double-sampling procedures given in the Forest Service Recreation Information Management Handbook.[4] However, because an earlier study had

[4]Forest Service Handbook 2309.11, Sec. 124.72, Forest Serv., U.S. Dep. Agr. September 1967.

shown that single on-the-hour counts are nearly as effective as day-long counts for estimating total visitor use, only some of the double-sampling data were needed. To provide on-the-hour counts, one of the eleven 45-minute counts made between 0915 (9:15 a.m.) and 2000 (8:00 p.m.) was selected at random from each completed sampling record form (fig. 2). To simplify recording and data processing, all times were recorded on a 24-hour basis.

The counts at 2015 for number of persons and for number of auto, tent, and trailer units were taken from the "overnight use" portion of each sampling record form as a basis for estimating nighttime use. It was assumed that most overnight visitors would be at their sites by 2015 and that the count would be representative of use for the night.

Because self-registration equipment was not installed until mid-June on one area and early July on the others, not all 12 sample dates at each site were usable in computations. Estimates for Green River Lakes Campground were based on eight sampling dates; for Panguitch Lake, 10 dates; and for Devil's Canyon, 11 dates.

The fact that each visitor count was taken between 15 and 60 minutes after the hour made coding of sample count times and arrival and departure times a bit awkward during the study. This awkwardness has been eliminated by modifying the sampling times in the instructions (see page 21).

Statistical Procedures

Situation 1, sampled site, season sampling takes place.--Relationships between visitor counts and self-registration data were established by regression analysis, and season-long estimates of visitor use were then made by applying these relationships to the season-long record of self-registration.

The on-the-hour daytime counts provided visitor values for up to 12 activities, giving up to 12 sets of Y's. These were designated Y_{1_i}, Y_{2_i}, Y_{3_i}, . . . Y_{11_i}, Y_{12_i}. Totaling of visitor use for each count provided another set Y_{T_i}. The counts for nighttime use provided an additional set of values designated Y_k.

The number of people registered as present during each on-the-hour visitor count was determined by the computer from the self-registration cards, providing a set of sample daytime values, X_i, and a set of sample nighttime values, X_k. The season-long number of all registered visitor-hours was also summarized by computer, with the daytime sum designated $\sum_{i=1}^{N} X_i$ and the nighttime sum designated $\sum_{k=1}^{N} X_k$, where N indicates the number of daytime or nighttime hours in the season.

For individual recreation sites, the regression of each set of Y values on the appropriate X values gave equations of the form $Y = a + bX$ for each daytime activity, for total daytime use, and for nighttime use. These equations give estimates of use for one hour. To give season-long estimates, these equations were used in the form

$$\Sigma Y = N(a) + b(\Sigma X)$$

where N is the season-long number of hourly values going into the season-long sum of registered visitor hours (ΣX). For example, a 100-day season with daytime hours defined as the 12 on-the-hour times 0800 to 1900 would give a value of $N = 100 \times 12 = 1200$.

CARD 1

USDA-FOREST SERVICE SAMPLING RECORD DEVELOPED RECREATION SITES (DOUBLE SAMPLE TECHNIQUE) *(Ref: FSH 2311.71)* PART I - DAILY SUMMARY	A. card no. (1-2) 01	B. region no. (3-4)	C. forest no. (5-6)
	D. dist. no. (7-8)	E. principal site no. (9-12)	kind (13-15)
	F. set no. (16-17)	G. principal site name (18-58)	

TRAFFIC WATER METER READINGS	STATION 1	STATION 2	STATION 3	STATION 4
0900 HOURS ON SAMPLE DAY				
0900 HOURS ON NEXT DAY				
24 HOUR DIFFERENCE	(59-63)	(64-68)	(69-73)	(74-78)

CARDS 2-13

TIME OF DAY	VISITS	NO. OF PERSONS ENGAGED IN COMPONENT ACTIVITIES												
	tallied 15 min. hr. at 1 entrance	43.1	41.1	21.0	22.1	22.2 & .3	boat launch		1.3	visitor service		1.1	other specify activity
		picnicking	camping (gen.)	team sports	swimming bathing	water sports	12.0 power	15.0 non-power	spectator sports	81.1 & .2 exhibits talks	81.3 & .4 tours	view scenery	(74-76) code
	(18-22)	(23-27)	(28-32)	(33-37)	(38-41)	(42-45)	(46-49)	(50-53)	(54-57)	(58-61)	(62-65)	(66-69)	(70-73)
0900													
0915	→												
1000													
1015	→												
1100													
1115	→												
1200													
1215	→												
1300													
1315	→												
1400													
1415	→												
1500													
1515	→												
1600													
1615	→												
1700													
1715	→												
1800													
1815	→												
1900													
1915	→												
2000													
2015	→												

CARD 14

TIME OF DAY	FACILITY GROUPINGS BY PERCENT OF DESIGNED CONST. CAPACITY UTILIZED						
	NO. OF FACILITY GROUPINGS						
	AT OR BELOW LOWER LIMIT				ABOVE UPPER LIMIT		
	vacant	"gear" only	below lower limit	within limits	less than 25% above	25% to 75% above	more than 75% above
1215	(18-20)	(21-23)	(24-26)	(27-29)	(30-32)	(33-35)	(36-38)
1815	(39-41)	(42-44)	(45-47)	(48-50)	(51-53)	(54-56)	(57-59)

OVERNIGHT USE (Post from 2015 round and or supplemental information			
NUMBER OF OVERNIGHT CAMPERS	TYPES OF OVERNIGHT EQUIPMENT IN USE (no. of)		
A. persons (60-64)	B. auto (65-67)	C. tent (68-70)	D. trailer (71-73)
E. observer	F. date of sample → month (74-75) day (76-77) yr. (78-79)		

2300-40 (4-67)

Figure [illegible].--Sampling record form.

Variance for each estimate was computed as

$$S^2_{\Sigma Y} = N(N-n)\, S^2_{y \cdot x} \left(\frac{1}{n} + \frac{(\bar{X}_N - \bar{X}_n)^2}{\Sigma x^2} \right)$$

where

N is as previously defined
n is the number of paired X and Y values used for the regression
$S^2_{y \cdot x}$ is the mean squared deviation from regression
Σx^2 is the sum of squared deviations from the mean for the set of X values used for regression
N and n as subscripts denote whether a mean is based on N or n values.

The term $N(N-n)$ is equivalent to N^2 times the finite population correction $1 - (n/N)$. In this the value N^2 converts the variance for $\bar{Y}$ to the variance for ΣY, where the summation is for N sampling hours.

When the estimate for total daytime use was combined with the estimate for total overnight use, variance for the combined estimate was computed as

$$Var_T = Var_1 + Var_2 + 2r\sqrt{Var_1\, Var_2}$$

where

Var_T is variance for the combined estimate
Var_1 is variance for the season-long estimate of daytime use
Var_2 is variance for the season-long estimate of nighttime use
r is the correlation coefficient between daytime and nighttime values of Y for the sampling times. (In case of an unequal number of daytime and nighttime samples, n was defined as the lesser number and r was computed from n pairs of sample counts.)

The term $2r\sqrt{Var_1\, Var_2}$ was required for 1967 data because daytime and nighttime samples were taken on the same dates and were correlated. However, if daytime and nighttime samples are selected independently, as was done in 1968, this term is not needed. Variance for the combined estimate then becomes

$$Var_T = Var_1 + Var_2$$

Confidence intervals for the combined estimate were computed as $\pm\, t\sqrt{Var_T}$ with n - 2 degrees of freedom, where n is the number of daytime or nighttime sample counts, whichever is smaller. This gives confidence intervals slightly larger than would be computed if the most appropriate value were used for degrees of freedom. This value lies somewhere between the number for the smaller sample and the combined number of daytime and evening samples. However, procedures for determining the most appropriate value are more complex than would be justified here.

Regression procedures were used also to estimate the average number of [illegible] units occupied for daytime and for overnight periods and to estimate the [illegible] percentage of camping equipment units in the categories of AUTO, TENT, and [illegible] (see "Nighttime Counts" page 22). Confidence intervals were computed for [illegible] facility groupings but not for camping equipment types.

---

[1] Cochran, William G. P. 73, in: Sampling techniques. New York: John Wiley and Sons, Inc. 1953.

Situation 2, sampled site, subsequent seasons.--The regression relationships, as established for a specific site during a season of sample visitor counts, permit estimation of use from the self-registration record alone during several subsequent seasons, provided there are no major changes in the site.

Situation 3, sites not sampled.--A set of area-wide regression relationships was developed from the combined data for the three sites.[6] For these regression relationships, counts of total visitors present for daytime (Y_{T_i}) and for nighttime (Y_k) were paired with the corresponding numbers of people registered (X_{1_i} or X_{1_k}). The number of facility groupings (designated X_2) at a site was added as a third variable, and the data for the three sampled sites were pooled. One regression was then run for the daytime data (Y_i, X_{1_i}, and X_2) and another for the nighttime data (Y_k, X_{1_k}, and X_2).

The number of campground units (X_2) was included to adjust for the likelihood that people are more likely to register after the site begins to fill. Registration may then seem needed as a "claim stake" to guarantee possession. However, the number of people who must be present before the site will seem full will depend on the number of facilities at the site. As a result, the same number of completed registrations might indicate different numbers of people present on sites of different sizes.

The two regressions resulting from the pooled data are of the form

$$Y = a + b_1X_1 + b_2X_2.$$

For season-long estimates, these are used in the form

$$\Sigma Y = N(a + b_2X_2) + b_1 (\Sigma X_1)$$

where N is the season-long number of hourly values going into ΣX_1.

If based on a representative group of recreation sites, area-wide regression relationships developed in this manner can, with caution, be applied within the same general vicinity to similar sites that have self-registration but no visitor sampling. The 1968 data from three sampled sites were used to develop area-wide regression relationships that were then applied to a fourth site that had no visitor sampling.

It must be recognized, however, that the combined data from several sites represent cluster sampling rather than strictly random sampling. As a result, confidence intervals can be underestimated.

When use was estimated from area-wide regression relationships, variance for each estimate was computed as

$$S^2_{\Sigma Y} = N^2 S^2_{y \cdot 12} \left\{ \frac{1}{n} + C_{11} (\overline{X}_{1_N} - \overline{X}_{1_n})^2 + C_{22} (\overline{X}_{2_N} - \overline{X}_{2_n})^2 + C_{12} (\overline{X}_{1_N} - \overline{X}_{1_n}) (\overline{X}_{2_N} - \overline{X}_{2_n}) \right\}$$

where

N is as previously defined

[6]The procedures were refined and applied to additional sites in 1968 (see p. 12).

$S^2_{y.12}$ is the mean squared deviation from regression
n is the number of sample counts used for the regression
N and n as subscripts denote whether a mean is based on N or n values
C_{11}, C_{22}, and C_{12} are the "multipliers" as used by Snedecor.[7]

When the estimate for total daytime use was combined with the estimate for total overnight use, variance for the combined estimate (1968 data) was computed as

$$Var_T = Var_1 + Var_2$$

where the symbols are as previously defined.

Confidence intervals for the combined estimate were then computed as $\pm t \sqrt{Var_T}$ at n-3 degrees of freedom. In this case n is the total number of sample counts going into the regression for daytime or nighttime, whichever is smaller. Again, t is based on fewer than the appropriate degrees of freedom to avoid complex approximation procedures and to give confidence intervals slightly larger than could be obtained by refined procedures.

This conservative approach may partly offset possible underestimation of confidence intervals, which could result because regressions for the combined data are based on cluster samples rather than strictly random samples. Nevertheless, estimates based on these procedures must still be applied with caution and should be treated as approximations rather than precise estimates.

Estimation of visitors.--Because rough estimates of visitors are sometimes needed for such purposes as news releases, computations were also programed to adjust the number of registered visitors by a ratio that indicates what proportion of visitors actually register:

$$\text{Estimated visitors} = RV \left(\frac{SUMN}{RHN} \right)$$

where

a visitor is defined as one person's use of a recreation site for as long as he occupies it, either in person or with his belongings[8]

RV is the number of registered visitors as found by summing the people per vehicle for all registration cards collected during the season. Thus a card listing five people contributes five registered visitors to RV

SUMN is the season-long regression estimate for nighttime use expressed in visitor-hours

---

[7]Snedecor, George W. P. 418, in: Statistical methods. 5th ed. Ames: Iowa State Univ. Press. 1956.

[8]As a unit of use, "visitor" is much different from the "visit" recorded in the traffic-counter method each time a person enters an area, whether he has already established occupancy there or not. As a result, many fewer visitors than visits are estimated.

RHN is the number of registered visitor hours included in nighttime periods during the visitor season. Thus, if the visitors who arrived in one vehicle registered three people as arriving at 1600 on one day and as leaving at 0900 the next, and if the nighttime period was defined as the 12 on-the-hour times 2000 to 0700, they would contribute 3 X 12 = 36 registered visitor hours to RHN.

The ratio for adjusting registered visitors is taken from nighttime data because results of the testing showed that many of the visitors who establish occupancy at a destination site are away from the site during the day. Therefore, they are missed during the daytime sample counts, and the ratio of registered visitors to actual visitors increases during daytime periods. For example, daytime registration at Green River Lakes actually exceeded the estimation of daytime use. Total visitors would obviously be grossly underestimated for some sites if registered visitors were adjusted by daytime data. However, most visitors have returned to the site by evening when sample counts for nighttime use are made. Thus nighttime sample counts provide a better indication of how many visitors actually are represented by each registered visitor.

Use of nighttime data for adjustment is based on the assumption that about the same percentage of visitors will register in daytime and nighttime. Actually, it is likely that daytime periods include more short-term visitors than do nighttime periods. Such visitors may stop only for water, to use the restrooms, or to take a quick look at the area, and may not bother to register; consequently, estimates of daytime visitors are likely to be low but will serve as a "floor," or minimum, that can be legitimately raised if it is known that many short-term visitors do not register.

Results and Discussion

Relationships for Individual Sites

Estimates of total visitor use from regression relationships based on self-registration data were as precise as estimates based on pneumatic traffic counter data (table 1).[9] However, the self-registration data were obtained with only one-sixth the man-hours of effort required for the traffic-counter method. Because of this greater efficiency, the self-registration method should permit cost reductions in obtaining estimates, increased precision of estimates, or some of both.

Two factors explain this increase in efficiency. First, a fairly constant proportion of visitors willingly registers at a given recreation site, yielding a consistent relationship of registrations to visitor use. By contrast, observations at recreation sites have demonstrated that axle counts from pneumatic counters vary widely between visitors. As a result, consistency between axle counts and visitors is too low for accurate prediction.

Second, a single, on-the-hour count per sample day is as closely related to self-registration records as is a day-long sequence of 12 hourly counts per sample day to traffic-counter records. Therefore, equally precise estimates of total use are obtained with the self-registration method with much less counting.

[9]Estimates calculated by slightly modified procedures for the following three campgrounds sampled on the Snoqualmie National Forest in western Washington during 1968 had a 90% likelihood of including actual use within these confidence intervals: ±18.90% at Cottonwood; ±15.24% at Sawmill Flat; ±12.53% at Cedar Springs.

Table 1.--Comparison of self registration and traffic-count [illegible] of visitor use on three National Forest campgrounds

Activity	Self-registration estimate[1] Visitors	Self-registration estimate[1] Visitor days[3]	Traffic-count [illegible] Visitors	Traffic-count [illegible] Visitor days
		DEVIL'S CANYON		
Picnicking		51(83.6)		[illegible]
Day camping		521(16.3)		[illegible]
Night camping		1,809(9.0)		[illegible]
Camping (all)		[4]2,550		[illegible]
Team sports		51(83.6)		[illegible]
View scenery		156(27.5)		[illegible]
Total	[4]1,687	2,588(11.1)	[illegible]	[illegible]
		PANGUITCH LAKE		
Picnicking		( )		[illegible]
Day camping		3,720(12.8)		[illegible]
Night camping		6,841(10.7)		[illegible]
Camping (all)		[4]10,560		[illegible]
View scenery		( )		[illegible]
Total	[4]1,647	10,560(11.2)	[illegible]	[illegible]
		GREEN RIVER LAKES		
Picnicking		( )		[illegible]
Day camping		919(30.4)		[illegible]
Night camping		4,331(13.5)		[illegible]
Camping (all)		[4]5,250		[illegible]
Nonpower boat launch		( )		[illegible]
View scenery		410(12.0)		[illegible]
Total	[4]1,164	5,660(17.7)	[illegible]	[illegible]

[1]Based on the following sampling done in 1967: [illegible] man-hours over [illegible] period (6/17-9/9) at Devil's Canyon; 20 man-hours over [illegible]-day period [illegible] at Panguitch Lake; and 16 man-hours over 83-day period (7/4-9/24) at Green River Lakes.

[2]Based on the following sampling done in 1967: 144 man-hours over [illegible] period at Devil's Canyon; 144 man-hours over a 99-day period at Panguitch Lake; and [illegible] man-hours over a 75-day period at Green River Lakes.

[3]Figures in parentheses give approximate errors in percent expressed at the [illegible] level of confidence. These can be expressed at the 0.90 level of confidence if multiplied by 1.8. Although computations are in visitor hours, final results [illegible] converted to visitor days. One visitor day equals 12 visitor hours.

[4]Error not computed.

[5]Missed during sampling.

For estimating participation in specific activities, however, the single count per sample day is less precise than the day-long sequence of counts. For example, because few people picnic during the morning hours, approximately half of the on-the-hour counts will record little or no picnicking, even though visitors are present. Picnicking was completely missed at Panguitch Lake and Green River Lakes (table 1). Therefore, sampling error for estimates of individual activities may be relatively high.

This problem can be solved in either of two ways. Often administrators will be able to estimate what proportion of use is in each activity if they have dependable estimates of total use. Or, time of day and time of season could be recorded and used in the analysis as additional predictor variables. This would only slightly complicate the data collection task, and would probably provide increased accuracy from a given amount of data. However, it would make the computer handling of the data much more complex and would require more computation time. The programs developed during the study will not handle the extra predictor variables.

Area-Wide relationships

If area-wide relationships are to be computed from the sampled-site data and then used to estimate visitor use at unsampled sites in the same vicinity, both patterns of use and registration equipment must be uniform from site to site. Otherwise the area-wide relationships will include too much variability to give usable estimates.

The problems of variability are illustrated by the three sites sampled during 1967. Ratios between visitors registered and visitors present differed substantially between destination and transient sites, especially during daytime when many registered visitors were away from the destination sites.

Table 2 shows that the proportion of visitors who register depends on how easy registration is made for them. Note that at Devil's Canyon Campground, where the signboard in the center of the road was easily reached by a seated driver, 72 percent of the estimated nighttime use was accounted for by registration cards. At Panguitch Lake, where the signboard on the right-hand side of the road was fairly easily reached by the passenger in an entering car, the percentage was 66. At Green River Lakes, the signboard on the left-hand side of the road could be reached only if someone from an entering car got out and crossed the road. Many visitors apparently didn't bother: only 44 percent of the estimated nighttime use was accounted for by registration cards.

On the basis of experience in 1967, four destination sites were selected for testing of area-wide relationships in 1968. These are on the Naches Ranger District of the Snoqualmie National Forest in western Washington and are within a few miles of each other. Sample counts were taken on three of the sites--the 15-unit Cottonwood Campground, the 19-unit Sawmill Flat Campground, and the 18-unit Cedar Springs Campground. The area-wide relationships computed from these sites were then applied to the 17-unit Hells Crossing Campground, which had visitor registration but no sample counts.

The estimate of total visitor use at Hells Crossing had a 90-percent likelihood of including actual use within ±49 percent. This probably is about the precision that can be expected for unsampled sites that have use patterns and registration procedures very similar to those on a group of sampled sites in the same vicinity. Precision might increase somewhat for larger sites, and some gain might result if registration boards are in the center of the road, rather than on the right-hand side as they were on the four sites reported here. However, as mentioned earlier, errors for area-wide estimates may be underestimated, and such estimates should be applied with caution.

Table 2.--Comparison between season-long regression estimates of visitor use and visitor use as shown on registration cards, according to type of site and placement of signboard bearing registration instructions

Site	Daytime			Nighttime		
	Regression estimates	Use shown on registration cards	Registration as percent of estimated use	Regression estimates	Use shown on registration cards	Registration as percent of estimated use
	-------Visitor days------			------Visitor days-------		
Devil's Canyon (transient site, signboard in center of road)	779	539	69.2	1,809	1,305	72.1
Panguitch Lake (destination site signboard on right-hand side of road)	3,720	3,579	96.2	6,841	4,481	65.5
Green River Lakes (destination site, signboard on left-hand side of road)	1,329	1,422	107.0	4,321	1,895	43.7

HOW TO USE THE SELF-REGISTRATION METHOD

The procedures described here will give reliable estimates of visitor use with a minimum of fieldwork if instructions are followed carefully and if field data are accurately collected.

The key tasks and timing are as follows:

Tasks	Timing
1. Selection of sites[10]	Prior to visitor-use season
2. Selection of sampling times	Prior to visitor-use season
3. Equipment and administration	Prior to and during visitor-use season

[10] The term "site" is used here to mean a campground, picnic area, or other place designated for one type of recreation. Within a site, the facilities normally used by one family or one group are called a "unit" or a "facility grouping."

4.	Visitor sampling	During visitor-use season
5.	Editing, coding, and keypunching of field data	During and immediately after visitor-use season
6.	Assembly and forwarding of punched data to processing center	When card punching is completed
7.	Computation of visitor estimates	When punched data are received

Instructions for each task follow:

Task 1--Selection of Sites

The suitability of sites for use of the self-registration method depends on four main factors. First, obviously, visitors must be asked to register or there is no basis for estimates. The method is especially well adapted to sites that already have a self-registration system used to enforce an entrance fee or permit. However, a self-registration system can be set up specifically for use estimation.

Second, the percentage of visitors registering should be fairly high for reliable estimates. The registration rate can be raised by good design and location of registration stations at the entrance sites. Registration can also be encouraged by the frequent presence of uniformed personnel.

Third, visitor-use estimates tend to be more accurate for large sites than for small sites.

Finally, the degree of uniformity within a group of sites should be fairly high if use for some sites is to be estimated from an area-wide relationship without sampling all sites. The sampled sites provide the basis for the estimate. Therefore, the unsampled sites must be matched with sampled sites that are similar in size, type of visitor use, and administration. Destination sites should be matched with other destination sites; one-night transient sites with other transient sites. Placement of the registration stations should be uniform. The amount of enforcement of registration and degree of "official presence" should also be similar for all sites to be grouped. Recreation attractions, provision for trailers, and climate are other factors to be considered in matching sites. These must be largely judgment decisions. Hard and fast rules cannot be written.

Task 2--Selection of Sampling Times

The sampling season should include the main-use period, Memorial Day to Labor Day for many sites.

Sampling schedules are developed in two stages. The first stage is to develop a sampling calendar for the amount of sampling one man could easily do without having to be in two places at the same time. The second stage is to divide the sampling load from one or more sampling calendars among several members of a crew so that each can be scheduled for workdays of normal length and can be given 2 consecutive days off each week.

The procedures for developing a sampling calendar are approximately the same whether sampling is to be done on one site or several sites. The only differences are in the number of sampling hours selected and whether they are assigned to one or several sites. In either case, the steps are as follow:

1. Determine the number of weekdays and nonweekdays in the season. For example, in figure 3 the season from May 29 to September 5 contains 100 days--67 weekdays and 33 nonweekdays. (It was judged that May 29 and July 3 would be more like nonweekdays than normal weekdays because they fall between a weekend and a holiday.)

2. Lay out calendar sheets for the use season, and number the weekdays consecutively (in Fig. 3, 1 to 67). Then number the nonweekdays (in Fig. 3, 1 to 33)--either in a different color or encircled--to distinguish them from the weekday numbers. In figure 3, each day is numbered in the lower right-hand corner of the space for each date.

3. Because 12 daytime and 12 nighttime sample times will be assigned for each recreation site, divide 12 into two segments, to the nearest whole number, in proportion to the number of weekdays and nonweekdays in the season. Thus, using the data in figure 3, 67/100 X 12 = 8 weekday counts during the daytime and 8 weekday counts during the nighttime for each recreation site. This leaves 4 nonweekday counts for daytime and 4 nonweekday counts for nighttime on each site. Note, however, that the assignment of dates for nighttime counts must be independent from the assignment of dates for daytime counts.

4. If one person will participate in the sampling of more than one site, multiply the number of counts of each kind by the average number of sites one person will sample. Figure 3, for example, is for four sites. Therefore, it includes 4 X 8 = 32 daytime counts for weekdays, 4 X 4 = 16 daytime counts for nonweekdays, 4 X 8 = 32 nighttime counts for weekdays, and 4 X 4 = 16 nighttime counts for nonweekdays. If only one site were to be sampled, the count numbers would simply be 8, 4, 8, and 4.

Generally no more than four sites should be assigned to one person for nighttime sampling. There are many more possible sampling hours in daytime than nighttime and if necessary, more than four sites may be assigned to one person for daytime sampling.

5. Select actual sampling times from a table of random numbers. If available tables of random numbers have more than two digits per number, simply use the last two digits in each. Make a separate selection for each category of sampling times (i.e., daytime weekday, daytime nonweekday, nighttime weekday, and nighttime nonweekdays). This is done in two steps. First, from the table of random numbers, select the first number within the range of numbered days on the calendar sheets. For example, in figure 3, numbers for weekdays can be selected between 01 and 67. Disregard larger numbers.

After each number for a day is selected, it is easiest to select daytime sampling hours by continuing along the random table until a number between 08 and 19 is reached. However, if both 2000 and 2100 are used as nighttime sampling hours, it is simpler to select the hour applicable to a date by tossing a coin rather than searching through the random table. For example, we might let "heads" equal 2000 and "tails" equal 2100. Sampling dates and hours are selected alternately until the required number have been selected.

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
Start 28	MAY holiday 29 D-1300 (1)	holiday 30 (2)	31 1	JUNE 1 A-2000 2	2 C-2000 3	3 A-2000 (3)
4 A-0900 (4)	5 B-2000 4	6 B-1800 5	7 D-1500 D-2000 6	8 D-1400 A-2000 7	9 8	10 (5)
11 (6)	12 9	13 B-2000 10	14 A-1500 11	15 A-1700 12	D-0800 16 C-1300 C-2000 13	17 C-1400 D-1900 (7)
18 (8)	19 14	20 C-1700 D-2000 15	21 D-2000 16	22 D-1600 17	23 A-1200 18	24 B-1200 D-2000 (9)
25 (10)	26 19	27 B-2000 20	28 B-1000 C-2000 21	29 A-2000 22	30 B-2000 23	JULY 1 A-2000 (11)
2 B-1400 D-2000 (12)	holiday 3 (13)	holiday 4 (14)	5 C-2000 24	6 D-2000 25	7 26	8 B-1500 (15)
9 D-1600 B-2000 (16)	10 C-2000 27	11 C-2000 28	12 29	13 D-1500 30	14 31	15 A-0800 C-1300 (17)
16 (18)	A-1400 17 B-1600 D-2000 32	18 C-1900 33	19 A-1800 C-2000 34	20 35	21 D-2000 36	22 C-2000 (19)
23 B-2000 (20)	24 A-1600 C-2000 37	25 B-0900 38	26 A-1000 B-1500 39	27 40	28 A-2000 41	29 B-1200 C-2000 (21)
30 A-1700 D-2000 (22)	31 C-1000 D-0800 42	AUGUST 1 A-0900 B-2000 43	2 B-1500 C-1700 B-2000 44	3 45	4 B-0900 A-2000 46	5 B-2000 (23)
6 C-1400 C-2000 (24)	7 C-0800 47	8 D-2000 48	9 49	10 50	11 D-1900 51	12 (25)
13 (26)	14 52	15 53	16 B-1000 54	17 55	18 C-1300 D-2000 56	19 A-1300 (27)
20 (28)	21 57	22 A-2000 58	23 59	24 B-2000 60	25 61	26 C-2000 (29)
27 D-2000 (30)	28 A-2000 62	29 B-2000 63	30 64	31 65	SEPTEMBER 1 D-1700 66	2 A-2000 (31)
3 A-2000 (32)	holiday 4 C-1100 D-1800 (33)	5 C-1500 A-2000 67	Finish 6	7	8	9

Figure 3.--Calendar worksheet.

Be sure that no site has more than one daytime or more than one nighttime sample on the same date. A site may have a daytime and a nighttime count on the same date, provided they were selected independently. Also, different sites may be sampled on the same date, provided that sampling hours are scheduled to give adequate time for each count and adequate travel time between sites. As an example, figure 3 was constructed with the assumption that no count should be scheduled at less than 2 hours from a count on another site.[11] However, if sites are small enough and close enough together to permit adequate sampling of two sites in 2 consecutive hours, this limitation would not apply.

After sampling calendars have been developed to include all sites to be sampled, combine them into a work schedule for the sampling crew. For example, figure 4 shows the work schedule for May 29 to June 30 for a crew of three people responsible for sampling eight recreation sites. Note that sample-count workweeks are irregular. However, workweeks scheduled around random sample counts may have advantages in allowing time for visitor contact, enforcement of entrance permits and fee collection, and prevention of vandalism.

It may be necessary to hire extra people--probably on a part-time basis--to help with nighttime counts. There are as many nighttime counts as daytime counts, but less time to make the counts, so the nighttime work may pile up.

Task 3--Equipment and Administration of Self-Registration System

The necessary equipment is (1) a registration station at the entrance to the site with instructions on a sign and a supply of cards and envelopes (fig. 5) and (2) a card deposit box at each unit within the site. Suggestions for installing registration stations are given below.

A registration station on an island in the center of the road is best. Island locations have resulted in higher registration percentages than locations on the right or left side of the road because drivers can conveniently read the instructions and take a registration card without leaving their cars. The right-hand location is second best.

The registration stations must be kept supplied with cards and envelopes at all times. Completed cards and envelope flaps should be collected from deposit boxes at least once a week. When the cards and flaps are collected, fill in any blank spaces if possible. If the party is still present, missing information should be obtained from them. If they are gone, neighboring visitors may be able to help.

The cards and flaps collected from each site are placed in a sturdy envelope marked with the name of the site. This is very important! If cards from two sites get mixed up, the use estimates for both sites are worthless.

---

[11]Because two sites could not be assigned during the 2 consecutive hours available for nighttime sampling, all nighttime samples were scheduled for 2000 and none for 2100. These samples are used only to determine how many overnight visitors there are, and if most overnight visitors have arrived by 2000, there is no point in extending sampling any later unless it permits one person to sample an additional site.

WORK SCHEDULE

May 29 through June 30

RALPH	DAVE	MRS. GILLESPIE
(Work hours: 0700-1600 except 1200-2100 on June 3 and June 30)	(Work hours: 1200-2100)	(Local resident hired on an hourly basis)
Days off: May 30-31, June 1, 7-8, 13-14, 21-22, 26-27	Days off: June 2-4, 9-10, 17-18, 23-24, 30	

May

	RALPH	DAVE	MRS. GILLESPIE
29	D-1300, H-1500		
30		H-1500	F-2000

June

	RALPH	DAVE	MRS. GILLESPIE
1		A-2000	H-2000
2			C-2000
3	F-1700, A-2000		
4	A-0900		F-2000
5		B-2000	E-2000
6	H-1600	B-1800, H-2000	
7		D-1500, F-1800, D-2000	
8		H-1200, D-1400, A-2000	E-2000
9	E-1200		
10	E-0900		
11	E-0900	F-2000	
13		B-2000	
14		A-1500, H-1900, H-2000	
15	E-0800	A-1700	G-2000
16	D-0800, C-1300	G-1400, F-2000	C-2000
17	C-1400		D-1900
20		C-1700, D-2000	
21		D-2000	
22		D-1600	
23	A-1200		
24	F-0900, B-1200		D-2000
25	G-1000		H-2000
27		B-2000	
28	B-1000	E-1100, G-2000	C-2000
29		E-1500, A-2000	H-2000
30	G-1800		B-2000

Figure 4.--Schedule for a crew sampling recreation sites A,B,C,D,E,F,G, and H.

Figure 8.--Registration station.

Collected cards and flaps may be sent to the central office once a week for key-punching. At the end of the season, send the central office a form 1 (fig. 6), with blocks 1 to 12 and any site closure information filled out, for every site for which use estimates from self-registration are to be made. This includes sites sampled in previous years (situation 2) and sites never sampled (situation 3). Form 1 provides key information for the computer.

Site closure data.--If a site is closed for one or more periods during the season, the number of periods must be shown in the shaded block labeled "No. of closed periods" on form 1. The dates of all closures must be shown on the back of form 1, where spaces are provided for up to eight closures. Note that the site must be closed at least half a day before that day can be included in a "closed" period.

If self-registration data are missing for one or more periods, these can be entered as site closures. Season-long estimates of visitor use may then require adjustment for the missing data.

Task 4--Visitor Sampling

Sample counts of visitors are made at least every fifth year to establish relationships between registration and visitor use at each sampled site. During the sampling year, a total of 24 randomly scheduled on-the-hour counts is required for each site--12 during daytime hours (normally 0800-1900) and 12 during nighttime hours (normally 2000-2100).

The schedule must be followed exactly. Once a count has been scheduled, do not change its time for any reason. It is better to miss a count completely than to reschedule a missed count.

Pilot Test Form 1 DAYTIME SAMPLING RECORD Developed Recreation Sites Self-registration Technique	Year (1-2) --	Serial no. (3-9) -------	Region (10-11) --	
	Forest (12-13) --	District (14-15) --	Principal Site (16-19) ---.-	Kind (20-22) --.-
	Principal Site Name (23-48)		Number of facility groupings (49-51) ---	
Season from (52-53)(54-55) month day to (56-57)(58-59) month day	Earliest sampling hour (60-61) --	Latest daytime sampling hour (62-63) --		
Percent confidence (64-65) --	No. of closed periods (Dates must be entered on reverse side.) - (66)	Complete shaded blocks only for last count of season.		
Number of daytime visitor counts (74-75) --	Number of evening visitor counts (76-77) --	Number of years since visitor counts made (78) -	Card No. (79-80) 01	

Activity Name and Code	Tally Space	Total
PICNICKING--43.1		(10-13) ----
CAMPING (general)--41.1		(14-17) ----
TEAM SPORTS--21.0		(18-21) ----
SWIMMING & BATHING--22.1		(22-25) ----
WATER SPORTS--22.2 & .3		(26-29) ----
BOAT LAUNCH. POWER BOATS--12.0		(30-33) ----
BOAT LAUNCH. NON-POWER BOATS--15.0		(34-37) ----
SPECTATOR SPORTS--1.3		(38-41) ----
VIS EXHIBITS, TALKS--81.1 & .2		(42-45) ----
VIS TOURS--81.3 & .4		(46-49) ----
VIEW SCENERY--1.1		(50-53) ----
OTHER		(54-57) ----
Number of facility groupings occupied		(70-72) ---

Date and hour of sample (73-74) month (75-76) day (77-78) hour	Card (79-80) 1 1	Observer ________

SITE CLOSURE (OR MISSING DATA) INFORMATION

(Year and Serial no. of site punched in columns 1-9)

INSTRUCTIONS:

1. Use one line below to record each period site is closed (or data missing) for one day or more.
2. For each period of closure (or missing data), use the first 4 spaces of the line to record the month and date for the first day of the period. For a day to qualify as "beginning date" the site must have been closed (or data missing) by noon or earlier.
3. For each period of closure (or missing data), use the last 4 spaces of the line to record the month and date for the last day of the period. For a day to qualify as "last date" the site must have been closed (or data missing) until noon or later.
4. Enter the number of lines used in space 66 in the shaded block labeled "No. of closed periods) on the reverse side of this form.

	Beginning date closed month	day	Ending date closed month	day
Line 1	(10-11)	(12-13)	(14-15)	(16-17)
Line 2	(18-19)	(20-21)	(22-23)	(24-25)
Line 3	(26-27)	(28-29)	(30-31)	(32-33)
Line 4	(34-35)	(36-37)	(38-39)	(40-41)
Line 5	(42-43)	(44-45)	(46-47)	(48-49)
Line 6	(50-51)	(52-53)	(54-55)	(56-57)
Line 7	(58-59)	(60-61)	(62-63)	(64-65)
Line 8	(66-67)	(68-69)	(70-71)	(72-73)

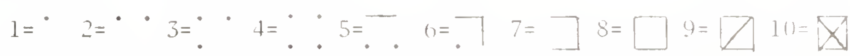
Card No. 1 9 (79-80)

Figure 6.--Daytime sampling record (Pilot test form 1); at right, reverse side is shown.

Make each of the 24 on-the-hour sample counts of visitor use during a systematic tour through the recreation site. This tour may be by vehicle or on foot. It should be planned so that all parts of the site are covered but none is double counted.

Start each sample count so that half the time spent in counting falls on each side of the hour scheduled for counting. For example, if it is estimated that 20 minutes would be needed to count all people present for a sample scheduled at 1600, start the count at 1550 and complete it at 1610. One person can normally complete an on-the-hour count in less than an hour. However, if a large area is heavily used, the count may be started as early as 45 minutes before the hour and continued as late as 45 minutes after the hour, providing up to an hour and a half for the count. If this still is not enough time, divide the counting between two or more people so that no counting needs to be more than 45 minutes from the scheduled hour. In such cases, divide the site along clearly recognizable lines so that no part is either covered twice or left uncovered.

Daytime counts.--During each daytime count, record visitor use by activities listed on form 1, Daytime Sampling Record (figure 6). Use a separate form for each count. Before starting a count, complete the unshaded blocks at the top of the form and the "Date and hour of sample" at the bottom of the form. Record the number of people participating in each activity in the "tally space," using the following tally system:



Note that dots and lines are added until each unit of 10 is completed. Thus:

Record visitors on the basis of the activity they are participating in when seen. If no specific category on form 1 seems to fit, record in the space labeled "Other." Don't make estimates for daytime visitors who seem to be temporarily away from their camp units. If present anywhere on the site, people away from camp units will be recorded under the activities listed on form 1.

The number of facility groupings occupied must be determined at each count. A facility grouping is recorded as occupied if people are present or if equipment is present.

Immediately after a visitor sample is completed, add the counts within each tally space and write the total for that activity in the column labeled "Total."

It is essential to write numbers on the form above blanks so that any unused blanks are to the left of the number. For example, 21 would be written _ _ 2 1. When the form has been completed, check it thoroughly, sign it, and store it in a safe place.

During the last count of the season, fill in the shaded blocks to show Serial no., Region, Principal Site, Kind, Number of facility groupings, Season (beginning and ending dates), Earliest sampling hour (normally 0800), Latest daytime sampling hour (normally 1900), Number of daytime visitor counts (normally 12), Number of nighttime visitor counts (normally 12), and Site closure data. Leave the remaining blanks to be filled in at the central office.

Pilot Test Form 2 NIGHTTIME SAMPLING RECORD Developed Recreation Sites Self-registration Technique	(1-2) Year 19 _ _	(3-9) Serial no. _ _ _ _ _ _ _	Region
	Forest	District	Principal Site Number
	Principal Site Name		

	Tally Space	Total
Number of overnight campers		(10-14) _ _ _ _ _
Types of overnight equipment (number of each) AUTO (Transportation vehicle used as shelter)		(15-17) _ _ _
TENT (Shelter carried within transportation vehicle)		(18-20) _ _ _
TRAILER (Shelter towed behind transportation vehicle)		(21-23) _ _ _
Number of facility groupings occupied		(70-72) _ _ _

Date and hour of sample (73-74) (75-76) (77-78) _ _ month _ _ day _ _ hour	Card (79-80) 12_	Observer ________________

Figure 7.--Nighttime sampling record (Pilot test form 2).

Nighttime counts.--Nighttime counts are made as a basis for estimating overnight use. Each count is tallied on form 2, Nighttime Sampling Record (figure 7). Procedures are similar but not identical to those used for the daytime counts. Before a count is started, fill in the blocks at the top of the form and the "Date and hour of sample" at the bottom of the form. Then count and record the number of overnight campers (individuals, not groups), the number of units of overnight equipment in categories of AUTO, TENT, and TRAILER, and the number of facility groupings occupied.

In most cases, campers will be at their camp units by the time nighttime counts are made (2000 or 2100). If campers gather together at one unit to visit during the evening, or if they are attending an organized campfire program within the same developed site, simply count them wherever they are seen. However, if there is evidence (such as equipment present but vehicle gone) that a camp unit will be occupied by people who are absent from the site when the count is taken, then estimate the number of campers who will be present for the night. This can be done (1) by reading the current registration card (if any) in the deposit box at the unit; (2) by asking people at a nearby unit; or (3) by estimation from the types and amounts of equipment present.

When form 2 has been completed, check it thoroughly, sign it, and place it in a safe place along with the Daytime Sampling Records.

Immediately after the end of the visitor season, send all forms to the central office.

Task 5--Editing, coding, and keypunching of field data

At the central office, site identification data, the self-registration data, and all sample-count data are edited, coded, and keypunched onto cards for computer processing. Self-registration cards and flaps can be edited, coded, and keypunched whenever they are received during the visitor season. However, it is easier to edit and punch the remaining data in one operation at the end of the season.

A self-registration card or flap can be used for estimation only if it shows (1) number of visitors, (2) arrival time and date, and (3) expected departure time and date. Because the proportion of incomplete cards and flaps is normally fairly consistent, the precision of estimates will not be affected much by omitting such cards and flaps.

Editing and coding of entries for keypunching should be done in red or some other color to distinguish them from the original entries. (A felt-tipped pen works well for this.)

Since visitors who use envelopes to pay on a daily basis may fill out several envelope flaps during a stay of several days, names and dates must be compared during editing of these flaps. All data for one stay must be combined on a single flap.

Data on each card and single flap representing a full visit are coded as follows:

Number of people in vehicle--2 digits (e.g., 05)

Month and day arrived--2 digits for month, 2 digits for day of month (e.g., June 6 is coded 0606; July 23 as 0723).[1]

Hour arrived--2 digits. This is the first on-the-hour time the visitor group is present. Thus an arrival time of 2:30 p.m. is coded as 15, 9:00 a.m. as 09, 10:50 p.m. as 23, etc.

Month and day will leave--2 digits for month, 2 digits for day of month.

Hour will leave--2 digits. This is the last on-the-hour time a visitor group is present. Thus a departure time of 2:30 p.m. is coded 14; 9:00 a.m., 09; 10:50 p.m., 22.

At least one copy of form 1 will be received for each site. For sites sampled during the current season, there will be a form 1 for each daytime visitor count. The last form 1 of the season will have most of the shaded blocks filled in. Any incomplete blocks can be filled in at the central office. This copy should be kept on file at the central office for use in completing the shaded blocks of form 1 in succeeding years.

For sites sampled during a previous year, there will be only one form 1. The first 12 blocks and any site closure information should have been completed. The remaining shaded blocks on this form can be completed in the central office by

---

[1] Normally the visitor-use samples will be in the summer months. However, if data extend into 2 calendar years, months during the second year must be coded as 12 plus month number. Thus January of the second year would be coded as 13, February as 14, etc.

reference to the form 1 kept on file from the sampling year. The difference between the current year and the sample-count year should be entered as "Number of years since visitor counts made." Thus, on a form 1 for the 1971 visitor season, with sampling done in 1968, the number of years would be 3.

For sites that have not been sampled but for which self-registration estimates are to be made, there will be a form 1 with the first 12 blocks and any site closure information completed. This should be checked for completeness, but nothing need be added.

A form 2 will be submitted for each nighttime sample count at sites sampled in the current year. This needs only checking for clarity and completeness.

Form 3 is a list of sampling dates and hours (figure 8). Normally four of these are completed at the central office from the forms 1 and 2 for each currently sampled site. Instructions on form 3 should be followed carefully, and the blanks should always be filled consecutively from the top down, without skipping.

Figure 8.--List of daytime or nighttime sampling dates and hours (Pilot test form 3).

Pilot Test Form 3 LIST OF DAYTIME / NIGHTTIME SAMPLING DATES & HOURS (cross out one) Developed Recreation Sites Self-registration Technique	Principal Site Name Year 19 __ __ (1-2) Serial No. __ __ __ __ __ __ __ (3-9)

INSTRUCTIONS:	MONTH DATE HOUR
Write principal site name in space provided. Write the year of sampling in spaces 1 and 2.	__ __ __ __ __ __ (10-15)
Write the serial number of the principal site sampled in spaces 3 to 9.	__ __ __ __ __ __ (16-21)
Sampling times (as months, dates, and hours) for spaces 10 to 75 of this form will come from spaces 73 to 78 at the bottom of the Form 1's and Form 2's for the same principal site.	__ __ __ __ __ __ (22-27) __ __ __ __ __ __ (28-33)
Normally there will be 12 daytime sampling dates and hours. The first 11 of these will be written in spaces 10 to 75 of one Form 3 and the number "02" will be written in spaces 79 and 80 of this form. The 12th date and hour will go in spaces 10 to 15 of a second Form 3 and the number "03" will be written in spaces 79 and 80 of this second form.	__ __ __ __ __ __ (34-39) __ __ __ __ __ __ (40-45) __ __ __ __ __ __ (46-51)
Procedures for evening sampling dates and hours are identical except that the first Form 3 is numbered "06" in spaces 79 and 80 and the second Form 3 is numbered "07" in spaces 79 and 80.	__ __ __ __ __ __ (52-57)
If there are less than 12 daytime or 12 nighttime sampling dates and hours, only one daytime or nighttime Form 3 is used. This is numbered "02" (daytime) or "06" (nighttime) in spaces 79 and 80.	__ __ __ __ __ __ (58-63) __ __ __ __ __ __ (64-69)
Cross out either DAYTIME or NIGHTTIME in block at upper left.	__ __ __ __ __ __ (70-75)
Form completed by: Signature Date	Card No. __ __ (79-80)

The cards to be keypunched from the self-registration data and forms 1, 2, and 3 are as follows (identification codes are shown in parentheses):

Site name card (01)

Site closure card, if needed (19)

List of daytime sampling dates and hours (02, 03)

List of nighttime sampling dates and hours (06, 07)

Self-registration data (10)

Daytime sample-count data (11)

Nighttime sample-count data (12).

On all cards for each site, columns 79 and 80 are used for the card identification codes indicated above.

On all cards for each site, columns 1 and 2 are used for the year and columns 3 to 9 for the serial number assigned by the data processing center for that particular site. These numbers permit cards for a specific year and site to be identified at any time.

Computer cards are punched directly from the coded self-registration cards and flaps and from forms 1, 2, and 3. No decimals are punched for any of the data.

Keypunching details for each type of card follow:

Site name cards.--Only one site name card is punched for each site for each season. The information is punched directly from the blocks at the top of form 1. (This form indicates column numbers for all punches.) For sites currently sampled, the form 1 for the last daytime visitor count of the season should be used, and columns 1 to 66 and 74 to 80 are punched Punching is the same for sampled sites in succeeding years when they are not sampled (situation 2). For unsampled sites, however, site name cards are punched only in columns 1 to 66 and 79 to 80.

Site closure card.--A site closure card is used only when one or more closures (or periods of missing self-registration data) are indicated by a punch in column 66 of the site name card (and in the shaded block labeled "No. of closed periods" on form 1). Data and instructions for punching the site closure card are given on the back side of the form 1 from which the site name card is punched.

Cards for sampling dates and hours.--These are punched directly from form 3 for all currently sampled sites. Again, column numbers are indicated on the form.

Cards for self-registration data.--Computer cards are punched directly from the edited and coded self-registration data from all sites. Information from three self-registration cards or flaps is punched onto one computer card, as follows:

Field number	Card field	Columns From	To
1	Year	1 -	2
2	Serial number	3 -	9
	FOR FIRST REGISTRATION CARD		
3	Number of people in vehicle	11 -	12
4	Arrived month	13 -	14
5	Arrived date	15 -	16
6	Arrived hour	17 -	18
7	Expected departure month	19 -	20
8	Expected departure date	21 -	22
9	Expected departure hour	23 -	24
10	Zip code	25 -	29
	FOR SECOND REGISTRATION CARD		
3	Number people in vehicle	31 -	32
4	Arrived month	33 -	34
5	Arrived date	35 -	36
6	Arrived hour	37 -	38
7	Expected departure month	39 -	40
8	Expected departure date	41 -	42
9	Expected departure hour	43 -	44
10	Zip code	45 -	49
	FOR THIRD REGISTRATION CARD		
3	Number people in vehicle	51 -	52
4	Arrived month	53 -	54
5	Arrived date	55 -	56
6	Arrived hour	57 -	58
7	Expected departure month	59 -	60
8	Expected departure date	61 -	62
9	Expected departure hour	63 -	64
10	Zip code	65 -	69
11	Blank	70 -	78
12	Card number	79 -	80

Cards for sample-count data.--These are punched only for currently sampled sites. For daytime sample-count information, one card is punched for the visitor-count portion of each form 1 completed during the sampling season. For each nighttime count, one card is punched for each form 2 completed during the season. Column numbers for all punches are specified (in parentheses) in the blocks of forms 1 and 2.

Area-wide ID cards.--In addition to the cards punched for individual sites, an area-wide ID card must be punched to identify each area and within it the kind of recreation sites for which area-wide relationships are to be used. The purposes of this card are (1) to provide a label for distinguishing one group of relationships from another; and (2) to list the site data to be used for each set of area-wide relationships.

Columns 1 and 2 of each area-wide ID card are punched with the current year. Columns 3 to 9 are punched with a code number that identifies the area and kind of sites included. This code number can have any combination of letters and numbers but should be consistent with procedures established by the data processing center. Columns 10 through 80 of each area-wide ID card can be used for any further identification desired. For example, these columns might be used for the message "R-4, FORESTS 8 & 9, SMALL TRANSIENT CAMPGROUNDS."

On the back of each area-wide ID card, a member of the central office recreation staff should write two headings and lists of numbers. The first heading is: Use "15" and "16" cards from. This heading is followed by the year and serial number for each site that is to contribute data to one set of area-wide relationships. The second heading is: Use "10" cards from. This heading is followed by the year and serial number for each site for which use is to be estimated by the same set of area-wide relationships. For example, the back of the area-wide ID card for small transient campgrounds might read as follows:

Use "15" and "16" cards from 680018732, 680018767, 680019014, and 670018747.

Use "10" cards from 680018745, 680018752, 680019525, 680019526, and 680019529.

This permits the processing center personnel to assemble the necessary information for developing area-wide relationships and making estimates of visitor use for unsampled sites.

Task 6--Assembly and Forwarding of Punched Data to the Processing Center

As soon as the central office personnel have completed all of the card punching, they should place the cards for each site in the order shown above. Cards should then be bound (with a rubber band) by individual sites and marked with site name and forest. The area-wide ID cards should also be bound together with a rubber band. All of the cards should then be sent to the data processing center or park administrative unit.

Task 7--Computation of Visitor Estimates

When the processing center personnel receive the punched cards from the transmitting office, they will prepare the estimates using the computer programs designed for self-registration data.[13] This will produce printout sheets similar to those on page 2.

[13]Copies of these computer programs are available upon request from the Intermountain Forest and Range Experiment Station, Ogden, Utah.

FOREST SERVICE CREED

The Forest Service of the U. S. Department of Agriculture is dedicated to the principle of multiple use management of the Nation's forest resources for sustained yields of wood, water, forage, wildlife, and recreation. Through forestry research, cooperation with the States and private forest owners, and management of the National Forests and National Grasslands, it strives — as directed by Congress — to provide increasingly greater service to a growing nation.

USDA FOREST SERVICE
RESEARCH PAPER INT-71
1970

THE MOUNTAIN PINE BEETLE IN LODGEPOLE PINE FORESTS

ARTHUR L. ROE AND GENE D. AMMAN

INTERMOUNTAIN FOREST & RANGE EXPERIMENT STATION
Ogden, Utah 84401

THE AUTHORS

ARTHUR L. ROE is leader of the Forest Ecosystems Work Unit of the Intermountain Station at Ogden, Utah.

GENE D. AMMAN is Entomologist on the Mensurational Aspects of Population Dynamics of Forest Insects Work Unit of the Intermountain Station at Ogden.

USDA Forest Service
Research Paper INT-71
1970

THE MOUNTAIN PINE BEETLE IN LODGEPOLE PINE FORESTS

Arthur L. Roe and Gene D. Amman

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401
Joseph F. Pechanec, Director

ABSTRACT

The mountain pine beetle depletes Rocky Mountain lodgepole pine stands by removing periodically the largest, most vigorous trees. Some stands are replaced by succeeding species in 80 to 100 years.

Intensities of mountain pine beetle and dwarfmistletoe damage are influenced by forest associations and elevation. Dwarfmistletoe infection reduces phloem depth and probably results in lower mountain pine beetle brood production.

The probability of lodgepole pine surviving to 16 inches d.b.h. is about two out of three in the Abies lasiocarpa/Vaccinium scoparium association, but only one out of four in the Abies lasiocarpa/Pachistima myrsinites association. The latter association offers the greatest risk to lodgepole pine. More effective beetle control and alternatives such as type conversion, shorter rotations, mixing species, and developing better size and age class distribution must be considered.

CONTENTS

INTRODUCTION

Lodgepole pine (Pinus contorta Dougl.) forests provide an important cover type on more than 15 million acres in 11 states in the western United States. These forests serve many purposes such as cover and scenic backdrops for recreational areas; protective cover for watersheds; habitat for game animals; grazing for domestic livestock; and a storehouse of raw material for lumber, poles, posts, and pulpwood. But without protection and management these forests are transient pioneers giving way to natural forces such as insects, disease, and in the absence of wildfire, to succeeding vegetation. Maintenance of lodgepole pine forests requires both a greater understanding of the continuing biological processes and a high level of management.

Historically, the mountain pine beetle, Dendroctonus ponderosae Hopk. has infested extensive areas of lodgepole pine and probably has been active in the ecosystem as long as there have been lodgepole pine trees. Thorne (1935) uncovered evidence of several early outbreaks including one that was active in the Horse Creek territory in Utah over 180 years ago. He reported other outbreaks occurring in different areas between the years: 1870 and 1880; 1915 and 1917; 1924 and 1925; 1929 and 1932.

Flint (1924) reported an epidemic between 1914 and 1918 in lodgepole pine stands near Monture Ranger Station, Lolo National Forest, Montana.

Beginning in 1909, a small mountain pine beetle outbreak was reported on the Flathead National Forest in the northern Rockies.[1] During a succeeding period of 25 to 30 years, new infestations appeared in the Rocky Mountains and increased to epidemics on the National Forests and Parks and extended as far south as the Cache National Forest in Utah despite some direct control efforts along the way. Infestations were recorded on the Flathead, Lolo, Bitterroot, Beaverhead, Gallatin, Targhee, Teton, Bridger, Cache, and Caribou National Forests and Yellowstone and Teton National Parks. The infestation was considerably reduced, particularly on the northern forests, when extremely low temperatures in December 1932 and again in February 1933 caused high mortality in overwintering broods.

Another extensive beetle outbreak is currently in progress in a number of the Intermountain forests where many extensive stands have reached a high state of susceptibility to beetle attack. Direct control efforts to contain the beetle populations have met with variable success and extensive tree mortality has occurred.

One of the primary silvicultural problems is how to manage lodgepole pine in the face of constant beetle pressure and recurring tree mortality. The objective and scope of this paper is to explore the role of the mountain pine beetle as an ecological agent in lodgepole pine stands primarily in the Teton, Targhee, and Bridger National Forests and in the Yellowstone and Teton National Parks; also, the study points out some research needs and management alternatives.

ROLE OF THE MOUNTAIN PINE BEETLE

The mountain pine beetle, an indigenous organism in lodgepole pine ecosystems, exerts numerous and varied effects upon lodgepole pine stands. The phloem layer of the tree comprises the feeding and breeding habitat of the beetles; they spend a large portion of their life cycle in this layer. The adult beetle feeds upon and constructs an egg gallery in the phloem. The beetle larvae feeding at right angles to the egg gallery, in conjunction with blue stain fungi, girdle the tree and cause its death.

---

[1]Evenden, James C. History of the mountain pine beetle infestation in the lodgepole pine stands of Montana. USDA Forest Insect Laboratory, Coeur d'Alene, Idaho, typewritten report, 25+ pp., illus. 1934.

TREE SELECTION

Not all lodgepole pine trees in infested stands are likely to be attacked and killed by the mountain pine beetle. The beetle first infests the larger diameter trees which usually have thick phloem and are a better food supply. The number of trees killed varies by environmental conditions as reflected in habitat types.

Diameter

Examination of three stands involved in the current epidemic show that the largest and most vigorous trees are attacked first. As the numbers of trees are reduced by mortality the beetles move into smaller trees until the epidemic subsides. Several studies support these conclusions.

Gibson[2] shows the intensity of beetle infestation by diameter classes observed in the Big Hole area of the Beaverhead National Forest from 1925 to 1940 (table 1). All the lodgepole pine trees 12 inches and larger in diameter were killed. But the percent of trees killed decreased rapidly in the smaller sizes below 12 inches in diameter. These data were collected from a lodgepole pine stand; the majority of this stand was in the Douglas-fir vegetational zone and was included in a severe outbreak that covered about 20,000 square miles.

Table 1.--Susceptibility of lodgepole pine trees to mountain pine and secondary bark beetle attacks by 2-inch diameter classes

Trees killed by	d.b.h. classes					
	2	4	6	8	10	12+
	Percent					
Mountain pine beetle	0.1	6.5	27.5	56.5	87	100
Secondary beetles	1.5	5.0	9.0	5.5	1.5	None

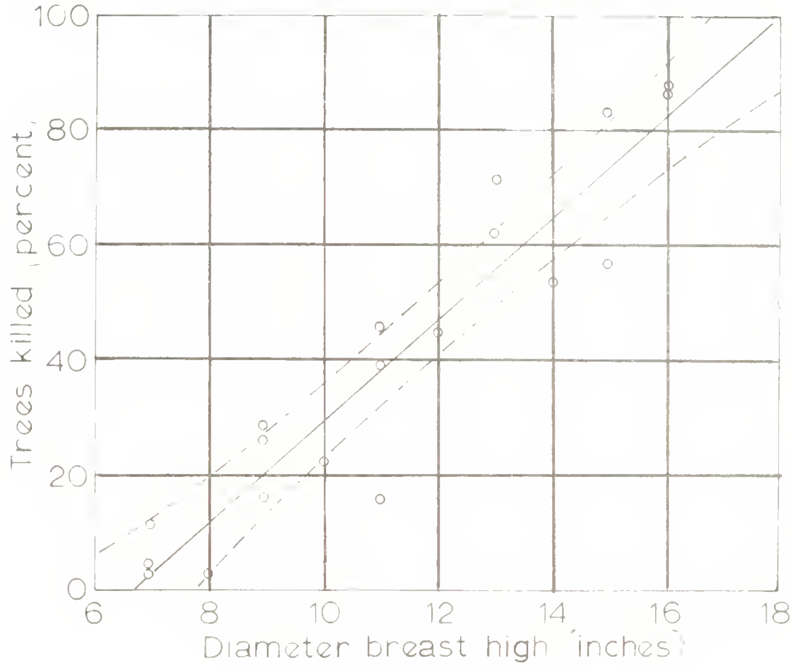
Cole and Amman (1969) concluded from their studies of two stands in northwestern Wyoming that the beetles strongly favor the larger diameter trees in the stand in any given year as well as throughout the duration of the epidemic. Trees killed by the beetles ranged from 1 percent of the 4-inch trees to 87.5 percent of the trees 16 inches d.b.h. and larger. Furthermore, Cole and Amman pointed out that large infestations of the mountain pine beetle are dependent upon the presence of large diameter trees (14 inches d.b.h. and greater) within a lodgepole pine stand. They also speculated that this beetle is a food-limited insect within a given area because only trees 14 inches d.b.h. and larger contribute sufficient numbers of beetles to maintain or cause an increase in infestations.

Studies by Hopping and Beall (1948) near Banff, Canada, revealed about a 5-percent increase in infestation intensity for each inch increase in diameter; few trees under 6 inches d.b.h. were attacked. Our study shows an increase in percent of trees killed of about 8.8 percent for each 1-inch increase in diameter (figure 1). In the areas examined very few trees below 7 inches in diameter were killed.

---

[2]Gibson, Archie L. Status and effect of a mountain pine beetle infestation on lodgepole pine stands. USDA Forest Insect Laboratory, Coeur d'Alene, Idaho, unpub. typewritten office report, 34 pp. 1943.

Figure 1.--Trees killed by mountain pine beetles is related to diameter of host trees. Confidence limits at the 95 percent probability level are shown by the dash lines.



Phloem Thickness

Considerable work is in progress to determine the effect of phloem thickness on beetle attack. Amman has shown in laboratory studies that successful brood development is correlated with phloem thickness. Trees having phloem less than about 0.12 inch thick do not produce enough brood per unit area of bark surface to sustain a successful infestation.

Phloem thickness among lodgepole pine trees is highly variable. However, we have observed that the beetles tend to attack and kill the trees having thicker phloem and pass up many trees of similar diameter that have thinner phloem. Observations show that the thickness of the phloem determines whether the insect can maintain or increase its numbers in the stand. During an epidemic Roe has observed beetles selecting trees in the stand possessing the thickest phloem; and sometimes beetles choose the portion of an individual tree having the thickest phloem. Hopefully, we will gain a greater understanding of the relationship between thickness of phloem and diameter of tree and this may help provide an index to tree susceptibility.

Habitat

Early work by Gibson[2] pointed to the differences in beetle infestation intensity that are related to elevation. He reported that the infestation appeared to be less intensive on the upper end of his sample strips than on the lower. In the Beaverhead National Forest data (table 2), the Elkhorn strip sample--located highest in elevation and in the subalpine fir-Engelmann spruce vegetational zone--showed the fewest beetle-killed trees. The Bitterroot Forest plot data in table 3 displayed the same trend except in the plot at the lowest elevation. Amman (1969) found that brood production in bark of a given thickness is inversely related to elevation. Differences in the rate of tree stocking do not seem to be great enough to explain the variation in infestation intensity in these studies.

Table 2.--Intensity of tree killing by the mountain pine beetle (Beaverhead National Forest 1923-1940)[1]

Location	Elevation	Vegetational zone	Trees per acre before infestation[2]		Trees per acre killed by the mountain pine beetle	
			Lodgepole pine	Other		
	Feet		- - - - -Number- - - - -		Number	Percent
Battlefield	6,400-7,300	Douglas-fir	1,203	21	209	17.4
Wise River	6,400-7,300	Douglas-fir	533	180	46	8.6
Elkhorn	7,200-7,950	Subalpine fir-Engelmann spruce	1,044	12	24	2.3

[1]Compiled from data collected by Archie Gibson.
[2]Includes trees 3 inches d.b.h. and larger.

Table 3.--Intensity of tree killing by the mountain pine beetle (Bitterroot National Forest 1923-1940)[1]

Plot	Elevation	Vegetational zone	Trees per acre in spring 1923[2]			Trees per acre killed by the mountain pine beetle	
			Lodgepole pine	Douglas-fir	Ponderosa pine		
	Feet		- - - - - - - - Number - - - - - - - -			Number	Percent
A	5,400	Douglas-fir	320	32	--	272	85.0
B	5,400	Douglas-fir	32		136	LPP 32 PP 116	100.0 85.3
C	5,100	Douglas-fir	260	72	--	216	83.1
D	6,000	Douglas-fir	172	40	--	140	81.9
E	7,100	Subalpine fir-Engelmann spruce	172	--	--	112	65.1
F	4,750	Douglas-fir	256	--	--	112	43.8

[1]Compiled from data collected by Archie Gibson.
[2]Includes trees 3 inches d.b.h. and larger.

Habitat types reflect differences in environments (Daubenmire 1952, 1961; Daubenmire and Reed;[3] Roe 1967; Illingworth and Arlidge 1960). Therefore, it is plausible that beetle behavior and survival will differ in the various habitat types also. Reconnaissance of 42 stands in three of the most extensive types containing lodgepole pine disclosed some differences in the intensity of beetle activity. Each stand visited was classed in one of four categories as follows:

Intensity class	Criteria
1	No beetle-killed trees present.
2	Less than one-third of the susceptible trees killed.
3	One-third to two-thirds of the susceptible trees killed.
4	Over two-thirds of the susceptible trees killed.

Trees 6.6 inches d.b.h. and larger were regarded as susceptible to beetle attack. The three habitat types considered were as follows:

Habitat type	Elevation (feet)		Exposure
	Mean	Range	
Abies lasiocarpa/ Vaccinium scoparium	7,470	6,550-8,450	All exposures
Abies lasiocarpa/ Pachistima myrsinites	7,183	6,700-7,800	Mostly northwest
Pseudotsuga menziesii/ Calamagrostis rubescens	6,474	6,000-7,750	All exposures and plateaus

In addition to beetle infestation, the intensity of dwarfmistletoe infection was also estimated in the same stands. Infected and noninfected dominant and codominant trees were counted and the proportion recorded in one of four categories as follows:

Intensity class	Criteria
1	All examined trees free of dwarfmistletoe.
2	Less than one-third of examined trees infected.
3	One-third to two-thirds of the examined trees infected.
4	More than two-thirds of the examined trees infected.

---

[3]Daubenmire, R., and R. M. Reed. Progress report on a study of forest types in the Wind River Mountains, Wyoming. Ditto report on file, Intermountain Forest and Range Experiment Station, Ogden, Utah; limited distribution, 3 pp. 1968.

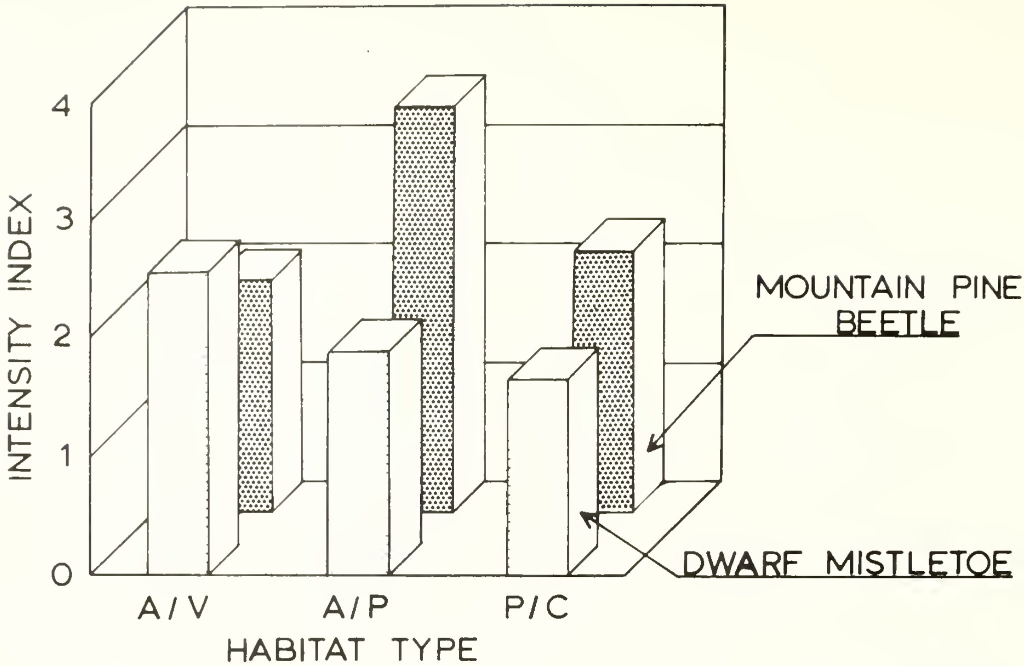


Figure 2.--Relative intensity of mountain pine beetle tree killing and dwarfmistletoe infection on three habitat types. A/V = Abies lasiocarpa/Vaccinium scoparium; *A/P =* Abies lasiocarpa/Pachistima myrsinites; *and P/C =* Pseudotsuga menziesii/Calamagrostis rubescens.

Intensity indexes for both beetle infestation and dwarfmistletoe infection were calculated as weighted indexes. The relative indexes derived simplify the comparisons by transforming the data to comparable units.

The higher elevation stands represented by the Abies lasiocarpa/Vaccinium scoparium habitat type show the lowest index of mountain pine beetle infestation as illustrated in figure 2. At the same time, these stands sustain the highest index of dwarfmistletoe infection. Whether or not this inverse relationship has biological meaning is largely unknown. However, the relationship is relevant if the ability of the mountain pine beetle to produce sufficient brood to sustain an infestation is related significantly to the thickness of the phloem layer. A small sample of 20 randomly selected trees taken in a lodgepole pine stand on the Moose Creek Plateau, Targhee National Forest, suggests that the thickness of the phloem in lodgepole pine trees is significantly reduced in trees moderately to heavily infected by dwarfmistletoe. The results are tabulated as follows:

Level of dwarfmistletoe infection	Radial thickness of phloem (Inches)	
No infection	0.170 ±0.0213	P = 0.95
Medium to heavy infection	0.112 ±0.0218	P = 0.95

A high proportion of the trees in the sampled area would not be suitable for sustaining an infestation if we assume that a radial phloem thickness of about 0.12 inch is needed.

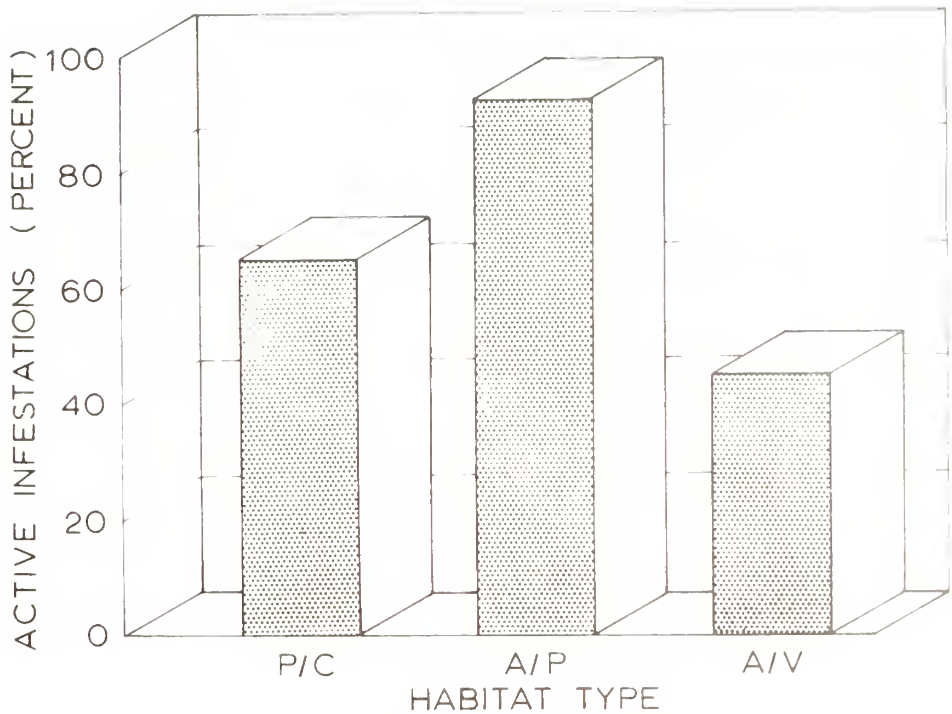


Figure 3.--The percent of stands showing active infestation within habitat types.

By far the most intense beetle activity was found in the Abies lasiocarpa/ Pachistima myrsinites habitat type which exists largely in the middle elevational zone. The high intensity index of 3.4 (figure 2) indicates that the bulk of the stands examined were classed in the medium to heavy categories of susceptible tree killing. The Dell Creek stand, which is described later in this report, exemplifies the state of advanced stand depletion, succeeded by subalpine fir growth commonly found in a large but undetermined portion of the Abies lasiocarpa/Pachistima myrsinites habitat type. The incidence of dwarfmistletoe infection ranked relatively low in this habitat type (see figure 2) with an intensity index of 1.9. There is no way of knowing how much past mortality was caused by dwarfmistletoe in these stands.

A large proportion of the stands examined in the Pseudotsuga menziesii/ Calamagrostis rubescens habitat type were in the light damage category resulting in a moderate intensity index of 2.2 (figure 2). This index places the type in an intermediate position among the three habitat types with respect to beetle activity. The lowest occurrence of dwarfmistletoe infection was found in the Pseudotsuga menziesii/Calamagrostis rubescens habitat type. The distribution of the disease was spotty with patches of heavy infection interspersed with extensive areas showing little or no infection.

A high proportion of the 42 stands examined sustained currently active mountain pine beetle infestations. The least activity, 44 percent of stands with active infestations, was found in the highest habitat type, Abies lasiocarpa/Vaccinium scoparium (figure 3). On the other hand, the Abies lasiocarpa/Pachistima myrsinites habitat type ranked first with active infestations in 92 percent of the stands examined. The pine grass type, Pseudotsuga menziesii/Calamagrostis rubescens, was midway with 64 percent of the stands sustaining active infestations.

Figure 4.--Lodgepole pine killed at Dell Creek (overall view).

Figure 5.--Lodgepole pine killed at Dell Creek (beetle killed, fallen timber).

All three habitat types showed evidence of repeated infestations. Eighty-six percent of the stands on all the habitat types showed evidence of one or more infestations but 47 percent have survived both the earlier and the more recent infestations. The occurrence of repeated attacks was about the same in all three habitat types.

EFFECTS OF BEETLE INFESTATIONS

The effects of mountain pine beetle infestations are very important in the dynamics of lodgepole pine stands. These effects vary from the abrupt stand depletion of single infestations to the long range genetic selection caused by repeated infestations.

Stand Depletion and Replacement

Lodgepole pine stands depleted by mountain pine beetle infestations usually are replaced in one of two ways. The decimated stands may be succeeded by other species in the absence of fire or they may be replaced by lodgepole pine seedlings following a fire.

Succession

Studies on three stands of lodgepole pine in the Targhee and Teton National Forests have provided some information concerning the effect of mountain pine beetle infestations. Specifically, three facts of interest were developed: namely, (1) beetle infestations do in some instances occur at varying intervals within the same stand until the lodgepole pine is largely eliminated; (2) residual trees accelerate their growth when the beetle-infested trees die; and (3) growth of succeeding tree species is stimulated either by the release of existing reproduction or the establishment of new trees in the stand openings created by the death of beetle-infested trees. The stand data were collected on 1/10-acre plots systematically located within the stands. Sample trees on each plot were bored to determine age and past diameters.

Dell Creek.--The most interesting stand studied grows in Dell Creek on the Teton National Forest. Many large lodgepole pine windfalls attest to past beetle infestations. Lodgepole pine trees killed in the most recent infestation, with a few exceptions, still remain standing; but the trees on the ground were killed by beetles in earlier infestations (figures 4 and 5). Although we were unable to date the fallen trees, they obviously had been on the ground for various lengths of time. Some were decayed to such an extent that only remnants of recognizable material were left. Despite an advanced state of decay in some of the older windfalls, beetle engravings were visible on small sound remnants of the decayed boles.

Evidence obtained from the increment cores taken in this stand suggests that at least four mountain pine beetle infestations have occurred since 1892. The subalpine fir in the present stand developed from an understory that has been released by the periodic death of lodgepole pine overwood to become the dominant stand presently on the area (figure 6 and table 4). The sampling errors for the total values of Table 4 generally did not exceed 10 percent at the 95 percent probability level. Significant periods of release found in the subalpine fir are shown in the following tabulation:

Period	Percent of sample trees showing significant release
1892-1907	95
1919-1927	60
1937-1947	45
1956-1964	40

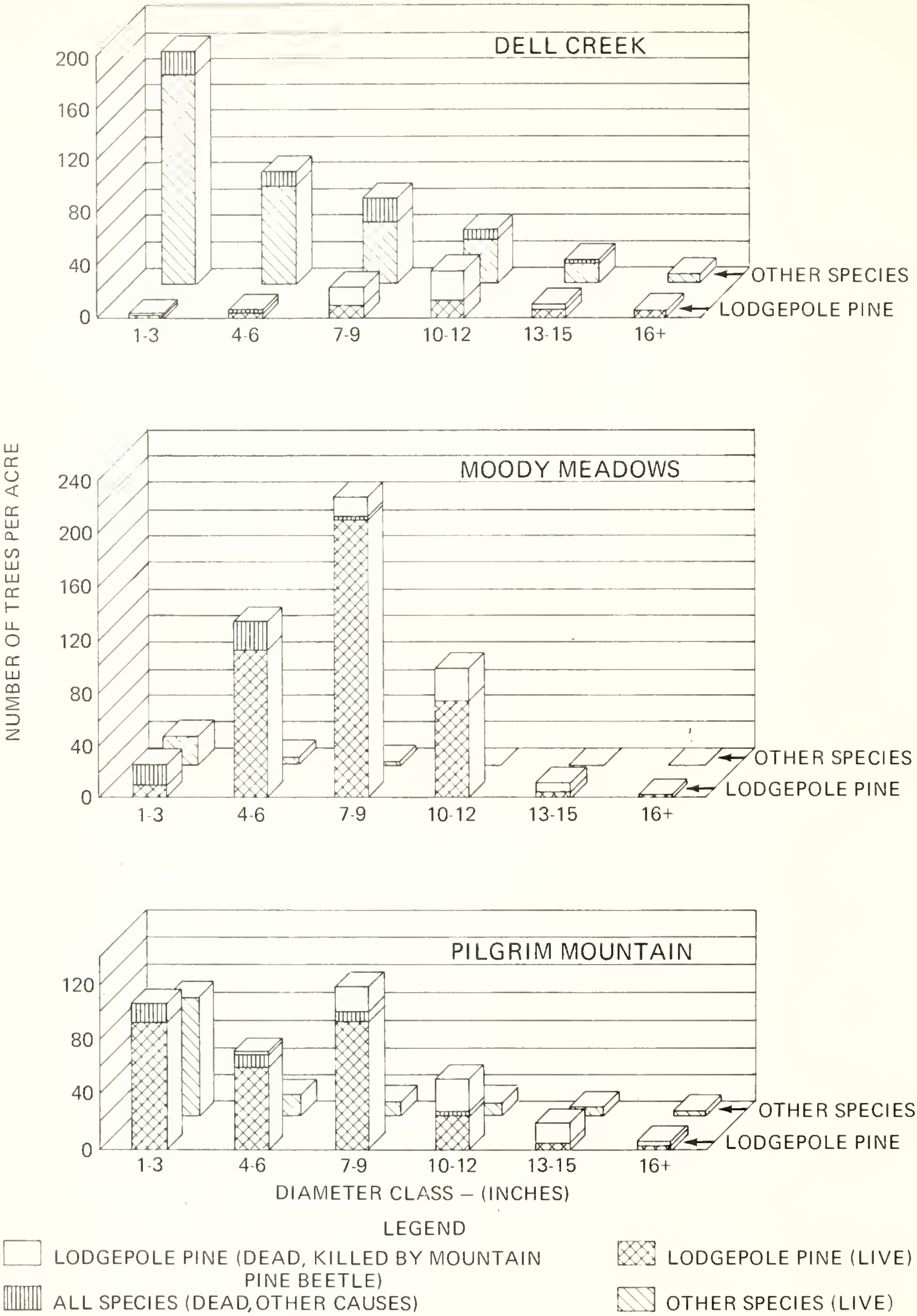
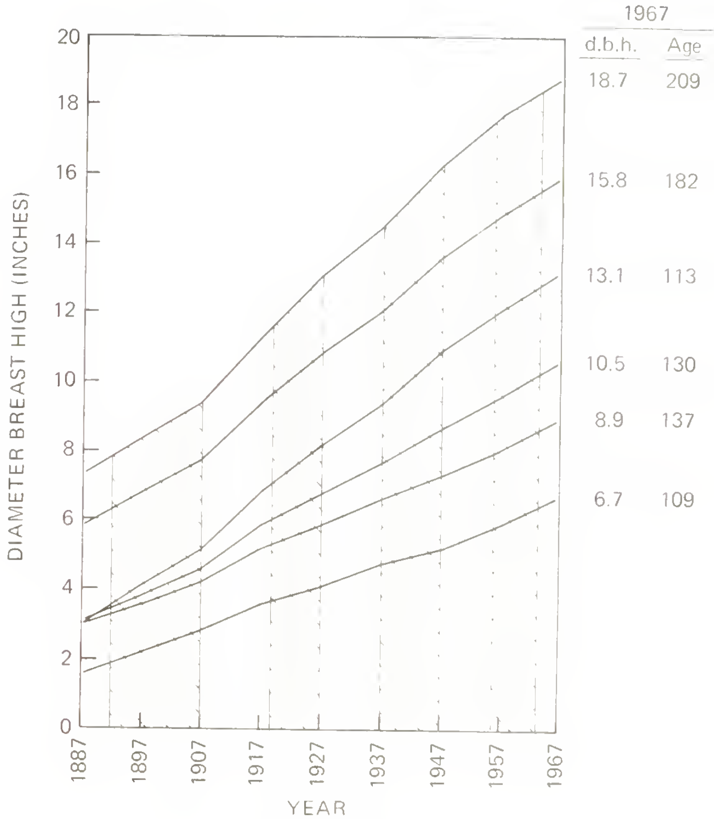


Figure 6.--The distribution of post-epidemic live and dead trees on Dell Creek and Pilgrim Mountain areas, Teton National Forest, and the Moody Meadows area, Targhee National Forest.

Figure 7.--Diameter trend curves of residual subalpine fir trees during four mountain pine beetle infestations in the lodgepole pine overwood, Dell Creek, Teton National Forest. The superimposed crosshatched bars show the periods of infestation.



Curves showing the trend of past diameters in the subalpine fir understory and the periods of beetle infestations superimposed over them are presented in figure 7. The changing upward trend in these curves reflects the release of the understory following the death of lodgepole pine in the overwood. For example, the rather abrupt upward change in the curves from 1907 to 1927 reflects an improvement in diameter increment during that period. It is noteworthy that all the trees in the stand did not show simultaneous release as would be expected from weather effects. Furthermore, the available weather records from the nearest but somewhat distant stations show generally below average precipitation between 1917 to 1937.

The greatest release of subalpine fir followed the first suspected infestation that occurred from 1892 to 1907. During that period 95 percent of the cores showed significant release and this is reflected in the upward trend of diameters following 1907. This trend continued for two decades into the middle of the moisture deficient period, 1917 to 1937, as well as through the second infestation. During the third infestation, 1937 to 1947, the diameter curves steepened again, probably reflecting the release during that period. While the larger trees showed the greatest release effect during the earliest infestation, the three smaller classes of trees displayed continued response following the later infestations. The earlier infestations apparently involved the death of greater numbers of lodgepole pine trees than the later ones; consequently, the earlier infestations had a greater release effect upon the subalpine fir stand. Furthermore, the larger subalpine fir trees had attained a more dominant position in the crown canopy by the time of the last infestation; therefore, they were not as subject to release as the smaller trees. The curves illustrate

Table 4.--Basal area summarized for three areas examined that have sustained one or more mountain pine beetle infestations

Tree condition	Dell Creek	Moody Meadows	Pilgrim Mountain
		Square feet	
		LODGEPOLE PINE	
Live	14.9	137.8	66.5
Dead[1]	27.5	28.8	46.8
Dead[2]	--	5.6	6.2
Total	42.4	172.1	119.5
		SUBALPINE FIR AND OTHER SPECIES	
Live	73.8	1.7	26.5
Dead[2]	17.0	--	--
Total	90.8	1.7	26.5
		ALL SPECIES	
Live	88.7	139.5	93.0
Dead[2]	44.5	34.3	53.0
Total	133.2	173.8	146.0

[1]Killed by mountain pine beetle.

[2]Other causes.

the development of the fir understory as the lodgepole pine overwood was reduced by repeated beetle infestations. Some mortality also occurred in the subalpine fir stand as reflected by the 17.0 square feet of basal area recorded under dead trees in table 4.

Moody Meadows.--Another lodgepole pine stand investigated by Roe near Moody Meadows on the Rexburg District of the Targhee National Forest has been infested twice. The first infestation occurred approximately 1937 to 1947. Some control effort, felling and spraying infested trees, was applied in the stand in 1946 (figure 8). This first infestation was light and was probably checked by the control effort or the beetles were unable to sustain themselves in the thin-barked trees in the stand. But now, 21 years later, the same stand is reinfested and the latter infestation is more intensive than the former--46.9 trees per acre killed in the current infestation as contrasted with 17.7 trees per acre in the first. The present infestation has killed trees in the 7- to 14-inch range amounting to 16.7 percent of the total basal area in the stand.

Trees in the residual stand with diameters 4 inches and larger range from 54 to 106 years in age with a mean age of 87 years. Some lodgepole pine trees up to 16 inches d.b.h. can be found in the stand. The Moody Meadows stand is stocked with 516 trees per acre, 1 inch d.b.h. and larger, and these are distributed among diameter classes as shown in figure 6.

Residual lodgepole pine trees in the Moody Meadows stand show definite release as illustrated by the upward trend in diameter following the 1937 to 1947 infestation (figure 9). The release effect appears to be most pronounced in the larger trees, particularly those that were located either in or near the margin of the openings

Figure 8.--View of a portion of the Moody Meadows stand on the Targhee National Forest, showing stumps and treated trees from the 1946 control effort. Note the denser stem of smaller trees in the background.

created in the earlier infestation. The released trees have continued to grow well to the present time, but trees in other parts of the stand showed signs of growth reduction for several years prior to 1967. Significant release has not yet become apparent from the thinning caused by the current infestation.

Losses to other causes are proportionately greater in the smaller trees as illustrated in figure 6. Few trees below about 6.5 inches were killed by the mountain pine beetle. This stand near Moody Meadows can still sustain a number of beetle infestations. Mortality has been light, probably because of the small size and thin bark of the trees. However, further growth of residual trees will provide suitable trees for future infestations.

A subalpine fir understory of about 29 trees per acre averages 2.62 inches in diameter and ranges from 1- to 7-inch trees. In addition, 1,115 subalpine fir seedlings 3 inches high to 1 inch d.b.h. per acre are growing in the stand which will fill the overwood openings as they are created by future beetle infestations (figure 10). The subalpine fir distribution by diameter classes simulates a J-shaped curve thereby demonstrating succession of lodgepole pine by subalpine fir.

Pilgrim Mountain.--This stand of lodgepole pine is in the northwestern part of the Teton National Forest bordering the Teton National Park. It is currently infested with its first known attack of mountain pine beetles. The stand contains 492 trees per acre that are 1 inch and larger in diameter. The age of the residual trees 4 inches d.b.h. and larger ranges from 33 years to 113 years with a mean age of 76 years. The distribution of trees by diameter groups is shown in figure 6 and stand basal areas are shown in table 4. The overwood includes trees up to 21 inches in diameter although all lodgepole pine trees 18 inches and larger have been killed in the current beetle infestation. Furthermore, trees down to and including 6.6 inches d.b.h. have been killed as shown in figure 4. Losses caused by factors other than the mountain pine beetle are proportionately greater in the smaller d.b.h. classes.

At present, no well defined release effect is evident in the diameter trends for the Pilgrim Mountain stand, and diameters show a steady increase through the life of the stand.

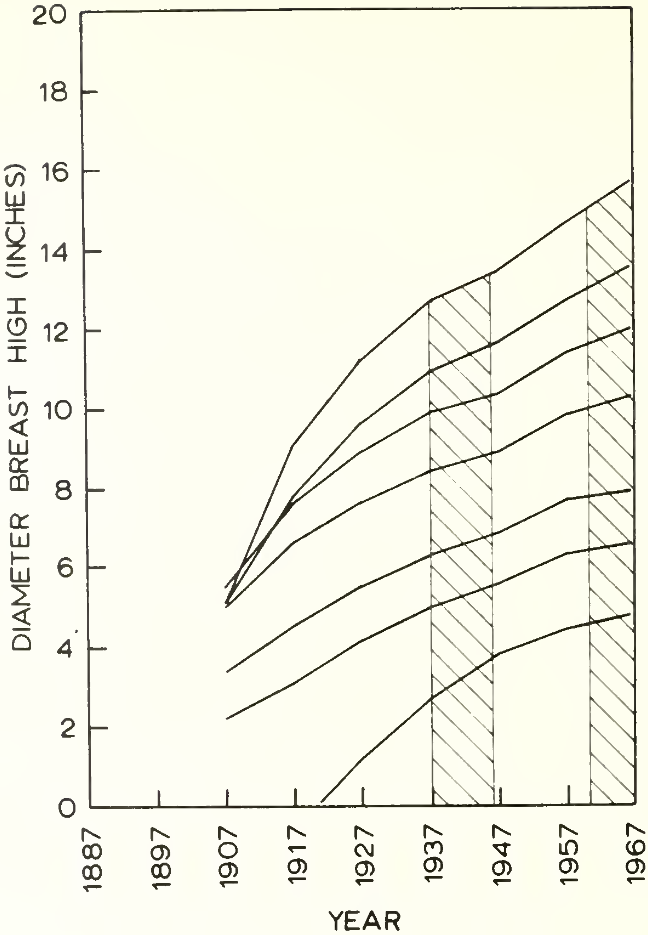


Figure 9.--Diameter trend curves of residual lodgepole pine trees in the Moody Meadows area, Targhee National Forest. The two periods of beetle infestation are shown by superimposed crosshatched bars.

The substantial understory consists mainly of subalpine fir and some Douglas-fir and comprises about 18.5 percent of the stand basal area shown in table 4. These trees average about 3.75 inches d.b.h. including trees from 1 to 15 inches in diameter. The distribution of these trees by diameter groups as illustrated in figure 4 resembles a J-shaped curve which is typical of succeeding species. A large number of seedlings (2,812 per acre) under 1 inch d.b.h. (mostly subalpine fir) provides a reservoir of trees not shown in figure 6. When released by the death of beetle infested lodgepole pines, these seedlings will grow to larger sizes and become more prominent in the stand.

One of the most obvious effects of tree killing by mountain pine beetles is the depletion of the lodgepole pine stand. This effect is rather dramatic and can be observed readily in the "red top" or faded trees that appear in the stand. The dead trees gradually fade from the conspicuous "red top" condition to a gray appearance in 2 to 3 years and begin to fall and accumulate on the ground within about 5 years after the infestation subsides (Flint 1924).

Individual trees live and grow in harmony with their environment which in turn is modified by the trees themselves. This modification results from processes such as shading the forest floor, intercepting snow and rain, reducing wind movement over the ground, utilizing soil moisture and nutrient materials, and adding organic matter to the soil as well as cycling minerals, and many others.

Figure 10.--Subalpine fir and Douglas-fir seedlings grow in stand openings created by mountain pine beetle infestations. Moody Meadows area, Targhee National Forest.

When a portion of the stand dies it causes changes in light, temperature, moisture accumulation, and soil moisture, among others, and thereby creates a new niche in the environment. This ecological niche is soon filled by the growth of newly established seedlings--chiefly more tolerant species--or the accelerated growth of existing trees or other vegetation. The Dell Creek data are a good example of a stand in which the displacement of lodgepole pine has progressed to an advanced stage. During the period of depletion the stand exists in varying degrees of mixtures of dead trees, green residuals, and succeeding species.

Stand structure in the Dell Creek stand, before stand depletion and accelerated understory growth changed it, probably compared well with the present stand structure in the younger Pilgrim Mountain stand (figure 6). Subalpine fir ranging from 6.7 to 18.7 inches in the present Dell Creek stand had a mean d.b.h. of 3.4 inches and a range of 1.6 to 7.3 inches in the stand 80 years ago. The subalpine fir contained in the present Pilgrim Mountain stand averages 3.8 inches d.b.h. and represents a range of 1 to 21 inches in diameter. We have been unable to reconstruct the depleted lodgepole pine stand in the Dell Creek area, but considering the volume of material on the ground it appears to have been a well stocked stand. If we assume the same rate of lodgepole pine depletion and subalpine fir understory growth on Pilgrim Mountain as occurred in Dell Creek, it is conceivable that the Pilgrim Mountain stand could arrive at nearly the same condition in about 80 years.

Regeneration

It is likely that many beetle-decimated lodgepole pine stands containing residual seed trees with serotinous cones have burned over in the past and reseeded promptly to establish new lodgepole pine stands. For example, the Sleeping Child Fire, touched off by a lightning strike in 1961, burned in excess of 25,000 acres of lodgepole pine and associated stands on the Bitterroot National Forest.[4] This fire burned lodgepole pine stands that had sustained heavy damage by a mountain pine beetle infestation from 1928 to 1932 when a large proportion of the dominant and codominant trees was destroyed. Following the fire, a large part of the burn (over 15,000 acres) restocked naturally

---

[4]Office report, Northern Region, U.S. Forest Service. Report on file at Intermountain Forest and Range Experiment Station, Ogden, Utah.

with lodgepole pine seedlings (figure 11). Four years after the burn, 10,000 acres were stocked so heavily with seedlings that thinning would be required to place the stand in good growing condition. In addition to providing conditions for area restocking, the fire cleaned up accumulated fuel that resulted from the beetle attack. Eighty to 90 years from now these newly established lodgepole pine trees will reach sizes attractive to the beetles; then these trees probably will be ready for another mountain pine beetle infestation.

All of the stands that originated during past years of high fire occurrence in the Rockies have reached simultaneously a stage of increased insect susceptibility. This means that the increased susceptibility is present over extensive areas. When these forests reached the proper stage of growth (i.e., diameter and phloem thickness) they provided the habitat in which the beetle populations could build up and sustain infestations. Furthermore, the outbreaks spread over wide areas because trees of susceptible diameter and age occurred extensively. However, repeated beetle infestations, dwarf-mistletoe infection, fire, and logging all have contributed to stand changes resulting in the variability of present lodgepole pine stands as well as conversion to other forest types. Tackle (1954) recognized at least six different stand types including both pure and mixed stands. He pointed out most of the above-mentioned factors in stand formation, but he failed to recognize insects, particularly the mountain pine beetle, among them. From our observations we conclude that the mountain pine beetle has exerted widespread, and in some instances rather dramatic, influence upon stand formation in Rocky Mountain forests.

The absence of fire in lodgepole pine stands, whether caused by organized fire protection or natural controls, combined with stand depletion by the mountain pine beetle, favors the displacement of lodgepole pine. The establishment and growth of succeeding trees, especially of Douglas-fir at the lower elevations and subalpine fir and spruce at the higher elevations, are encouraged by the environment in the beetle-decimated stands. Unless wildfire runs through these stands before repeated beetle infestations and other agents of mortality remove most of the residual seed-bearing lodgepole pine, the stand eventually will convert to climax species. The historical role of fire in stand formation and in the sustaining of lodgepole pine was stressed by Horton (1956) in Alberta. Fire or logging may intervene to reverse the successional trend and reestablish lodgepole pine as happened in the Sleeping Child fire.

Growth Potential

Mountain pine beetle infestations remove the most vigorous element of the stand because they prefer the largest trees, usually with the thickest phloem. The residual trees are usually of the intermediate and suppressed crown classes with some slow growing dominants and codominants. Occasionally the smaller residual trees are older than the larger trees in the stand. The stand structure becomes less favorable for rapid tree growth with each repeated infestation.

Even though the residual trees are released they rarely grow as large, within the same time, as those which had been killed by the mountain pine beetle. The limited number of residual lodgepole pines in heavily depleted stands is made up of old (sometimes nearly 300 years), extremely thin barked trees. These trees often grow extremely slowly with 10-year diameter increments of as little as 1/10 inch or less.

Genetic Selection

Genetic selection, a more subtle effect, probably is accomplished through the selective killing of lodgepole pine trees by the beetle. Because each beetle infestation removes the most vigorous element (i.e., the largest trees) of the stand, it is

Figure 11.--Extensive areas of the Sleeping Child Burn became stocked so heavily that thinning has been required to promote tree growth.

reasonable to speculate that the faster growing genotypes are being destroyed before the lodgepole pine trees can restock the area. Trees as young as 62 years have sustained beetle infestations so that selection sometimes begins early in the life of these stands. If wildfire strikes the stand before the selection process has progressed too far and seeds from serotinous cones are released to regenerate the stand, such selection may not be of much consequence. However, if fires or other stand-regeneration processes do not occur before the stand reaches an advanced stage of depletion the selection is likely to have more effect.

Some Secondary Effects

Populations of secondary beetles, such as Ips pini Say, build up in harmony with mountain pine beetle infestations (Gibson[2]). Emerging from trees either killed or weakened by mountain pine beetles, these secondary beetles may be present in sufficient numbers to kill trees. The secondaries attack principally smaller trees and therefore do not have the devastating effect on the stand that the mountain pine beetle does. In some instances, the tree killing by Ips beetles may amount to a thinning of the smaller residual trees.

Windthrown beetle-killed trees often cause destruction or damage to trees in the succeeding understory. The beetle-killed trees begin to topple within 5 years after an infestation has declined (Flint 1924) and such windthrow may continue for 10 or more years following the end of the infestation according to Gibson.[2] Gibson observed heavy damage among the trees in the very small diameter classes and even among seedlings.

Depending upon the amount of stocking present, this reduction in numbers may be somewhat beneficial to the stand; or, in sparsely stocked stands the removal of a few trees may seriously hamper natural restocking. Furthermore, the mechanical injury of these understory trees makes them more subject to heart rots and other fungus infections by providing the avenue of entrance in the scarred boles. This type of damage may be rather difficult to predict. The effect of damage and subsequent fungus attack may not manifest itself until many years after the epidemic.

Gibson also pointed out that direct windthrow of residual green trees in heavily attacked stands results when these trees lose the protection of trees killed by the beetles.

Increased fire hazard resulting from tree killing and windthrow has been pointed out by many writers including Flint (1924) and Gibson.[2] Flint estimated that the amount of labor necessary to control a fire in areas having large accumulations of beetle-killed trees may be doubled. There is no question but that the cost of fire suppression in beetle-decimated stands will be considerably higher for two reasons: (1) the physical job of removing the extra load of windfalls requires more labor and machine time for operations such as fireline construction; and (2) the large volume of dead material, either standing or on the ground, creates a much hotter fire than would normally occur resulting in a more difficult suppression job. The hotter burn also may have more far-reaching effects on soils than more normal cooler fires. More research is required to increase our knowledge of the effect of such hot fires on soils.

MANAGEMENT ALTERNATIVES

The nearly constant mountain pine beetle pressure being exerted in the Intermountain lodgepole pine forests poses perplexing management problems. Among them are such problems as successful beetle control, acceptable risk from stand decimating forces, and long term management goals and plans to cope with the beetle.

BEETLE CONTROL

Expensive stopgap measures such as direct control involving the spraying of standing or felled trees with penetrating toxic chemicals provide only a holding action until the potentially susceptible trees can be disposed of in some other way.[5] A great deal of mortality results despite any immediate success of the control measures. The unpredictability of these control measures and the relative certainty of reinfestation of the stand later on leaves the manager with relatively little choice of action. He must cut and regenerate the lodgepole pine stand as soon as possible if he wishes to avert further loss, or risk the loss of the stand to further depletion by beetle activity and ultimate displacement by other species which are sometimes considered less desirable.

One of the critical needs is to develop more effective and predictable beetle control measures, especially for use in combination with silvicultural practices.

Pheromones (chemicals produced and used for communication by insects) offer, at this time, some remote promise of control through population manipulation. The pheromones of several species of bark beetles have been identified (Renwick 1967; Silverstein et al. 1966a, 1966b, 1968). More recently, research sponsored by the

---

[5]Memorandum dated 10/11/68 from Floyd Iverson, Regional Forester, Region 4, to Chief of Forest Service, reporting on the R-4 field survey. Report on file at Intermountain Forest and Range Experiment Station, Ogden, Utah.

Montana-Northern Idaho Pest Action Council (Cox 1968) resulted in identification of a chemical attractive to the mountain pine beetle (Pitman et al. 1968). This research is directed toward manipulation of mountain pine beetle populations to reduce losses in the western white pine type.

Although tests have shown beetle response to pheromones, the practical field use of these chemicals has not been demonstrated. Atkins (1968) points out a number of obstacles to successful field use, particularly lack of understanding many of the basic physiological-behavioral aspects of bark beetle ecology.

LONG TERM MANAGEMENT GOALS AND PLANS

The management of lodgepole pine is handicapped by such factors as mountain pine beetle infestations, dwarfmistletoe infections, and lack of sufficient markets. Markets can and will develop with increased demands for timber and shortage of supplies in other areas. Dwarfmistletoe infections can be controlled through proper cutting methods and treatments applied to the cutover areas. However, in the absence of wholly effective control methods, the mountain pine beetle is apt to remain a threat to the lodgepole pine resource.

Acceptable Risk

Every forest management action assumes some calculated risk and growing lodgepole pine trees in the face of mountain pine beetle depredations is no exception. For example, as seen in figure 1, the probability of an 18-inch tree surviving a beetle epidemic is practically zero, whereas 12-inch trees have about a 50-50 chance of surviving and 10-inch trees show about a 70 percent chance of surviving.

Data presented from the reconnaissance of the 42 stands in the Targhee-Teton-Yellowstone area show that approximately 86 percent sustained one or more infestations. Therefore, the probability of a stand being infested in this area appears to be rather high. If we assume 86 percent probability of infestation in the stand and 50 percent probability that the 12-inch trees will be infested, then the product of these two (86 X 50 = 43 percent) would provide an empirical estimate of the probability of loss. On this basis there is about a 57 and 74 percent probability that 12-inch and 10-inch lodgepole pine trees, respectively, will not be killed by the mountain pine beetle. The utility of these probabilities is only to illustrate the point, but their applicability to other lodgepole areas is questionable. Much variability exists in the probabilities even locally, so widespread use of these values is not recommended.

Although the probability of attack by tree age is not known, nevertheless age and diameter are correlated so that probabilities by diameter classes do reflect age relationships.

As previously stated, the probability of infestation varies by habitat type. For example, in the Abies lasiocarpa/Vaccinium scoparium habitat type the probability of an infestation occurring is about 44 percent (figure 3). However, the probability of an active infestation in the Abies lasiocarpa/Pachistima myrsinites habitat type exceeds 90 percent. Therefore, habitat types must also be taken into account when considering risks to be assumed in management. For example, the risk of growing 16-inch trees on the Abies lasiocarpa/Pachistima myrsinites habitat type would be very high (92 X 82 = 75 percent probability of loss) where only 25 percent or less of the 16-inch trees could be expected to survive. On the other hand, a 44 percent probability in the Abies lasiocarpa/Vaccinium scoparium habitat type would present a brighter picture where (82 X 44 = 36 percent loss) 64 percent or nearly two-thirds of the 16-inch trees could be expected to survive.

When making the decision to grow lodgepole pine the forest manager will be faced with the choice of how much of a risk he is willing to accept. He may therefore decide that a 64 percent survival of 16-inch trees in the *Abies lasiocarpa/Vaccinium scoparium* habitat type is an acceptable risk, but the 25 percent expected survival in the *Abies lasiocarpa/Pachistima myrsinites* habitat type may be judged as an unacceptable risk. He could then consider other management alternatives for the *Abies lasiocarpa/Pachistima myrsinites* habitat type.

Management Practices

If the risk of lodgepole pine management is too high there are a number of management practices to be considered. Some of these are described below.

Type Conversion

Some objectives of management may be met as well with one forest type as another. For example, a subalpine fir-Engelmann spruce or a Douglas-fir stand could serve watershed management, recreation, range, wildlife, and in some instances timber objectives as well as a lodgepole pine stand. The type conversion can be accomplished naturally through culturing the understory or artificially by a cutting that is followed by planting or seeding.

Rotation

Another practice might be to select as an objective the smallest tree size that will fulfill product requirements and to select the shortest rotation to grow trees to this size. The size selection should be based upon the greatest beetle risk that the manager is willing to accept. Thus, he would probably select a small size objective of possibly 10, 12, or 14 inches and a short rotation for growing trees on the high risk *Abies lasiocarpa/Pachistima myrsinites* type and, at the same time, set a larger size objective with a longer rotation on the lower risk *Abies lasiocarpa/Vaccinium scoparium* type.

Species and Age Class Mixtures

A third practice could be to develop mixed stands including lodgepole pine. Presumably, beetles will infest the mixed lodgepole pine stands as readily as the pure stands (Flint 1924). However, some of the lodgepole pine will survive to 16-inch trees even in mixtures, and the other species will help to maintain a higher stocking rate than would be the case in pure decimated lodgepole pine stands. Overall production would probably be higher in mixed than in pure stands. Such mixed stands would meet the recreational, wildlife, and watershed objectives as well or better than pure lodgepole pine.

Achieving a desirable mix and juxtaposition of age classes provides yet another practice but this plan also entails some risk of loss. This would require long-range planning to avoid cuttings that would establish extensive areas of single age classes; also, this practice would require the use of the best known beetle control measures in reserved stands. Breaking up a stand into several age classes and separating similar age classes by interspersing others would probably do two things: (1) it would eventually place the minimum area in beetle-susceptible stands, making prompt removal of these stands, or the application of control measures more feasible when such stands become infested; and (2) it would limit the size of the areas and this separation of stands might help to hold the beetle population at lower levels. This is an objective which can only be met through long-range planning, good markets, adequate road systems, and the passage of time.

Preservation of Genotypes

The speculation that the faster growing genotypes may be diminishing under beetle pressure emphasizes the importance and urgency of preserving the best genotypes. Because this consideration is purely theoretical, studies of genetic variability in these beetle-infested stands are urgently needed to show the validity of the theory. If this is a valid theory then some attempt should be made soon to preserve the better genotypes. Great variation in tree growth does exist in lodgepole pine stands and a program to search out and propagate best phenotypes could be undertaken even before completion of the above studies.

LITERATURE CITED

Amman, Gene D.
1969. Mountain pine beetle emergence in relation to depth of lodgepole pine bark. USDA Forest Serv. Res. Note INT-96, 8 pp.

Atkins, M. D.
1968. Scolytid pheromones--ready or not. Can. Entomol. 100: 1115-1117.

Cole, Walter E., and Gene D. Amman.
1969. Mountain pine beetle infestations in relation to lodgepole pine diameters. USDA Forest Serv. Res. Note INT-95, 7 pp.

Cox, Royce G.
1968. Potentialities of reducing mountain pine beetle populations through the use of attractants. Paper presented at the Northwest Scientific Association's Annual Meeting, Ellensburg, Washington, March 23, 1968.

Daubenmire, R.
1952. Forest vegetation of northern Idaho and adjacent Washington, and its bearing on concepts of vegetation classification. Ecol. Monogr. 22: 301-330.

______
1961. Vegetative indicators of rate of height growth in ponderosa pine. Forest Sci. 7(1): 24-34, illus.

Flint, H. R.
1924. Various aspects of the insect problem in the lodgepole pine region. U.S. Forest Serv. D-1 Appl. Forest. Notes 54, 4 pp.

Hopping, Geo. R., and Geoffrey Beall.
1948. The relation of diameter of lodgepole pine to incidence of attack by the bark beetle (*Dendroctonus monticolae* Hopk.). Forest. Chron. 24: 141-145.

Horton, K. W.
1956. The ecology of lodgepole pine (*Pinus contorta*) in Alberta and its role in forest succession. Can. Dep. North. Aff. and Nat. Resources, Forest Res. Div. Tech. Note 45, 29 pp., illus.

Illingworth, K., and J. W. C. Arlidge.
1960. Interim report on some forest site types in lodgepole pine and spruce-alpine fir stands. British Columbia Forest Serv. Res. Note 35, 44 pp., illus.

Pitman, G. B., J. P. Vité, G. W. Kinzer, and A. F. Fentiman, Jr.
1968. Bark beetle attractants: Trans-verbenol isolated from *Dendroctonus*. Nature 218(5137): 168-169.

Renwick, J. A. A.
1967. Identification of two oxygenated terpenes from the bark beetles *Dendroctonus frontalis* and *Dendroctonus brevicomis*. Boyce Thompson Inst. Contrib. 23(10): 355-360.

Roe, Arthur L.
1967. Productivity indicators in western larch forests. U.S. Forest Serv. Res. Note INT-59, 4 pp.

Silverstein, Robert M., J. Otto Rodin, and David L. Wood.
1966a. Sex attractants in frass produced by male Ips confusus in ponderosa pine. Science 154(3748): 509-510.

________, J. O. Rodin, D. L. Wood, and L. E. Browne.
1966b. Identification of two new terpene alcohols from frass produced by Ips confusus in ponderosa pine. Tetrahedron 22: 1929-1936.

________, R. G. Brownlee, T. E. Bellas, D. L. Wood, and L. E. Browne.
1968. Brevicomin: principal sex attractant in the frass of the female western pine beetle (Dendroctonus brevicomis). Science 159(3817): 889-891.

Tackle, David.
1954. Lodgepole pine management in the Intermountain Region--a problem analysis. U.S. Forest Serv., Intermountain Forest and Range Exp. Sta., Misc. Pub. 2, 53 pp., illus.

Thorne, Gerald.
1935. Nemic parasites and associates of the mountain pine beetle (Dendroctonus monticolae) in Utah. J. Agr. Res. 51(2): 131-144, illus.

Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field Research Work Units are maintained in:

- Boise, Idaho
- Bozeman, Montana (in cooperation with Montana State University)
- Logan, Utah (in cooperation with Utah State University)
- Missoula, Montana (in cooperation with University of Montana)
- Moscow, Idaho (in cooperation with the University of Idaho)
- Provo, Utah (in cooperation with Brigham Young University)

ABOUT THE FOREST SERVICE . . .

As our Nation grows, people expect and need more from their forests—more wood; more water, fish, and wildlife; more recreation and natural beauty; more special forest products and forage. The Forest Service of the U. S. Department of Agriculture helps to fulfill these expectations and needs through three major activities:

- Conducting forest and range research at over 75 locations ranging from Puerto Rico to Alaska to Hawaii.
- Participating with all State Forestry agencies in cooperative programs to protect, improve, and wisely use our Country's 395 million acres of State, local, and private forest lands.
- Managing and protecting the 187-million acre National Forest System.

The Forest Service does this by encouraging use of the new knowledge that research scientists develop; by setting an example in managing, under sustained yield, the National Forests and Grasslands for multiple use purposes; and by cooperating with all States and with private citizens in their efforts to achieve better management, protection, and use of forest resources.

Traditionally, Forest Service people have been active members of the communities and towns in which they live and work. They strive to secure for all, continuous benefits from the Country's forest resources.

For more than 60 years, the Forest Service has been serving the Nation as a leading natural resource conservation agency.

USDA Forest Service
Research Paper INT-72
1970

COMMERCIAL THINNING TO PRODUCE PONDEROSA PINE SAWLOGS IN THE INLAND EMPIRE

Marvin W. Foiles

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Ogden, Utah 84401

MARVIN W. FOILES is a Silviculturist at the Intermountain Station's Forestry Sciences Laboratory in Moscow, Idaho. After receiving his B.S. degree in Forestry from Colorado State University in 1947 he joined the Northern Rocky Mountain Station and since then has been engaged in silvicultural research in the northern Rockies. From 1948 to 1957 he worked in the Western White Pine Project at the Inland Empire Research Center in Spokane, Washington. From 1957 to 1967 he was assigned to the Ponderosa Pine Silviculture Research Project in Boise, Idaho.

USDA Forest Service
Research Paper INT-72
1970

COMMERCIAL THINNING TO PRODUCE PONDEROSA PINE SAWLOGS IN THE INLAND EMPIRE

Marvin W. Foiles

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401
Joseph F. Pechanec, Director

CONTENTS

ABSTRACT

Moderate commercial thinning of young, merchantable ponderosa pine stands can provide an immediate income from the land with only a small reduction in volume growth. This experiment compared growth for 10 years following: (1) moderate thinning that removed 30 percent of the volume; (2) heavy cutting that removed 75 percent of the volume; and (3) no cutting. Net annual increment per acre averaged 338 board feet following no cutting and 308 board feet following moderate thinning compared to only 161 board feet following the heavy cutting.

INTRODUCTION

Farmers' woodlots play an important role in the timber production of the Inland Empire (northeastern Washington, northern Idaho, and western Montana). Small, privately owned timberlands total nearly 2 million acres in this territory, but their importance is even greater than the acreage indicates. They generally occupy productive sites located at lower elevations on gentle terrain and are easily accessible. Logging operations have been concentrated on these accessible pine lands since the first settlements were established by white men in the Inland Empire.[1]

Considerable logging of second-growth ponderosa pine (Pinus ponderosa Laws.) occurred in the years during and immediately following World War II. Many stands were partially cut shortly after trees reached merchantable size. Most of the cuttings were heavy, removing the largest trees and drastically reducing the growing stock at a time when the stands had just begun a period of rapid growth of sawtimber. Many foresters believed it would be beneficial to delay cutting to take advantage of the rapid sawtimber growth, but in many cases the landowners wanted an immediate income from their young stands and were not willing to wait. Another alternative would have been a moderate commercial thinning to stimulate the growth of the better trees in the stand while retaining sufficient stocking to capture most of the growth potential of the site.

A series of experiments (designed and established by Donald W. Lynch, USDA Forest Service, Pacific Southwest Forest and Range Experiment Station) was started in 1950 to provide comparisons of growth responses and volume production following the usual "heavy cutting" versus a moderate "commercial thinning." These experiments also demonstrate to landowners the returns in terms of immediately harvestable volume and subsequent growth and production of residual stands following each type of cutting. A third treatment, "no cutting," was also included in the study to show growth and production as a result of holding the timber for future harvest.

STAND DESCRIPTION

In the Inland Empire ponderosa pine grows on the lower slopes of the mountains and on valley floors at altitudes of 1,500 to 3,500 feet. Precipitation ranges from 15 to 30 inches per year. The pine grows on coarse and well drained soils such as sandy alluvium, gravelly or sandy till, and loams with high stone content.

Ponderosa pine grows in pure stands on the relatively warm, dry sites where timberline borders on the prairie. The more moist sites occur farther up the mountain slopes. On these cooler, more moist sites ponderosa pine is commonly associated with one or more tree species, including Douglas-fir (Pseudotsuga menziesii var. glauca (Beissn.) Franco), lodgepole pine (Pinus contorta Dougl.), western larch (Larix occidentalis Nutt.), and grand fir (Abies grandis (Dougl.) Lindl.). Stocking is irregular with dense clumps, sparse stands, and openings occurring in uneven patterns, especially on the poorer sites.

METHODS

Study areas were located in five widely scattered ponderosa pine stands of northeastern Washington and northern Idaho. Three plots, variable in size but ranging from 2 to 6 acres, were laid out at each study area and one of the following treatments was randomly assigned to each plot:

---

[1] Behre, C. Edward. Preliminary yield tables for second growth western yellow pine in the Inland Empire. The University of Idaho Bull. 23 (20), 19 pp. 1928.

1. No cutting.

2. Moderate crown thinning which removed about 30 percent of the basal area and sawtimber volume by cutting defective trees, wolf trees, and additional trees to favor about 80 to 100 of the best trees per acre.

3. Heavy cutting from above, removing all trees larger than a specified diameter limit which was 16 inches in four tests and 14 inches in one test. This treatment was intended to resemble the "logger's choice" cutting that is commonly applied to these young merchantable stands.

Treatments were compared on the basis of mean annual growths for 10 years after cutting. Analyses of variance and multiple-range tests were used to test treatment differences.

The original intent was to establish the tests on farmers' woodlots to serve as demonstration areas. However, as suitable stands in woodlots were difficult to find, three of the five tests were located on Indian reservations. One test (Tensed, Idaho plots) was never completed because the plot assigned the moderate crown thinning was not cut. Growth data from the incomplete test are presented in table 7 in the appendix. However, these plots were not included in the statistical analyses.

The five test stands are not exactly comparable in age, species composition, and site index, but as a group they are quite representative of second-growth ponderosa pine stands in the Inland Empire (table 1).

Table 1.--Description of commercial thinning test sites and stands before treatment

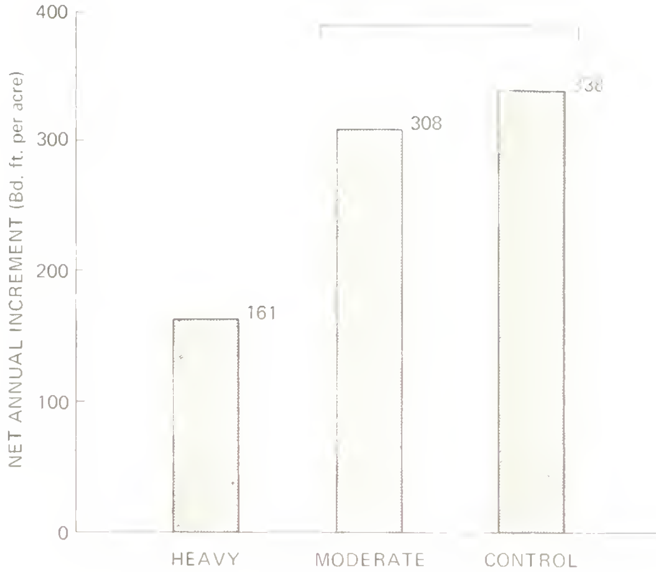
Location	Elevation	Aspect	Soil	Date of treatment	Stand age	Site index[1]	Av. d.b.h.
	Feet				Years		Inches
Chewelah, Wash.	1,900	Southeast	Sandy-loam	1950	90	90	11.9
Springdale, Wash.	2,480	Flat	Sandy-loam	1950	90	100	14.4
Usk, Wash.	2,100	Flat	Sandy-loam	1951	90	90	12.7
Colbert, Wash.	1,700	Flat	Sandy	1951	115	75	14.4
Tensed, Idaho	2,550	Flat	Loam	1951	70	110	14.5

[1]Meyer, Walter H. Yield of even-age stands of ponderosa pine. USDA Tech. Bull. No. 630, 59 pp., illus. 1938.

RESULTS

Growth and development of four experimental stands for 10 years following the cuttings are shown in tables 3 to 6 in the appendix. Growth on the Tensed plots has been measured for only 5 years (appendix, table 7). Board-foot values are important from a practical viewpoint because the principal product currently harvested from ponderosa pine stands is sawlogs. Periodic net annual sawlog increment on the control, moderately cut, and heavily cut plots averaged 338 board feet, 308 board feet, and 161 board feet, respectively (figure 1). The 30-board-foot growth difference between the control and moderately thinned stands was not statistically significant.

Figure 1.--Average annual board-foot growth per acre following commercial thinning. (Increments connected by brackets are not significantly different, $P < 0.05$.)



While mortality following cutting varied considerably among plots, treatment effects were obscured by other causes. In terms of sawtimber volume, overall differences were slight, averaging between 37 and 45 board feet per acre per year for the three treatments.

Cutting treatments affected cubic volume increment in the same way they affected board-foot growth (figures 1 and 2). Heavy cutting significantly reduced the growth of the residual stand while moderate cutting resulted in cubic volume growth nearly equal to that of the uncut stand. On the average, the heavily cut stands produced only 25 cubic feet per acre per year compared to 53 cubic feet and 49 cubic feet on the control and lightly cut stands.

Both of the cutting treatments accelerated diameter growth of the residual trees, but this effect was not evident until during the second 5-year period following cutting (table 2). Average diameter growth for 5 years was slightly more on the treated plots, but the increase was not statistically significant. However, during the second 5-year period differences between all three treatments were significant. Apparently it took several years for the released trees to fully utilize the increased growing space. During the second 5 years, trees on the moderately cut plots grew 50 percent faster than trees on the control plots, and trees on the heavily cut plots grew 100 percent faster than the controls.

Irrigation and fertilization also have been shown to increase diameter growth in stands similar to those in the commercial thinning experiment.[2] Some combinations of these intensive practices with thinning may be feasible methods of growing high quality sawlogs on Inland Empire woodlots, especially if management is started early in the life of the stand.

---

[2]Mosher, Milton M. Irrigation and fertilization of ponderosa pine. Wash. Agr. Exp. Sta. Circ. 365. 1960.

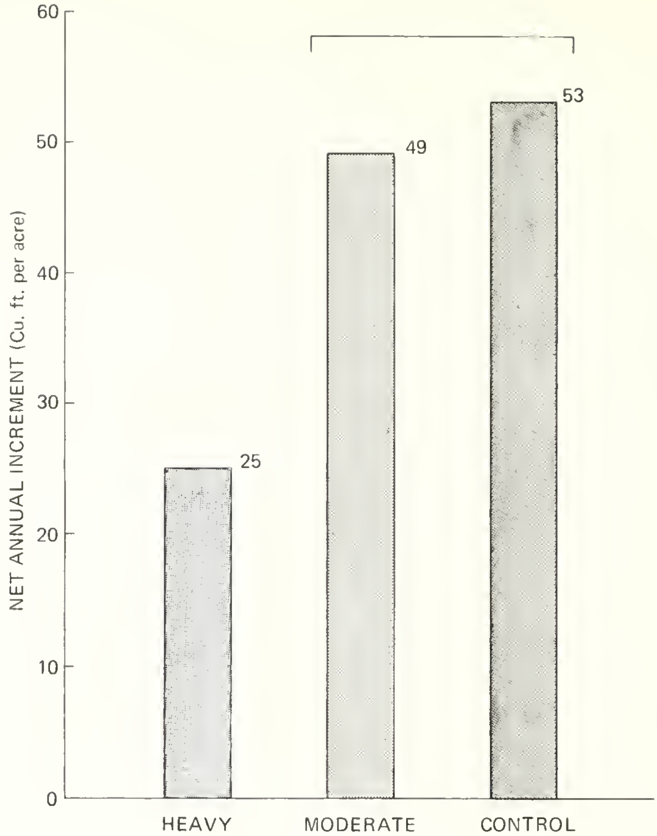


Figure 2.--Average net annual cubic volume growth per acre following commercial thinning. (Increments connected by brackets are not significantly different, $P < 0.05$.)

Table 2.--Average annual diameter growth per tree for two 5-year periods following cutting

Treatment	Periods following cutting: 1-5 years	Periods following cutting: 5-10 years
	- - - - - - - - - Inches - - - - - - - - -	
Heavy cut	0.13	0.16
Moderate cut	.12	.12
Control	.11	.08

CONCLUSIONS

This experiment was conducted to supply information which would help woodlot owners decide what to do with their young merchantable ponderosa pine stands. Growth data from the plots support the conclusion that a commercial thinning, removing about 30 percent of the volume, can provide an immediate income and improve the quality of the residual stand with no reduction in stand growth. Biologically, thinning presents an alternative to liquidation cutting or no cutting. The woodlot owner should also consider other factors such as future management plans for the tract, his need for immediate income, alternative uses for the money invested in the timber stand, and market conditions before choosing the alternative most beneficial to his particular situation.

APPENDIX

Stand Growth and Development, Tables 3-7

Table 3.--Per acre growth and development following cutting on Chewelah, Washington, plots.[1]

Date	Number of trees per acre			Basal area			Cubic volume			Sawlog volume		
	Control	Heavy	Moderate	Control	Heavy	Moderate	Control	Heavy	Moderate	Control	Heavy	Moderate
				Square feet			Cubic feet			Board feet		
1950 before cutting	149	98	130	115	95	107	3,563	2,976	3,147	13,992	12,762	12,378
1950 cut	0	25	22	0	50	31	0	1,808	1,007	0	9,302	4,645
1950 after cutting	149	73	108	115	45	76	3,563	1,168	2,140	13,992	3,460	7,733
1954	140	58	98	123	42	78	3,730	1,147	2,277	15,214	3,796	9,698
Increment, 1950-54	-9	-15	-10	8	-3	2	167	-21	137	1,222	336	965
1959	143	64	105	133	50	87	4,145	1,456	2,666	17,823	5,323	10,685
Increment, 1954-59	3	6	7	10	8	9	415	309	389	2,609	1,527	1,987
Average net annual periodic increment				2.0	0.5	1.2	64.7	32.0	58.5	426	207	328
Average annual mortality				2.9	3.3	1.7	13.9	16.8	6.9	35	43	8
Average gross annual periodic increment				4.9	3.9	2.9	78.6	48.8	65.4	461	250	336

[1]Number of trees, basal area, and cubic volumes include all trees 5.6 inches d.b.h. and larger; sawlog volumes, Scribner rule, include trees 9.6 inches d.b.h. and larger.

Table 4.--Per acre growth and development following cutting on Springdale, Washington, plots[1]

Date	Number of trees per acre: Control	Heavy	Moderate	Basal area: Control	Heavy	Moderate	Cubic volume: Control	Heavy	Moderate	Sawlog volume: Control	Heavy	Moderate
				- - Square feet - - -			- - - - Cubic feet - - -			- - - - Board feet - - - -		
1950 before cutting	104	95	90	117	107	103	4,188	3,537	3,687	18,719	15,421	16,634
1950 cut	0	27	24	0	59	31	0	2,009	1,105	0	10,388	5,070
1950 after cutting	104	68	66	117	48	72	4,188	1,528	2,582	18,719	5,033	11,564
1955	99	65	62	124	52	79	4,338	1,609	2,862	19,978	5,917	13,346
Increment, 1950-55	-5	-3	-4	7	4	7	150	81	280	1,259	884	1,782
1960	98	75	61	128	57	85	4,639	1,808	3,202	21,662	6,815	15,521
Increment, 1955-60	-1	10	-1	4	5	6	301	199	340	1,684	898	2,175
Average net annual periodic increment				1.1	0.9	1.3	45.1	28.0	62.0	294	178	396
Average annual mortality				0.7	1.0	0.3	25.2	27.1	6.3	102	75	22
Average gross annual periodic increment				1.8	1.9	1.6	70.3	55.1	68.3	396	253	418

[1]Number of trees, basal area, and cubic volumes include all trees 5.6 inches d.b.h. and larger; sawlog volumes, Scribner rule, include trees 9.6 inches d.b.h. and larger.

Table 5.--Per acre growth and development following cutting on Usk, Washington, plots[1]

Date	Number of trees per acre			Basal area			Cubic volume			Sawlog volume		
	Control	Heavy	Moderate	Control	Heavy	Moderate	Control	Heavy	Moderate	Control	Heavy	Moderate
				- - - Square feet - -			- - - Cubic feet - - - -			- - - - Board feet - - - -		
1951 before cutting	113	146	141	99	109	114	3,206	3,452	3,652	12,926	12,826	14,061
1951 cut	0	42	20	0	59	22	0	2,089	802	0	9,843	3,579
1951 after cutting	113	104	121	99	50	92	3,206	1,364	2,850	12,926	2,983	10,482
1956	111	86	108	108	49	94	3,578	1,385	3,037	15,201	3,692	12,117
Increment, 1951-56	-2	-18	-13	9	-1	2	372	21	187	2,275	709	1,635
1961	106	88	107	114	56	101	3,939	1,667	3,423	17,389	5,132	14,361
Increment, 1956-61	-5	2	-1	6	7	7	361	282	386	2,188	1,440	2,244
Average net annual periodic increment				1.5	0.6	0.9	73.3	30.3	57.3	446	215	388
Average annual mortality				1.5	4.2	4.6	12.6	19.8	21.9	31	23	58
Average gross annual periodic increment				3.0	4.8	5.5	85.9	50.1	79.2	477	238	446

[1]Number of trees, basal area, and cubic volumes include all trees 5.6 inches d.b.h. and larger; sawlog volumes, Scribner rule, include trees 9.6 inches d.b.h. and larger.

Table 6.--Per acre growth and development following cutting on Colbert, Washington, plots[1]

Date	Number of trees per acre			Basal area			Cubic volume			Sawlog volume		
	Control	Heavy	Moderate	Control	Heavy	Light	Control	Heavy	Light	Control	Heavy	Light
				Square feet			Cubic feet			Board feet		
1951 before cutting	81	78	78	92	82	92	2,935	2,638	2,962	13,236	11,996	13,490
1951 cut	0	27	14	0	54	20	0	1,977	686	0	10,148	3,265
1951 after cutting	81	51	64	92	28	72	2,935	661	2,276	13,236	1,848	10,225
1956	80	47	62	96	27	72	3,116	662	2,323	14,322	1,943	10,680
Increment, 1951-56	-1	-4	-2	4	-1	0	181	1	47	1,086	95	455
1961	81	58	63	101	32	76	3,239	771	2,445	15,107	2,285	11,449
Increment, 1956-61	1	11	1	5	5	4	123	109	122	785	342	769
Average net annual periodic increment				0.9	0.4	0.4	30.4	11.0	16.9	187	44	122
Average annual mortality				0.1	0.5	0.5	1.7	12.0	14.8	4	38	61
Average gross annual periodic increment				1.0	0.9	0.9	32.1	23.0	31.7	191	82	183

[1]Number of trees, basal area, and cubic volumes include all trees 5.6 inches d.b.h. and larger; sawlog volumes, Scribner rule, include trees 9.6 inches d.b.h. and larger.

Table 7.--Per acre growth and development on Tensed, Idaho, plots[1]

Date	Number of trees per acre			Basal area			Cubic volume			Sawlog volume		
	Control	Control	Heavy	Control	Control	Heavy	Control	Control	Heavy	Control	Control	Heavy
				- - - Square feet - - -			- - - - Cubic feet - - -			- - - - Board feet - - -		
1951 before cutting	128	140	93	147	160	130	4,800	5,297	4,389	22,516	23,631	21,155
1951 cut	0	0	29	0	0	68	0	0	2,664	0	0	14,383
1951 after cutting	128	140	64	147	160	62	4,800	5,297	1,725	22,516	23,631	6,772
1956	107	131	52	144	168	52	5,086	5,803	1,661	24,557	27,045	6,935
Increment 1951-56				-3.0	8	-10	286	506	-64	2,041	3,414	163
Average net annual periodic increment				-0.6	1.6	-2	57.2	101	-12.8	408	683	33
Average annual mortality				3.0	1.0	1.3	86.4	30	33.4	292	146	83
Average gross annual periodic increment				2.4	2.6	-0.7	143.6	131	20.6	700	829	116

[1]Number of trees, basal area, and cubic volumes include all trees 5.6 inches d.b.h. and larger; sawlog volumes, Scribner rule, include trees 9.6 inches d.b.h. and larger.

Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field Research Work Units are maintained in:

- Boise, Idaho
- Bozeman, Montana (in cooperation with Montana State University)
- Logan, Utah (in cooperation with Utah State University)
- Missoula, Montana (in cooperation with University of Montana)
- Moscow, Idaho (in cooperation with the University of Idaho)
- Provo, Utah (in cooperation with Brigham Young University)

FOREST SERVICE CREED

The Forest Service of the U. S. Department of Agriculture is dedicated to the principle of multiple use management of the Nation's forest resources for sustained yields of wood, water, forage, wildlife, and recreation. Through forestry research, cooperation with the States and private forest owners, and management of the National Forests and National Grasslands, it strives — as directed by Congress — to provide increasingly greater service to a growing nation.

INFLUENCE OF COMPETITION ON THE RESPONSE OF IDAHO FESCUE TO CLIPPING

W. F. MUEGGLER

USDA Forest Service
Research Paper INT-73, 1970

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Ogden, Utah 84401

THE AUTHOR

DR. MUEGGLER has been with the Station since 1949. He is currently stationed at the Forestry Sciences Laboratory in Bozeman, Montana. In his previous assignments, he was stationed at Spokane, Washington, from 1955 to 1961, and at Dubois, Idaho, from 1949 to 1955. He obtained his B.S. degree in Forestry (Range) at the University of Idaho (1949); his M.S. in Botany (Ecology) at the University of Wisconsin (1953); and his Ph.D. in Botany (Ecology) at Duke University (1961).

USDA Forest Service
Research Paper INT-73
1970

INFLUENCE OF COMPETITION ON THE RESPONSE OF IDAHO FESCUE TO CLIPPING

W. F. Mueggler

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U. S. Department of Agriculture
Ogden, Utah 84401
Joseph F. Pechanec, Director

Contents

Page

Abstract

Partly reducing competition increased by 40 percent the herbage volume produced by Idaho fescue (*Festuca idahoensis* Elmer) the following year and more than tripled the number of flower stalks. Eliminating competition almost tripled herbage volume and increased the number of flower stalks fourfold. The relative depressant effects of clipping were much reduced by concurrent reductions in competition. Partly reducing competition more than compensated for the effects of heavy clipping on herbage volume and flower stalk production, and eliminating competition more than offset the effects of extreme clipping. Volume increases caused by reducing competition resulted from increases in live basal area rather than stimulation of height growth. The number of flower stalks appeared to be a more sensitive indicator of plant vigor than either herbage volume or leaf and flower stalk lengths.

Introduction

Interpreting results from clipping studies on range plants is frequently confounded by the conditions under which the plants are clipped. Such studies are usually conducted in one of three ways: (1) clipping selected plants *in situ* without disturbing the surrounding vegetation; (2) clipping entire plots of vegetation and observing the reaction of selected species; and (3) clipping plants grown in pots without competing vegetation. Each approach imposes different stresses on the treated plants in addition to that of clipping. Obviously, clipping an individual plant without disturbing the surrounding vegetation subjects the weakened plant to much greater competition for moisture and nutrients than does clipping both the plant and the surrounding vegetation. Moisture and nutrient limitations to pot-grown plants would, of course, depend primarily upon the watering regimen and the amount and fertility of soil within the pot.

Different clipping studies reported for the same species often yield conflicting results. In many cases, these differences in plant response can be attributed to competition differences. For example, Hormay and Talbot[1] found that clipping Idaho fescue (*Festuca idahoensis* Elmer) to 1.5-inch stubble height during the flowering stage of growth reduced flower stalk production the following year by 95 percent and basal area by more than 85 percent. Apparently, the Idaho fescue was clipped as individual plants in unaltered surrounding vegetation. On the other hand, Mueggler[2] reported that

[1] *Hormay, A. L., and M. W. Talbot. Rest-rotation grazing . . . a new management system for perennial bunchgrass ranges. U.S.D.A. Forest Serv. Prod. Res. Rep. 51, 43 pp. 1961.*

[2] *Mueggler, W. F. Response of mountain grassland vegetation to clipping in southwestern Montana. Ecology 48(6): 942-949. 1967.*

Idaho fescue clipped to a 1-cm. stubble height at flowering, but with equal removal of surrounding vegetation, produced double the number of flower stalks and over 20 percent more herbage the following year.

The variable effects of competition are usually ignored in clipping studies. The investigator often justifies his actions by holding competition more or less constant in any one study and by expressing results in relative terms. Unfortunately, the results from such studies are often used on an actual rather than relative base and applied by the land manager to conditions where competition is completely different from that of the study. Is it correct to use herbage removal guides developed from species grown under full competition for the same species grown on range where competition from surrounding vegetation has been reduced by grazing? To answer this question, we must first know how much influence competition has on the effects of herbage removal.

This paper describes the results of a study that gives some indication of the relative effects of competition on the ability of Idaho fescue to withstand heavy and extremely heavy clipping.

Methods

The study area, a natural mountain grassland on Montana State University's Red Bluff Ranch in southwestern Montana, was part of a gently sloping broad, north-facing swale, approximately 6,000 feet in elevation. The soils, derived from granite, are fairly deep and productive. The vegetation, moderately grazed until the year of the study, was in good condition and protected from grazing during the course of the study. The vegetation was dominated by Idaho fescue, bluebunch wheatgrass (*Agropyron spicatum*), and lupine (*Lupinus argenteus*). Secondary species were more or less typical of those usually associated with the above in this part of Montana, and range from rose pussytoes (*Antennaria rosea*) to rabbitbrush (*Chrysothamnus nauseosus*). Wherever the vegetation and soils were disturbed by rodents, cheatgrass (*Bromus tectorum*) was abundant. Precipitation in the general area did not differ appreciably from normal during the study period.

One hundred and thirty-five vigorous, mature Idaho fescue plants, each approximately 3 to 5 cm. in basal diameter, were selected from the abundant number growing on the study area. These were randomly assigned to nine separate treatments, yielding 15 replications per treatment.

The nine treatments consisted of all combinations of three levels of clipping and three degrees of competition. The three clipping levels for the selected fescue plants were "none," "heavy," and "extreme." The "none" level was an unclipped control. The "heavy" level of clipping consisted of 75 percent of the herbage volume removed at the flowering development stage (July 13), with no further treatment. The "extreme" level consisted of 100 percent (to a 1-cm. stubble) of the herbage removed at flowering, followed by removing 75 percent of the regrowth near the seed-ripe developmental stage of the control plants (August 8). The plants were clipped during one growing season only.

The different degrees of competition were created immediately before the clipping treatments were begun. A degree of no ("none") competition was achieved by tilling the soil within a 60-cm. radius and from 5 to 8 cm. deep around the selected fescue plant. This tilling was combined with careful hoeing immediately adjacent to the plant to effectively remove all competing vegetation. Conceivably, such tillage might also increase aeration, infiltration, and nitrogen availability within the soil. The tilled areas were weeded periodically to maintain a competition-free condition throughout the study.

A degree of "partial" competition was created by clipping to ground level all vegetation within a 60-cm. radius of the selected fescue plants. This was done only at the time the fescue plants were first clipped in July; the competing vegetation was then permitted to regrow without further hindrance. The partial reduction treatment might be considered somewhat similar to very heavy grazing of all competing vegetation, followed by complete rest.

"Full" competition was obtained by allowing the undisturbed vegetation to remain around the selected fescue plants.

Plant response was evaluated shortly after flowering in 1968 by measuring live basal area (total basal area minus unoccupied openings), leaf length, and number and length of flower stalks. An index of herbage volume production was obtained by multiplying live basal area by average leaf length. These data were subjected to an analysis of variance (Snedecor 1959; 12.5),[3] followed by a comparison of treatment means by Keul's test (Snedecor 1959; 10.6).[3]

---

[3] *Snedecor, George W. Statistical methods. 534 pp. Ames, Iowa: Iowa State College Press. 1959.*

Results

As expected, increasing the severity of clipping and of competition successively decreased the growth and vigor of Idaho fescue during the year following treatment (figures 1 and 2).

Subjecting Idaho fescue to extreme clipping while under full competition reduced herbage volume the following year by 84 percent. Extreme clipping under both partial and no competition reduced herbage volume 66 and 47 percent, respectively, when compared with the unclipped plants under both partial competition and no competition. Thus, the relative depressant effects of clipping were lessened when competition was reduced.

The normally suppressing effect of competition on individual plants of Idaho fescue is clearly shown by the volume

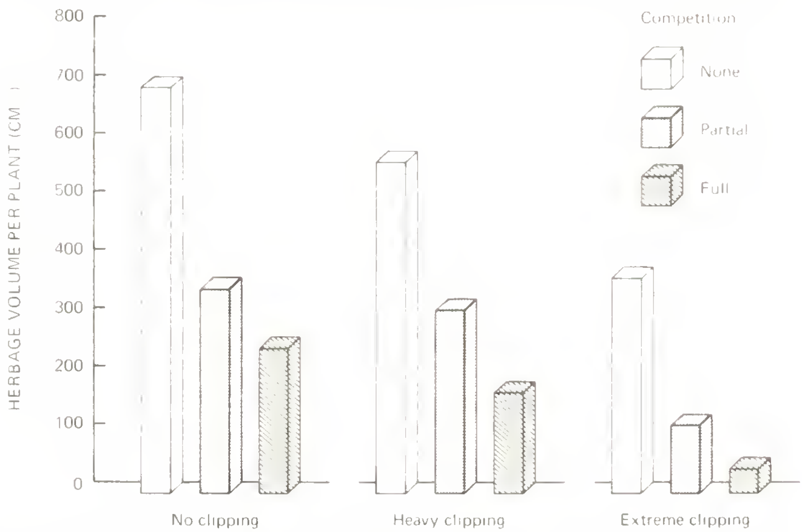


Figure 1. Herbage volume production of Idaho fescue the year following clipping under different levels of competition. (The column third from the left represents volume of check plants — no clipping, full competition.)

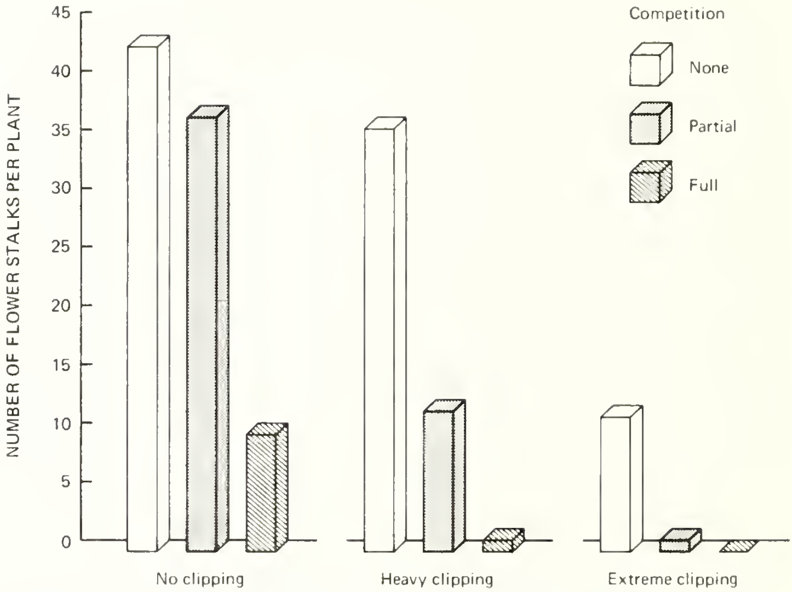


Figure 2. Flower stalk production of Idaho fescue the year following clipping under different levels of competition. (The column third from the left represents flower stalk numbers of check plants — no clipping, full competition.)

data for the unclipped plants that were subjected to different competition treatments (figure 3). Unclipped plants freed from competition almost tripled their volume in 1 year. Relative volume differences are even more pronounced when the plants are placed under the additional stress of clipping. Plants clipped to an extreme degree and without competition produced nine times more herbage than those subjected to full competition. Interestingly, elimination of competition more than compensated for the very harmful effects of extreme clipping.

The length of Idaho fescue leaves was affected more by differences in clipping intensity than by differences in competition (figure 3). Competition alone did not noticeably affect leaf length. However, the dual effect of competition and clipping reduced leaf length up to 40 percent. The response of average leaf length to the various treatment combinations closely paralleled that of maximum leaf length. Increased herbage volume that was caused only by reductions in com-

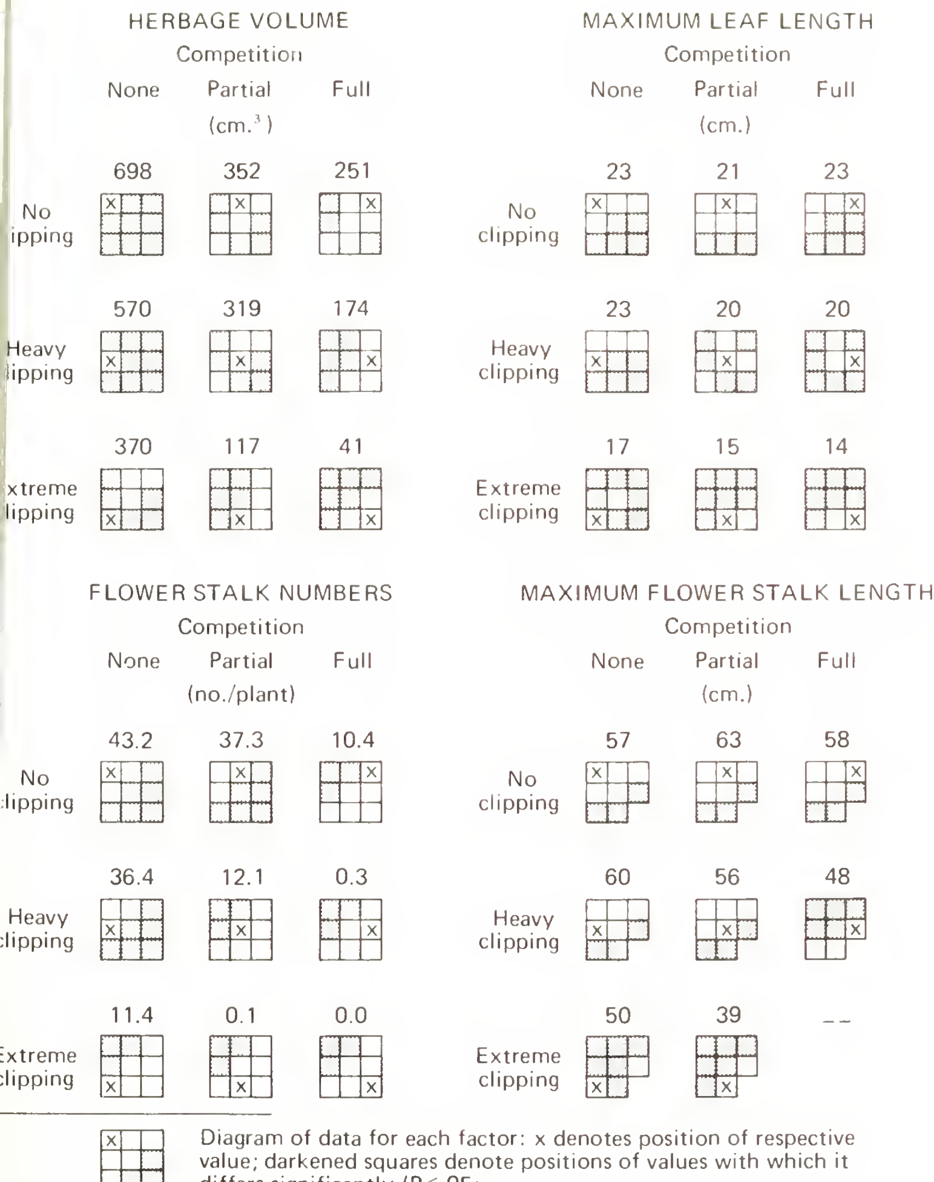


Figure 3. Herbage volume, number of flower stalks, and maximum leaf and flower stalk lengths of Idaho fescue the year following clipping and competition treatments.

petition reflected increased live basal area rather than increased plant height.

Each of the treatments, clipping and competition, affected the number of flower stalks produced by Idaho fescue very similarly (figures 2 and 3). Plants clipped heavily and extremely while subjected to the added stress of full competition virtually failed to flower. Even under partial competition, plants extremely clipped still produced virtually no flower stalks, but the heavily clipped plants produced as many flower stalks as the check plants that received no clipping and full competition. Flower stalk production was even better under no competition where even the extremely clipped plants produced as many flower stalks as the check plants.

Reducing natural competition obviously enhances flower stalk production. Eliminating competition permitted a fourfold increase in the number of flower stalks produced by unclipped plants; even partially reducing competition increased flower stalk production almost as much.

Flower stalk lengths were affected much less by clipping than were flower stalk numbers (figure 3). The combined detrimental effects of heavy clipping and full competition reduced both maximum and average flower stalk lengths by 17 percent. When competition was reduced, only extreme clipping caused a significant reduction in flower stalk lengths. Competition reductions alone did not significantly affect flower stalk lengths. Thus, neither flower stalk lengths nor leaf lengths appear to reflect vigor in Idaho fescue as readily as herbage volume and flower stalk numbers.

Although none of the fescue plants died under even the most severe treatment, many failed to produce flower stalks (table 1); this was particularly true for plants that were subjected to extreme clipping.

Table 1. — Percentage of Idaho fescue plants producing flower stalks the year following clipping and competition treatments

Clipping	Competition		
	None	Partial	Full
None	100	100	100
Heavy	100	100	20
Extreme	73	7	0

Discussion

This study demonstrates how effectively competition restricts growth of Idaho fescue. A partial removal of competition stimulates a substantial increase in herbage volume; elimination of competition permits a very great increase in volume. However, only a partial reduction in competition is almost as effective as complete elimination for increasing flower stalk production since both treatments nearly quadrupled the number of flower stalks.

Leaf and flower stalk lengths appear to be relatively rigid characteristics of Idaho fescue. Neither changed when plant vigor was increased by reducing competition. Apparently, under a normal climatic regimen, healthy Idaho fescue plants achieve their potential height growth even under the stress of full competition from associated vegetation.

Although heavy clipping is very detrimental to herbage production, it is even more harmful to flower stalk production. Leaf and flower stalk lengths are also reduced by heavy clipping, but these changes are relatively small compared to changes in herbage volume and flower stalk numbers. Since the number of flower stalks also increases most readily following reductions in competition, this characteristic is apparently a better indicator of Idaho fescue vigor than either leaf length, flower stalk length, or herbage volume.

The detrimental effects of clipping on Idaho fescue become progressively less as competition decreases. For example, extreme clipping reduced herbage volume the following year about 85 percent under full competition, 65 percent under partial competition, and 45 percent under no competition. Elimination of competition completely offsets the effect of extreme clipping on both volume and flower stalk production. A partial reduction of competition, as achieved in this study, more than compensates for the detrimental effect of heavy clipping.

These data exemplify the need for caution when applying results from clipping studies to plants being grazed on the range. The level of competition to which a plant is subjected during clipping trials can greatly influence actual herbage and flower stalk production; even the relative effects of different clipping intensities might be altered. If possible, studies simulating grazing of individual species should be conducted under conditions of competition similar to those encountered in the plant community where the results will be applied.

The results of this study imply certain considerations in managing Idaho fescue rangelands. Idaho fescue can withstand at least occasional heavy removal of its herbage if the surrounding vegetation is also used heavily. However, this is only part of the knowledge required for the formulation of sound management procedures. The response of plants, soils, and animals to repeated high-intensity use is of major importance. This has yet to be determined.

Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field Research Work Units are maintained in:

- Boise, Idaho
- Bozeman, Montana (in cooperation with Montana State University)
- Logan, Utah (in cooperation with Utah State University)
- Missoula, Montana (in cooperation with University of Montana)
- Moscow, Idaho (in cooperation with the University of Idaho)
- Provo, Utah (in cooperation with Brigham Young University)

ABOUT THE FOREST SERVICE . . .

As our Nation grows, people expect and need more from their forests — more wood; more water, fish, and wildlife; more recreation and natural beauty; more special forest products and forage. The Forest Service of the U. S. Department of Agriculture helps to fulfill these expectations and needs through three major activities:

- Conducting forest and range research at over 75 locations ranging from Puerto Rico to Alaska to Hawaii.
- Participating with all State forestry agencies in cooperative programs to protect, improve, and wisely use our Country's 395 million acres of State, local, and private forest lands.
- Managing and protecting the 187-million acre National Forest System.

The Forest Service does this by encouraging use of the new knowledge that research scientists develop; by setting an example in managing, under sustained yield, the National Forests and Grasslands for multiple use purposes; and by cooperating with all States and with private citizens in their efforts to achieve better management, protection, and use of forest resources.

Traditionally, Forest Service people have been active members of the communities and towns in which they live and work. They strive to secure for all, continuous benefits from the Country's forest resources.

For more than 60 years, the Forest Service has been serving the Nation as a leading natural resource conservation agency.

PHYSICAL FUEL PROPERTIES OF PONDEROSA PINE FOREST FLOORS AND CHEATGRASS

BY JAMES K. BROWN

USDA FOREST SERVICE
RESEARCH PAPER INT-74,197

INTERMOUNTAIN FOREST & RANGE EXPERIMENT STATIO
Ogden, Utah

USDA Forest Service
Research Paper INT-74
1970

PHYSICAL FUEL PROPERTIES OF PONDEROSA PINE FOREST FLOORS AND CHEATGRASS

James K. Brown

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401
Joseph F. Pechanec, Director

THE AUTHOR

JAMES K. BROWN received his bachelor's degree from the University of Minnesota in 1960, his master's from Yale University in 1961, and his Ph. D. from the University of Michigan in 1968; all in Forestry. From 1961 to 1965, he did research on field measurement of fuel properties and fire-danger rating systems while with the Lake States Forest Experiment Station. In 1965 he transferred to the Northern Forest Fire Laboratory, Missoula, Montana, where he is responsible for research on the physical properties of fuel. This paper is based upon a portion of the author's dissertation for his Ph. D. degree, which was entitled "Quantitative Description of Certain Physical Properties of Ponderosa Pine Forest Floor and Cheatgrass Fuels."

The author wishes to express his appreciation to Orval Gastineau, Forest Research Technician at the Northern Forest Fire Laboratory, who performed many of the field and laboratory measurements and computations.

CONTENTS

ABSTRACT

Physical fuel properties were determined utilizing measurements of volume, surface area, and weight for ponderosa pine forest floors and cheatgrass. Average values of these properties for ponderosa pine needle litter and cheatgrass were respectively: surface area-to-volume ratio (σ), 57.6 and 144.0 cm.^{2}/cc.; particle density, 0.51 and 0.34 g./cc.; loading, 324 and 53 g./m.^{2}; void volume-to-surface area ratio (λ), 0.8 and 12.5 cc./cm.^{2}; average particle spacing, 0.66 and 1.70 cm.; bulk density, 0.016 and 0.00032 g./cc.; and $\sigma\lambda$, 37.5 and 1810. Also presented are volume and surface area proportions of the forest floor litter and of the cheatgrass. A goodness-of-fit test showed that pine needles were randomly oriented in the horizontal plane and that cheatgrass particles were nonrandomly oriented in the vertical plane. Correlation analysis indicated that bulk density and particle spacing could be substituted for λ, a fairly difficult variable to measure.

INTRODUCTION

Objective, reliable assessment of potential fire behavior, especially for land managers not intimately familiar with fuels and fire behavior, depends upon the ability to recognize and describe quantitatively certain physical properties of fuel. Development and use of mathematical models for assessment of probable fire behavior on wildfires and prescribed burns particularly require quantification of fuel properties. Quantitative description of fuel properties will be a necessity as the science of fire is developed and more of its principles are applied to solving practical problems.

Like most living things, forest and range fuels are assortments of plant parts and have definite bodily form depending on inherent qualities and environmental conditions. The individual plant is composed of distinctly different parts or organs; for example, flowers, stems, leaves, roots, buds, petioles, bark, and thorns. The wide variety of living and dead plant parts that exist are actually *fuel particles* of varying sizes and shapes. A collection of fuel particles can be termed a *fuel complex*.

This paper reports values for the following physical properties and their relationships to one another for ponderosa pine (*Pinus ponderosa* Laws.) forest floor and cheatgrass (*Bromus tectorum* L.) fuels:

1. Particle size - σ (ratio of particle surface area to volume)

2. Particle density (weight per unit volume)

3. Loading (weight per unit ground area)

4. Porosity:

    a. Ratio of void volume in fuel complex to surface area of fuel - λ

    b. Particle spacing (average distance between fuel particles)

    c. Bulk density (weight per unit volume of fuel complex)

5. $\sigma\lambda$ (a dimensionless fuel complex parameter)

6. Particle orientation (position in space).

Except for particle orientation, the fuel properties were chosen for study because of their significant influence on ignition probability, rate of fire spread, and fire intensity. For example, the ratio σ is a particularly meaningful measure of fuel particle size because of its relationship to rates of change in fuel temperature and in moisture content. Temperature and moisture content of thin fuel particles having a high surface-to-volume ratio generally fluctuate more rapidly than thick particles having a low surface-to-volume ratio (Fons 1950; King and Linton 1963). Controlled combustion studies have shown that ignition time varies inversely with σ (Curry and Fons 1938) and rate of fire spread varies in direct proportion to σ (Rothermel and Anderson 1966).

Particle density is primarily an important fuel property because of its influence on thermal conductivity and consequent influence on time to ignition.[1] Whether or not ignition of a fuel is of the pilot-flame or spontaneous type also depends on particle density.

---

[1]D. S. Stockstad. Ignition properties of fine forest fuels. Unpublished problem analysis, Intermountain Forest and Range Exp. Sta., Ogden, Utah. 1967.

Loading is an important property of fuel because it expresses an amount of fuel energy or potential fire intensity. Taken alone, however, it is not an adequate predictor of fire behavior because other fuel properties, such as moisture content, porosity, particle size, and chemical composition, also determine the amount and rate of fuel energy release.

Porosity is the inverse expression of compactness. Porosity relates to the spacing of fuel particles and affects ignition time and combustion through its influence on oxygen supply and radiant energy transfer between particles. Several studies using wooden cribs and pine needle beds have shown that various measures of burning rate increase with increasing porosity up to a certain point (Curry and Fons 1940; Gross 1962; Byram et al. 1964; Anderson et al. 1966). According to Byram, increasing the stick spacing in a fuel complex increases the transmission of radiant heat in the direction of the unburned fuel. But if spacing is too great, unburned particles may not receive enough heat for ignition. If sticks are too closely spaced, sustained burning will not be possible because of restricted airflow. Maximum fire spread occurs between these limits.

Recent research shows that burning characteristics are related to $\sigma\lambda$ (a dimensionless variable) (Rothermel and Anderson 1966). Both particle size and porosity are incorporated in $\sigma\lambda$. Burning characteristics of different fuels possibly may be rated on the basis of $\sigma\lambda$, although more research is needed to demonstrate this conclusively. Past combustion studies involving $\sigma\lambda$ have dealt only with a single particle size. Mixtures of particle sizes certainly need study as well.

The significance of particle orientation in combustion of forest and range fuels is probably minor compared to other fuel properties, although its exact role is not understood. Particle orientation does affect the aerodynamic drag in a fuel complex and probably affects exposure to incident radiation. The forced convection heat transfer coefficient for blue spruce (*Picea pungens* Engelm.) foliage has been shown to vary according to orientation of foliage with respect to direction of airflow (Tibbals et al. 1964).

The fuels studied were collected in western Montana and occur widely throughout the West and are highly flammable. No effort was made to inventory fuel characteristics throughout areas where these two types occur; rather, we sought to obtain an idea of the range in values of fuel properties encountered in these types of fuel and to test techniques of measurement.

SAMPLING PROCEDURES

Ponderosa Pine Forest Floors

Forest floor material was sampled in 13 ponderosa pine stands within 20 miles of Missoula, Montana. The stands ranged from open to closed in density. They were 52 to 99 years of age and occurred on poor, medium, and good sites (figs. 1 and 2). Pine needles and miscellaneous particles, which include staminate flowers, cone scales, cones, bark flakes, branches, grass, and flat leaves, comprised the forest floor (fig. 3).

In each stand, five plots, 1 foot square, were randomly located and photographed in stereo to provide a permanent visual record of the fuel before disturbance. Depth of the litter, or L layer,[2] was measured at four positions (fig. 4) using a rule sliding

---

[2]The layers of the forest floor are defined in a glossary of terms approved by the Terminology Committee of the Soil Science Society of America (1965) as: L layer--the surface layer of the forest floor consisting of freshly fallen leaves, needles, twigs, stems, bark, and fruits; F layer--a layer of partially decomposed material with portions of plant structures still recognizable; and H layer--a layer occurring in mor humus consisting of well-defined organic matter of recognizable origin.

Figure 1.--This [illegible]-year-old open stand of ponderosa pine, which contained 220 trees per acre and 110 square feet of basal area, averaged 231 grams per square meter (2,060 lbs./acre) of fuel in the litter layer.

through a wood frame that measured 1 by 4 [illegible] rule was placed at the top of the F layer [illegible] as the top of the L layer. Depth was recorded [illegible] Occasional single needles sticking above the [illegible] pressed. Identification of the top of the F layer [illegible] condition (resulting from fungal mycelium) of the [illegible] used to calculate the volume of the fuel [illegible]

A metal frame, 1 foot square, was positioned [illegible] particles crossing under the frame was counted [illegible] of particle spacing (fig. 4). Particle orientation [illegible] minimum of 10 particles per side. The angle [illegible] with an imaginary extension of the bottom of the [illegible] adjacent 30°-wide sectors. Orientation was [illegible] practically all particles lie in this direction due [illegible]

Figure 2.--This 60-year-old dense stand of ponderosa pine, which contained 2,700 trees per acre and 230 square feet of basal area, averaged 415 grams per square meter (3,680 lbs./acre) of fuel in the litter layer.

---

[3] Ibid.

Figure 3.--Grass blades (top); cone scale, staminate flower leaf of woody plant, bark flake (from left to right, middle); and branchwood (bottom) were miscellaneous particles found in the litter.

data was used to estimate randomness of particle orientation and for testing a planar intersect method for estimating fuel volume and surface area.[4]

After the litter was collected, the depth of the F layer was measured where the perpendicular bisectors intersected the edges of the plot. Bulk density was computed on an ovendry weight basis. Very little material collected below the L layer could be identified as H layer material (Soil Sci. Soc. Amer. 1965, p. 9).

Cheatgrass

Cheatgrass plots were established on a slight slope in a south-facing area approximately 1 acre in size 6 miles west of Missoula, Montana (fig. 5). Six kinds of fuel particles--stalks, leaves, peduncles, glumes, spikelets, and awns--were sampled separately (fig. 6).

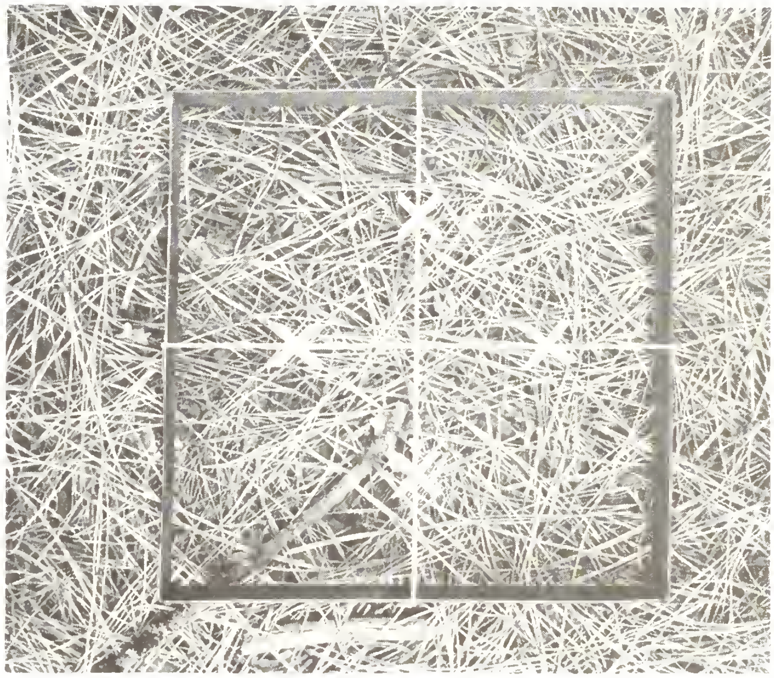
Three zones containing heavy, moderate, and sparse amounts of fuel were delineated on the ground. Plots 30 by 45 centimeters in size were randomly located in all three zones. All fuel and approximately 5 centimeters of soil were lifted undisturbed into flats and transferred to the laboratory for measurements. The measurements were actually taken from an area 10 by 25 centimeters in each plot. A larger amount of fuel than needed for measurements was collected to avoid disturbing fuel along the small plot edges during the lifting process.

In the laboratory, 15 sampling planes were randomly positioned through the fuel in each plot using a sliding wire frame to delimit the sampling plane (fig. 7). The wire frame, 2.5 centimeters wide, was moved horizontally through the fuel at various elevations for a distance of 10 centimeters. Numbers of particles, by kinds, passing through or touching the sampling plane were recorded; their angle of orientation with respect to the sampling plane was estimated ocularly. For cheatgrass, locating sampling planes horizontally facilitated the counting of particle intersections since particles were oriented dominantly in the vertical direction. Particle orientation was judged only with respect to the vertical direction.

---

[4]J. K. Brown. A planar intersect method for sampling fuel volume and surface area. Intermountain Forest and Range Exp. Sta., Ogden, Utah 84401. (In preparation.)

Figure 4.--The metal frame delineates a 1-foot-square plot upon the forest floor of ponderosa pine. Depth of the L layer was measured along perpendicular bisectors of the plots at locations marked "X."



Depth of fuel complex was measured as the distance from the ground to an average height regarded as the general level across the top of the cheatgrass. Occasional cheatgrass parts existing above what appeared as the general top level were excluded from all measurements. All cheatgrass inside the 10- by 25-centimeter plots was carefully clipped, removed, and dissected into the six kinds of particles for determining surface area and volume. The small amount of litter present (mostly fallen spikelets) was excluded from measurements.

VOLUME, SURFACE AREA, AND DENSITY MEASUREMENTS

Volume and surface area of pine needles and cheatgrass were determined from volume-per-gram and surface-per-gram factors multiplied by weight in grams of each type of particle on each plot. These factors were determined from measurements of surface area, volume, and weight for a subsample of particles collected from the study areas.

Figure 5.--Cheatgrass, the predominant vegetation in this area, averages 53 grams per square meter (470 lbs./acre). Other plant species visible are balsamroot (Balsamorhiza sagittata *Nutt.*), *moth mullein* (Verbascum blattaria *L.*), *and daisy* (Erigeron *spp.*).

Figure 6.--Drawing showing parts of a cheatgrass plant.

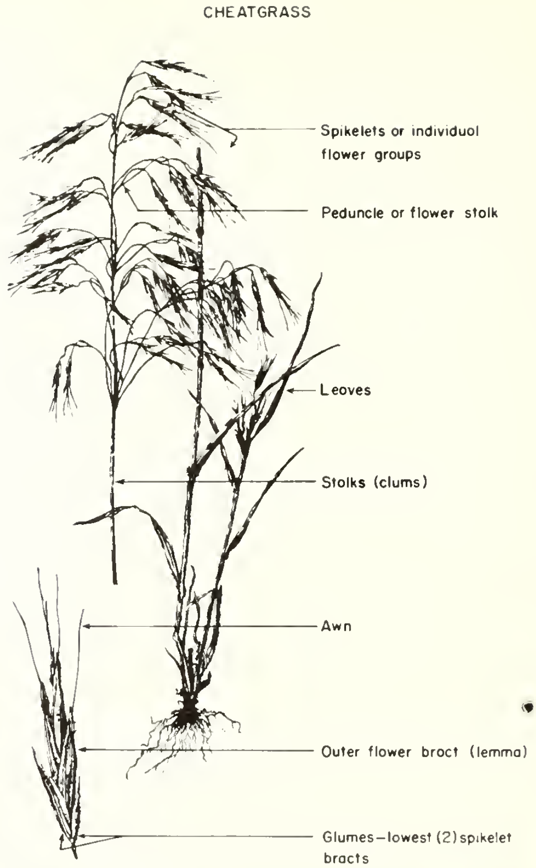
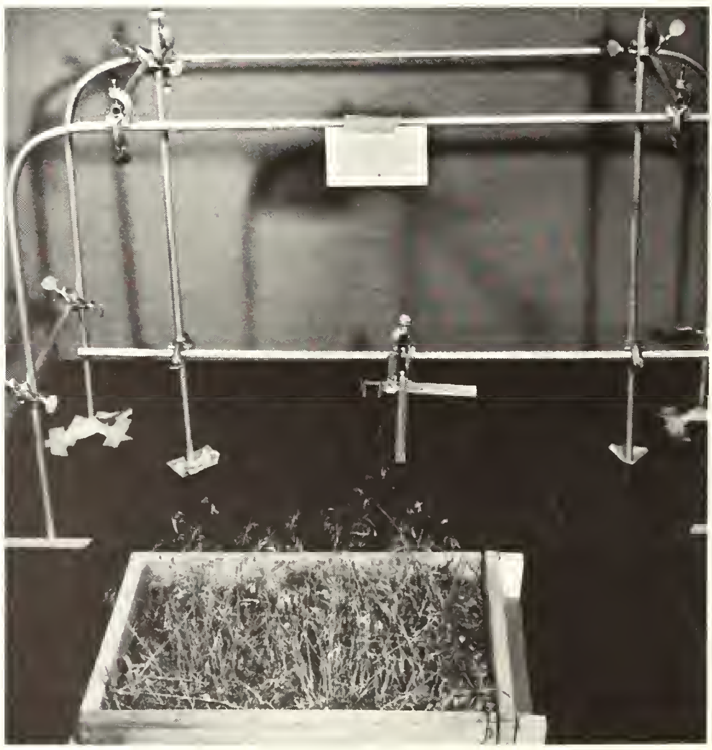


Figure 7.--Apparatus for sampling cheatgrass. The two wires on a movable tract in the center of the picture delineate the sampling plane.



Both surface area and volume were measured on the same fuel specimen to aid in accurately determining surface-to-volume ratios. Sample material was at a moisture content of 5 to 8 percent. For long, narrow particles (pine needles, cheatgrass stalks, peduncles, awns, and spikelets), volume and surface area were determined using measurements of particle cross-sectional area, perimeter, and length. Cross-sectional area and perimeter of pine needles were measured using photomicrographs of right-angled cross sections. Diameters measured microscopically permitted calculation of cross-sectional area and perimeter of the cheatgrass particles.

For flat particles (cheatgrass leaves and glumes and miscellaneous leaves in the forest floor), volume and surface area were determined using measurements of leaf thickness and blueprint outlines of leaf areas.

An electrolytic technique similar to that developed by Tibbals et al. (1964) employing silver castings was used to estimate surface area for cone scales. Volume was determined by displacement in water. Volume and surface area for the staminate flowers, bark flakes, and grass were determined from counts of number of particles in each plot and estimates of their average dimensions. For complete details on measurement of volume and surface area see Brown (1970).

Particle density was determined using ovendry weights and airdry (5- to 8-percent moisture content) volumes.

CALCULATIONS OF $\sigma\lambda$, PARTICLE SPACING, AND ORIENTATION

Most of the properties are calculated from measurements in a manner obvious from their definitions. Calculations of $\sigma\lambda$, particle spacing, and orientation, however, are not so obvious. It is necessary to determine an average σ in calculating $\sigma\lambda$ for fuel complexes, where more than one particle size is present. In this study, where six to eight different particles existed, σ was calculated as an average, weighted by volume of each type of particle present.

Spacing of particles, as viewed in the sampling plane, is computed from

$$Sp = \sqrt{Vd} - \sqrt{A} \qquad (1)$$

where:

Sp = average particle spacing,

Vd = void space per particle, and

A = average cross-sectional area of particles.

It is assumed that particles are square in cross section and that void space is distributed evenly about each particle. Solution of equation (1) requires knowledge of average right cross-sectional area of particles and sample information on the number of particle intersections with a sampling plane. Void space per particle equals the area of sampling plane divided by number of particle intersections.

The following two hypotheses were subjected to the chi-square test for goodness-of-fit for evaluating randomness of particle orientation: (1) Ponderosa pine needles are randomly oriented in a horizontal plane; (2) cheatgrass particles are randomly oriented in a vertical plane.

The number of particle intersections in each of the six 30°-wide sectors arcing about one side of the sampling plane was compared with the expected number of particle intersections in these sectors.

The expected number of particle intersections (E) was calculated from

$$E_{(0° - 30°)} = 0' \int_{0°}^{30°} \sin \theta d\theta$$

$$E_{(30° - 60°)} = 0' \int_{30°}^{60°} \sin \theta d\theta$$

$$E_{(60° - 90°)} = 0' \int_{60°}^{90°} \sin \theta d\theta$$

where 0' equals total number of observed particle intersections in all six 30°-wide sectors.

These calculations are appropriate because the probability of a randomly positioned plane intersecting a particle is proportional to the sine of the angle between particle and plane (Kendall and Moran 1963). Consequently, the number of particles intersected at any angle is also proportional to the sine of the angle of intersection.

RESULTS AND DISCUSSION

Surface-to-Volume Ratios

Two observations of σ on each of 13 ponderosa pine needles of average thickness averaged 57.57 square centimeters per cubic centimeter with a standard deviation of 6.81 square centimeters per cubic centimeter.

Average σ for the entire cheatgrass plant was 144.03 square centimeters per cubic centimeter. This average, as well as average density, was weighted according to volume of each particle found on all plots. Table 1 summarizes average values of σ for the six cheatgrass particles.

Table 1.--Averages and measures of variation of surface area-to-volume ratios for six particles comprising cheatgrass

Kind	Average surface-to-volume ratio	Number of observations	Standard deviation	Coefficient of variation
	$Cm.^2/cc.$		$Cm.^2/cc.$	Percent
Stalks	75.8	880	5.8	7.6
Leaves	167.4	50	17.7	10.6
Peduncles	277.3	100	14.1	5.1
Spikelets	321.5	5	([1])	([1])
Awns	331.7	20	75.4	22.7
Glumes	709.1	9	130.3	18.4

[1]Not calculated.

Table 2.--Average density and its variation for six particles comprising cheatgrass

Kind	Average density	Number of observations	Standard deviation	Coefficient of variation
	G./cc.		G./cc.	Percent
Stalks	0.36	10	0.03	8.4
Leaves	.25	10	.02	7.9
Peduncles	.51	10	.06	12.0
Spikelets	.57	5	([1])	([1])
Awns	.59	15	.28	46.6
Glumes	.21	15	.03	12.7

[1]Not calculated.

Density

Density of ponderosa pine needles free of decay averaged 0.51 gram per cubic centimeter with a standard deviation of 0.046 gram per cubic centimeter for thirteen 10-needle samples. Decay of needles ordinarily reduces their density as was evidenced in another sample of needles, some slightly gray in color and harboring incipient decay. Density of this sample, determined for 620 needles from three stands, averaged 0.47 gram per cubic centimeter.

Density for the entire cheatgrass plant averaged 0.34 gram per cubic centimeter (table 2). Density of stalks is based on a volume figure containing some void space, since the centers of the larger stalks are hollow. Consequently, density of stalk material itself should be greater than density of the entire stalks. Density of awns varied considerably, most likely because their shapes were assumed to be frustrums of right cones; whereas in truth, they vary from elliptical to circular in cross section. Their irregular shape and minute size made accurate determination of their volume difficult.

Table 3.--Fuel properties of the forest floor L layer from 13 stands of ponderosa pine

Fuel property	Highest stand[1]	Lowest stand	Average	S.E.[2]
Loading (g./m.^{2})[3]	601	129	324	62
λ (cc./cm.)	1.23	.45	.82	.08
Particle spacing (cm.)	.90	.44	.66	.04
Bulk density (g./cc.)[3]	.0429	.0049	.0158	.0033
$\sigma\lambda$	58.5	20.0	37.5	4.9

[1]Stand values are averages from five plots.

[2]Standard error of stand averages equals $\sqrt{\frac{\text{mean square for error}}{\text{treatment replications}}}$ where values for this calculation are provided from an analysis of variance with stands as treatments (Steel and Torrie 1960, page 104).

[3]Ovendry basis.

Loading of Fuel Complex

Loading for the ponderosa pine forest floor litter averaged 324 grams per square meter (2,890 lbs./acre) and ranged between 129 and 601 grams per square meter (table 3). These values compare with 630 grams per square meter for litter in natural red pine (*Pinus resinosa* Ait.) stands and 380 grams per square meter for litter from jack pine (*Pinus banksiana* Lamb.) plantations in the Lake States (Brown 1966). In Alabama, litter in second-growth longleaf pine (*Pinus palustris* Mill.) stands ranged from 290 to 477 grams per square meter (Boyer and Fahnestock 1966).

The litter layers ranged from 1 to 3 centimeters in depth. The entire forest floor (decomposed and undecomposed material together) averaged 5 centimeters in depth and 2,623 grams per square meter (23,400 lbs./acre).

Loading for cheatgrass averaged 53 grams per square meter (470 lbs./acre), as shown in table 4. This average is not necessarily typical of cheatgrass production in western Montana but is probably low, since little rain fell during the spring growing season, which resulted in small yields. At Arrowrock, Idaho, cheatgrass yielded 42 grams per square meter (airdry) one year and 388 grams per square meter the next year (Hull and Pechanec 1947). This tenfold increase shows how production of cheatgrass can vary from year to year.

Table 4.--Averages for fuel properties from a 1-acre cheatgrass community

Item	Dense zone[1]	Moderate zone	Sparse zone	All plots[2]
Number of plots	11	20	7	38
Loading (g./m.^{2})[3]	77.1 [4](4.7)	53.2 (6.1)	15.7 (.7)	53.1
λ (cc./cm.^{2})	6.98 (2.06)	10.97 (4.72)	25.47 (8.46)	12.49
Particle spacing (cm.)	1.22 (.15)	1.76 (.58)	2.29 (.30)	1.70
Bulk density (g./cm.^{3})[3]	4.42×10^{-4} ($.66 \times 10^{-4}$)	3.16×10^{-4} (1.10×10^{-4})	1.24×10^{-4} ($.45 \times 10^{-4}$)	3.17×10^{-4}
$\sigma\lambda$	1010 (30)	1590 (60)	3690 (100)	1810

[1]The zones were delineated on the ground according to visual inspection of density of the cheatgrass.
[2]Mean weighted by number of plots.
[3]Ovendry basis.
[4]The numbers in parentheses are standard deviations.

Porosity of Fuel Complex

Void Volume-to-Surface Area

Porosity values determined in this study may be of particular interest for relating laboratory research on fire propagation to field conditions. One expression of porosity, λ, is the amount of void space associated with a unit area of fuel surface. Generally, movement of air and gases is freer as λ increases because the space between particles is greater. However, the distance that radiant heat must travel between particles is also greater.

Cheatgrass, averaging 12.5 cubic centimeters of void per square centimeter of surface, was 15 times more porous than the ponderosa pine forest floor litter which averaged 0.8 cubic centimeter per square centimeter. The greater porosity of cheatgrass is no doubt more conducive to rapid fire spread than the lower porosity of ponderosa pine litter.

Particle Spacing

Particle spacing is also a measure of the porosity of a fuel complex. Spacing between cheatgrass particles was 2-1/2 times greater than was spacing between particles in the ponderosa pine forest floors. Particle spacing, λ, and bulk density, even though they all indicate porosity, do not correlate perfectly because they are measured differently. Among the three, particle spacing showed the least difference between the forest floor litter and cheatgrass.

Bulk Density

Bulk density is an approximate measure of porosity of a fuel complex. It fails to precisely express the amount of fuel complex occupied by actual fuel volume because the specific gravity of fuel is disregarded. Thus, only weight, and not volume of fuel, is corporated in an expression of bulk density. Nonetheless, it does indicate a degree of porosity and has the practical advantage of being easy to measure.

The bulk density of cheatgrass averaged 0.00032 gram per cubic centimeter, which was 50 times less dense than the average of 0.016 gram per cubic centimeter for the litter. The F layer from the forest floors averaged 0.076 gram per cubic centimeter and ranged from 0.039 to 0.105 gram per cubic centimeter. This is approximately one-half as dense as bulk densities reported for humus of western white pine (*Pinus monticola* Dougl.), hemlock (*Tsuga heterophylla* (Rafn.) Sarg.), and Douglas-fir (*Pseudotsuga menziesii* (Poir.) Britt.) forests (Mader 1953) but practically the same as reported for red pine forests (Brown 1966). Depth of the F layer averaged 3 centimeters.

Proportions of Particles

Pine needles, averaged over all stands, comprised a little over one-half of the volume in the forest floor litter and approximately 90 percent of the fuel surface area. Miscellaneous particles accounted for the remainder. The proportions of needles and miscellaneous particles in the litter varied substantially from stand to stand. Needles comprised 43 to 79 percent of the volume and 78 to 97 percent of the surface area of the forest floor litter.

Among the miscellaneous particles, branches contributed by far the most volume but only slightly more surface area than cone scales as shown in the following tabulation:

Particle	Volume (Percent)	Surface area (Percent)
Branches	51.2	26.4
Cones	21.4	4.3
Cone scales	11.4	25.1
Bark	8.0	13.2
Staminate flowers	4.9	4.4
Leaves	2.4	19.6
Grass	.7	7.0
	100.0	100.0

In cheatgrass, stalks comprised almost two-thirds of the volume but only one-third of the surface area. The panicles (spikelets, glumes, and peduncles) comprised only a small portion of the total volume but a little over one-third of the surface area as shown in the following tabulation:

Plant part	Volume (Percent)		Surface area (Percent)	
Stalks	61		32	
Leaves	25		29	
Panicles:	14		39	
Spikelets		9		19
Glumes		3		15
Peduncles		2		5
	100		100	

Randomness of Particle Orientation

Forest and range fuels are composed of particles oriented in many directions. However, apparently no studies have been conducted that analytically define the randomness of particle orientation or the type of predominant orientation. Particle orientation should be taken into account when designing and using sampling methods for measuring fuel properties in the field.

Pine needles were randomly oriented (at the 0.01 confidence level) in the horizontal plane for all stands combined as well as for 12 of the 13 stands individually. In the one stand, the tip of a branch fell across the sampling plane on one plot so that a large number of needles attached to the branch lay in one direction. Such situations can be expected to occur sporadically in the forest. All stands grew on flat to moderately sloping terrain. Whether or not the generally random orientation of needles would hold on steep slopes is conjecture.

All six kinds of cheatgrass particles were nonrandomly oriented in the vertical plane. Except for glumes, the other particles were oriented predominantly within 30° of true vertical. A considerably greater number of glumes than expected under a random assumption were oriented within 30° of true horizontal.

Relationships Between Properties

Relationships between fuel properties were examined to see whether or not some fuel properties may be replaced by or estimated from other fuel properties or from sample data on number of particle intersections. The relationships between the three properties describing porosity are shown by the correlations in figure 8.

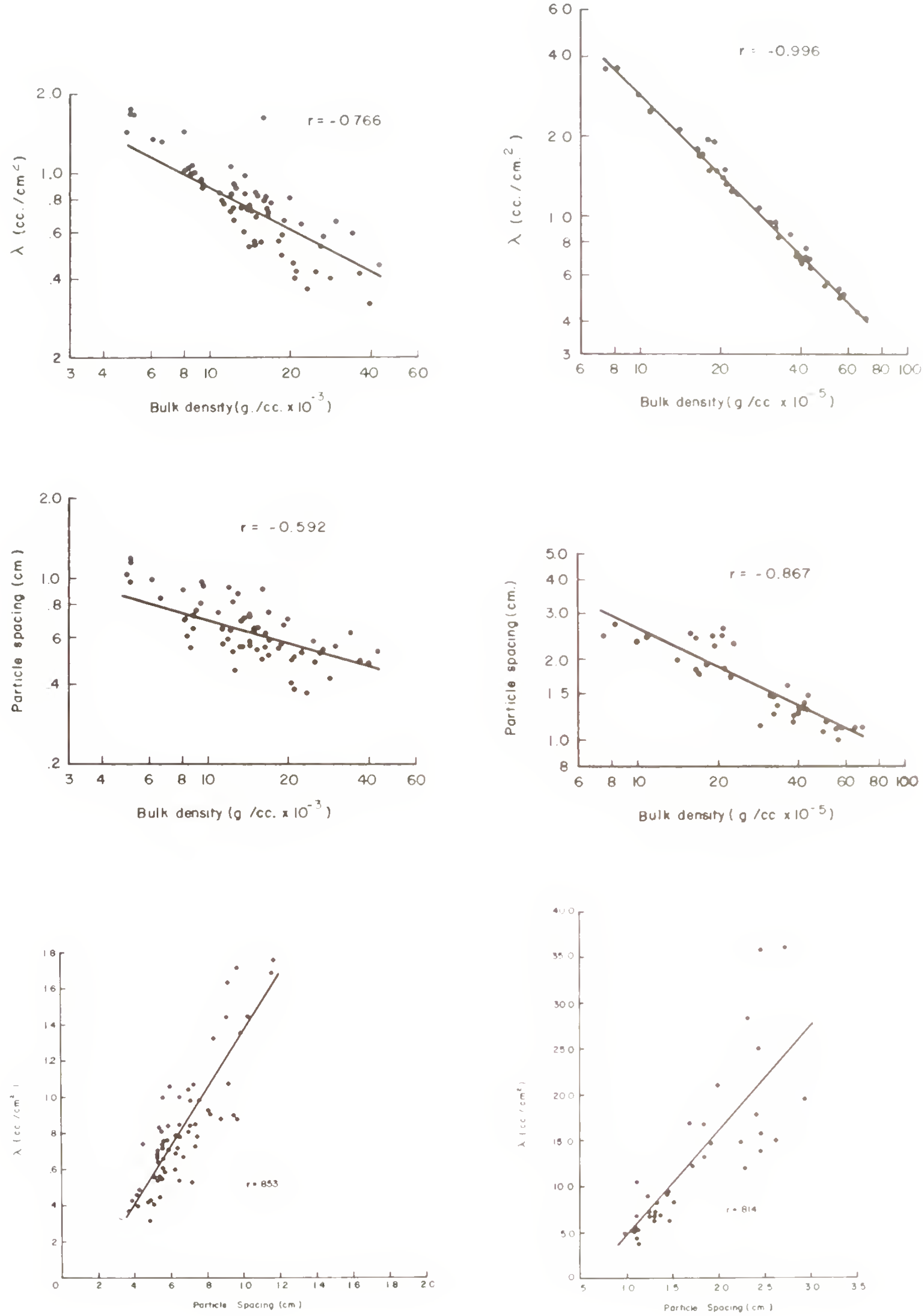


Figure 8.--Correlations between measures of the porosity of a fuel complex for ponderosa pine forest floor litter (left) and cheatgrass (right). The r values are significant at the 0.01 probability level and lines fitted by method of least squares.

The practical implication from these correlations is that particle spacing and bulk density possibly may be used as a substitute for λ or to estimate λ in other fuels as well as those studied. Measurement of λ entails considerable work because knowledge of fuel surface area and volume is required for its computation. In many fuels, it would be easier to determine spacing by actually sampling the distances between particles or by counting the number of particle intersections with a sampling plane. Bulk density can be determined readily by measuring fuel weight and dimensions of the fuel complex from a sample of plots. It is uncertain which of the three properties--bulk density, particle spacing, or λ--provides the most accurate description of porosity. Perhaps more accurate expressions of porosity than these three can be developed.

REFERENCES

Anderson, Hal E., A. P. Brackebusch, R. W. Mutch, and R. C. Rothermel.
1966. Mechanisms of fire spread, research progress report no. 2. U.S. Forest Serv. Res. Pap. INT-28, 24 p., illus.

Boyer, W. D., and G. R. Fahnestock.
1966. Litter in longleaf pine stands thinned to prescribed densities. U.S. Forest Serv. Res. Note SO-31, 4 p., illus.

Brown, James K.
1966. Forest floor fuels in red and jack pine stands. U.S. Forest Serv. Res. Note NC-9, 3 p., illus.

______ 1970. Ratios of surface area to volume for common fine fuels. Forest Sci. 16(1): 101-105, illus.

Byram, G. M., H. D. Clements, E. R. Elliott, and P. M. George.
1964. Technical report no. 3--an experimental study of model fires. U.S. Forest Serv., Southeastern Forest Exp. Sta., 36 p., illus.

Curry, J. R., and W. L. Fons.
1938. Rate of spread of surface fires in the ponderosa pine type of California. J. Agr. Res. 57(4): 239-267.

______ and W. L. Fons.
1940. Forest-fire behavior studies. Mech. Eng. 62: 219-225, illus.

Fons, W. L.
1950. Heating and ignition of small wood cylinders. Ind. and Eng. Chem. 42: 2130-2133, illus.

Gross, D.
1962. Experiments on the burning of cross piles of wood. J. Res. Nat. Bur. Stand., C. Eng. and Instrum., 66 C., pp. 99-105, illus.

Hull, A. C., and J. F. Pechanec.
1947. Cheatgrass--a challenge to range research. J. Forestry 45: 555-564, illus.

Kendall, M. G., and P. A. P. Moran.
1963. Geometric probability. New York, Hofner Publishing Co., 125 p.

King, A. R., and M. Linton.
1963. Moisture variation in forest fuels: the rate of response to climate changes. Aust. J. Appl. Sci. 14(1): 38-49, illus.

Mader, D. L.
1953. Physical and chemical characteristics of the major types of forest humus found in the United States and Canada. Soil Sci. Soc. Amer. Proc. 17: 155-158.

Rothermel, R. C., and H. E. Anderson.
1966. Fire spread characteristics determined in the laboratory. U.S. Forest Serv. Res. Pap. INT-30, 34 p., illus.

Soil Sci. Soc. Amer.
1965. Glossary of soil science terms. Soil Sci. Soc. Amer. Proc. 29(3): 330-351.

Steel, R. G. D., and J. H. Torrie.
1960. Principles and procedures of statistics with special reference to the biological sciences. 481 p., illus. New York, McGraw-Hill Book Co., Inc.

Tibbals, E. C., E. K. Carr, D. M. Gates, and F. Krieth.
1964. Radiation and convection in conifers. Amer. J. Bot. 51: 529-538, illus.

AFLC/HAFB, Ogden

Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field Research Work Units are maintained in:

- Boise, Idaho
- Bozeman, Montana (in cooperation with Montana State University)
- Logan, Utah (in cooperation with Utah State University)
- Missoula, Montana (in cooperation with University of Montana)
- Moscow, Idaho (in cooperation with the University of Idaho)
- Provo, Utah (in cooperation with Brigham Young University)

USDA FOREST SERVICE
RESEARCH PAPER INT-75
1970

EQUATIONS AND COMPUTER SUBROUTINES FOR ESTIMATING SITE QUALITY OF EIGHT ROCKY MOUNTAIN SPECIES

James E. Brickell

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Ogden, Utah 84401

THE AUTHOR

JAMES E. BRICKELL is an Associate Mensurationist in the Station's forest survey research work unit located in Moscow at the Forestry Sciences Laboratory. He received his bachelor's degree in forest management from Washington State University in 1961 and joined the Station's staff in 1964 after taking graduate studies at the University of Washington. He gratefully acknowledges the assistance and advice given him by Albert R. Stage, leader of the Station's timber measurement work unit at the Laboratory in Moscow.

USDA Forest Service
Research Paper INT-75
1970

EQUATIONS AND COMPUTER SUBROUTINES FOR ESTIMATING SITE QUALITY OF EIGHT ROCKY MOUNTAIN SPECIES

James E. Brickell

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401
Joseph F. Pechanec, Director

CONTENTS

INTRODUCTION

Computer programs for such purposes as the compilation of forest inventory data must contain instructions for operations that were done by hand only a few years ago. At that time, tables, graphs, and alinement charts were indispensable to the forester. The information which was contained therein is still indispensable, but today we must be able to store this information in a computer program in a form readily accessible for use. Computer use of charts or graphs to describe site or yield functions is impractical, but information stored in tabular form could be used However, this would require either a very extensive table for each species or interpolation within a small table. The core storage required for a number of extensive tables, in addition to the rest of the program and the data being processed, might well be more than available on smaller computers, while interpolation can lead to inaccuracy.

The existence of an alinement chart or a smooth curve, or tables made therefrom, implies the existence of a mathematical relationship between the variables involved. Sometimes the relationship is known, as when a table is made by repeated solution of an equation. Some charts and tables were derived altogether by graphic methods. When this is the case, an approximate mathematical relationship can usually be derived. However, the resulting approximation equation, complex and sophisticated as it may appear, can never be any better than the hand-drawn curve that it is supposed to represent.

Data collected 40 years ago represent our only source of information on site quality and yield capability for some species. Yield capability, as used by Forest Survey, is defined as mean annual increment of growing stock attainable in fully stocked natural stands at the age of culmination of mean annual increment. Yields may be substantially higher with thinning and other intensive management. Yield capability is measured in cubic feet per acre per year.

Site index, together with associated yield information, provides a means of assessing yield capability or, in other words, productive capacity of the land. However, all variation in yield capability from one site to another cannot be explained by conventional "site index." Short of direct measurement of stand growth itself, it is not generally known what stand parameter(s) could be used to account for variation not explainable by site index.

Despite its shortcomings, site index does provide a means of rating sites in terms of volume yield capacity--a more meaningful expression than site index alone.

Another factor may affect yield capability of a stand--the extent to which an area may be stockable. It may be that available soil is interspersed with areas of rock or gravel that will not support tree growth. Any yield capability figure expressed in this report on a per-acre basis will refer to an acre of tree-supporting soil, not to an acre of land containing some nonstockable area. Where full stocking is not possible, the yield capability estimate should be adjusted. This might be done by multiplying the yield capability estimate by the ratio of productive land area to total land area. The result would be a yield capability estimate for the entire area, including non-stockable portions.

Growing stock is defined, for Forest Survey purposes, as the live, noncull trees of commercial species in the stand 5.0 inches d.b.h. and larger. However, the sources of information from which the material presented in this report was derived used differing size standards, so the definition of growing stock that was necessarily used for each species will be given with the equations for that species.

The equations presented in this report can be used to estimate site index and/or yield capability for each of the following species:

1. Western white pine (*Pinus monticola* Dougl.)

2. Ponderosa pine (*Pinus ponderosa* Laws.)

3. Lodgepole pine (*Pinus contorta* var. *latifolia* S. Wats.)

4. Western larch (*Larix occidentalis* Nutt.)

5. Engelmann spruce (*Picea engelmannii* Parry)

6. Inland Douglas-fir (*Pseudotsuga menziesii* var. *glauca* (Mirb.) Franco)

7. Grand fir (*Abies grandis* (Dougl.) Lindl.)

8. Quaking aspen (*Populus tremuloides* Michx.)

For western white, ponderosa, and lodgepole pines, and for western larch and grand fir, the yield capabilities that are supposed to be equivalent to given levels of site index are shown in table 1. For Engelmann spruce, inland Douglas-fir, or quaking aspen, yield capability equations cannot be given because the necessary information was not available.

Table 1.--Yield capability according to site index for western white pine, ponderosa pine, lodgepole pine, western larch, and grand fir

Site index (50-year base age)	Yield capability				
	Western white pine[1]	Ponderosa pine[1]	Lodgepole pine[2]	Western larch[2]	Grand fir[1]
	Cubic feet per acre per year				
20	49.5	19.4	12.4	--	56.5
25	58.1	24.2	16.4	--	65.2
30	66.8	29.6	21.6	21.8	73.9
35	75.4	35.5	27.8	26.7	82.6
40	84.1	42.1	35.1	33.8	91.3
45	92.7	49.6	43.5	42.5	100.0
50	101.4	57.9	53.0	52.2	108.7
55	110.1	67.3	63.6	62.7	117.4
60	118.7	77.9	75.3	73.8	126.1
65	127.4	89.9	88.0	85.3	134.8
70	136.0	103.4	101.8	97.2	143.5
75	144.7	118.7	116.8	109.3	152.2
80	153.3	136.1	132.7	121.7	160.9

[1]Based on all surviving trees in the stand at the age of culmination of cubic mean annual increment.
[2]Based on all trees larger than 5.0 inches d.b.h.

SITE INDEX AND YIELD CAPABILITY EQUATIONS

The information in this section was derived either from published material or from data in the files of the Intermountain Forest and Range Experiment Station, as will be noted for each particular species. The mathematical details of equation construction or derivation have been omitted because use of the equations or computer subroutines does not require a complete description of the means by which they were derived.

Except for quaking aspen, all site indices are referred to at a base age of 50 years. For the user's convenience, computer programs that contain the calculating procedure are presented whenever the calculations required to obtain site index or yield capabilities for a species involve more than the simplest equation. The programs are written in FORTRAN IV. They have been tested on an IBM 360, Model 67 computer and they can be expected to function on any IBM 360 having the minimum of a FORTRAN IV, Level E compiler available. The programing might not always be the most efficient for the IBM 360 because the programs are designed to allow modification to other versions of FORTRAN. These programs have been written as subroutines because it is expected that their use will be implemented through a larger program.

The user is cautioned that extrapolation of statistically fitted equations beyond the range of the basic data may lead to inaccurate predictions. The probability that this will occur is greater when the equations are more complex. Mistakes in input data, poor selection of site trees, or the sampling of a site quality not represented in the data basic to an equation can prevent the iterative process from reaching a solution. It may well be that this trouble will never be encountered, but it is something of which the user should be aware.

WESTERN WHITE PINE

Site Index

Site index for even-aged stands of western white pine can be estimated by the equation:

$$S = b_0 H\ [1 - b_1 \cdot \exp\ (b_2 A)]^{b_3}, \text{ where}$$

S = site index at a base age of 50 years

H = average height of dominant and codominant trees

A = age of the oldest dominant tree in the even-aged stand

$b_0 = 0.37504453$

$b_1 = 0.92503$

$b_2 = -0.0207959$

$b_3 = -2.4881068.$

This equation was obtained by fitting an equation of suitable form to the height/age data in table 24 of Haig's (4) yield tables, then algebraically solving the latter equation for site index. Written in FORTRAN IV (IBM 360) the equation is:

```
S = 0.375045 * H * (1.0 -0.92503 * EXP (-0.020796*A))**(-2.48811).
```

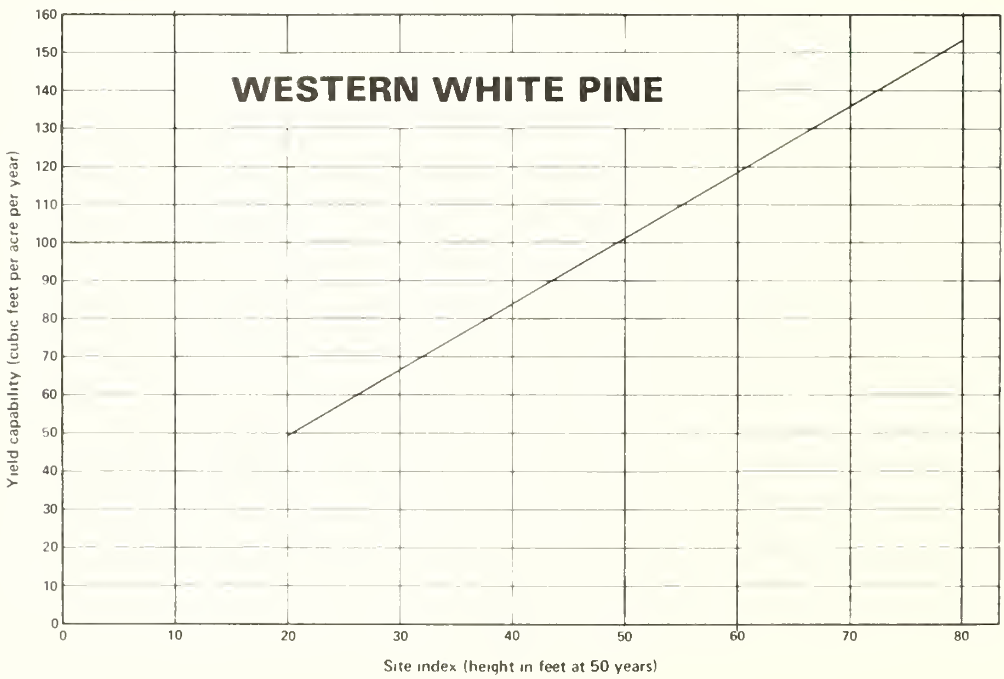


Figure 1.--Relationship between site index and yield capability.

Yield Capability

Yield capability of western white pine can be estimated by the equation:

$YC = b_0 + b_1S$, where

YC = yield capability in cubic feet per acre of mean annual increment on all trees at the age of culmination of increment

S = site index at a 50-year base age

b_0 = 14.849891

b_1 = 1.7311563.

This equation was derived from table 7 of Haig's (4) yield tables which show average mean annual increment of all trees in so-called normal stands for various ages and levels of site index. For western white pine, cubic mean annual increment culminates at a stand age of about 105 years, regardless of site quality, according to Haig's table. Consequently, this equation expresses the relationship between site index and cubic volume mean annual increment at a stand age of 105 years, as shown in figure 1.

PONDEROSA PINE

Site Index

The estimating procedure for even-aged stands of ponderosa pine is based on the curves developed by Lynch (7). The index base age was changed from 100 years to 50 years and the base of logarithms in the equation was changed so as to use natural rather than common logarithms.[1/] The surface of dominant stand height over age and site index remains unchanged, because the conversion of the curves resulted only in a rescaling of the independent variables. Lynch's system of site index curves takes into account the reduction in height growth due to overdense stocking on lower quality sites. Because one or the other of two equations is to be used, depending on whether or not stocking and site conditions have reduced height growth, the estimation procedure has been put into a computer program subroutine, shown in figure 2.

```
      SUBROUTINE PPSITE(A,H,B,SI50,SD)
      U=1.+0.2432*(100./A-1.)
      PI=(H*10.**(0.0437*(100./A-1.)))**(1./U)
      SD=B*(0.2918+0.0065*H-0.0467*H/A+29.752/A)
      IF(SD-100.0)3,3,1
    1 IF(PI-75.0)2,3,3
    2 Z=(SD-100.)*(75.-PI)
      RZ=EXP(-0.35123E-03*Z+0.276308E-06*Z*Z)
      GO TO 4
    3 RZ=1.
    4 PA=EXP(-1.19222*(100./A-2.))
      QA=0.195623*(100./A-2.)
      SI50=(H/(PA*RZ))**(1./(1.+QA))
      RETURN
      END
```

Figure 2.--Site index estimating subroutine for ponderosa pine.

[1/] Natural or Naperian logarithms are to the base e, where e = 2.71828. Common logarithms are to the base 10. In conventional notation, which will be used in this report, ln X means the natural logarithm of X, while log X means the common logarithm of X.

The mnemonics used in the subroutine are as follows:

A = total stand age

H = average height of trees in the dominant stand

B = stand basal area per acre

SI50 = site index at a 50-year base age

SD = stand density in percent as expressed by Lynch (7), where density is relative to the average for a particular age and site index. That is, when SD = 100 percent the stand is of average density; when SD = 50 percent the stand is half average density, and when SD = 200 percent twice average density is indicated.

Average density of Lynch's sample plots was a little less than normal for most ages and sites. The extremes were 83.3 percent and 111 percent of what Meyer (8) called normal.

Yield Capability

The plot data used in Lynch's study are the basis for the equation or procedure. A regression equation was fitted to the relationship between age, site index, stand density, and net cubic foot volume yield of the plots. When stands are assumed to be of average density for the sample (SD = 1), the equation reduces to:

$$\ln Y = b_0 + b_1 \ln S - b_2 A^{-2} - b_3 \ln S - b_4 + (b_5 - b_6) S - b_7 A^{-1} S^{-1},$$

or

$$Y = c_0 S^{c_1} \cdot \exp\,(c_2 S - b_2 A^{-2} - b_7 A^{-1} S^{-1}),$$

where

Y = net yield of all trees in cubic feet per acre

S = site index at a 50-year base age

A = stand age

$c_0 = \exp(b_0 - b_4) = 13{,}100.281$

$c_1 = b_1 - b_3 = -0.4930327$

$c_2 = b_5 - b_6 =$ 0.26782874E-01[2/]

$b_2 = 467.59461$

$b_7 = 1843.6671$

then, mean annual increment = Y/A.

[2/] According to FORTRAN notation, E±n following a number means that the number is to be multiplied by $10^{(\pm n)}$. In this instance, the E-01 indicates that the decimal point should be moved one place to the left (0.026782874).

On any particular site, the maximum mean annual increment is reached at the age when

$$\partial \, m.a.i./\partial \, A = 0.$$

Evaluating the indicated derivative and solving the equation for age, we find that mean annual increment is a maximum when

$$A = \frac{b_7 \, S^{-1} + \sqrt{b_7{}^2 S^{-2} + 8 \, b_2}}{2},$$

so the age at which mean annual increment is maximized can be expressed as a function of site index. Then,

$$YC = c_0 \, S^{c_1} \cdot \exp \left(c_2 S - b_2 A^{-2} - b_7 A^{-1} S^{-1}\right) \cdot A^{-1},$$

where

A = the age of mean annual increment culmination expressed as a function of site index, as shown above.

These equations have been put into a computer subroutine, which is shown in figure 3, and the relationship between site index and yield capability is shown in figure 4.

```
      SUBROUTINE PPYCAP (S,YCAPP)
      A=(1843.67/S+SQRT(.339911E+7/(S*S)+.374076E+4))/2.
      YCAPP=(13100.281*S**(-0.4930327)*EXP(0.267829E-01 *S-467.595  /(A
     1*A)-1843.67  /(A*S)))/A
      RETURN
      END
```

Figure 3.--The ponderosa pine yield capability subroutine.

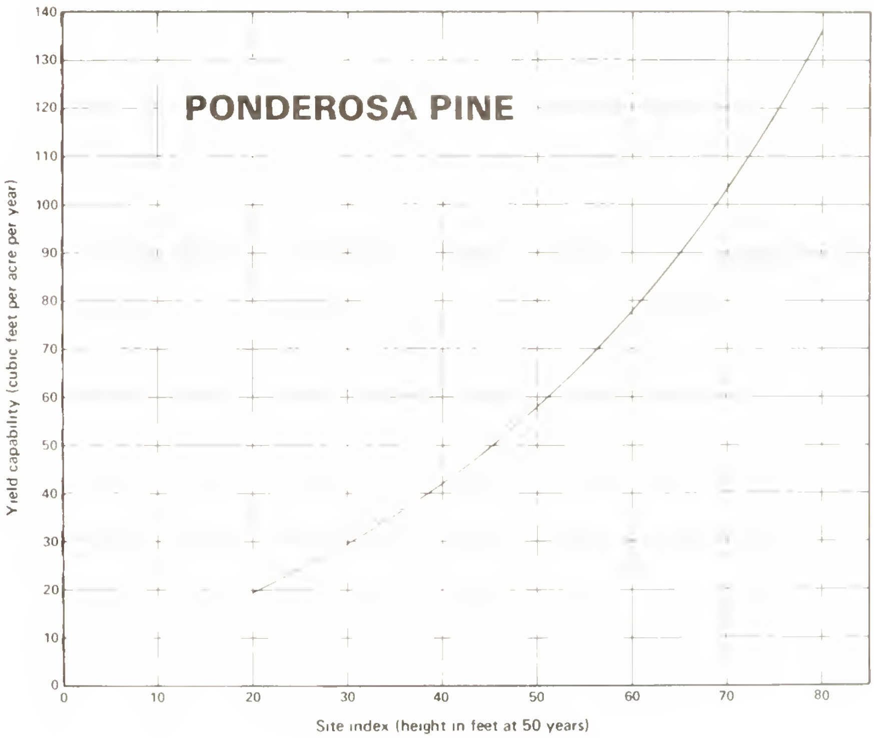


Figure 4.--Relationship between site index and yield capability.

LODGEPOLE PINE

Site Index

The procedure for estimating site index is based on the curves developed by Alexander (1). Like Lynch's curves for ponderosa pine, Alexander's curves for lodgepole pine can be used when stand density is heavy enough to have inhibited height growth of the dominant stand. This is thought to take place at densities where the crown competition factor[3] is greater than 125. Thus, two different procedures have been devised for estimating site index; where CCF is 125 or less a straightforward calculation by means of two equations will suffice.

The equations are:

$$SI = H + b_1 (\ln A - \ln 100) + b_2 (A^2 - 100^2) + b_3 (A^3 - 100^3)$$
$$+ b_4 [(H/A) - (H/100)] + b_5 [(H/A^2) - (H/100^2)] +$$
$$b_6 [(H/A^{2.5}) - (H/100^{2.5})],$$

where

SI = site index at a base age of 100 years

H = height of dominant stand

A = total age of an even-aged stand

$b_1 = 18.310745$

$b_2 = -0.21973907 \times 10^{-2}$

$b_3 = 0.61670435 \times 10^{-5}$

$b_4 = -64.32135$

$b_5 = 9528.3711$

$b_6 = -34848.289$

and

$$S = c_0 + c_1 SI,$$

where

S = site index at a 50-year base age

$c_0 = 1.029546$

$c_1 = 0.6297251.$

In stands where CCF exceeds 125 site index must be adjusted upward to compensate for the reduction in height of the dominant stand due to stocking density. Let $g(A)$ be a function of age:

$$g(A) = b_4[(1/A) - 0.01] + b_5[(1/A^2) - 0.0001] + b_6[(1/A^{2.5}) - 0.00001]$$

and

$$k = 0.8188667 \times 10^{-3} (CCF-125).$$

Then

$$P = 1-k[g(A) + 1].$$

---

[3] For an explanation of crown competition factor, see Krajicek, Brinkman, and Gingrich (6).

Within the range of the data on which these equations were based, P will range in value between zero and unity, so dividing SI, as computed above, by P gives the proper adjustment to compensate for the reduction in stand height.

These equations were not based on data including ages over 200 years. Therefore we recommend that ages older than 200 be reduced to 200 years.

```
      SUBROUTINE LPSITE(A,H,CCF,S)
      DIMENSION B(9)
      DATA B/18.310745,0.21973907D-02,0.61670435D-05,64.32135,9528.3711,
     1 34848.289,0.81836702D-03,1.029546,0.6297251/
      IF(A)2,2,1
    1 IF(H)2,2,3
    2 WRITE(6,201)
      S=0.0
      RETURN
    3 CCFT=CCF-125.0
      FA=B(1)*(ALOG(A)-4.6051702)-B(2)*(A*A-10000.0)+B(3)*(A**3-10.0**6)
      GA=-B(4)*(1.0/A-.01)+B(5)*(1./(A*A)-.0001)-B(6)*(A**(-2.5)-.00001)
      P0=FA+H*(GA+1.0)
      IF(CCFT)4,4,5
    4 CCFT=0.0
    5 EK=B(7)*CCFT
      P1=EK*(GA+1.0)-1.0
      SI =-P0/P1
      S=B(8)+B(9)*SI
      RETURN
  201 FORMAT(62HOEITHER AGE OR HEIGHT OF A LODGEPOLE PINE IS NEGATIVE OR
     1 ZERO.)
      END
```

Figure 5.--The site index estimating subroutine for lodgepole pine.

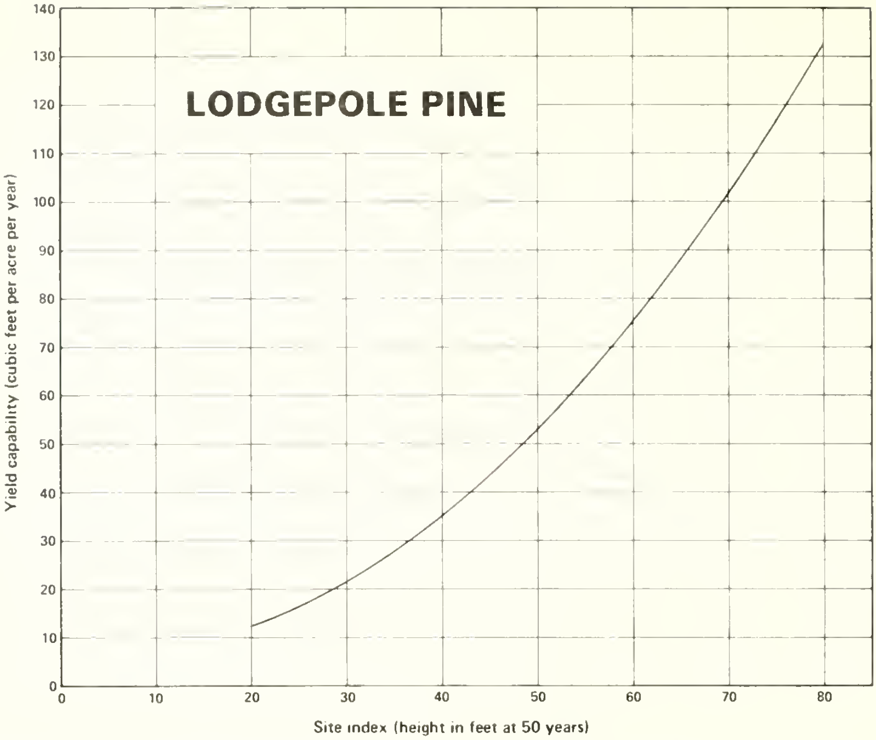


Figure 6.--Relationship between site index and yield capability.

Yield Capability

The equation for lodgepole pine was obtained by projecting yields of hypothetical stands according to the method published by Myers (9). The projection procedure differed from that of Myers in that we maintained a different stocking level for each level of site index. Myers used stocking levels of 80 for poorer sites and 100 for better sites. By 80 and 100 are meant stocking regimes that bring the stand to 80 or 100 square feet per acre of basal area at the time when average[4] stand diameter at breast height (d.b.h.) is 10 inches. Thereafter the stocking level is kept by thinning at 80 or 100 square feet of basal area per acre, even though average stand d.b.h. will increase. In making stand projections to derive a yield capability equation, the levels of stocking used for each site index were a linear function of site index, as shown below.

Site index at a 50-year base age	Stocking level
20	74.0
30	84.5
40	94.8
50	105.0
60	115.2
70	125.7
80	136.0

[4] The d.b.h. of the tree of average basal area.

Site index at a 50-year base age was used rather than at 100 years as in Myers' published example. Stand projection by Myers' method depends on the use of a predicting equation for future d.b.h., which has site index as one of the independent variables. Projections were made for hypothetical stands at higher site index levels than were found on any of the plots that served as the data base for Myers' equation. Nevertheless, the results obtained appeared entirely reasonable, so projections of stands at the higher site index levels were included in the estimates used to derive the yield capability equation.

For each site index, a curve of net yield before thinning was plotted over age. It was assumed that the volumes removed in thinnings would be lost to mortality in natural stands. The age of culmination of net cubic volume mean annual increment was estimated by drawing a line from the origin of coordinates tangent to the yield curve. The point of tangency indicated the age of m.a.i. culmination and the net stand yield at that age. Dividing the yield thus obtained by the culmination age gave the m.a.i. at the age of culmination, or the yield capability associated with that site index. Plotting yield capability over site index resulted in the curve shown in figure 6. This curve is described by the equation:

$$YC = b_0 + b_1S + b_2S^2,$$

where

YC = yield capability — $b_0 = 6.9091271$

S = site index at a 50-year base age — $b_1 = -0.16172109$

$b_2 = 0.021683019$

WESTERN LARCH

Site Index

The following equation for height of western larch in even-aged stands was developed by Arthur L. Roe:[5]

$$\log H = \log S - b_1 \ (1/A - 1/50),$$

where

$\log H$ = the common logarithm (to the base 10) of dominant stand height

$\log S$ = the common logarithm of site index at a 50-year base age

A = total stand age

b_1 = 21.036.

This equation can be easily solved for site index:

$$\log S = \log H + b_1 \ (1/A - 1/50)$$

$$S = 0.37956 \ H \cdot \exp \ (48.4372/A)$$

The last equation shown above can be used in computer programs to estimate site index of even-aged stands of western larch.

[5] Principal Silviculturist, Intermountain Forest and Range Experiment Station.

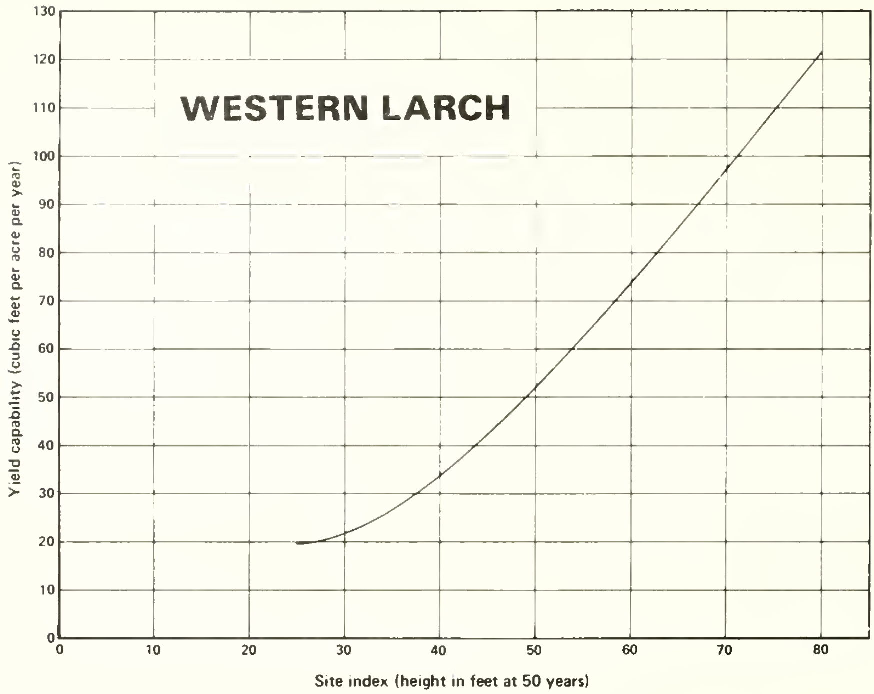


Figure 7.--Relationship between site index and yield capability.

Yield Capability

The yield capability equation for western larch is based on current work being done by Roe and John H. Wikstrom.[6] For cubic volume yield capability in stems 5.0 inches d.b.h. and larger, the equation is:

$$YC = b_0 + b_1 S + b_2/S,$$

where

YC = yield capability in cubic feet per acre per year of mean annual increment

S = site index (50-year base age)

b_0 = -126.05

b_1 = 2.7974081

b_2 = 1919.3157.

This equation cannot be used when site index is less than 26 feet, because the table from which it was made gives no information below site index 30.

[6] Principal Economist, Intermountain Forest and Range Experiment Station.

To derive this equation, the yield curves were plotted for each level of site index. Then a series of lines was drawn, passing through the origin of coordinates and tangent to each yield curve. From the point of tangency the following was read: (a) the age of culmination of mean annual increment, and (b) the yield at that age for each level of site index. The mean annual increment at its culmination age for each site index level was obtained by dividing (a) intc (b). The relationship between site index and yield capability was approximated by the least squares fitting of a suitable curve form to the series of points plotted from site index and yield capability. This is shown in figure 7.

ENGELMANN SPRUCE

Site Index

An equation with which site index can be estimated directly from measurements of tree age and tree height is given by Brickell (2). This equation is:

$$S = H + \sum_{i=1}^{11} b_i X_i ,$$

where

S = site index at a 50-year base age

H = total tree height

A = total tree age

and

$b_1 = 0.10717283\text{X}10^2$ $\qquad X_1 = (\ln A - \ln 50)$

$b_2 = 0.46314777\text{X}10^{-2}$ $\qquad X_2 = [(10^{10}/A^5) - 32]$

$b_3 = 0.74471147$ $\qquad X_3 = H[(10^4/A^2) - 4]$

$b_4 = -0.26413763\text{X}10^5$ $\qquad X_4 = H\ (A^{-2.5} - 50^{-2.5})$

$b_5 = -0.42819823\text{X}10^{-1}$ $\qquad X_5 = H\ (\ln A - \ln 50)^2$

$b_6 = -0.47812062\text{X}10^{-2}$ $\qquad X_6 = H^2[(10^4/A^2) - 4]$

$b_7 = 0.49254336\text{X}10^{-5}$ $\qquad X_7 = H^2[(10^{10}/A^5) - 32]$

$b_8 = 0.21975906\text{X}10^{-6}$ $\qquad X_8 = H^3[(10^{10}/A^5) - 32]$

$b_9 = 5.1675949$ $\qquad X_9 = H^3[A^{-2.75} - 50^{-2.75}]$

$b_{10} = -0.14349139\text{X}10^{-7}$ $\qquad X_{10} = H^4[\ (100/A) - 2]$

$b_{11} = -9.481014$ $\qquad X_{11} = H^4[A^{-4.5} - 50^{-4.5}].$

The standard error of estimate (S_{yx}) for this equation is 0.69 foot of site index units. An example of how this equation might be programed in FORTRAN IV (IBM 360) is shown in figure 8.

```
      SUBROUTINE ESSITE(A,H,SI)
      DIMENSION X(11),B(11)
      Q=A
      P=H
      DATA B/10.71728,0.4631478E-2,0.7447115,-26413.76,-0.428198E-1,-0.4
     1791206E-2,0.4925434E-5,0.2197591E-6,5.167595,-0.1434914E-7,-9.4810
     2214/
      SI=0.0
      Q2=Q*Q
      Q3=Q2*Q
      Q4=Q2*Q2
      Q5=Q2*Q3
      RECQ5=1.0/Q5
      P2=P*P
      P3=P2*P
      P4=P2*P2
      X(1)=ALOG(Q)-3.912023
      X(2)=1.0E10*RECQ5-32.0
      X(3)=P*(1.0E4/Q2-4.0)
      X(4)=P*(SQRT(RECQ5)-5.656854E-5)
      X(5)=P*X(1)*X(1)
      X(6)=P*X(3)
      X(7)=P2*X(2)
      X(8)=P*X(7)
      X(9)=P3*(SQRT(RECQ5*SQRT(1.0/Q))-2.127318E-5)
      X(10)=P4*(100.0/Q-2.0)
      X(11)=P4*((1.0/Q4)/SQRT(Q)-2.262742E-8)
      DO 1 I=1,11
    1 SI=SI+B(I)*X(I)
      SI=SI+H
      RETURN
      END
```

Figure 8.--A site index estimating subroutine for Engelmann spruce.

If a shorter but less precise equation is desired, the following is recommended:

$$S = H + \sum_{i=1}^{5} k_i Z_i,$$

where

$k_1 = 0.32158242$ $\quad Z_1 = H\ [(10^4/A^2) - 4]$

$k_2 = -0.98468901\text{X}10^4$ $\quad Z_2 = H\ (A^{-2.5} - 50^{-2.5})$

$k_3 = -0.12253415\text{X}10^{-2}$ $\quad Z_3 = H^2[(10^4/A^2) - 4]$

$k_4 = 1.0662061$ $\quad Z_4 = H^3[A^{-2.75} - 50^{-2.75}]$

$k_5 = -0.80894818\text{X}10^{-8}$ $\quad Z_5 = H^4[(100/A - 2]$.

For this equation, $S_{yx} = 1.22$ feet.

These equations are valid for trees between the ages of 20 and 200 years and for site indices ranging from 10 to 95. A site index estimate should be computed for each sample tree. The average of the individual tree estimates will be the average site index for the stand. If trees older than 200 years must be used as site trees, estimate the site index as if tree age were 200. Above that age, height increases very little.

INLAND DOUGLAS-FIR

Site Index

A site index equation, similar to the one given for Engelmann spruce, has been derived for inland Douglas-fir by Brickell (3). The equation is:

$$S = H + \sum_{i=1}^{18} b_i X_i ,$$

where

S = site index at a 50-year base age

H = total height of a sample tree in the dominant stand

A = total age of a sample tree

and

$b_1 = 40.984664 \qquad X_1 = (A^{-1/2} - 50^{-1/2})$

$b_2 = 4521.1527 \qquad X_2 = (A^{-2.5} - 50^{-2.5})$

$b_3 = 123059.38 \qquad X_3 = (A^{-3.5} - 50^{-3.5})$

$b_4 = -0.5332868X10^{-8} \qquad X_4 = (A^4 - 50^4)$

$b_5 = 0.37808033X10^{-10} \qquad X_5 = (A^5 - 50^5)$

$b_6 = 216.64152 \qquad X_6 = H(A^{-1.5} - 50^{-1.5})$

$b_7 = -158121.49 \qquad X_7 = H(A^{-4} - 50^{-4})$

$b_8 = 1894030.8 \qquad X_8 = H(A^{-5} - 50^{-5})$

$b_9 = -0.10230592X10^{-9} \qquad X_9 = H(A^4 - 50^4)$

$b_{10} = -6.0686119 \qquad X_{10} = H^2(A^{-2} - 50^{-2})$

$b_{11} = -25351.090 \qquad X_{11} = H^2(A^{-5} - 50^{-5})$

$b_{12} = 0.33512858X10^{-4} \qquad X_{12} = H^2(A - 50)$

$b_{13} = 0.17024711X10^{-2} \qquad X_{13} = H^3(A^{-1} - 50^{-1})$

$b_{14} = 398.36720 \qquad X_{14} = H^3(A^{-5} - 50^{-5})$

$b_{15} = -0.88665409X10^{-8} \qquad X_{15} = H^3(A^{1.5} - 50^{1.5})$

$b_{16} = 0.40019102X10^{-14} \qquad X_{16} = H^3(A^4 - 50^4)$

$b_{17} = -0.46929245X10^{-8} \qquad X_{17} = H^5(A^{-1/2} - 50^{-1/2})$

$b_{18} = -0.16640659X10^{-20} \qquad X_{18} = H^5(A^{4.5} - 50^{4.5}).$

The standard error of estimate for this equation is 0.24 of site index. A computer program in FORTRAN IV (360) to evaluate this equation is shown in figure 9.

```
      SUBROUTINE DFSITE(A,H,SI)
      DIMENSION B(18),X(18)
      Q=A
      P=H
      DATA B/40.98466,4521.153,123059.4,-5.332868E-9,3.780803E-11,216.64
     115,-158121.5,1894031.,-1.023059E-10,-6.068612,-25351.09,3.351286E-
     25,1.702471E-3,398.3672,-8.866541E-9,4.00191E-15,-4.692924E-9,-1.66
     34066E-21/
      SI=0.0
      P2=P*P
      P3=P2*P
      P4=P2*P2
      P5=P4*P
      Q12=SQRT(Q)
      Q15=Q*Q12
      Q2=Q*Q
      Q4=Q2*Q2
      X(1)=1.0/Q12-0.14142132
      X(2)=1.0/(Q2*Q12)-5.656854E-5
      X(3)=1.0/(Q2*Q*Q12)-1.131371E-6
      X(4)=(Q2-2500.0)*(Q2+2500.0)
      X(5)=Q*Q4-3.125E8
      X(6)=P*(1.0/Q15-2.828426E-3)
      X(7)=P*(1.0/Q4-1.6E-7)
      X(8)=P*(1.0/(Q4*Q)-3.2E-9)
      X(9)=P*X(4)
      X(10)=P2*(1.0/Q2-0.0004)
      X(11)=P*X(8)
      X(12)=P2*(Q-50.0)
      X(13)=P3*(1.0/Q-0.02)
      X(14)=P*X(11)
      X(15)=P3*(Q15-353.5534)
      X(16)=P2*X(9)
      X(17)=P5*X(1)
      X(18)=P5*(Q4*Q12-0.4419416E8)
      DO 1 I=1,18
    1 SI=SI+B(I)*X(I)
      SI=SI+H
      RETURN
      END
```

Figure 9.--A site index estimating subroutine for inland Douglas-fir.

Although it provides less precise results, a shorter equation is:

$$S = H + \sum_{i=1}^{5} k_i Z_i,$$

where

$k_1 = 101.08708$ $\qquad Z_1 = (A^{-1/2} - 50^{-1/2})$

$k_2 = 122.04763$ $\qquad Z_2 = H\,(A^{-1.5} - 50^{-1.5})$

$k_3 = 0.14082397 \times 10^{-12}$ $Z_3 = H\ (A^5 - 50^5)$

$k_4 = -13{,}140.717$ $Z_4 = H^2(A^{-5} - 50^{-5})$

$k_5 = 0.13492191 \times 10^{-4}$ $Z_5 = H^5(A^{-3} - 50^{-3})$.

For this equation the standard error of estimate is 0.90 foot.

These equations are valid for ages from 20 to 200 years and for site indices from 10 to 110. The site index of trees older than 200 years should be estimated as if age were 200.

GRAND FIR[7]

Site Index

Information on productivity of grand fir has been developed using a direct index of relative productivity (Q) rather than site index. Procedures for calculating Q from stand age and height have been published (10). Figure 10 shows a FORTRAN program RPGF.

```
      SUBROUTINE RPGF( C,H,T,CR,IER )
      DOUBLE PRECISION A,B,C,D,X,BT,DET,TOL,VAL,BRAC,ALGCR
      DIMENSION C(5)
      DATA C /-10.29862, 2.0, 0.018167, -2.7 , 2.0 /
      DIV = 0.5
      IER = 0
      IGT = 1
      COR = 0.
      I = 0
      BT =-C(3)*(T + C(4))
      IF ( T - 90. ) 91,91,92
   91 TOL = 0.0D0
      GO TO 95
   92 TOL = ALOG( 0.8*H/T )
   95 ALGCR = ALOG(H-4.5) - (ALOG(CR)-3.747474-8.218305/T)*18.786/T
      TS = TOL
   99 IF ( TOL .GT. 20.) GO TO 101
      DET = BT*DEXP( TOL )
      IF ( DET ) 991,100,100
  991 BRAC = 1.0D0 - DEXP(DET)
      IF (BRAC) 100,100,992
  992 TOL = C(1) + C(2)*(ALGCR - C(5)*DLOG(BRAC) )
      I = I + 1
  996 GO TO ( 21,22,23),IGT
   21 X = TOL
      A = X - TS
```

(con. next page)

[7] The section on grand fir was contributed by Albert R. Stage, Principal Mensurationist, Intermountain Forest and Range Experiment Station.

```
      B = -A
      IGT = 2
      GO TO 99
   22 VAL = X - TOL
C        START ITERATION LOOP
      IF ( VAL) 1,7,1
C        EQUATION IS NOT SATISFIED BY X
    1 B = B/VAL - 1.0D0
      IF(B) 2,8,2
C        ITERATION IS POSSIBLE
    2 A = A/B
      X = X + A
      B = VAL
      TOL = X
      IGT = 3
      GO TO 99
   23 VAL = X - TOL
C        TEST ON SATISFACTORY ACCURACY
      D = DABS(X)
      TOL = 0.C008*D
    4 IF ( DABS(A)-TOL) 5,5,6
    5 IF(DABS(VAL)-1.0D0*TOL) 7,7,6
    6 IF ( I - 20 ) 1,1,10
C        END OF ITERATION LOOP
    7 Q = DEXP(X)
      RETURN
C        ERROR RETURN IN CASE OF ZERO DIVISOR
    8 IER = -2
      RETURN
C        NO CONVERGENCE AFTER 20 ITERATION LOOPS. ERROR RETURN
   10 IER = I
      RETURN
C        ERROR CONDITION ON INITIAL ITERATION
   12 IER = -3
      RETURN
   14 IER = -4
      RETURN
  100 GO TO (12,12,102),IGT
  101 GO TO ( 14,14,102),IGT
  102 X = X - A
      A = DIV*A/B
      DIV = DIV*DIV
      I = I + 1
      GO TO 2
      END
```

Figure 10.--FORTRAN subroutine to calculate relative productivity.

The variables in the calling sequence are:

Q = the measure of relative productivity

H = height in feet

T = age in rings at 4.5 feet above ground

CR = ratio of live crown to total height in percent

IER = an integer used to flag possible errors in calculation. (Should be zero if no errors.)

If required, site index can be approximated from Q by the FORTRAN equation:

```
SI = 4.5 + SQRT(Q) * 172.32 * (1. - EXP(-.6905*Q))**2.
```

Yield Capability

The yield equation also already has been published (11). The maximum m.a.i. for average stocking corresponding to this equation can be solved by the FORTRAN function CUPGF illustrated in figure 11. The single argument to the function is Q obtained from the previous subroutine RPGF in figure 10. Figure 12 shows the linear approximation of the relationship between yield capability and site index.

Figure 11.--The function subprogram for grand fir yield capability.

```
FUNCTION CUPGF(S)
B = 89.761/S - 22.701
A = B *(0.5 + SQRT(0.25 + 12./(S*B)))
CUPGF = 22228.*EXP(-B/A)/(A + 12./S)
RETURN
END
```

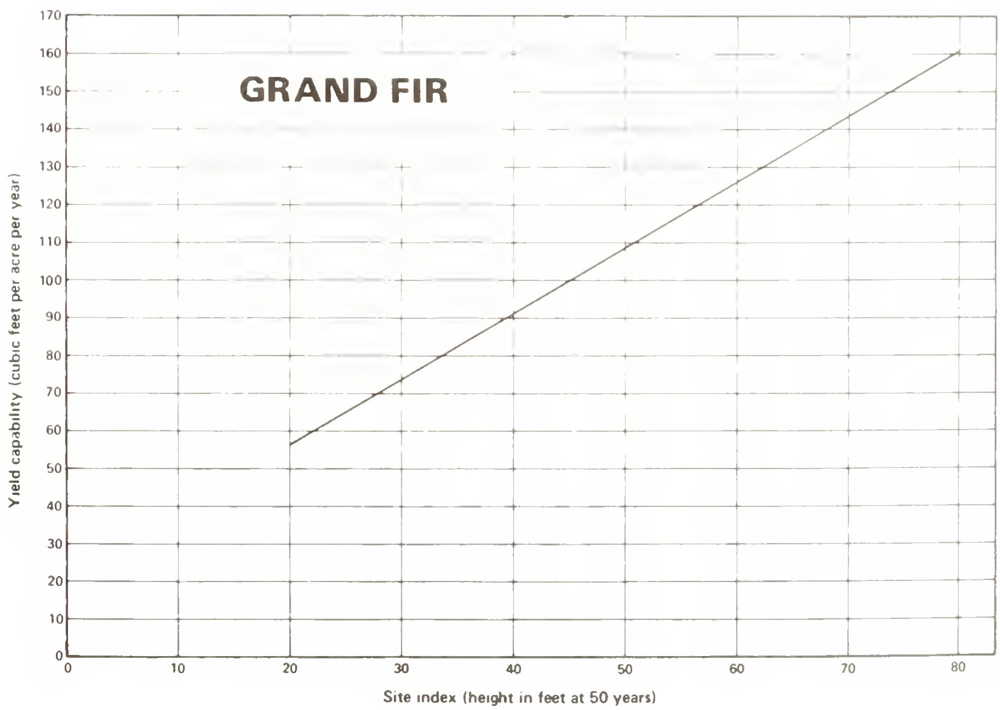


Figure 12.--Relationship between site index and yield capability.

QUAKING ASPEN

Site Index

A table published by Jones (5) gives site index of quaking aspen according to stand age and dominant height. Age at breast height is used, and it is important that average dominant height not be estimated from trees that are all of the same clone. In Jones' table a site index base age of 80 years is used. Equations were fitted by regression methods to the site index values in Jones' table, using stand age and height as independent variables. The best of several equations fitted is:

$$S = H + \sum_{i=1}^{10} b_i X_i ,$$

where

S = site index at an 80-year base age

A = stand age at breast height

H = average height of the dominant stand

$b_1 = -8.7810841$	$X_1 = [(100/A) - 1.25]$
$b_2 = -5.1824560$	$X_2 = (\ln A - \ln 80)$
$b_3 = -40.260849$	$X_3 = H[((\ln A)/A) - ((\ln 80)/80)]$
$b_4 = 1.8589039$	$X_4 = H[(100/A) - 1.25]$
$b_5 = 0.34567436 \times 10^{-11}$	$X_5 = H[A^5 - 3{,}276{,}800{,}000]$
$b_6 = -0.16454828 \times 10^{-6}$	$X_6 = H[A^3 - 512{,}000]$
$b_7 = -11{,}647{,}641.0$	$X_7 = H[\exp(-A) - \exp(-80)]$
$b_8 = 0.19235397 \times 10^{-3}$	$X_8 = H^2[\sqrt{A} - \sqrt{80}]$
$b_9 = 0.30310790 \times 10^{-14}$	$X_9 = H^2[A^5 - 3{,}276{,}800{,}000]$
$b_{10} = -0.84256893 \times 10^{-3}$	$X_{10} = H^2[(10{,}000/A^2) - 1.5625]$.

The standard error of estimate for this equation is 0.55 foot. The equation is valid for breast high ages between 20 and 160 years, and site indices (base age 80) between 20 and 90. Figure 13 shows how this equation might be programed in FORTRAN IV (360). This equation will not be valid for ages beyond 160 years. Older trees should be treated as if age were 160 years.

```
      SUBROUTINE ASPSIT(A,H,S)
      DIMENSION X(10),B(10)
      DATA B/-8.781084,-5.182456,-40.26085,1.858904,0.3456744E-11,-0.164
     1154828E-6,-1.164764E1,1.92354E-4,3.031079E-15,-0.8425689E-3/
      S=0.0
      Q=A
      P=H
      P2=P*P
      RECQ=100.0/Q
      Q2=Q*Q
      Q3=Q*Q2
      QLN=ALOG(Q)
      X(1)=RECQ-1.25
      X(2)=QLN-4.382027
      X(3)=P*(QLN/Q-0.5477533E-1)
      X(4)=P*X(1)
      X(5)=P*(Q2*Q3-32768.0E5)
      X(6)=P*(Q3-512.0E3)
      X(7)=P*(((1.0E3/EXP(Q/2.0))**2)-1.804351E-29)
      X(8)=P2*(SQRT(Q)-8.944272)
      X(9)=P*X(5)
      X(10)=P2*(1.0E4/Q2-1.5625)
      DO 1 I=1,10
    1 S=S+B(I)*X(I)
      S=S+P
      RETURN
      END
```

Figure 13.--A site index estimation program for quaking aspen.

LITERATURE CITED

1. Alexander, Robert R.
   1966. Site indexes for lodgepole pine with corrections for stand density: Instructions for field use. U.S. Forest Serv. Res. Pap. RM-24, 7 p., illus.

2. Brickell, James E.
   1966. Site index curves for Engelmann spruce in the northern and central Rocky Mountains. U.S. Forest Serv. Res. Note INT-42, 8 p., illus.

3. ________.
   1968. A method for constructing site index curves from measurements of total tree age and height--its application to inland Douglas-fir. U.S. Forest Serv. Res. Pap. INT-47, 23 p., illus.

4. Haig, Irvine T.
   1932. Second-growth yield, stand, and volume tables for the western white pine type. U.S. Dep. Agr. Tech. Bull. 323, 67 p., illus.

5. Jones, John R.
   1966. A site index table for aspen in the southern and central Rocky Mountains. U.S. Forest Serv. Res. Note RM-68, 2 p.

6. Krajicek, John E., Kenneth A. Brinkman, and Samuel F. Gingrich.
   1961. Crown competition factor, a measure of density. Forest Sci. 7: 35-42.

7. Lynch, Donald W.
   1958. Effects of stocking on site measurements and yield of second-growth ponderosa pine in the Inland Empire. Intermountain Forest and Range Exp. Sta. Res. Pap. 56, 36 p., illus.

8. Meyer, Walter H.
   1938. Yield of even-aged stands of ponderosa pine. U.S. Dep. Agr. Tech. Bull. 630, 59 p., illus.

9. Myers, Clifford A.
   1967. Yield tables for managed stands of lodgepole pine in Colorado and Wyoming. U.S. Forest Serv. Res. Pap. RM-26, 20 p., illus.

10. Stage, Albert R.
    1966. Simultaneous derivation of site-curve and productivity rating procedures. Soc. Amer. Foresters Proc. 1966: 134-136.

11. ________.
    1969. Computing procedure for grand fir site evaluation and productivity estimation. USDA Forest Serv. Res. Note INT-98, 6 p., illus.

AFLC/HAFB, Ogden

Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field Research Work Units are maintained in:

- Boise, Idaho
- Bozeman, Montana (in cooperation with Montana State University)
- Logan, Utah (in cooperation with Utah State University)
- Missoula, Montana (in cooperation with University of Montana)
- Moscow, Idaho (in cooperation with the University of Idaho)
- Provo, Utah (in cooperation with Brigham Young University)

ABOUT THE FOREST SERVICE . . .

As our Nation grows, people expect and need more from their forests—more wood; more water, fish, and wildlife; more recreation and natural beauty; more special forest products and forage. The Forest Service of the U. S. Department of Agriculture helps to fulfill these expectations and needs through three major activities:

- Conducting forest and range research at over 75 locations ranging from Puerto Rico to Alaska to Hawaii.
- Participating with all State Forestry agencies in cooperative programs to protect, improve, and wisely use our Country's 395 million acres of State, local, and private forest lands.
- Managing and protecting the 187-million acre National Forest System.

The Forest Service does this by encouraging use of the new knowledge that research scientists develop; by setting an example in managing, under sustained yield, the National Forests and Grasslands for multiple use purposes; and by cooperating with all States and with private citizens in their efforts to achieve better management, protection, and use of forest resources.

Traditionally, Forest Service people have been active members of the communities and towns in which they live and work. They strive to secure for all, continuous benefits from the Country's forest resources.

For more than 60 years, the Forest Service has been serving the Nation as a leading natural resource conservation agency.

USDA Forest Service
Research Paper INT 76
1970

TIMELAG AND EQUILIBRIUM MOISTURE CONTENT OF REINDEER LICHEN

R.W. Mutch and O.W. Gastineau

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Ogden, Utah 84401

USDA Forest Service
Research Paper INT-76
1970

TIMELAG AND EQUILIBRIUM MOISTURE CONTENT OF REINDEER LICHEN

R. W. Mutch and O. W. Gastineau

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401
Joseph F. Pechanec, Director

THE AUTHORS

ROBERT W. MUTCH received his bachelor's degree in biology from Albion College, Michigan, in 1956 and his master's degree in forestry from the University of Montana in 1959. His interest in fire dates back to two seasons with the smokejumper project in Missoula in 1954-1955. He was superintendent of the Priest River Experimental Forest in northern Idaho from 1958 to 1960. Since 1960, he has been engaged in wildland fuels research at the Northern Forest Fire Laboratory.

ORVAL W. GASTINEAU, JR. received his bachelor's degree in forestry from the University of Montana in 1970. From 1964 to 1966 he was a smokejumper at the Aerial Fire Depot in Missoula, Montana. Since 1966, he has been in wildland fuels research and computer programming at the Northern Forest Fire Laboratory.

The authors gratefully acknowledge the support which Richard Barney, Alaska Fire Control Methods Project, Institute of Northern Forestry, College, Alaska, gave to this study.

CONTENTS

ABSTRACT

Almost one-half of the 220 million acres in central Alaska is covered with tundra, a highly flammable fuel complex. Reindeer lichen (*Cladonia* spp.), one component of tundra, was collected near Fairbanks, Alaska, for adsorption and desorption laboratory tests of timelags below fiber saturation and equilibrium moisture contents. Time responses recorded for five timelag periods differed widely, increasing over periods 2 and 3, then decreasing. Semilogarithmic plots for reindeer lichen did not fit the strictly linear form predicted by the timelag equation. Average desorption timelag was 1.7 times faster than the adsorption timelag. Equilibrium moisture content data indicated a slight hysteresis loop between adsorbing and desorbing conditions. The National Fire-Danger Rating transitional moisture curve approximates the equilibrium moisture content of reindeer lichen as determined in this study.

INTRODUCTION

An understanding of fine fuel moisture responses is necessary for effective interpretation and application of the National Fire-Danger Rating System. As improvements are made in the National Fire-Danger Rating System, knowledge of the moisture responses of common wildland fuels in the United States becomes increasingly important. This report summarizes results of laboratory tests to determine adsorption-desorption timelags below fiber saturation and equilibrium moisture contents of reindeer lichen, (*Cladonia* spp.). The fuel tested was collected in the vicinity of Fairbanks, Alaska, in August 1967. Byram[1] described the usefulness of timelag in comparisons of the drying characteristics of forest fuels. He defined desorption timelag as the time required for a fuel to lose 63.3 percent of its initial moisture content above equilibrium (or to lose $1 - \frac{1}{e}$ of its moisture content above equilibrium where e is the base of natural logarithms). Under adsorbing conditions, timelag is the time required for a fuel to gain 63.3 percent of the initial moisture content below equilibrium. Equilibrium moisture content is the moisture level finally attained that is uniformly present in fuels exposed in an atmosphere of fixed temperature and humidity; this occurs when vapor pressure in the fuel equals vapor pressure in the atmosphere.

METHODS

Intact sections of lichen fuels were placed in an environmental chamber for the duration of adsorption and desorption timelag tests (fig. 1). For adsorption tests, the temperature was kept constant at 80°F. while the humidity was stepped from 20 to 90 percent. For desorption tests, the temperature was held at 80°F. while humidity

Figure 1.--Reindeer lichen samples suspended on microscale transducers in environmental chamber. The solar radiation lamps in the top of the compartment were not used in these tests.

[1]George M. Byram. An analysis of the drying process in forest fuel material. (Paper presented at the Int. Symp. on Humidity and Moisture, Wash., D.C., May 20-23, 1963.)

Figure 2.--Reindeer lichen sample and microscale transducer. Sample was placed on aluminum foil sheet in 3- by 4-inch weighing basket.

was dropped from 90 to 20 percent. Samples were continuously weighed on microscale transducers (fig. 2). Timelags for the five drying periods were determined from adsorption and desorption weight-change traces.[2]

The adsorption and desorption equilibrium moisture contents of reindeer lichen were determined in a controlled temperature cabinet. Six salt solutions were used to establish varying levels of relative humidity. Temperature was held constant at 80°F. and humidity was varied between 7 and 88 percent. Samples were weighed continuously. When equilibrium was reached at each humidity level, several samples were withdrawn from the cabinet and their moisture contents measured in a vacuum oven at 122°F. for 24 hours.[3] Dew point was monitored in the equilibrium moisture content cabinet using a Cambridge dew hygrometer.

RESULTS

In a given timelag period, response times varied considerably among replicates, especially during adsorption tests (table 1). Nor are we the first to observe variability within a given timelag; Kübler,[4] for instance, reported that the response times of equal-sized wood samples of the same species vary by one order of magnitude. Also of interest are the variations in response times we recorded for the five timelag periods (fig. 3). Our studies of reindeer lichen showed that timelag increases

---

[2]Drying periods were defined by the following percentages of moisture change between initial and equilibrium moisture content: 63.3, 86.5, 95.0, 98.1, and 99.3.

[3]Vacuum drying at 122°F. was comparable to regular ovendrying at 221°F.

[4]H. Kübler. Studien über die Holz Feuchtebewegung. Holz als Roh-und Werkstoff. 15: 453-468. 1957.

Table 1.--Adsorption and desorption timelag constants of *Cladonia*. Adsorption conditions: 80°F. and humidity step change from 20 to 90 percent. Desorption conditions: 80°F. and humidity step change from 90 to 20 percent

Timelag period	Adsorption replicates 1	2	3	Average timelag constant
	Minutes			Minutes
1	50	55	30	45
2	80	115	100	98
3	140	120	90	116
4	120	90	60	90
5	110	70	20	67
Average	100	90	60	83

Timelag period	Desorption replicates 1	2	3	Average timelag constant
	Minutes			Minutes
1	50	42	42	43
2	85	53	45	61
3	95	67	48	70
4	45	43	35	41
5	30	20	25	25
Average	61	45	39	48

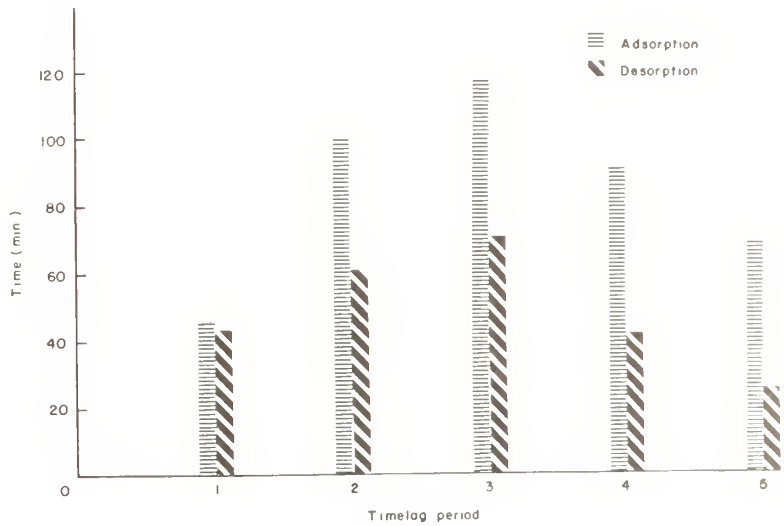


Figure 3.--Adsorption and desorption timelag periods of reindeer lichen.

over periods 2 and 3, then declines for remaining periods. We have observed this trend in tests of other fuels also. Because diffusivity is moisture dependent, the quadratic term in the diffusion equation prevents a simple mean value approximation from being made.[5] Adsorption and desorption curves for reindeer lichen show fuel responses to humidity step changes at 80°F. (figs. 4 and 5). The equilibrium moisture content results are shown in table 2 and plotted in figure 6.

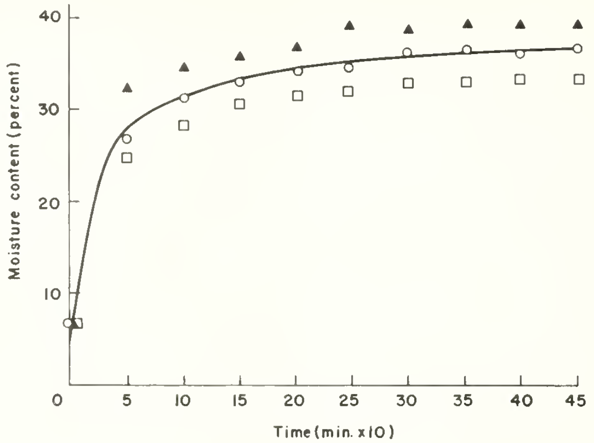


Figure 4.--Adsorption curve of reindeer lichen for a humidity step change of 20 to 90 percent at 80°F. Symbols represent replicates.

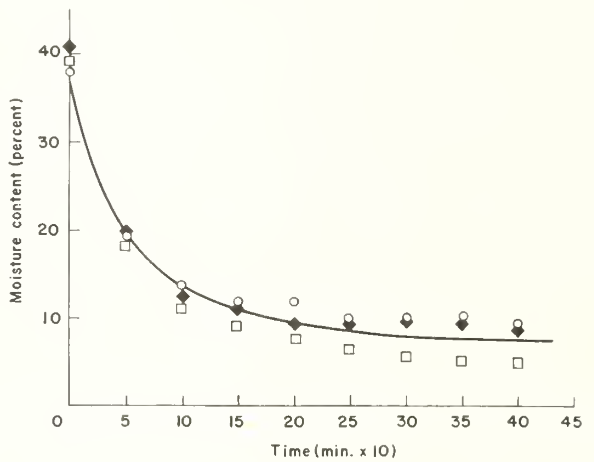


Figure 5.--Desorption curve of reindeer lichen for a humidity step change of 90 to 20 percent at 80°F. Symbols represent replicates.

---

[5]M. A. Fosberg, R. W. Mutch, and H. E. Anderson. Laboratory and theoretical comparison of desorption in ponderosa pine dowels. USDA Forest Serv., Rocky Mountain Forest and Range Exp. Sta., Fort Collins, Colo. (In preparation.)

Table 2.--Adsorption and desorption equilibrium moisture contents of reindeer lichen

Salt solution	Dry bulb[1]	Relative humidity	Average adsorption moisture content	Dry bulb	Relative humidity	Average desorption moisture content
	°F.	Percent	Percent	°F.	Percent	Percent
P_2O_5				80	7.2	3.9
LiCl	80	16	6.5	80	15.0	7.5
$MgCl_2$	80	33	10.2	80	35.0	11.4
$Mg(NO_3)_2$	80	53	11.6	80	56.0	12.6
NaCl	80	68	16.6	80	68.0	16.9
KNO_3	80	88	20.8			

[1]Dry bulb temperature was controlled at 80°F. ± 1°.

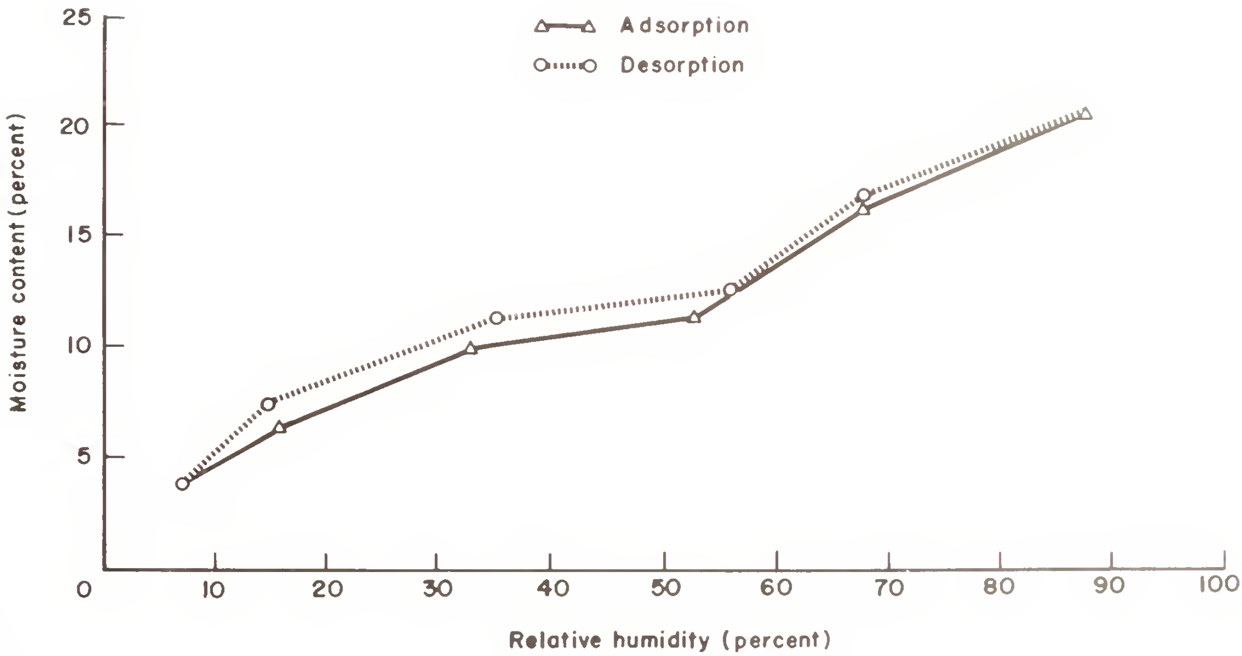


Figure 6.--Adsorption and desorption equilibrium moisture contents of reindeer lichen at air temperature of 80°F.

DISCUSSION

Timelag is a parameter characteristic of all physical and chemical processes that occur at an exponentially decreasing rate.[6] The question arises as to how closely the process of either adsorption or desorption of moisture in natural fuels approximates an exponential function. Our tests on reindeer lichen showed that response times varied widely for the five timelag periods; time increased over the second and third periods, then decreased. Nelson stated that a plot of E versus time on semilogarithmic graph paper should be linear if the following timelag equation is obeyed:

$$\frac{\bar{m} - m_e}{m_o - m_e} = E = Ke^{\frac{-t}{\tau}}$$

where:

$\bar{m}$ = average moisture content of fuel

m_e = equilibrium moisture content

m_o = initial moisture content

E = fraction of total evaporable moisture remaining in the fuel at time t

K = a dimensionless constant for any given fuel shape

e = base of natural logarithms, 2.718

t = time

τ = timelag

Plots of E versus time for adsorption and desorption runs of reindeer lichen are shown in figure 7. As Nelson[7] found with sawdust, wood, and paper samples, our experimental curves for reindeer lichen were curvilinear rather than strictly linear as predicted by the timelag equation. Where Nelson's semilogarithmic plots fell into three distinct regions, reindeer lichen data plotted into two straight-line portions with differing slopes.

Although the duration of the timelag periods varied, the variances do not negate the practical application of the timelag concept. Observed deviations in timelag do not appear to be significant in terms of general National Fire-Danger Rating applications.

The average desorption timelag for reindeer lichen was 1.7 times faster than the adsorption timelag. Simard,[8] in comparing the average rates of wetting and drying twig samples above fiber saturation, found that drying was about 1.4 times as fast as wetting. This difference he laid to the added diffusion potential of evaporation during the drying process.

---

[6]Ralph M. Nelson, Jr. Some factors affecting the moisture timelag of woody materials. USDA Forest Serv. Res. Pap. SE-44, 16 p., illus. 1969.

[7]Ibid.

[8]A. J. Simard. The moisture content of forest fuels. II: Comparison of moisture content variations above the fibre saturation point between a number of fuel types. Forest Fire Res. Inst. Inform. Rep. FF-X-14, 47 p., Ottawa, Ontario. 1968.

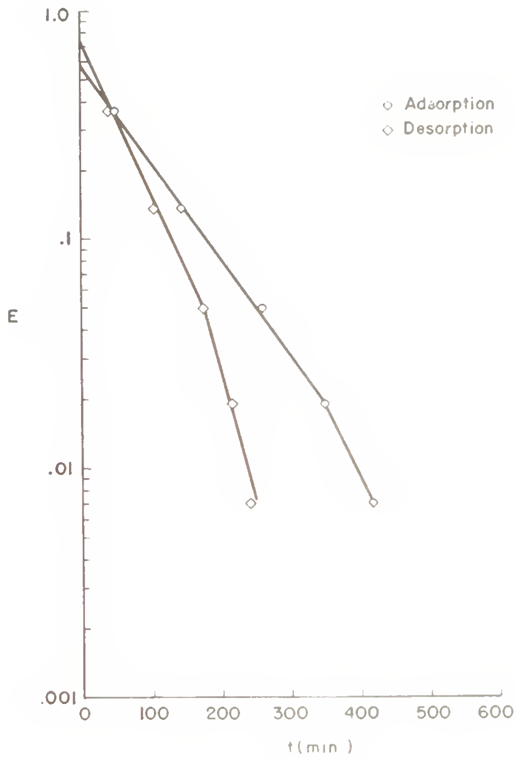


Figure 7.--Average adsorption and desorption curves of reindeer lichen at 80° F.; adsorption condition was a relative humidity step change from 20 to 90 percent; desorption condition was a relative humidity step change from 90 to 20 percent. The fraction of total evaporable moisture in the sample, E, was plotted against time.

The equilibrium moisture content data indicated a slight hysteresis loop between adsorbing and desorbing conditions. Reindeer lichen data (averages of the adsorption and desorption moisture content values) were plotted with the National Fire-Danger Rating transitional and cured moisture curves and the equilibrium moisture content data in the "Wood handbook."[9] All data used were based on an air temperature of about 80°F. The National Fire-Danger Rating transitional moisture curve comes closest to approximating the equilibrium moisture content of reindeer lichen determined by this study (fig. 8).

Field inspection in Alaska showed that lichens become dry and brittle following exposure to direct sunlight. Insolation heats fuel surfaces and is important to determinations of moisture content in living reindeer lichen. Future tests will include insolation as an influencing factor on equilibrium moisture content and timelag.

---

[9]U.S. Dep. Agr., Forest Serv. Wood handbook. Agr. Handb. 72, 528 p., Forest Prod. Lab., Madison, Wis. 1955.

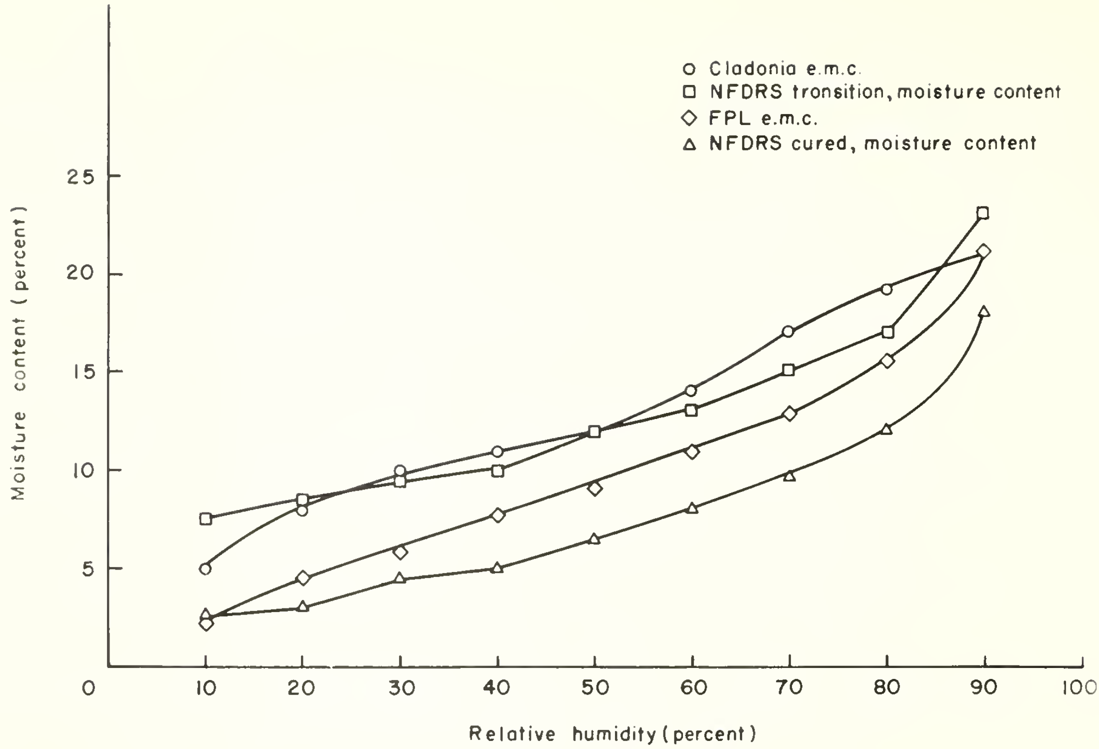


Figure 8.--Equilibrium moisture content of reindeer lichen compared with National Fire-Danger Rating System's moisture content data and Forest Products Laboratory's equilibrium moisture content data.

Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field Research Work Units are maintained in:

- Boise, Idaho
- Bozeman, Montana (in cooperation with Montana State University)
- Logan, Utah (in cooperation with Utah State University)
- Missoula, Montana (in cooperation with University of Montana)
- Moscow, Idaho (in cooperation with the University of Idaho)
- Provo, Utah (in cooperation with Brigham Young University)

LOGGING RESIDUES ON SAW LOG OPERATIONS, IDAHO AND MONTANA

Alvin K. Wilson, Robert E. Green, and
Grover A. Choate

USDA Forest Service
Research Paper INT-77, 1970

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Ogden, Utah 84401

COVER PHOTO

A large rot column. Several exploratory cuts (and an unusually lengthy longbutt) were needed here to locate enough sound wood for log making.

USDA Forest Service
Research Paper INT-77, 1970

LOGGING RESIDUES ON SAW LOG OPERATIONS, IDAHO AND MONTANA

ALVIN K. WILSON, ROBERT E. GREEN,
and GROVER A. CHOATE

INTERMOUNTAIN FOREST AND RANGE
EXPERIMENT STATION

Ogden, Utah 84401

THE AUTHORS

ALVIN K. WILSON designs and conducts special studies for Forest Survey at the Intermountain Forest and Range Experiment Station in Ogden, Utah. After working in Forest Survey at the Northeastern Forest Experiment Station, he spent several years in forest management research for the Intermountain Station and returned to Forest Survey work in 1957. He is the author of numerous publications on forest management and forest resources.

ROBERT E. GREEN is a statistician in Region 4, U.S. Forest Service, headquarters in Ogden, Utah. At the time of this study, he was employed as a mathematician by the Intermountain Forest and Range Experiment Station, during which time he served as crew chief of the field crew on this study and developed the original computer programs for data compilation.

GROVER A. CHOATE was, at the time of writing this publication, Principal Resource Analyst for Forest Survey at the Intermountain Forest and Range Experiment Station, Ogden, Utah. His career includes work in the Lake States, Washington, D.C., the Pacific Northwest, and Southeast Asia. He retired from the Forest Service in late 1969.

CONTENTS

* Note: See Terminology for definitions of many of the terms used in this paper.

TABLES

ABSTRACT

Reports results of a survey made of logging operations to estimate the volume of logging residues in relation to the volume of saw logs harvested in Idaho and Montana. Results show: conversion factors that can be applied to product volume to estimate total removals from inventory; residue volume as a percentage of saw log volume; the relative importance of felling and skidding as causes of residues; and the numbers of trees removed from growing stock inventory by logging. Survey methods and reliability of data are discussed.

INTRODUCTION

The volume of timber cut or killed during logging operations and left in the woods represents a reduction in the inventory volume available for future management and harvesting. Consequently, the volume of unused timber should be taken into consideration if differences between successive inventories are to be more fully understood. Estimates of the amount of logging residue potentially marketable as chips are of interest also.

In 1965, Forest Survey at the Intermountain Forest and Range Experiment Station conducted a survey of logging residues in Idaho and Montana. Logging residue surveys yield various types of information,[1] but only data considered to be sufficiently reliable for purposes of this report were used here. Information not included in the present paper may be combined with data from future residue surveys of other areas to provide adequate reliability for further analyses. Since 1965, Forest Survey has surveyed logging residues in Arizona, New Mexico, Colorado, Utah, Wyoming, and in South Dakota west of the 103d meridian. If present plans are adhered to, residues will be resurveyed periodically in all Mountain States.

---

[1]Conversion factors to be applied to product volumes for estimates of total volumes removed from inventory in commercial logging; average conversion factors used to express product volume in several units of measure (cubic feet, International 1/4-inch rule, and Scribner log rule); the diameter distribution of trees removed from inventory by logging; the proportion of timber products harvested from growing stock trees compared to that of products from nongrowing stock trees; cull and breakage losses by species; the relative importance of felling and skidding as causes of residues; and the proportion of logging residue volume made up of pieces of various size classes.

This report includes statistics for Idaho and Montana combined, for each of these States individually, and for northern Idaho-western Montana.[2] Statistics for other breakdowns are not shown because they would not be generally useful or because estimates could be unreliable. The northern Idaho-western Montana combination is included because data are sufficient for reliability. Moreover, the area is homogenous in many respects and frequently is considered to be an economic unit in resource analyses.

REMOVAL ESTIMATES

Expansion factors are computed to permit calculation of the inventory that remains following commercial logging operations. To adjust the inventory, removals (volume of products plus residues from felling and skidding) must be subtracted from the prelogging inventory. However, the removal volume should omit material that was not included in the inventory, i.e., the portions of tree stems overutilized by inventory standards. Such material can come from cutting below the minimum stump height (1 foot by Forest Survey standards) or from harvesting product volume beyond specified top diameters. It also can come from harvesting saw logs from growing stock trees of less than the sawtimber size specified for inventory or by cutting roundwood products from cull trees.

Overutilized material (by Forest Survey standards) was excluded from the removal volume when the conversion factors shown in table 1 were developed. How-

[2]Northern Idaho includes the following counties: Benewah, Bonner, Boundary, Clearwater, Idaho (north of the Salmon River), Kootenai, Latah, Lewis, Nez Perce, and Shoshone. Western Montana, that part of the State west of the Continental Divide, includes all of or portions of the following counties: Deerlodge, Flathead, Granite, Lake, Lewis and Clark, Lincoln, Mineral, Missoula, Powell, Ravalli, Sanders, and Silver Bow.

Table 1.--*Conversion factors to estimate total net removals from inventory, Idaho and Montana*

Unit of measurement and minimum top diameter	Idaho	Montana	Northern Idaho western Montana	Idaho-Montana
Cubic foot 4 inches	1.123	1.160	1.146	1.140
Board foot[1] Variable	1.054	1.067	1.064	1.060
Board foot[1] 7 inches	1.058	1.056	1.062	1.057

[1]International 1/4-inch log rule.

ever, the overutilized volume normally is part of the reported product volume to which these factors will be applied.

Therefore:

$$\text{conversion factor} = \frac{\text{removal volume}}{\text{product volume}}, \text{ which is}$$

equivalent to

$$\frac{\text{net product volume (excluding overutilization)} + \text{residue volume}}{\text{product volume (including overutilization)}}$$

In both Idaho and Montana, the net volume of timber removed from growing stock inventory averages 1.14 times the cubic-foot volume of saw logs harvested (table 1). The removal rate is somewhat lower in Idaho (1.12 times the saw log volume) and higher in Montana (1.16 times the saw log volume).

Factors for estimating removals from sawtimber[3] in inventory are somewhat smaller numerically than the factors used for estimating removals from growing stock. Factors derived for board-foot measurements to the minimum variable top standards used by Forest Survey (see *Sawtimber volume* in Terminology) are not much different from those derived for the minimum fixed top of 7 inches. By both top diameter standards, conversion factors used to estimate removals in Idaho and Montana combined amount to 106 percent of saw log volume; the proportion is slightly less for Idaho than for Montana.

Correction factors are numerically less for board-foot measure than for cubic-foot measure because considerable material scaled as net cubic-foot residue is not included in the net board-foot scale. Such material consists of (1) the upper stem portion beyond the minimum top diameter for board-foot measure, (2) the volume in destroyed growing stock trees of less than sawtimber size, and (3) portions of sound trees that are cull (because of crook) for saw logs.

LOGGING RESIDUES AND PRODUCT VOLUME

The net volume of logging residues represents underutilization by one standard or another. By Forest Survey's cubic-foot standards, residues include all unused net volume between a 1-foot stump and a 4-inch minimum top diameter inside bark (d.i.b.). By board-foot standards, net residue volume consists of unused material in sawtimber trees from a 1-foot stump to either the variable or the fixed top diameters. Merchantable logs missed in skidding are included in sawtimber residues.

The net volume of logging residues from harvesting a given volume of saw logs can be estimated by the use of table 2. For example, residues from the reported

---

[3]Board-foot volumes used in this report are International 1/4-inch log rule volumes.

Table 2.--*Net volume of logging residues from saw log operations as a percent of net product volume, Idaho and Montana*

Unit of measurement and minimum top diameter	Idaho	Montana	Northern Idaho-western Montana	Idaho-Montana
Cubic foot 4 inches	12.27	16.26	14.75	14.09
Board foot[1] Variable	6.16	8.22	7.32	7.07
Board foot[1] 7 inches	6.48	7.44	7.07	6.90

[1]International 1/4-inch rule.

1966 harvest of 249,414 MCF of saw logs from growing stock in Idaho are estimated to be:

$$249{,}414 \times 0.1227 = 30.6 \text{ MMCF}$$

The largest part of residue volume results from felling. Most of this is material from trees from which saw logs have been cut. Skidding losses are relatively minor and, as shown by the following tabulation, amount to less than 7 percent of cubic-foot residue volume in Idaho and Montana combined.

	Felling				
	Product trees	*Other trees*	*All trees*	*Skidding*	*Total*
			Percent		
Idaho	76.63	18.19	94.82	5.18	100.00
Montana	86.16	6.05	92.21	7.79	100.00
Northern Idaho, western Montana	83.12	10.37	93.49	6.51	100.00
Idaho, Montana	81.63	11.82	93.45	6.55	100.00

It should be pointed out that residue volumes derived by the use of factors in table 2 are not totally available for chipping. A more detailed and intensive survey would be necessary to assess residue characteristics and to determine what portion of these residues could be used under prevailing market conditions.

DIAMETER CLASS REMOVALS

Information on the number of growing stock trees harvested or destroyed[4] in each diameter class is essential for derivations of diameter class cutting rates used in most stand-table projections of growth and inventory. Reliable data of this kind usually are difficult to obtain. However, logging residue surveys provide means for estimating the distribution of trees removed per unit volume of saw logs harvested.

Table 3 shows the total number of growing stock trees (product trees and others), removed per 1 MCF of product volume in Idaho and Montana. These figures can be applied to a given volume of saw log harvest to estimate trees removed in each diameter class. In turn, this estimate can be related to an inventory stand table in order to compute cutting rates.

SURVEY METHODS AND RELIABILITY OF ESTIMATES

A basic need in the logging residue surveys was to develop factors that could be applied to a reported volume of saw log harvest to estimate the resulting volume of logging residues. Estimates of residue volume are based on product volume rather than acreage logged because such information usually is more reliable and available (at least to Forest Survey) than are estimates of area cutover. The survey design

---

[4]Either occurrence removes the trees from inventory.

Table 3.--*Growing stock trees removed from inventory in saw log operations per 1 thousand cubic feet of net product volume, Idaho and Montana*

Class (inches)	Idaho	Montana	Northern Idaho-western Montana	Idaho-Montana
	Number of trees			
2	6.0522	8.9259	8.4669	7.3587
4	2.8277	6.1291	4.5296	4.3287
6	3.0261	3.0348	3.0314	3.0301
8	1.1906	2.9158	1.5679	1.9749
10	.9426	4.7010	2.0557	2.6513
12	1.0418	4.3439	2.2648	2.5431
14	1.2402	4.1654	2.5436	2.5701
16	1.2402	2.6778	2.1951	1.8938
18	1.5875	2.2612	2.2300	1.8938
20	1.0914	1.1901	1.3937	1.1363
22	.6945	.5951	.6969	.6493
24	.7441	.2380	.5226	.5140
26	.5457	.2975	.4530	.4329
28	.3969	.1190	.2787	.2705
30+	1.6371	1.4281	1.4983	1.5421
All classes	24.2586	43.0227	33.7282	32.7896

prescribed three basic types of measurements of growing stock trees on active logging operations to meet this objective:

1. Net volume of saw logs harvested from *product* trees measured on a logging operation;

2. Net volume of residues from the *same* trees;

3. Net volume of residues from *other* trees cut or destroyed in the process of felling and skidding product trees.

All three sets of measurements were used to determine the residue volume as a percent of saw log volume. Scaling was done in detail to permit estimates of gross and net cubic-foot volumes for all measured growing stock trees, and to provide gross and net board-foot volumes to fixed and variable tops for measured sawtimber trees. Species, diameter breast height (d.b.h.), total height, overutilization (by Forest Survey standards), and cause of residue (felling or skidding) were recorded.

The number of basic sample units used in the survey corresponded to the number of logging operations on which measurements were taken. Before starting fieldwork in a State, an estimate was made of the number of sample units needed to assure a standard error of total residue volume of not more than ±20 percent to meet Forest Survey objectives. For the survey reported here, 41 sample units--18 in Idaho and 23 in Montana--were drawn from a list of known active logging operations in the two States. These were drawn at random from strata defined by geographic subunits, land ownership, and operator size class. Four subunits were used--northern Idaho, southern Idaho, western Montana, and eastern Montana. Two ownership classes were used--National Forest and other owners. Operator size class corresponded to the production class of the sawmill for which the logging was being done. Two size classes were used--small (less than 10 MMBF per year) and large (10 MMBF or more per year).

Enough trees were measured on each sample unit to provide a product volume of between 4 to 10 MBF per sample unit. On the basis of previous survey experience, guides were developed so that field crews could estimate the number of trees to be measured to meet volume objectives. The number of trees varied with the range in average tree size, timber type, and stand age (young or old growth). From 10 to 30 trees were recommended for each sample. Actually, 597 product trees were used, an average of nearly 15 per sample unit. The net product volume scaled was 41,214 cubic feet (equivalent to nearly 258,000 board feet), an average of 6.3 MBF per sample unit.

Trees felled for products were measured in place to determine both product and residue volumes. Residue volume from other trees destroyed or cut when product trees were felled also was measured. Skidding damage to trees along skid trails was determined after logs reached a landing, except in those cases where crews had been on hand to witness damage as it occurred.

In clear-cut operations (usually in lodgepole pine stands), where there was difficulty in relating felling and skidding damage to individual product trees, a slightly different procedure was used. In such cases, product trees were those whose stumps were within a circular plot. All product trees on the plot were measured, and felling and skidding damage assessed within plot boundaries after skidding.

Data compilation was accomplished by means of a set of computer programs developed especially for these studies. The output included standard errors of the ratios for residue volumes. For example, table 4 indicates that the standard error of the cubic-foot ratio in Idaho is ±10.5 percent and in Montana, ±13.7 percent.

Table 4.--*Standard errors of ratios for logging residue volumes by net cubic- and board-foot[1] measures, Idaho and Montana*

Unit of measurement and minimum top diameter	Area[2]			
	Idaho (18)	Montana (23)	Northern Idaho-western Montana (32)	Idaho-Montana (41)
	Percent			
Cubic foot 4 inches	10.512	13.713	10.061	9.254
Board foot Variable	16.126	17.869	13.960	12.622
Board foot 7 inches	15.353	19.688	14.084	12.517

[1]International 1/4-inch log rule.

[2]Number of logging operations sampled in parentheses.

Caution is recommended if estimates shown in this report are to be applied to any subdivisions of Idaho, Montana, or of the northern Idaho-western Montana area. The amount of residue per unit product can vary widely from one area to another due to several interrelated factors. Among these are: stand conditions (size and soundness of trees, species, stocking, etc.); markets for various species; size and quality of timber; and logging costs and techniques as determined by accessibility, terrain, etc.

TERMINOLOGY

Cull trees.--Live trees of commercial species that will not now or in the future qualify as sawtimber trees because of dimensions, form, rot, or damage. Also includes all live trees of noncommercial species.

Cull volume.--Portions of a tree that are unusable for industrial wood products because of rot, form, or other defect.

Diameter classes.--A classification of trees based on diameter breast height (d.b.h.) outside bark. Two-inch diameter classes used by Forest Survey are identified by the diameter at the approximate midpoint of each class. For example, the 2-inch class includes trees 1.0 to 2.9 inches d.b.h.

Growing stock trees.--Live trees of commercial species, except those that are cull because of form, rot, or other defect.

Growing stock volume.--Net volume in cubic feet of growing stock trees 5.0 inches d.b.h. and over from a 1-foot stump to a minimum 4.0-inch top diameter inside bark (d.i.b.) of the central stem or to the point where the central stem breaks into the limbs.

Logging residues.--The unused portions of trees cut or killed by logging.

Net volume.--Gross volume less deductions for rot, sweep, or other defects affecting use for timber products.

Poletimber trees.--Growing stock trees likely to grow into merchantable sawtimber trees. They must not show evidence of rot in the main stem nor have serious damage, crook, or stagnation. Softwoods must be from 5.0 to 8.9 inches d.b.h. and hardwoods from 5.0 to 10.9 inches d.b.h.

Sawtimber trees.--Growing stock trees containing at least a 12-foot saw log and not more than two-thirds of the gross board-foot volume in cull material. Softwoods must be at least 9.0 inches d.b.h. and hardwoods at least 11.0 inches d.b.h.

Sawtimber volume.--Net volume (in board feet International 1/4-inch rule) of sawtimber trees between a 1-foot stump and a specified merchantable top--fixed or variable. A fixed top is 7 inches in diameter inside bark. A variable top varies with d.b.h. as follows:

Range in d.b.h. *Inches*	*Top d.i.b.* *Inches*
9.0 - 10.9	5
11.0 - 14.9	6
15.0 - 18.9	7
19.0 - 20.9	8
21.0 - 24.9	9
25.0+	10

Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field Research Work Units are maintained in:

- Boise, Idaho
- Bozeman, Montana (in cooperation with Montana State University)
- Logan, Utah (in cooperation with Utah State University)
- Missoula, Montana (in cooperation with University of Montana)
- Moscow, Idaho (in cooperation with the University of Idaho)
- Provo, Utah (in cooperation with Brigham Young University)

LOGGING RESIDUES ON SAW LOG OPERATIONS, ARIZONA AND NEW MEXICO

Theodore S. Setzer, Alvin K. Wilson, and Grover A. Choate

USDA Forest Service
Research Paper INT-78, 1970

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Ogden, Utah 84401

COVER PHOTO

Although the longbutt shown has a large rot column, it also has a measurable volume of sound wood, which may be salvageable.

USDA Forest Service
Research Paper INT-78, 1970

LOGGING RESIDUES ON SAW LOG OPERATIONS, ARIZONA AND NEW MEXICO

Theodore S. Setzer, Alvin K. Wilson, and Grover A. Choate

INTERMOUNTAIN FOREST AND RANGE
EXPERIMENT STATION

Ogden, Utah 84401

THE AUTHORS

THEODORE S. SETZER specializes in the products and timber removals phase of the Forest Survey Unit at Intermountain Forest and Range Experiment Station. Before coming to the Intermountain Station in 1965 he spent a number of years as a sawmill operator and also some time in forestry research and conservation planning.

ALVIN K. WILSON designs and conducts special studies for Forest Survey at the Intermountain Forest and Range Experiment Station in Ogden, Utah. After working in Forest Survey at the Northeastern Forest Experiment Station, he spent several years in forest management research for the Intermountain Station and returned to Forest Survey work in 1957. He is the author of numerous publications on forest management and forest resources.

GROVER A. CHOATE was, at the time of writing this publication, Principal Resource Analyst for Forest Survey at the Intermountain Forest and Range Experiment Station, Ogden, Utah. His career includes work in the Lake States, Washington, D. C., the Pacific Northwest, and Southeast Asia. He retired from the Forest Service in late 1969.

CONTENTS

*Note: See Terminology for definitions of many of the terms used in this paper.

TABLES

ABSTRACT

Reports results of a survey made of logging operations to estimate the volume of logging residues in relation to the volume of saw logs harvested in Arizona and New Mexico. Results show: conversion factors that can be applied to product volume to estimate total removals from inventory; residue volume as a percentage of saw log volume; the relative importance of felling and skidding as causes of residues; and the numbers of trees removed from growing stock inventory by logging. Survey methods and reliability of data are discussed.

INTRODUCTION

The volume of timber cut or killed during logging operations and left in the woods represents a reduction in the inventory volume available for future management and harvesting. Consequently, the volume of unused timber should be taken into consideration if differences between successive inventories are to be more fully understood. Estimates of the amount of logging residue potentially marketable as chips are of interest also.

In 1968, Forest Survey at the Intermountain Forest and Range Experiment Station conducted a survey of logging residues in Arizona and New Mexico. Logging residue surveys yield various types of information,[1] but only data considered to be sufficiently reliable for purposes of this report were used here. Information not included in the present paper may be combined with data from future residue surveys of other areas to provide adequate reliability for further analyses. Since 1965, Forest Survey has surveyed logging residues in Idaho, Montana, Colorado, Utah, Wyoming, and in South Dakota west of the 103d meridian. If present plans are adhered to, residues will be resurveyed periodically in all Mountain States.

---

[1]Conversion factors to be applied to product volumes for estimates of total volumes removed from inventory in commercial logging; average conversion factors used to express product volume in several units of measure (cubic feet, International 1/4-inch rule, and Scribner log rule); the diameter distribution of trees removed from inventory by logging; the proportion of timber products harvested from growing stock trees compared to that of products from nongrowing stock trees; cull and breakage losses by species; the relative importance of felling and skidding as causes of residues; and the proportion of logging residue volume made up of pieces of various size classes.

LOGGING RESIDUES AND PRODUCT VOLUME

The net volume of logging residues represents underutilization by one standard or another. By Forest Survey's cubic-foot standards, residues include all unused net volume between a 1-foot stump and a 4-inch minimum top diameter inside bark (d.i.b.). By board-foot standards, net residue volume consists of unused material in sawtimber trees from a 1-foot stump to either the variable or the fixed top diameters. Merchantable logs missed in skidding are included in sawtimber residues.

The net volume of logging residues from harvesting a given volume of saw logs can be estimated by the use of table 2. For example, residues from the reported 1966 harvest of 61,813 MCF of saw logs from growing stock in Arizona are estimated to be:

$$61{,}813 \times 0.1220 = 7.5 \text{ MMCF}.$$

The largest part of residue volume results from felling. Most of this is material from trees from which saw logs have been cut. Skidding losses are relatively minor and, as shown by the following tabulation, amount to less than 20 percent of cubic-foot residue volume in the Arizona-New Mexico area, as well as in each of the two States.

	Felling				
	Product trees	*Other trees*	*All trees*	*Skidding*	*Total*
	Percent				
Arizona	74.20	6.78	80.98	19.02	100.00
New Mexico	70.53	15.42	85.95	14.05	100.00
Arizona-New Mexico	72.74	10.22	82.96	17.04	100.00

Table 2.--*Net volume of logging residues from saw log operations as a percent of net product volume, Arizona and New Mexico*

Unit of measurement and minimum top diameter	Arizona	New Mexico	Arizona-New Mexico
Cubic foot 4 inches	12.20	12.18	12.19
Board foot[1] Variable	5.27	6.36	5.70
Board foot[1] 7 inches	5.11	6.15	5.52

[1]International 1/4-inch rule.

It should be pointed out that residue volumes derived by the use of factors in table 2 are not totally available for chipping. A more detailed and intensive survey would be necessary to assess residue characteristics and to determine what portion of these residues could be used under prevailing market conditions.

DIAMETER CLASS REMOVALS

Information on the number of growing stock trees harvested or destroyed[3] in each diameter class is essential for derivations of diameter class cutting rates used in most stand-table projections of growth and inventory. Reliable data of this kind usually are difficult to obtain. However, logging residue surveys provide means for estimating the distribution of trees removed per unit volume of saw logs harvested.

---

[3]Either occurrence removes the trees from inventory.

Table 3 shows the total number of growing stock trees (product trees and others), removed per 1 MCF of product volume in New Mexico, in Arizona, and in the New Mexico-Arizona area. These figures can be applied to a given volume of saw log harvest to estimate trees removed in each diameter class. In turn, this estimate can be related to an inventory stand table in order to compute cutting rates.

SURVEY METHODS AND RELIABILITY OF ESTIMATES

A basic need in the logging residue surveys was to develop factors that could be applied to a reported volume of saw log harvest to estimate the resulting volume of logging residues. Estimates of residue volume are based on product volume rather than acreage logged because such information usually is more reliable and available (at least to Forest Survey) than are estimates of area cutover. The survey design prescribed three basic types of measurements of growing stock trees on active logging operations to meet this objective:

1. Net volume of saw logs harvested from *product* trees measured on a logging operation;
2. Net volume of residues from the *same* trees;
3. Net volume of residues from *other* trees cut or destroyed in the process of felling and skidding product trees.

All three sets of measurements were used to determine the residue volume as a percent of saw log volume. Scaling was done in detail to permit estimates of gross and net cubic-foot volumes for all measured growing stock trees, and to provide gross and net board-foot volumes to fixed and variable tops for measured sawtimber trees. Species, diameter breast height (d.b.h.), total height, overutilization (by Forest Survey standards), and cause of residue (felling or skidding) were recorded.

Table 3.--*Growing stock trees removed from inventory in saw log operations per 1 thousand cubic feet of net product volume, Arizona and New Mexico*

D.b.h. class (inches)	Arizona	New Mexico	Arizona-New Mexico
		Number of trees	
2	47.6224	33.0149	41.8077
4	27.6987	20.8377	24.9676
6	6.5949	4.6189	5.8084
8	2.2215	1.7846	2.0476
10	1.1801	.7348	1.0029
12	.5554	.4199	.5014
14	1.1454	1.2597	1.1909
16	1.7008	.7348	1.3163
18	1.9091	1.6271	1.7968
20	2.2215	1.4697	1.9222
22	.5901	.9973	.7522
24	1.3884	1.3122	1.3581
26	.7983	.6299	.7313
28	.5901	1.1022	.7939
30+	1.6314	2.0470	1.7968
All classes	97.8481	72.5907	87.7941

The number of basic sample units used in the survey corresponded to the number of logging operations on which measurements were taken. Before starting fieldwork in a State, an estimate was made of the number of sample units needed to assure a standard error of total residue volume of not more than ±20 percent to meet Forest Survey objectives. For the survey reported here, 39 sample units--23 in Arizona and 16 in New Mexico--were drawn from a list of known active logging operations in the two States. These were drawn at random from strata defined by land ownership and operator size class. Two ownership classes were used--National Forest and other owners. Operator size class corresponded to the production class of the sawmill for which the logging was being done. Two size classes were used--small (less than 10 MMBF per year) and large (10 MMBF or more per year).

Enough trees were measured on each sample unit to provide a product volume of between 4 to 10 MBF per sample unit. On the basis of previous survey experience, guides were developed so that field crews could estimate the number of trees to be measured to meet volume objectives. The number of trees varied with the range in average tree size, timber type, and stand age (young or old growth). From 10 to 30 trees were recommended for each sample. Actually, 574 product trees were used, an average of 15 per sample unit. The net product volume scaled was 52,107 cubic feet (equivalent to 328,269 board feet), an average of 8.4 MBF per sample unit.

Trees felled for products were measured in place to determine both product and residue volumes. Residue volume from other trees destroyed or cut when product trees were felled also was measured. Skidding damage to trees along skid trails was determined after logs reached a landing, except in those cases where crews had been on hand to witness damage as it occurred.

In clear-cut operations where there was difficulty in relating felling and skidding damage to individual

Table 4.--Standard error of ratios for logging residue volumes by net cubic- and board-foot[1] measures, Arizona and New Mexico

Unit of measurement and minimum top diameter	Area: Arizona (23)	New Mexico (16)	Arizona-New Mexico (39)
	------------	Percent	------------
Cubic foot 4 inches	13.171	12.975	9.347
Board foot Variable	17.169	14.796	11.717
Board foot 7 inches	16.421	14.115	11.187

[1] International 1/4-inch rule.

Number of logging operations sampled in parentheses.

product trees, a slightly different procedure was used. In such cases, product trees were those whose stumps were within a circular plot. All product trees on the plot were measured, and felling and skidding damage assessed within plot boundaries after skidding.

Data compilation was accomplished by means of a set of computer programs developed especially for these studies. The output included standard errors of the ratios for residue volumes. For example, table 4 indicates that the standard error of the cubic-foot ratio in Arizona is ±13.2 percent, and in New Mexico, ±13.0 percent.

Caution is recommended if estimates shown in this report are to be applied to any subdivisions of Arizona and New Mexico. The amount of residue per unit product can vary widely from one area to another due to several interrelated factors. Among these are: stand conditions (size and soundness of trees, species, stocking, etc.); markets for various species; size and quality of timber; and logging costs and techniques as determined by accessibility, terrain, etc.

TERMINOLOGY

Cull trees.--Live trees of commercial species that will not now or in the future qualify as sawtimber trees because of dimensions, form, rot, or damage. Also includes all live trees of noncommercial species.

Cull volume.--Portions of a tree that are unusable for industrial wood products because of rot, form, or other defect.

Diameter classes.--A classification of trees based on diameter breast height (d.b.h.) outside bark. Two-inch diameter classes used by Forest Survey are identified by the diameter at the approximate midpoint of each class. For example, the 2-inch class includes trees 1.0 to 2.9 inches d.b.h.

Growing stock trees.--Live trees of commercial species, except those that are cull because of form, rot, or other defect.

Growing stock volume.--Net volume in cubic feet of growing stock trees 5.0 inches d.b.h. and over from a 1-foot stump to a minimum 4.0-inch top diameter inside bark (d.i.b.) of the central stem or to the point where the central stem breaks into the limbs.

Logging residues.--The unused portions of trees cut or killed by logging.

Net volume.--Gross volume less deductions for rot, sweep, or other defects affecting use for timber products.

Poletimber trees.--Growing stock trees likely to grow into merchantable sawtimber trees. They must not show evidence of rot in the main stem nor have serious damage, crook, or stagnation. Softwoods must be from 5.0 to 8.9 inches d.b.h. and hardwoods from 5.0 to 10.9 inches d.b.h.

Sawtimber trees.--Growing stock trees containing at least a 12-foot saw log and not more than two-thirds of the gross board-foot volume in cull material. Softwoods must be at least 9.0 inches d.b.h. and hardwoods at least 11.0 inches d.b.h.

Sawtimber volume.--Net volume (in board feet International 1/4-inch rule) of sawtimber trees between a 1-foot stump and a specified merchantable top--fixed or variable. A fixed top is 7 inches in diameter inside bark. A variable top varies with d.b.h. as follows:

Range in d.b.h. *Inches*	*Top d.i.b.* *Inches*
9.0 - 10.9	5
11.0 - 14.9	6
15.0 - 18.9	7
19.0 - 20.9	8
21.0 - 24.9	9
25.0+	10

Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field Research Work Units are maintained in:

- Boise, Idaho
- Bozeman, Montana (in cooperation with Montana State University)
- Logan, Utah (in cooperation with Utah State University)
- Missoula, Montana (in cooperation with University of Montana)
- Moscow, Idaho (in cooperation with the University of Idaho)
- Provo, Utah (in cooperation with Brigham Young University)

USDA Forest Service
Research Paper INT-79
1970

CONE AND SEED YIELDS IN YOUNG WESTERN WHITE PINES

R.T. Bingham and G. E. Rehfeldt

INTERMOUNTAIN FOREST AND RANGE
EXPERIMENT STATION
Ogden, Utah 84401

USDA Forest Service
Research Paper INT-79
1970

CONE AND SEED YIELDS IN YOUNG WESTERN WHITE PINES

R. T. Bingham and G. E. Rehfeldt

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401
Joseph F. Pechanec, Director

THE AUTHORS

RICHARD T. BINGHAM is leader of the Moscow, Idaho, Forestry Sciences Laboratory Research Unit studying Resistance to Blister Rust in Western White Pine. He is Acting Leader of another of the Intermountain Forest and Range Experiment Station's Research Units--Breeding Conifers for the Northern Rocky Mountains--that is also headquartered at Moscow. He has had broad experience in the pathology, silviculture, and genetics of western white pine; also, he is author of numerous publications on the genetics of blister rust resistance, and on the genetics of western white pine.

GERALD E. REHFELDT, presently a Plant Geneticist for the Intermountain Forest and Range Experiment Station, Moscow, Idaho, obtained his B.S. degree in Forestry from Utah State University in 1963 and his M.S. and Ph.D. from the University of Wisconsin in 1965 and 1967, respectively. His first assignment was at Moscow, Idaho, in 1967 and dealt with breeding of conifers for the Northern Rocky Mountains.

CONTENTS

ABSTRACT

Eighteen years of cone and seed yields from 179 30- to 50-year-old western white pines (*Pinus monticola* Dougl.) representative of 13 geographic localities were compared. Each tree averaged 28 cones per tree, and each cone contained about 104 filled seeds. However, not only was annual cone production highly variable, but geographic localities and individual trees varied greatly in productivity within a given year. Recognition of these components of variation in cone production for western white pine can lead to maximal efficiency in cone collection.

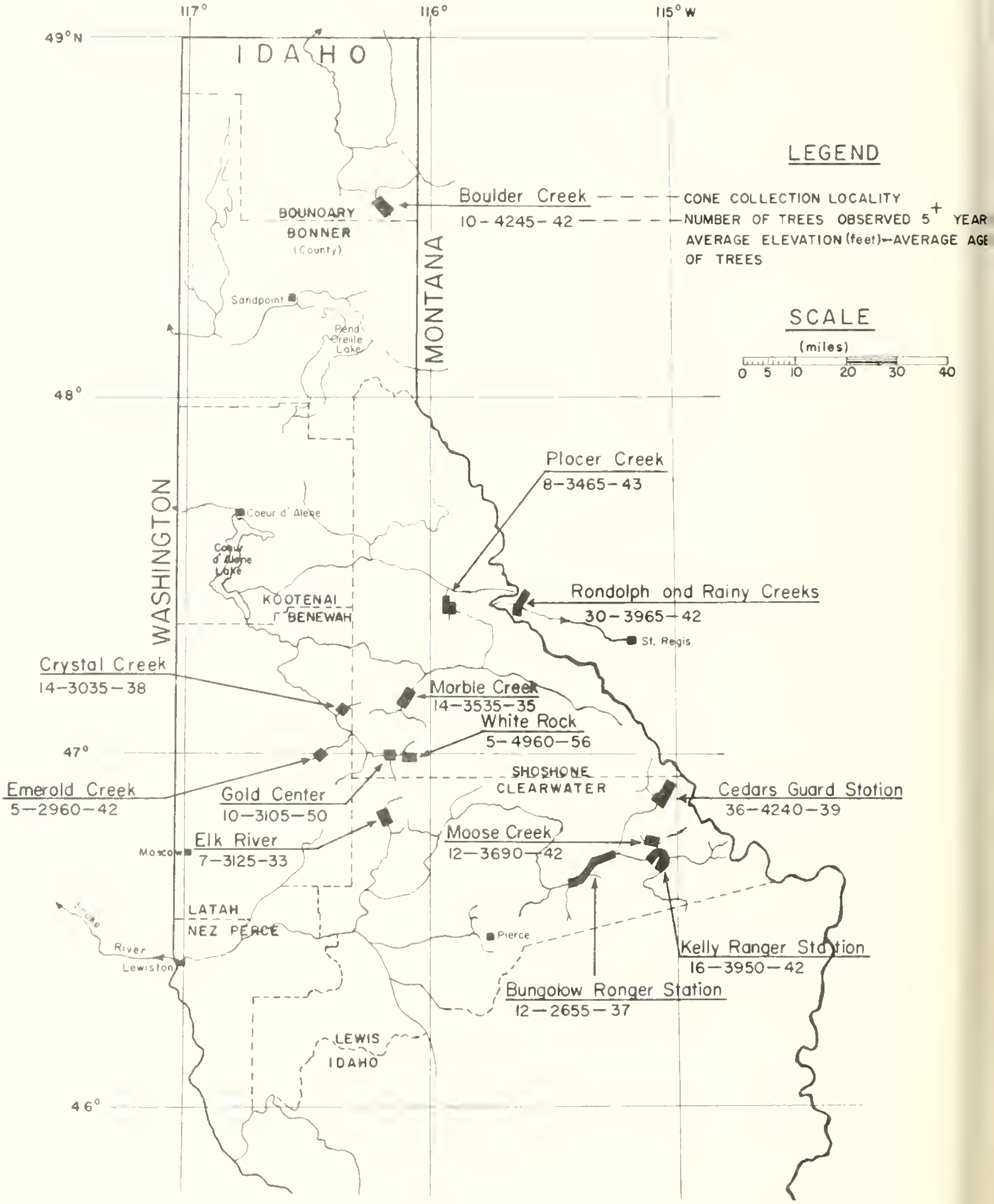


Figure 1.--*Map of northern Idaho illustrating the 13 geographic localities from which cones were collected and the number, average elevation, and average age of trees represented within each locality.*

INTRODUCTION

Forest managers normally recognize and anticipate periodicity in cone production of forest trees. However, variation in cone production among geographic localities and individual trees within localities is largely unexplored, for rarely are cones collected in consecutive years from the same trees.

In the course of breeding western white pine (*Pinus monticola* Dougl.) for resistance to blister rust (see Bingham, Olson, Becker, and others 1969 and earlier), 18 years of data on cone and seed yields of individual trees from different geographical localities have been accumulated. The protection of cones during development minimized losses due to insects and rodents; therefore, these data simulate the full reproductive potential of young trees in natural stands. Annual variation in cone production among geographic localities and individual trees thus is represented in these data. This information is indispensable for practices of seed collection and seed orchard management which rely on knowledge relating to cone yields of individual trees and possibly on yields derived from controlled pollinations.

MATERIALS AND METHODS

During the years 1950 to 1967, cone and seed yields were obtained from 179 30- to 50-year-old western white pines. Trees were representative of 13 geographic localities (figure 1) within which they varied in elevation by about 400 feet; within two localities, however, trees differed in elevation by about 1500 feet.

Comparisons of yields between seed years, localities, and trees within localities were made on the basis of mean yield; statistical analyses were not attempted because yields for each maternal tree and locality were not available for each year. Criteria for including yields of individual trees in the basic data were: (1) five or more years of observation were available; and (2) observations were for consecutive or nearly consecutive years. Since periodicity in cone production of western white pine tends to follow 3- and 4-year cycles,[1] yields for each tree were represented for nearly all stages of cyclic production. It is therefore assumed that minimal confounding is represented in the data.

RESULTS AND DISCUSSION

Yield of Cones

At tree ages of 30 to 50 years, annual production of cones averaged about 28 per tree. This mean characterizes cone production inadequately because yield is subject to an interaction of exogenous and endogenous factors. The interaction causes tremendous variation in cone production among seed years, geographic localities, and maternal trees within each locality.

Within the 18-year period, mean yield of cones for individual seed years differed by as much as 55 cones per tree (table 1). In fact, the mean yield of cones per tree, in successive seed years, differed by as much as 34 cones. These differences in yield among seed years reflect a periodicity in cone production which is documented elsewhere in greater detail.[1]

Mean yield for geographic localities over all years of observation differed by as much as 64 cones per tree (table 2). However, the degree of difference between localities depended on the seed year. For instance, in 1967 which was a year of high mean yield, localities differed by as much as 78 cones per tree; but in 1956 when few cones were produced, maximum differences between localities were only 20 cones per tree. Thus, differences in yield among localities were evident, especially in years of high yield. Localities characterized by low cone yields, however, produced few cones even in favorable seed years.

---

[1]G. E. Rehfeldt, A. R. Stage, and R. T. Bingham. Time series analysis for production of female strobili in western white pine. Manuscript in preparation.

Table 1.--*Mean yields of cones per tree according to the seed year and the localities with the lowest and highest mean yield for each year*

	Yields per year		Yields per locality			
			Locality of lowest yield		Locality of highest yield	
Year	Trees observed	Mean (cones/tree)	Trees observed	Mean (cones/tree)	Trees observed	Mean (cones/tree)
1950	26	23.2	4	0	1	53.0
1951	29	27.8	4	2.0	12	50.6
1952	29	16.4	3	0	2	195.0
1953	38	18.2	5	0	5	74.4
1954	34	49.8	2	7.5	13	71.6
1955	7	40.8	1	22.0	1	55.0
1956	85	10.5	2	3.5	6	23.6
1957	11	16.5	1	5.0	5	27.0
1958	87	38.0	10	20.4	5	130.8
1959	87	28.3	31	18.5	4	159.5
1960	107	18.0	8	6.1	5	36.6
1961	146	21.8	3	3.3	9	60.9
1962	136	29.1	4	2.5	4	82.5
1963	119	25.3	4	0.8	9	86.2
1964	95	59.3	4	25.0	5	148.8
1965	91	40.3	2	28.5	5	84.0
1966	80	51.0	2	10.5	10	90.4
1967	76	65.3	3	21.0	10	99.1

Table 2.--*Mean yields of cones per tree for each year according to the locality, and the tree within each locality with the highest and lowest mean yield*

Locality	Trees observed	Mean years of observation	Mean (cones/tree/year)	Yield per tree: Tree of lowest yield: Years observed	Yield per tree: Tree of lowest yield: Mean (cones/year)	Yield per tree: Tree of highest yield: Years observed	Yield per tree: Tree of highest yield: Mean (cones/year)
Emerald Creek	5	6.8	4.6	9	3.7	6	7.5
Gold Center	10	8.0	15.2	7	2.8	8	33.8
Placer Creek	8	6.5	16.2	7	4.6	5	55.4
Cedars Guard Station	36	7.2	20.5	6	0	6	89.1
Bungalow Ranger Station	12	6.6	22.7	7	4.0	10	58.1
Rainy and Randolph Creeks	30	7.4	23.4	7	0.6	11	69.8
Moose Creek	12	6.2	23.6	6	11.0	7	29.4
Elk River	7	7.1	30.3	6	6.0	12	46.1
Kelly Ranger Station	16	5.6	42.7	5	10.6	5	73.6
Marble Creek	14	5.8	55.2	5	8.2	8	122.9
Crystal Creek	14	11.1	56.1	8	1.6	18	129.7
White Rock	5	11.0	63.0	9	19.9	9	87.2
Boulder Creek	10	5.2	68.5	5	15.2	5	114.2

Cone yields also varied among individual trees within localities (table 2). Differences in cone production of individual trees within localities were directly proportional to the effect of the seed year just as were differences in yield among localities. Moreover, differences in cone yield per year among individual trees depended on the overall yield of the locality. Although cone production by trees in high-yielding localities differed by as much as 100 cones per tree for each year, trees within localities of low mean yield showed little difference in production. Thus, each locality contained trees that characteristically produced few cones, even in good seed years; differences among localities apparently resulted from varying proportions of trees that produced large crops of cones in generally high-yielding years.

Of the exogenous factors that affect cone yield, the one that cannot be assessed at this time, due to lack of data, is the influence of microsites on the yield of trees within localities. However, other factors can be assessed; tree age, elevation, and latitude can be related to mean cone yield by correlation analyses (table 3). Although unequal sampling and possible intercorrelations among age, elevation,

Table 3.--*Correlation of tree age, tree elevation, and locality latitude with cone yield of: individual trees; trees within localities; and localities*

Cone yield	Tree age	Tree elevation	Locality latitude	d.f.
	----*Correlation coefficient, r*----			
Individual trees	0.33**	0.42**	--	177
Trees within localities (pooled r)	.45**	.44**	--	166
Localities	--	--	.66*	11

**Significant at the 1 percent level of probability.
*Significant at the 5 percent level of probability.

and latitude make interpretation difficult, cone yield per tree and locality appears weakly associated with tree age and tree elevation. Significance of the indicated correlation between cone yield of localities and locality latitude is doubtful because values for Boulder Creek (highest latitude and high elevation) exert enough influence to inflate the correlation coefficient over the 5 percent level of significance.

Yield of Seeds Per Cone

The average wind-pollinated cone yielded approximately 104 filled seeds; thus, each tree produced nearly 3,000 filled seed per year. However, yields of filled seeds per cone were positively associated with the yield of cones ($r = .79$, significant at the 1 percent level of probability). Mean yield of filled seeds per cone thus varied according to seed years (table 4), localities (table 5), and trees within localities (table 5). In fact, yields of seeds per cone ranged from 25 to 149 for two trees in different localities and in different seed years.

Exogenous variables cannot entirely account for the tremendous variation in total number of filled seed per tree. Tree 212 near Cedars Guard Station and tree 58 in the Crystal Creek area (see figure 1) outwardly were similar in terms of age, size, dominance, and local stand density (table 6). Although the cone yield of tree 212 was about one-half that of tree 58, the seed yield of 212 was less than one-fourth that of 58. Possible genetic control of these traits requires elucidation; their importance in seed orchards might be great.

Yields From Wind-, Cross-, and Self-Pollinated Cones

Statistical analyses (paired "t" tests) of balanced samples of filled seeds per cone (table 7) indicate that yields derived from self-pollinations were less (1 percent level of probability) than those of wind- or cross-pollinations; no differences were detected

Table 4.--*Mean yields of filled seeds per cone according to the seed year and the localities with the lowest and highest mean yield for each year*

	Yields per year		Yields per locality			
			Locality of lowest yield		Locality of highest yield	
Year	Trees observed	Mean (seeds/tree)	Trees observed	Mean (seeds/tree)	Trees observed	Mean (seeds/tree)
1950	17	77.3	3	28.0	1	156.0
1951	18	75.2	6	42.2	10	97.2
1952	8	77.5	6	72.0	2	94.0
1953	20	93.1	5	69.0	2	142.5
1954	25	149.5	3	114.3	11	164.1
1955	5	106.4	1	77.0	4	113.8
1956	14	82.6	4	75.8	4	88.7
1957	4	107.5	--	--	--	--
1958	17	124.2	5	106.2	2	177.5
1959	15	92.1	3	63.0	7	105.1
1960	8	61.0	2	50.0	4	62.5
1961	22	77.7	6	49.3	2	128.5
1962	32	94.4	2	41.5	3	151.3
1963	17	72.4	2	18.0	6	104.5
1964	18	130.5	1	37.0	1	147.0
1965	18	73.4	2	50.0	1	114.0
1966	21	98.7	2	61.5	2	123.0
1967	24	99.9	1	81.0	3	143.0

Table 5.--*Mean yields of filled seeds per cone according to the locality and tree within each locality with the highest and lowest mean yields*

Locality	Trees observed	Mean years of obser-vation	Mean (seeds/tree/year)	Yield per tree: Tree of lowest yield: Years observed	Yield per tree: Tree of lowest yield: Mean (seeds/year)	Yield per tree: Tree of highest yield: Years observed	Yield per tree: Tree of highest yield: Mean (seeds/year)
Gold Center	6	5.5	70.6	7	50.7	5	93.8
Rainy and Randolph Creeks	5	6.2	85.0	6	45.8	5	116.4
Cedars Guard Station	8	6.4	90.9	8	24.8	5	133.4
Crystal Creek	11	10.1	97.8	6	52.3	7	112.7
Marble Creek	3	5.3	102.2	6	91.2	5	123.6
White Rock	5	8.0	112.5	9	75.1	11	155.6
Elk River	3	7.0	119.0	6	95.3	6	149.5

Table 6.--*Variation in cones, seeds, and total seed yield of several low and high yielding trees*

Item	Low yielding trees					High yielding trees				
	Tree number					Tree number				
	134	35	37	183	212	266	20	109	54	58
Locality	Rainy and Randolph Creeks	Gold Center	Gold Center	Cedars G.S.	Cedars G.S.	Marble Creek	Crystal Creek	Marble Creek	White Rock	Crystal Creek
Age in 1967	52	52	56	43	52	28	50	44	60	50
Year measured	1956	1951	1951	1956	1956	1961	1952	1959	1952	1952
Height (feet)	50	49	64	53	60	34	68	62	55	60
Diameter breast high (inches)	8.5	11.6	11.3	6.0	19.6	9.9	13.1	16.5	13.5	11.7
Dominance class	Inter- med.	Dom.	Dom.	Dom.	Dom.	Dom.	Dom.	Dom.	Dom.	Dom.
Stand density	Med.- dense	Open	Med.- open	Open	Open	Open	Med.- open	Open	Med.	Open
Mean cones/year	10.1	10.4	12.4	14.4	52.6	75.1	96.1	122.9	74.5	11[illegible].7
Years cones observed	7	10	11	10	11	7	11	8	14	18
Mean filled seed/cone	45.8	50.7	63.8	81.5	24.8	123.6	111.7	91.2	155.6	1[illegible]2.7
Years yield observed	6	7	5	6	8	5	7	6	11	15
Mean total filled seed/year	463	527	791	1174	1304	9282	10,734	11,061	11,592	1[illegible],927

between yields of the latter two groups. Lowered seed yields accompanying self-pollination in western white pine is well documented (Bingham and Squillace 1955; Squillace and Bingham 1958; Barnes, Bingham and Squillace 1962).

As noted previously (Bingham and Squillace 1955), the yield of total seeds (filled plus hollow) was essentially the same regardless of the type of pollination (table 7). The large proportion of hollow seeds that develop after self-pollination apparently result from embryo abortion because full-sized hollow seeds failed to develop following earlier failures in pollination, pollen tube growth, or fertilization in *Pinus sylvestris* L. (Sarvas 1962).

Table 7.--*Yield of filled and hollow seeds per cone from wind-, cross-, and self-pollinations. Comparisons are based on yields from trees on which observations were available in the same seed years*

Comparisons			Pollen type	Yield of seeds per cone		
Group	Trees observed	Years observed		Filled	Hollow	Total
A	28	9	Wind	111.2	12.0	123.2
			Cross	102.7	21.4	124.1
			Self	60.9	57.4	118.3
B	40	11	Wind	102.1	13.7	115.8
			Cross	94.4	21.3	115.7
			Self	--	--	--
C	141	12	Wind	--	--	--
			Cross	95.4	22.9	118.3
			Self	51.8	58.6	110.4

Approximately one-third of all control-pollinated cones, whether cross- or self pollinated, failed to reach maturity. Since losses of cones due to insects, rodents, or breakage were known and minimal, losses of control-pollinated cones were almost entirely due to abortion of cones during development. Sarvas (1962) suggested that conelet abortion in pines is associated with high ovule abortion rates accompanying poor pollination. Conelet abortion of pines also appears to be associated with soil moisture stresses during the period of conelet elongation in *P. monticola*[2] and *P. radiata* D. Don (Pawsey 1960).

SUMMARY AND CONCLUSIONS

Between the ages of 30 and 50, western white pines average 28 cones per year. Each cone contains about 104 filled seeds which means that each tree produces about 3,000 filled seeds; however, tremendous variations occur. Annual production of cones is highly variable. Also, within a given seed year certain localities and individual trees within localities vary greatly in productivity. Of additional importance is the direct relationship between the proportion of filled seed and the size of the cone crop. Increased efficiency in seed collection can be realized by avoidance of low-yielding localities, trees and seed years. Also, by collecting only in high-yielding localities, cone and seed procurement can be maximized with a minimum of effort. This is particularly true when cone production is generally low.

It is further noteworthy that once techniques are mastered and proper timing is ascertained, yields derived from controlled pollinations of western white pine almost equal those of wind pollination.

---

[2] Ibid.

LITERATURE CITED

Barnes, B. V., R. T. Bingham, and A. E. Squillace.
1962. Selective fertilization in *Pinus monticola* Dougl. II. Results of additional tests. Silvae Genet. 11: 103-111.

Bingham, R. T., R. J. Olson, W. A. Becker, and M. A. Marsden.
1969. Breeding blister rust resistant western white pine. V. Estimates of heritability, combining ability, and genetic advance based on tester matings. Silvae Genet. 18: 28-38.

____________ and A. E. Squillace.
1955. Self-compatibility and effects of self-fertility in western white pine. Forest Sci. 1: 121-129.

Pawsey, C. K.
1960. Cone production reduced, apparently by drought, in the south-east of south Australia. Austr. Forest. 24: 74-75.

Sarvas, Risto.
1962. Investigations on the flowering and seed crop of *Pinus silvestris*. Commun. Inst. Forestalis Fenniae 53, 198 p.

Squillace, A. E., and R. T. Bingham.
1958. Selective fertilization in *Pinus monticola* Dougl. I. Preliminary results Silvae Genet. 7: 188-196.

Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field Research Work Units are maintained in:

- Boise, Idaho
- Bozeman, Montana (in cooperation with Montana State University)
- Logan, Utah (in cooperation with Utah State University)
- Missoula, Montana (in cooperation with University of Montana)
- Moscow, Idaho (in cooperation with the University of Idaho)
- Provo, Utah (in cooperation with Brigham Young University)

USDA Forest Service
Research Paper INT-80
1970

MEASUREMENT OF WATER POTENTIAL WITH THERMOCOUPLE PSYCHROMETERS: CONSTRUCTION AND APPLICATIONS

Ray W. Brown

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Ogden, Utah 84401

USDA Forest Service
Research Paper INT-80
1970

MEASUREMENT OF WATER POTENTIAL WITH THERMOCOUPLE PSYCHROMETERS: CONSTRUCTION AND APPLICATIONS

Ray W. Brown

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401
Joseph F. Pechanec, Director

THE AUTHOR

RAY W. BROWN, Plant Physiologist on the Watershed Rehabilitation project at Logan, Utah, joined the staff of the Intermountain Station in 1965. He holds a B.S. degree in Forestry and an M.S. in Range Ecology from the University of Montana. He is currently completing the requirements for a Ph.D. in Plant Physiology at Utah State University.

CONTENTS

ABSTRACT

Basic theory of water potential in the soil-plant-atmosphere continuum is considered, together with a review of the use of thermocouple psychrometers. The construction, methods of water potential measurement, and calibration of thermocouple psychrometers are discussed in detail. The effects of protective ceramic cups on the rate of water vapor exchange between the soil mass and the internal psychrometer cavity are compared with the effects of fine screen cups. The ceramic cup imposes a much greater resistance to vapor exchange than the screen cups; the magnitudes of possible errors resulting from this resistance in estimates of water potential are discussed. Possible uses of thermocouple psychrometers for measuring water potentials of soils and plants under intensive forest management practices are considered.

INTRODUCTION

In recent years, researchers in the environmental sciences have become interested in developing a means of measuring and expressing the free energy status of water in the soil-plant-atmosphere continuum. During the last decade a substantial amount of research was devoted to this problem, and from this has emerged a whole new theoretical approach based on thermodynamic principles and terminology. This research marked a notable turning point in the science of soil-plant water relations; also, these studies offered a fresh insight into the question of water and energy transfer. Certainly, some of the most important contributions emanating from this work are the great number of experimental techniques and methods now available for research in water relations. The principal technique, thermocouple psychrometry, is used to describe the free energy status of water in the soil-plant continuum in quantitative terms consistent with modern thermodynamic theory.

There is abundant literature dealing with the specific details of construction and the theory of operation of these instruments; however, this literature is rather extensive and specialized. It is the purpose here to briefly review the theoretical considerations of water relations, to review the more pertinent aspects of thermocouple psychrometry, and to describe in detail the construction, calibration, and use of a rapid-response thermocouple psychrometer designed for measuring the free energy status of water in the dynamic soil-plant complex.

Measurement of the free energy status of water is essential to studies of the relationships between water in the soil and in plants and its consequent loss to the atmosphere. Water in the soil-plant-atmosphere continuum is dynamic and is rarely, if ever, in equilibrium with water in adjacent locations. The driving forces responsible for water transfer are gradients of decreasing free energy resulting from plant transpiration, evaporation, vapor pressure gradients, temperature gradients, and various other forces. Thus, water in the soil-plant-atmosphere continuum follows a gradient of decreasing free energy from the soil, through the plant, out to the atmosphere. During periods of high transpiration demand, particularly steep energy gradients may result within very small distances between the soil and roots, within the plant itself, and between the plant and surrounding atmosphere. Plant responses to water stress are more closely related to the energy required to remove a unit of water from the soil than any other single factor. Therefore, to be most useful, measurements of water in dynamic systems should include as many aspects of the component factors controlling water transfer as possible.

There are a number of methods available for describing the water status in soils and plants; these methods are mainly based on measurements of water quantity. However, an alternate method based on determination of water-free energy also offers many advantages. One of the most obvious advantages of this latter method is that of directly expressing soil water in terms of the energy required for the removal of a unit of water from the soil by plants. Measurements of soil water energy have merit because they are more directly comparable among different textural classes. A given soil water energy level has the same implications with respect to root absorption, evaporation, or other forces, regardless of the physical properties of the soil. Also, recent advances in techniques now permit direct measurements of the *in situ* energy status of water in soils and plants with a minimum of disturbance. These measurements can be accomplished simultaneously in soil and plants and results are expressed in the same meaningful terms.

STATE OF WATER IN THE SOIL-PLANT-ATMOSPHERE CONTINUUM

Theoretical Considerations

Transpiration loss by a plant results in reduced turgor pressure, and, consequently, reduced potential energy of water in the leaves. This reduction of water creates an energy gradient in the water column from the soil through the roots and xylem tissue of the stem to the leaves. Actually, the transpiration process itself results from a decreasing energy gradient of the water from the leaves to the surrounding atmosphere. Thus, we can speak of a soil-plant-atmosphere continuum with respect to the gradient of decreasing free energy in water from the soil, to the plant, and out to the atmosphere. Evaporation from the soil surface also results from a decreasing energy gradient from the soil to the atmosphere. The driving force for water movement is the decreasing energy gradient of water in the system under consideration. Therefore, an understanding of the processes of water transfer must begin with the energy relations of soil and plant water in terms of thermodynamic principles. A brief review of these principles is presented here, but the interested reader is referred to the following references for a more rigorous mathematical treatment of the theoretical considerations of energy relations of water: Slatyer 1967; Gardner 1965; Kramer and others 1966; Taylor and others 1961; Taylor 1964, 1965; Taylor and Stewart 1960; Spanner 1964; and Briggs 1967.

The concept of energy status of water in a system is best explained in terms of free energy, or more correctly, Gibbs free energy (describes spontaneity). The free energy of a component (water, in this case) in a system (soil or the plant) is an expression of the capacity of the component to do work. The free energy of water depends on the mole fraction of water available or the concentration of the water molecules in the system relative to the concentration of other components in the same system. Since the actual free energy is difficult to calculate, the free energy of water in the soil or in plant tissue can be expressed as the difference between the free energy of pure free water and the free energy of the water in the system at the same temperature and pressure. The resulting net free energy of water has been referred to as the chemical potential, or the more widely accepted term, water potential (Slatyer and Taylor 1960, Taylor and Slatyer 1962).

The water potential is affected by factors that change the free energy of water molecules in the system. The presence of solutes (ionized or nonionized molecules), colloids (clay or very large molecules), large particles such as clays, silt, and sand, all decrease the water potential. The water molecules in the system, such as soil or a plant, interact with these components and decrease the free energy of the water below that of pure free water. Water potential can be defined, then, as the minimum additional work required to remove water from the soil (or any other system) in excess of the work required to remove pure free water from the same location. On the other hand, the partial specific Gibbs free energy, or the water potential of water in a multicomponent system, is an expression of the ability of a unit mass of water to do work compared to the work that an equal mass of pure free water can do. Since the presence of other components (such as solutes) reduces the free energy of water, the potential for water to do work in a multicomponent system is less than that of pure water, and thus the water potential will be negative.

The manner in which solutes and other components reduce the water potential in soil and plants can be expressed in terms of their effects on the chemical activity of water. "Activity" is a thermodynamic term for the tendency of water to react or move in a system, and this value is equal to the relative vapor pressure of the water in the system. Therefore, water potential is described in terms of the relative vapor pressure of the water in the system to that of pure free water at the same temperature and pressure, and can be written as:

$$-\psi = RT \ln \frac{e}{e_o} \qquad (1)$$

where,

- $-\psi$ is the symbol for water potential, expressed as a negative value,
- R is the universal gas constant,
- T is the absolute temperature in °K,
- e is the actual vapor pressure of the water in the system,
- e_o is the vapor pressure of pure free water.

This equation implies that water potential is expressed in energy units, such as ergs mole^{-1}, but these units are somewhat inconvenient to convert from energy units to pressure units (atmospheres or bars), in which case, equation (1) becomes:

$$-\psi = \frac{RT}{\bar{V}} \ln \frac{e}{e_o} \qquad (2)$$

where,

$\bar{V}$ is the partial molal volume of water (18.015 cm.^{3} mole^{-1}).

(See Appendices 1, 2, and 3 for energy-pressure conversions, definition of units, and equivalent relative vapor pressures for various solution concentrations.)

Components of Water Potential

There are a number of component forces affecting the water potential, the most important of which are:

Osmotic potential (ψ_π): the osmotic component (π) of the total water potential (ψ) reduces the chemical free energy of a solution as a function of the presence of dissolved substances in the solution. Dissolved substances, such as salts, sugars, and other solutes, are either ionized in solution or have an asymmetrical distribution of surface electrical changes so that they attract the highly polar water molecules. The attractive forces of these oppositely charged ions and molecular surfaces are reduced by the high dielectric constant of water. The force of this attraction, resulting in neutralizing ion-dipole bonds, reduces the chemical-free energy or water potential of the solution below that of pure free water.

Matric potential (ψ_m): the matric component (m) reduces the water potential as a function of capillary or colloidal adsorptive forces by soil particles, cellular colloids, and cell walls. In normal, nonsaline soils the energy status of water is more closely related to the thickness of the absorbed film of water on the soil particle than to any other factor. The force of adsorption between the matrix surface and the water molecules reduces the chemical free energy or water potential below that of pure free water.

Pressure potential (ψ_p): the pressure component (p) may raise or lower the water potential depending on whether the molecules are subjected to pressures above or below atmospheric pressure. Under either natural conditions or simulated conditions in the laboratory, only atmospheric positive pressures will be of concern. Under atmospheric pressure conditions, the effect of the pressure component on an open system, such as soil, is zero. Positive pressure against the vacuolar membrane and cell wall in plants (turgor pressure) resulting from hydrostatic forces of water will add free energy to the system, and the water potential will be increased. At wilting, the pressure component will approach, or reach, zero and will not affect water potential appreciably.

In addition to these three principal components, the water potential is affected by temperature and gravitational forces. The water potential decreases as the temperature decreases because of a loss of heat (free energy) from the individual water molecules. Effects of gravity may be important to considerations of water movement over a considerable vertical distance, such as water columns in tall trees, but gravity can usually be neglected in studies of soils and most plants. Water potential is usually determined at the ambient temperature and then corrected back to 25°C. (or the temperature of calibration under isothermal conditions) at normal atmospheric pressure, and over a very small vertical extent. The effect of temperature is eliminated by this adjustment. As previously stated, the influence of gravitational forces is usually negligible.

Under most conditions in the soil-plant system, the most important variables affecting water potential (other than temperature influences which must be corrected) are the osmotic, matric, and pressure potentials. Since the pressure component does not affect the soil water potential appreciably, an equation expressing the sum of the components affecting the total soil water potential can be written as:

$$\psi = \psi_\pi + \psi_m \tag{3}$$

where:

ψ is the total water potential;
subscript π is the osmotic component; and,
subscript m is the matric component.

In the plant, an equivalent expression for the total plant water potential is:

$$\psi = \psi_\pi + \psi_m + \psi_p \tag{4}$$

where:

ψ_p is the pressure potential.

It is important to understand that equations (3) and (4) express water potential (a negative quantity) as the algebraic sum of osmotic potential (negative) matric potential (negative), and pressure potential (positive). Usually the matric potential is not considered a major component in the plant water potential, and there is a tendency to combine it with the osmotic potential. The distinction between these two components can become somewhat arbitrary, but there are recent convincing arguments that they are not strictly additive quantities (Salisbury and Ross 1969). More detailed discussion of the characteristics of the individual components of the water potential are beyond the scope of this paper, but they are presented elsewhere (Boyer 1967, Wiebe 1966, Wilson 1967, and Slatyer 1967).

When water potential gradients are established, there will be a tendency for water to diffuse from the region of higher free energy to a region of lower free energy. Thus, equilibrium will be favored even though true equilibrium may never be reached under natural conditions. The thermodynamic principles that explain the theory of water potential serve to adequately predict the direction, but not the rate, of either diffusion or energy transfer. Transfer rates are strongly dependent upon the nature and sources of resistances imposed on the diffusion pathway, but a thorough treatment of these principles is beyond the scope of this paper. The interested reader is referred to Slatyer (1967), Taylor and Cary (1965), Biggar and Taylor (1960), Letey (1968), and Briggs (1967).

METHODS OF MEASURING WATER POTENTIAL

Nonpsychrometric Methods

Several techniques are available for determining the water potential in the soil-plant system, but some of them have a rather limited application; others are undesirable in view of recent advances in water relations technology. Techniques for measuring soil water potential that are still in wide use but of limited applicability include: tensiometers capable of measuring matric potential only between 0 and -1 bar; freezing point depression; electrical resistance units with a sensitive range for matric potential of -0.5 to -15 bars; and the pressure membrane or plate technique for inferring matric potential from water content. Of course, these techniques can be valuable depending upon the specific parameter of soil water being investigated, but inference of soil water potential from them can lead to considerable error. Of particular danger is the inference of water potential from soil water content. The relationships between free energy and water content are different for each kind of soil (and perhaps between samples of the same kind of soil), changes in temperature, and because of hysteresis. These techniques and their probable errors are discussed in detail by Taylor and others (1961) and Slatyer (1967).

Many techniques are based on direct measurements of plant water content still in wide use for evaluating the water status in plant tissue. Although Barrs (1968) believes there is some doubt concerning whether water content or water potential is the more important parameter affecting plant growth, there is little argument that water absorption, water transfer from cell to cell, and transpiration losses result from water potential gradients. This question is considered, together with a thorough analysis of methods of determination of water deficits in plant tissues, by Barrs (1968).

The Thermocouple Psychrometer Method

Spanner (Peltier) and Richards and Ogata (Wet-loop) Psychrometers: In recent years considerable research has produced instrumentation capable of sensing the vapor pressure of water in a system. Equations (1) and (2) show that vapor pressure is a sensitive indicator of the water potential; most of the other component potentials also could be measured from vapor pressure. However, since the relative vapor pressure of soil water and plant tissue within the range of usual physiological interest (0 to -75 bars) lies very close to the saturated vapor pressure (95 to 100 percent), the method must be capable of detecting very small changes in vapor pressure. Spanner (1951) first demonstrated that sufficiently sensitive measurements of the relative vapor pressure of water in this very narrow range of interest can be made with small sensitive thermocouples. This led to a great deal of research on the development and use of thermocouple psychrometers for measurements of water potential. This method offers great sensitivity and accuracy and can be used either in the laboratory with very small samples or in the field over extended periods.

The Spanner psychrometer consists of a small thermocouple sealed either in a small chamber or other housing (figure 1). The thermocouple is usually constructed of 0.001-inch diameter chromel-constantan (although Spanner originally used bismuth-bismuth-5 percent tin) wires with a small welded bead at the junction; these thermocouple wires are attached to copper lead wires connected to a galvanometer, recorder, or a microvoltmeter. In laboratory models the thermocouple is suspended directly over a soil or leaf sample all of which are inside a sealed chamber, and the chamber is then immersed in a water bath to maintain a constant temperature. Under these isothermal conditions, the vapor pressure of the atmosphere above the sample and around the thermocouple will come into equilibrium with the water potential of the sample, usually within a few hours. After vapor and temperature equilibria are achieved, the water potential of the sample can be determined. A small amount of water is condensed on the thermocouple junction

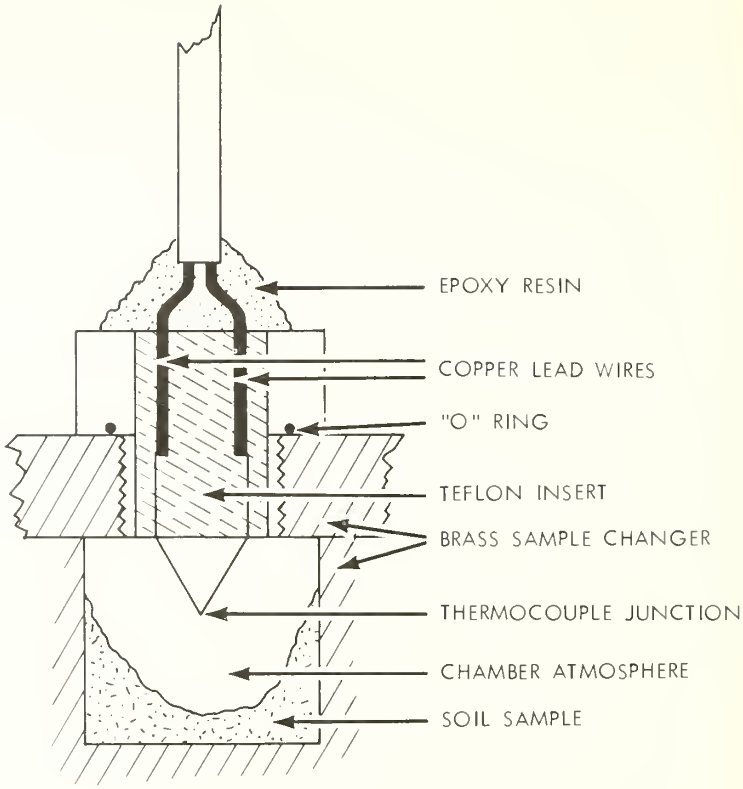


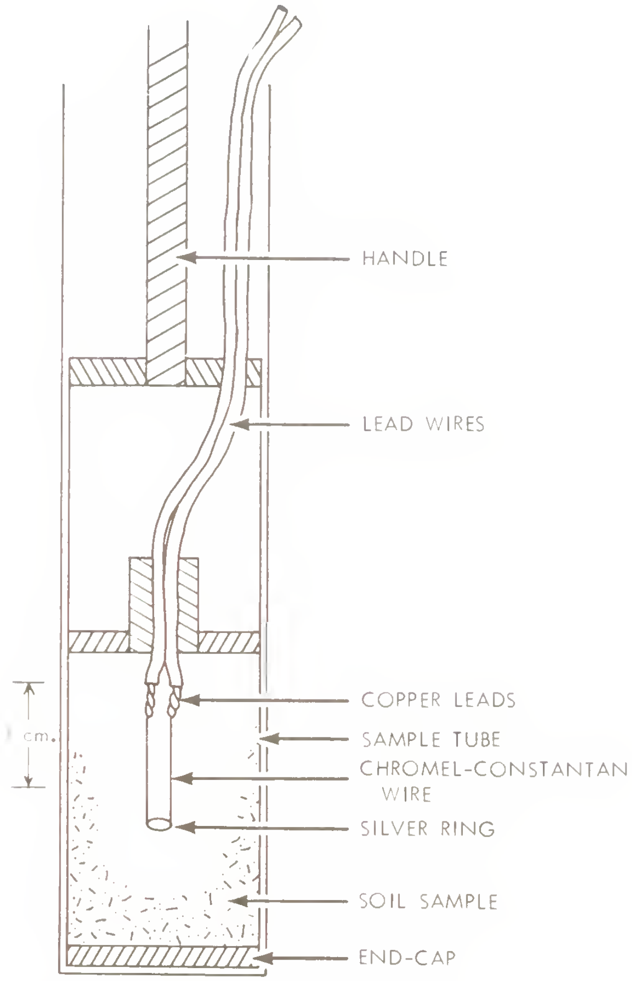
Figure 1.-The Spanner (Peltier) thermocouple psychrometer and a psychrometer chamber are shown with the soil sample. The entire assembly is sealed and immersed in a water bath to maintain constant temperature.

by passing a small electric current through the junction for a short time in a direction which causes it to cool below the dew point of the atmosphere (Peltier effect). After this cooling, the current is immediately stopped, allowing the condensation to evaporate back to the atmosphere in the chamber. The rate of evaporation is a function of the vapor pressure in the chamber, hence of the water potential of the sample. The evaporation cools the junction as a function of the vapor pressure, and the difference in temperature between the sensing junction and the reference junctions causes a minute voltage output from the thermocouple. The magnitude of this voltage output is also a function of the sample water potential, and is recorded with a microvoltmeter.

Richards and Ogata (1958) suggested a modification of the Spanner psychrometer, consisting of a small silver ring attached to the ends of the chromel-constantan thermocouple wires (figure 2). A small water drop (3-5 μ liter) is placed on the ring, and then is sealed in the chamber containing the sample. Readings are made when the rate of evaporation from the water droplet reaches a steady value, and hence when the temperature depression of the thermocouple is constant. The primary difference between the Spanner and the Richards and Ogata types of psychrometers is that the Spanner thermocouple permits measurements of both dry and wet-bulb temperatures, whereas with the Richards and Ogata psychrometer the dry bulb temperature can only be inferred from bath temperature.

Considerable attention has been given in recent years to the relative performance of these two psychrometers for measuring water potentials of soil and plant tissue. Rawlins (1966) rigorously reviewed the performances of these two psychrometers and suggested sources of possible errors and design criteria for reducing the magnitude of inaccuracies of water potential determinations. Barrs (1965) found that because of the permanently wet junction in the Richards and Ogata psychrometer, the observed temperature depression was between the reference junction temperature and wet bulb temperature, and this led to low estimates of water potential. Zollinger and others (1966)

Figure 2.–The Richards and Ogata thermocouple psychrometer showing the silver ring used to support the water droplet.



also found greater errors in estimates of water potential with the Richards and Ogata (wet-loop) psychrometer. Either psychrometer will cause the true water potential to be somewhat disturbed, but the wet-loop psychrometer adds vapor to the system resulting in high estimates of water potential. The small amount of vapor withdrawn from the atmosphere with the Spanner thermocouple will have a negligible influence in most cases (Zollinger and others 1966).

A number of modifications and advances in techniques have been suggested for both types of psychrometers; but even with these advances, the Spanner psychrometer has come into more general use. The theory of the Spanner psychrometer and design criteria for its construction, together with sources of error in its use, have been thoroughly investigated (Rawlins 1966; Peck 1968, 1969; Dalton and Rawlins 1968; and Barrs 1968). Special techniques and precautions to follow during construction are discussed by Merrill and others (1968), Campbell and others (1968), and Wiebe (1970). Some of these points are discussed below.

One of the most useful adaptations for laboratory analysis of leaf and soil water potentials is the rapid sample changer suggested for use with Peltier psychrometers by Campbell and others (1966). I have used a modification of this sample changer for several years, and have obtained very satisfactory determinations of water potential. The sample changer consists of six chambers lined with small (0.75 $cm.^3$) Teflon cups in which the leaf or soil samples are placed. The same Peltier thermocouple is used to measure all six samples by rotating the sample changer after each measurement. This technique has the advantage of being simple to use, easy to calibrate, and the same thermocouple is used to make all measurements. Also, one or more of the six sample chambers may be used as calibration chambers by saturating a filter paper lining inside the Teflon cup with standard KCℓ solutions.

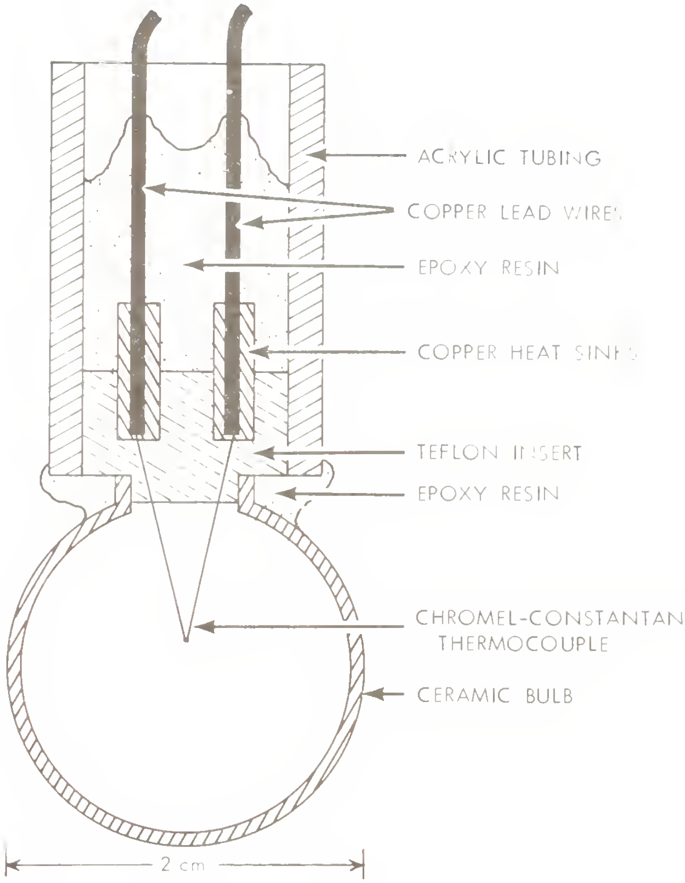
Measurements of water potential in situ: The adaptability of psychrometers for use under field conditions is the most important and significant improvement resulting from research in psychrometric technology. These recent contributions have opened a whole new frontier in soil-plant water relations and for the first time enable the researcher to gain a quantitative and true measure of the water status in natural systems. Because thermocouple psychrometers have such a high degree of sensitivity to temperature fluctuations, their use in natural systems, which are subject to large ambient temperature changes, has evolved only recently. Rawlins and Dalton (1967) explained that there are at least four ways in which changes in ambient temperature can cause changes in thermocouple output. First, the relationship between water potential and vapor pressure is temperature dependent, as shown in equation (2). Second, the relationship between wet-bulb depression and internal vapor pressure in the chamber is temperature dependent. Changes in psychrometer sensitivity due to temperature shifts can be explained by the temperature dependence of thermal conductivity of the chamber air; water vapor diffusivity of the chamber air; and the heat of vaporization of water. Third, changes in ambient temperature produce slight temperature gradients between the sensing junction and reference junctions in the thermocouple (figure 1). Fourth, an increasing temperature will result in an increased water-vapor-holding capacity within the sample chamber, and the relative humidity of the air will decrease until vapor equilibrium is again achieved. If the sample chamber was sealed, the resulting error would be about 1 bar per 0.01°C. at 25°C.; but if the chamber was open or porous to free vapor exchange, the error would be considerably less.

In an attempt to meet the requirements of ambient temperature fluctuations and the resistance to vapor flow, Rawlins and Dalton (1967) constructed a psychrometer designed for use directly in the soil mass (figure 3). Surrounding the thermocouple was a ceramic bulb through which vapor exchange must occur between the soil and the internal atmosphere. They concluded that this instrument estimates the soil water potential within a few tenths of a bar. Rawlins and others (1968) used this same psychrometer for *in situ* measurements of soil water potential in a greenhouse study on water relations of a pepper plant.

In a somewhat unique approach to soil-plant water relations, Wiebe and others (1970) used a variation of the Rawlins and Dalton pyschrometer (figure 4) consisting of a small ceramic cup surrounding the thermocouple; this system measured the water potential gradients in trees from the soil, up through the trunk, and through the branches. These instruments were buried in the soil at various depths, and were installed about 1 cm. under the cambium in the tree trunk. Diurnal fluctuations in the water potential gradient were recorded for periods of up to 6 weeks. The psychrometers had to be moved periodically in some species because of wood decay and resin exudation into the cavity.

Hoffman and Splinter (1968a, 1968b) used a psychrometer design similar to that of the Rawlins and Dalton model but without the ceramic cup. The thermocouple was centered in a small Teflon cup open at the bottom end, and was then buried in the soil or mounted on a tobacco leaf surface with an adhesive. This design provides a psychrometer which has a geometry that is identical for both calibration and measurement of soil and leaf water potential. However, there is the danger of the exposed thermocouple becoming damaged or bent after placing the psychrometer in the soil. Lang (1968) used a Spanner

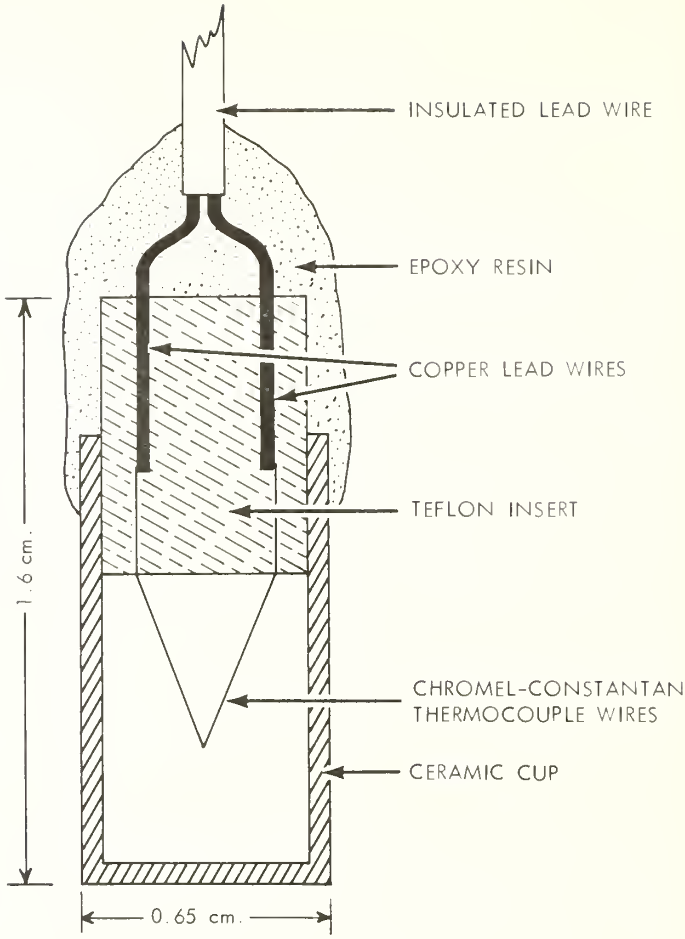
[illegible]



psychrometer encased in a wire gauze cage of 100-mesh stainless steel for measurements of soil water potential. The wire cage provides a protective covering for the thermocouple, and thus would be superior to the model used by Hoffman and Splinter (1968a). However, Lang's psychrometer was especially constructed to be inserted into the wire cage sometime after the cage was buried in the soil. This approach may lead to drying of the soil immediately adjacent to the wire cage, and it may also offer a considerabl degree of difficulty in properly inserting the exposed psychrometer into an access ho in the soil.

The most important recent development for *in situ* measurements of leaf water potential is the double junction thermocouple psychrometer (Wiebe 1970). This instrument consists of two chromel-constantan thermocouple junctions and three reference junctions attached within a Teflon insert. Three copper leads are joined within the Teflon insert by the two thermocouple junctions; the chromel wires of both junctions are attached to two of the copper leads, and the constantan wires of both junctions are attached to the third copper lead. The two sensing junctions produce opposing e.m.f.'s so that the cooling current is passed through one junction and the output is read from the other. The output is then proportional to the temperature difference between both sensing junctions, and since both are in the same thermal environment, one junction compensates for rapid temperature changes which may easily occur on an attached leaf surface. This entire assembly can be placed in a Teflon cup open at the bottom end, and mounted on a leaf surface similar to the method of Hoffman and Splinte (1968a, and 1968b).

Figure 4.--Cross section of the ceramic cup thermocouple psychrometer used by Wiebe and others (1970).



IMPROVED DESIGN CRITERIA FOR THERMOCOUPLE PSYCHROMETERS

Considerations of Instrument Design

The thermocouple psychrometers described by Rawlins and Dalton (1967) and Wiebe and others (1970) would appear to offer excellent opportunities for the measurement of soil and plant (tree trunks) water potentials under natural conditions. However, the question of resistance offered by the ceramic cup to the transfer of water, particularly water vapor, has not been adequately investigated. Rawlins and Dalton (1967) concluded that in order to maintain a water potential difference of less than 0.1 bar between the chamber and the soil, the conductivity of the ceramic wall must be at least 4 μg. $cm.^{-2}$ bar hour for each degree per hour change in temperature. They indicated that the saturated conductivity of porous ceramic is about six orders of magnitude greater than this, and that resistance to water transfer was not limiting. However, they did not discuss the implications resulting when liquid contact between the soil particles and the ceramic cup is broken, wherein water transfer between the chamber and the soil will occur only through vapor exchange. If a resistance to vapor exchange between the ceramic chamber and the surrounding medium results, significant errors in estimates of water potential will result.

The primary function of the ceramic bulb or the ceramic cup is to maintain a fixed dimension in the soil, and to offer protection for the thermocouple. If these same

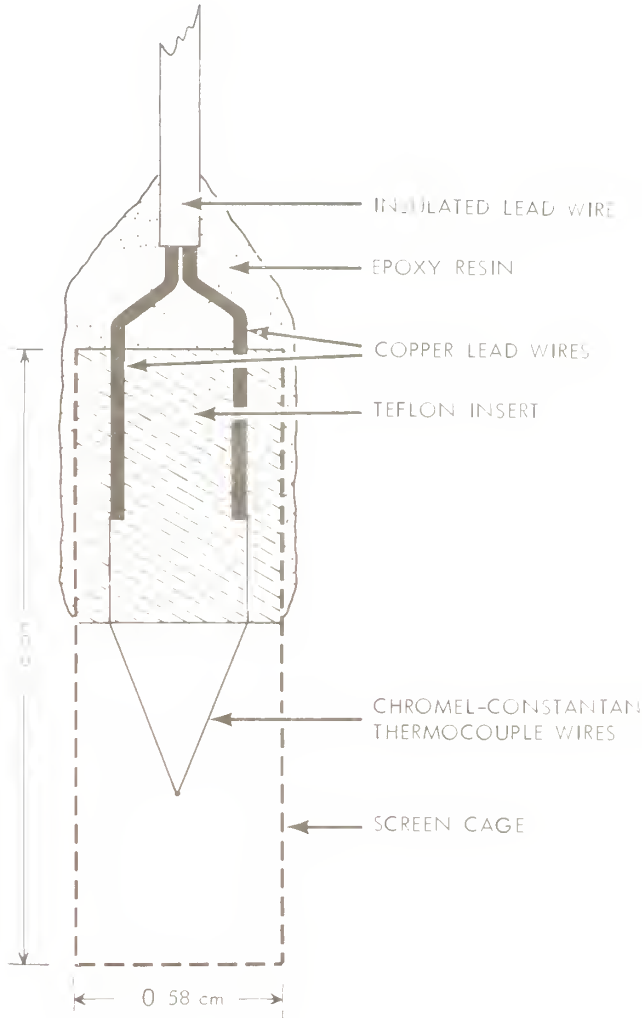


Figure 5.--The screen thermocouple psychrometer.

criteria could be accomplished without imposing a resistance to vapor exchange, at least the accuracy of the instrument would be improved; this improvement would result from reduction of a lag in response to a change in water potential where water transfer is in the vapor phase. Even though a rigid ceramic cup imposes a substantial lag to vapor exchange, a fine mesh noncorrosive screen cup appears to meet the essential criteria quite well, and permits heat and vapor exchange with negligible resistance. These features were incorporated into a psychrometer built by the author, quite independent of Lang's (1968) instrument, and considerably simpler in design and of greater versatility. This psychrometer somewhat resembles the instrument used by Wiebe and others (1970), except that the ceramic cup was replaced with a screen cup. A large number of these psychrometers that were used over the last 2 years in the laboratory at Logan for measurements of soil water potential have proven this design to be stable and reliable.

Construction and Equipment

The essential parts of the pyschrometer (figure 5) consist of a screen cup constructed of fine-mesh stainless-steel wire and attached to a Teflon insert. Within this insert the copper lead wires are attached to the thermocouple. After cutting the Teflon insert (see Appendix 4 for sources of supply) to the proper length (0.475 cm. diameter rod cut to 0.635 cm.), make two holes approximately 0.025 cm. in diameter through the long axis of the Teflon with a fine dissecting needle. Then insert the chromel and constantan thermocouple wires (0.0025 cm. diameter) through the holes from the bottom side of the Teflon insert, from which about a 4-cm. length of each wire is allowed to protrude. About 0.5 cm. of the ends of the copper lead wires (Beldon #8640, 26 gage) are scraped clean of all insulation and inserted into the holes from the top side of the Teflon insert. The positive copper lead is tightly wedged into the hole with the chromel wire and the negative lead with the constantan wire. This provides a tight contact between the copper and thermocouple wires. An alternative method of attaching the thermocouple wires to the copper lead wires is to solder the chromel wire to the positive copper lead and the constantan to the negative copper lead. A high grade of silver solder should be used.

The chromel and constantan wires protruding from the bottom of the Teflon insert are twisted together with an "L"-shaped piece of wire (26 gauge, 3 cm. long with an "L" bend of about 3 mm.). The "L"-shaped tool is held between the thumb and forefinger, and is twirled slowly around the two thermocouple wires, twisting the two wires tightly together. The wires are twisted together until their junction is about 3 mm. away from the Teflon, then the "L"-shaped tool is inserted between the chromel and constantan wires and the junction pulled out to exactly 4 mm. from the Teflon insert. This tightens the junction and provides a uniform length to the thermocouple assembly. The excess twisted wire can be cut away with a scissors, leaving about 3 mm. of twisted wire below the junction. The thermocouple is now ready to be welded or soldered; however, welding is preferred because soldered thermocouples tend to age rather quickly and do not have a linear response throughout the range of vapor pressures of interest (Campbell and others 1968).

Welding can be accomplished as suggested by Campbell and others (1968). Also, a somewhat simplified technique may be used wherein the negative lead from the arc-welder is attached to the ends of both copper leads from the thermocouple. (A diagram of the electrical circuit used in my arc-welder is given in Appendix 5.) The positive lead from the arc-welder is attached to a sharpened graphite rod (4H graphite lead), which is used to provide the arc for welding. Welding is accomplished by touching the graphite rod to the end of the twisted thermocouple wires. The twisted thermocouple wires should be welded slowly (by adjusting the voltage output from the welder) at first, building up a bead of fused metal. Welding should continue until about one twist remains beyond the beaded junction. The bead should be about three times the diameter of the thermocouple wires, although the most successful psychrometers will have as large a bead as possible. The largest junction diameter possible with this technique appears to be about five times the wire diameter (Campbell and others 1968). The best results will be achieved if the entire thermocouple assembly process is accomplished with the aid of a binocular scope with a 7X to 10X magnification.

A legitimate argument can be raised concerning the advisability of welding thermocouples in normal air rather than in nitrogen gas or oil. In the presence of relatively high oxygen partial pressures, the welding process leaves a deposit of oxidized material on the thermocouple junction. This deposit may influence thermocouple output and psychrometer calibration. A number of workers have used some rather elaborate devices to hold the thermocouples in place during construction and welding. In general, a jig is used to hold the thermocouple securely, which is then placed in a sealed enclosure and flushed with nitrogen gas (Lopushinsky and Klock 1970). A somewhat simplified yet equally effective method is to perform the welding operation in a small pool of lightweight optically clear oil such as 10-weight motor oil or even commercial salad oil.[1] The thermocouple assembly is completely immersed in a petri dish of oil, and the junction is welded by touching the graphite rod to the junction until the bead is formed. In this manner a greater degree of control can be exercised over the rate of welding, and incidences of overheating and breaking the junction are much less frequent than when welding is done in a gas. The thermocouple should be dipped into acetone and slightly agitated to remove all traces of oil.

---

[1] Eric Campbell, personal communication, 1969.

The screen cup is made from 200-mesh stainless steel screen with an opening width of 0.0074 cm. (74 microns). Each screen cup is made by cutting pieces of screen 1.8 cm.² and then rolling the screen over a short piece of 0.475 cm. diameter Teflon rod. The screen overlaps slightly and is then soldered with a high grade silver solder along the seam. The outside diameter of the screen cup is 0.551 cm., and the inside diameter is 0.475 cm., which facilitates a snug fit over the Teflon insert. A circular disk of 0.475 cm. diameter screen is silver-soldered on one end of the screen to close the tube. After soldering, the screen is boiled in distilled water, followed by a rinse in acetone, and rinsed again in distilled water to remove all traces of solder flux. The screen is then slipped all the way up on the Teflon insert and permanently fixed in place with epoxy resin. The inside volume within which the thermocouple is housed is 0.188 cm.³.

Calibration and Measurement Procedures

Calibration of these instruments is achieved by mounting the complete psychrometer in a small test tube lined with filter paper moistened with various KCl solutions (see Appendix 3 for water potentials of various molal solutions). The filter paper lining should include a disk at the bottom of the test tube (1.1 cm. by 9.9 cm. inside dimensions) together with a strip of filter paper around the inside circumference of the tube; the filter paper should extend up the side walls about 1 inch from the bottom (Whatman #1 chromatography paper). About 6 to 8 drops of solution are sufficient to fully moisten the filter paper. The psychrometer is lowered into the test tube until the screen cup containing the thermocouple is below the filter paper lining, and is then sealed with a rubber stopper through which the copper lead wires extend. The stopper and lead wires can be coated with vacuum grease or RTV to insure a tight seal.

The test tubes containing the psychrometers are then completely immersed into a constant temperature bath at 25°C. Usually temperature and vapor equilibrium can be achieved within 30 minutes (figure 6), but at least 2 hours should be allowed to eliminate all temperature gradients. Because the thermocouple psychrometers are very temperature sensitive, calibration is repeated at several temperatures between 10°C. and 35°C. However, it has been found (Wiebe and others 1970) that chromel-constantan psychrometers follow a rather simple relation between e.m.f. output vs. temperature. This relation is expressed by:

$$CF = \frac{1}{0.027T + 0.325} \tag{5}$$

where CF is a correction factor to be multiplied by the output in μv at the known psychrometer temperature, T(°C.). Equation (5) permits calibrations to be made at 25°C. from which water potentials at any other temperature can be determined. In some cases, however, individual thermocouple differences may cause the temperature response to deviate slightly from the theoretical value expressed by equation (5) (Wiebe 1970). Therefore, it is recommended that thermocouple psychrometers be calibrated at several temperatures as described above.

To obtain actual psychrometer readings, two basic instruments are used: (1) a sensitive microvoltmeter; and (2) a special circuit used for cooling the thermocouple wet junction. The most commonly used voltmeters include a Hewlett-Packard Model 419A, or the Keithley Model 155 (figure 7), both of which are portable and permit measurements to the nearest 0.1 μv. In addition to these, even more sensitive recording instruments are often used, such as strip-chart recorders with an amplifier and more sensitive microvoltmeters (Appendix 4). A diagram of the cooling circuit ("switchbox") is shown in Appendix 6, together with a list of the component parts. The switchbox (figure 7) is mounted in an insulated aluminum box to prevent rapid temperature fluctuations. The switchbox permits a direct connection of the thermocouple to either the voltmeter or the cooling circuit.

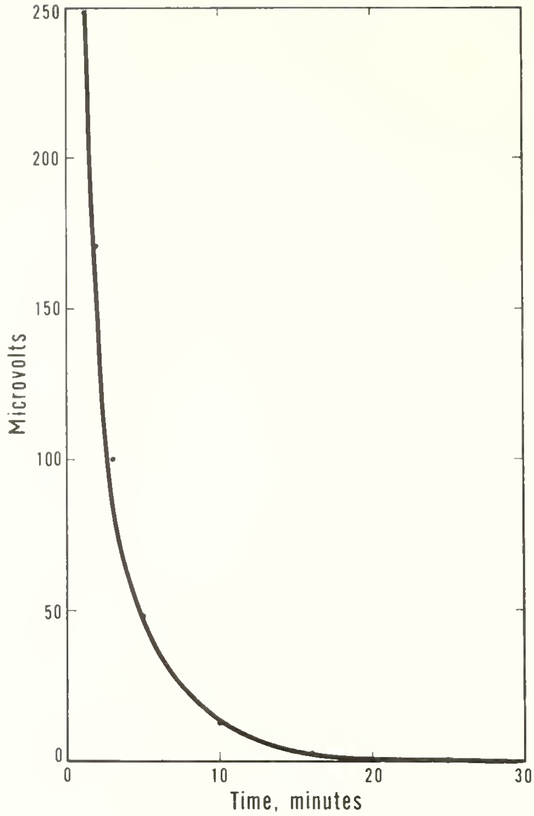
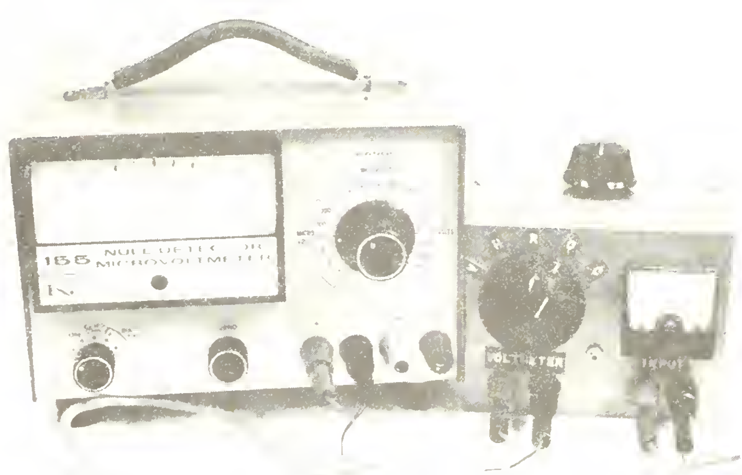


Figure 6.--The influence of temperature gradients between the thermocouple reference junctions and sensing junction. At temperature equilibrium thermocouple output is zero.

Since at temperature equilibrium (no temperature gradients between the sample and the psychrometer) the two reference junctions of the psychrometer are at the same temperature as the sensing junction, the e.m.f. output of the thermocouple is zero. When the thermocouple output is switched via the switchbox directly through the voltmeter ("read" position), the voltmeter is adjusted to "zero" or some other convenient position with the "zero-adjust" knob on the switchbox. Then the thermocouple is immediately switched to the cooling position for 15 seconds, which cools the sensing junction with a 5 ma. current. After 15 seconds, the thermocouple is immediately switched back to the "read" position, and the e.m.f. deflection is read on the voltmeter. The difference stated in μv between the e.m.f. prior to cooling and immediately after cooling (maximum deflection) is the output for that particular water potential. This subtraction of the e.m.f. before cooling from the e.m.f. after cooling corrects for temperature differences between the sensing junction and reference junction, and also cancels any parasitic e.m.f.'s resulting from temperature differences between the various junctions in the thermocouple circuit. Furthermore, this subtraction reduces the need for thermal grounding normally required at junctions and terminals in the circuit during low voltage measurements (Rawlins and Dalton 1967).

The circuit diagram for the switchbox in Appendix 6 provides for the functions of "read," "zero," "cool," "heat," and "voltage check." The "heat" position is the reverse of the "cool" position and provides a slight heating current which can be used to quickly dry residual water from the thermocouple junction if needed. The "voltage check" position measures the internal voltage of the switchbox, and is used only with a recorder and amplifier in the system. The circuit shown in Appendix 6 has an internal voltage output of about 10 μv which can be used to calibrate the scale on a linear recorder. All solder junctions in the switchbox should be made with thermal-free solder, and binding posts should be gold-plated to reduce parasitic e.m.f.'s at the terminal connections.

Figure 7.—A commonly used microvoltmeter (Keithley model 155) and a switch-box used for measuring psychrometer output.



The μv output of the thermocouple for each KCl standard solution can be plotted as a function of water potential to give a calibration curve for each psychrometer (figure 8). It can be seen from the curve in figure 8 that thermocouple output varies about 0.5 μv bar^{-1} on the lower portion of the curve (below -10 bars) but decreases at lower water potentials. If the cooling time were extended beyond 15 seconds (to about 30 seconds), the linearity of the curve would be extended to lower water potentials (more negative), and the usable range of the psychrometer would be expanded to near -100 bars. However, even when using a 60-second cooling time there appears to be a lower limit between -75 and -100 bars for these psychrometers. This lower limit for chromel-constantan thermocouples results because the Peltier effect is a somewhat inefficient cooling method, allowing a temperature depression of only about 0.6°C. (Rawlins[2]).

Recalibration of the psychrometer should be performed after each extended period of use. Calibration points have been observed to change by 1 μv over a period of 3 months, indicating that errors as great as 3 bars can result. The thermocouple junction will age somewhat due to corrosion, and adherence of foreign matter to the junction will also contribute to a change in the calibration. I have used several exceptionally well made psychrometers here at Logan that showed no sign of calibration drift even after 3 months of use. However, after each use of the psychrometer it is strongly recommended that a fairly vigorous cleaning routine be followed. For instance, I use the following procedure for routine cleaning:

1. Thoroughly wash the psychrometer in tap water to remove soil or other particles from the screen cup.

2. Then rinse in distilled water.

3. Boil for 10 minutes in distilled water.

4. Rinse in acetone.

5. Rinse in warm distilled water, let dry.

---

[2]S.L. Rawlins, personal communication, 1970.

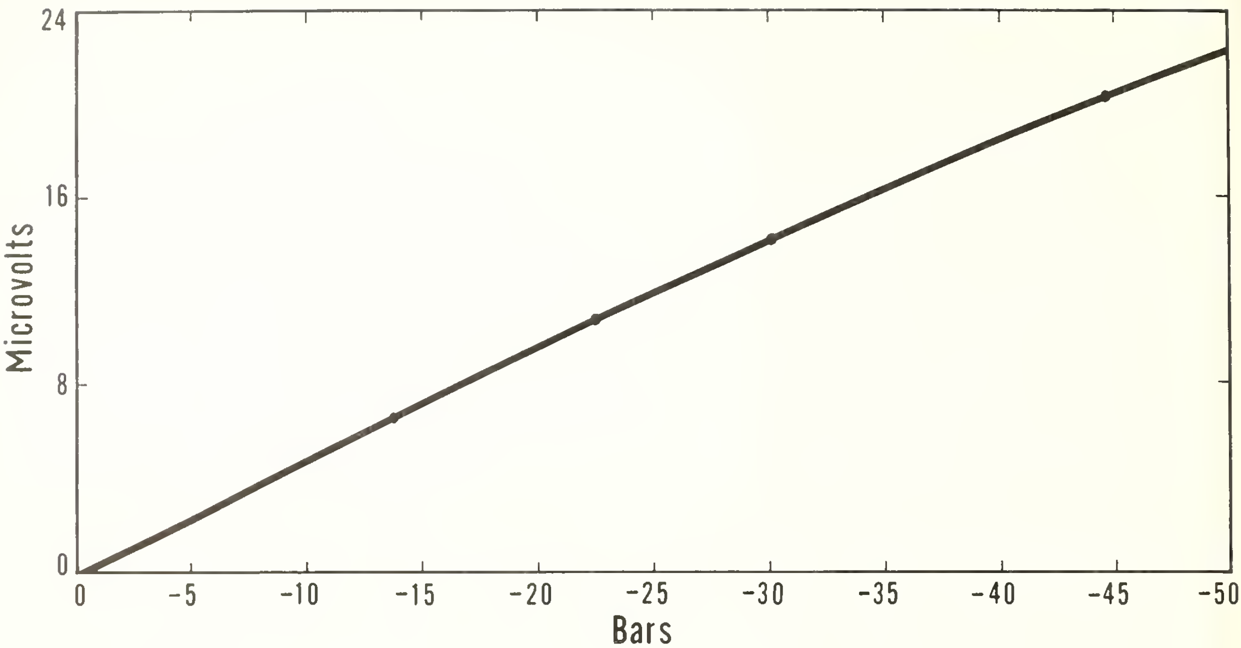


Figure 8.--Calibration curve for a chromel-constantan thermocouple psychrometer (output in μv vs. osmotic potential of KCℓ solutions in bars) at 25°C.

Psychrometer Response to Changing Water Potentials

If the screen psychrometer is to give accurate estimates of water potential, it should offer a negligible resistance to vapor and heat flux. To determine the magnitude of psychrometer lag in response to actual water potential, laboratory experiments were conducted in which the response of the screen psychrometers, ceramic cup psychrometers, and bare unshielded psychrometers were compared. The ceramic cup psychrometers used were of the same design as shown in figure 4 (Wiebe and others 1970), and the unshielded psychrometers were constructed as described above, except that the screen cup was not used. The exposed thermocouple was assumed to offer no resistance to vapor transfer, hence to yield accurate estimates of water potential.

In an attempt to determine the relative magnitude of the resistance imposed by various psychrometers to the transfer of water vapor, psychrometer response to various equilibrium vapor pressures was measured under isothermal conditions. The bare unshielded, screen, and ceramic cup psychrometers were sealed in test tubes containing standard KCℓ solutions of known vapor pressures at 25°C. Summarized in figure 9 are the relative magnitudes of psychrometer response with time, and the length of time required for vapor equilibrium in a 0.3 molal (m) KCℓ solution. Time in minutes began when the psychrometers were placed in the water bath; temperature equilibrium as measured by thermocouple output was achieved within 20 minutes for all the psychrometers. However, vapor pressure equilibrium required a longer period of time for both the screen and ceramic cup psychrometers. The unshielded psychrometers reached vapor equilibrium at about the same time that temperature equilibrium was reached (20 minutes). The screen psychrometers reached vapor equilibrium some 13 minutes later, but the ceramic cup psychrometers did not reach equilibrium until about 2-1/2 hours later.

From the data in figure 9 it is quite apparent that the ceramic cup psychrometers offer a far greater resistance and lag to vapor exchange than do the screen psychrometers. It is interesting to observe that the screen does offer a relatively small

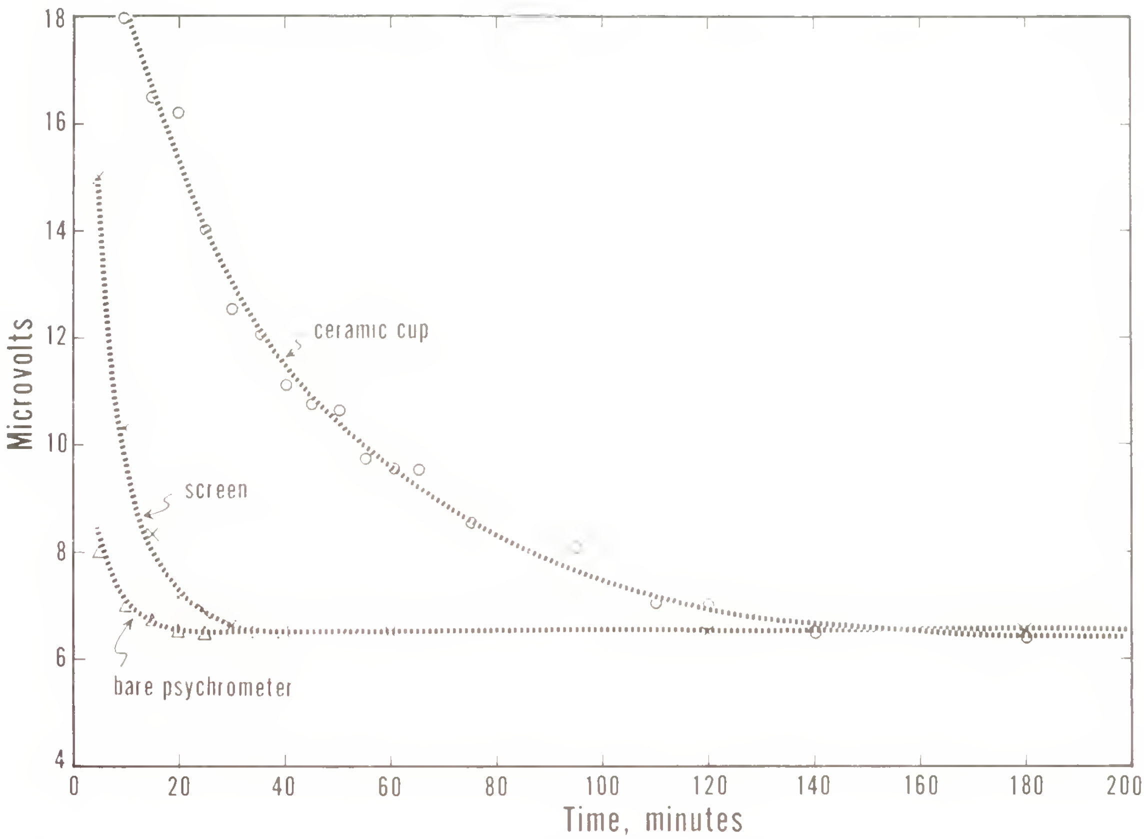


Figure 9.--Lag in [illegible]

resistance to vapor transfer, but this appears to be negligible and may even be reduced by use of a larger mesh screen. In standard KCl solutions, vapor equilibrium for the three psychrometers was achieved somewhat sooner in solutions having a lower water potential because of the slightly reduced water potential gradient between the solutions and the psychrometers. However, the relative magnitudes of lag, as shown in figure 9 for 0.5 m KCl, remained about the same between the screen and ceramic cup psychrometers for different water potential gradients.

A more meaningful comparison of the relative responses of the screen and ceramic cup psychrometers to changing water potential was conducted in soil under severe evaporation conditions. Screen and ceramic psychrometers were taped together so that the sensors remained exposed, yet were adjacent to each other. These were buried in the soil of pots containing month-old corn plants that were rapidly transpiring. A copper-constantan thermocouple was buried with each pair of sensors to measure soil temperature. The pots were placed in an environmental growth chamber with a programed environment for air temperature at 25°C., 0.5 cal. cm.$^{-2}$ min.$^{-1}$ radiation (0.3 to 3.0 μ), windspeed at 45 cm. sec.$^{-1}$, and a vapor pressure deficit of 19 mm. Hg. The soil was brought to saturation (ψ = 0 bars) initially, and then allowed to dry until severe wilting occurred 3 days later. During this period the psychrometers were read every few hours; the assumption was made that the soil water potential adjacent to the pair of psychrometers (a screen and a ceramic unit taped together) would be the same for both psychrometers. Outputs were converted to 25°C. using equation (5) above.

The water potential data were plotted in figure 10, and a regression analysis yielded an equation for a simple linear relationship between the two kinds of sensors. This relationship between sensors shows a definite lag in the response of the ceramic psychrometers as compared to the response of the screen psychrometers. At relatively high water potentials (above -2 bars) the ceramic psychrometers indicated a water potential of 0 bars, but the screen psychrometers were indicating values somewhat lower. As the water potential continued to decrease, the difference in the water potential values indicated by the two types of psychrometers increased. Within the growing range for most plants (-0.5 to -3.0 bars), the ceramic psychrometers showed a lag of from 1 to 2 bars behind the screen psychrometers. The magnitude of this lag increased until at -30 bars the difference in the indicated soil water potential was about 8 bars.

These water potential data clearly show that once liquid contact is lost between the soil and the psychrometer, the ceramic cup offers a significant resistance to vapor exchange. Also, the magnitude of the resistance apparently increases as the ceramic cup dries. The rate of soil drying in this experiment was somewhat greater than might be expected under natural conditions, with the soil water potential decreasing from 0 to less than -30 bars over a 3-day period. It may be reasonable to assume that if the rate of drying was slower, the ceramic psychrometers would then be capable of maintaining a closer equilibrium with the true energy status of water in the soil. However, it should be noted that if the sensor offers a resistance to vapor exchange under rapidly changing water potential conditions, its use under natural conditions would be subject to error and question. The magnitude of this error would be a function of the resistance to vapor exchange imposed by the ceramic cup and the rate at which the soil water potential was changing. Therefore, from the standpoint of psychrometer response to a changing water potential, and the ease of construction, the screen psychrometer would seem to offer several obvious advantages over the ceramic cup psychrometer.

DISCUSSION

Evaluation of Thermocouple Psychrometers

Under conditions where the free energy status of water is changing rapidly, it is apparent that ceramic cup psychrometers lead to spurious estimates of water potential. This clearly points out the need to evaluate the response characteristics of instruments under the environmental conditions for which they are to be used. For instance, although the rate of soil drying under natural conditions may usually be somewhat less than reported for the data in figure 10, there are conditions where the soil water potential can be expected to decrease more rapidly. A decrease in soil water potential of over 30 bars in a few days is not unusual in the soil surface of high-elevation harsh sites where high radiation loads, steep vapor-pressure gradients, and high windspeeds are common. If ceramic cup psychrometers are used under natural conditions where a high rate of decreasing water potential can reasonably be expected, then erroneous data should be suspected, especially where water transfer occurs only in the vapor phase. Although the response-capability limits of screen psychrometers have not been determined, these instruments are free of the sources of error that affect the ceramic cup psychrometers.

The foregoing discussion suggests that there are several significant points to be considered in the evaluation of a thermocouple psychrometer which include: (1) the capability of distinguishing small differences in vapor pressure; (2) a linear response to water potential over the range of interest; (3) ease of construction and calibration; (4) a stable calibration with relatively long periods of use; and (5) the ability to respond to rapidly changing water potential conditions. The screen cup thermocouple psychrometer discussed above appears to meet all of these criteria.

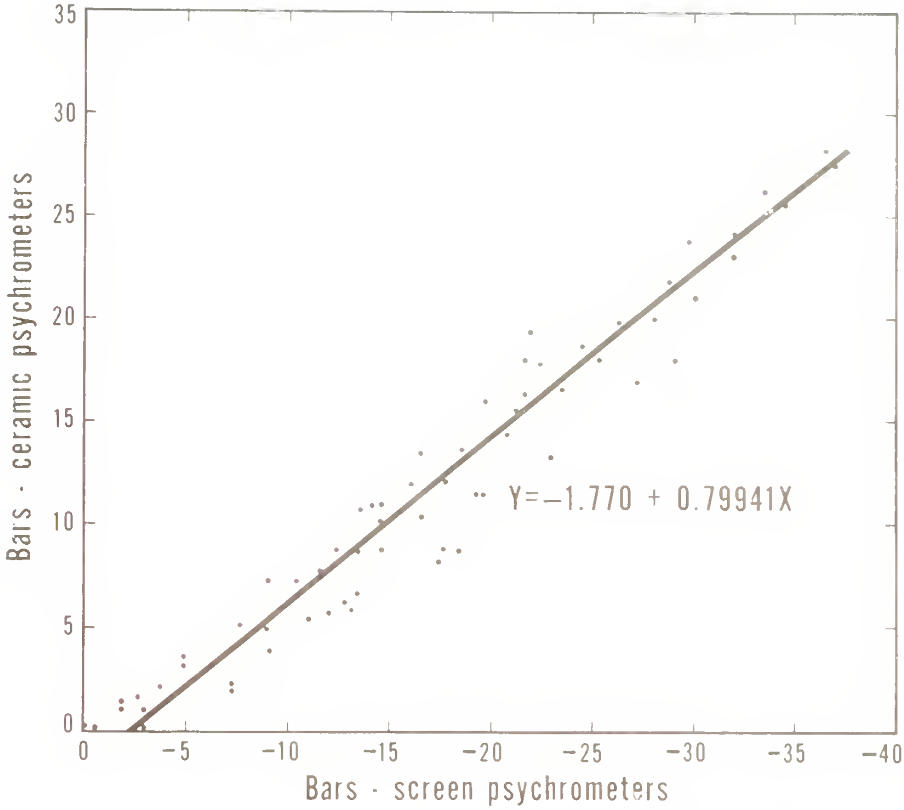


Figure 10.--Relationship of the response of the ceramic psychrometers to that of the screen psychrometers [illegible]

Potential Uses of Thermocouple Psychrometers

The screen cup psychrometer discussed here is particularly well suited for measurements of soil water potential. However, certain precautions must be observed because the copper lead wires are excellent heat conductors, and thermal gradients within the thermocouple may result if these are not damped out of the system. This damping can easily be accomplished by burying a short portion of the lead wire (several inches are usually enough) behind the thermocouple in the soil. For water potential measurements near the soil surface, the psychrometer should be buried in a position parallel to the surface so that a short length of the lead wire can also be buried for insulation against thermal gradients. Because the psychrometer output varies with temperature, a copper-constantan thermocouple (26 gage or smaller) should be attached to the psychrometer within the epoxy resin just above the screen cup so that psychrometer temperature at the time of reading can be determined.

The screen cup psychrometer is also well adapted for measuring the water potential gradients in stems of trees or large shrubs, using a technique similar to Wiebe and others (1970). Under this method, the sensing unit of the psychrometer is placed in carefully drilled holes to a depth of about 1 cm. or less inside the cambium layer. The hole is then sealed with a waterproof compound to prevent evaporation and entrance of disease. The psychrometer and a short segment of the lead wires should be insulated with polyurethane foam or other insulating material to damp out temperature gradients. The smallest diameter stems that have been studied with this size of a psychrometer is 2 cm., but with miniaturization of the psychrometer assembly it should be possible to work with much smaller stems.

The most important application of thermocouple psychrometry will come from its further development and subsequent application to measurements of the water status in the soil-plant continuum under natural conditions. Previous attempts to understand the dynamic relationships between the energy status of water in soils and plants have been severely limited because the natural equilibrium was disturbed by removing samples from the system. It would appear that for *in situ* determinations of soil water potential and plant water potential of stems, the instrumentation presently available will provide accurate estimates of the energy status of water. This is not to say, however, that further improvements in the design and operation of thermocouple psychrometers are not needed. Certainly, the work of Hoffman and Splinter (1968a, 1968b), Rawlins and others (1968), and other workers, and particularly the development of the double-junction psychrometer, indicate that the *in situ* measurement of leaf water potential is now a definite possibility. My own experience with the double-junction psychrometer for measuring *in situ* leaf water potentials was very encouraging.

There are many possible applications of thermocouple psychrometers to research problems in all areas of the environmental sciences; only a few applications are described here. In research on physiological responses of plants under natural conditions, thermocouple psychrometry provides the best method for determining the diurnal and seasonal magnitudes of water potential gradients from the soil, through the plant stem, to the leaves. Psychrometers thus permit integrated field determinations of the water potential gradient throughout the soil-plant continuum. This capability has application in many areas of research, including: theoretical physiology and soil physics; range and forest revegetation; watershed; range; forest management research; fire control research; and, research in plant pathology. Thermocouple psychrometers appear to be primarily useful as research tools; however, at least one application to land management problems comes to mind. This application is in the area of fire-danger rating; the application of thermocouple psychrometers appears to offer an excellent opportunity for evaluating the potential flammability of live standing vegetation, ranging from large tree stems to fine leaf material. This would require some preliminary research, but the potential application is clear. There are, without doubt, other applications to land management problems; hopefully, the possibility of such applications will stimulate the imagination of the reader.

LITERATURE CITED

Barrs, H.D.
1965. Comparison of water potentials in leaves as measured by two types of thermocouple psychrometer. Aust. J. Biol. Sci. 18: 36-52.

__________.
1968. Determination of water deficits in plant tissues. P. 235-368 in Water Deficits and Plant Growth, Vol. 1. T. T. Kozlowski (ed.) New York: Academic.

Biggar, J.W., and S.A. Taylor.
1960. Some aspects of the kinetics of moisture flow into unsaturated soils. Soil Sci. Soc. Amer. Proc. 24: 81-85.

Boyer, J.S.
1967. Matric potentials of leaves. Plant Physiol. 42: 213-217.

Briggs, G.E.
1967. Movement of Water in Plants. 142 p. Philadelphia: F.A. Davis Co.

Campbell, G.S., W.D. Zollinger, and S.A. Taylor.
1966. Sample changer for thermocouple psychrometers: construction and some applications. Agron. J. 58: 315-318.

__________, J.W. Trull, and W.H. Gardner.
1968. A welding technique for Peltier thermocouple psychrometers. Soil Sci. Soc. Amer. Proc. 32: 887-889.

Dalton, F.N., and S.L. Rawlins.
1968. Design criteria for Peltier-effect thermocouple psychrometers. Soil Sci. 105: 12-17.

Gardner, W.R.
1965. Dynamic aspects of soil-water availability to plants. Annu. Rev. Plant Physiol. 16: 323-342.

Hoffman, G.J., and W.E. Splinter.
1968a. Instrumentation for measuring water potential of an intact plant-soil system. Amer. Soc. Agr. Eng. Trans. 11: 38-42.

__________, and W.E. Splinter.
1968b. Water potential measurements of an intact plant-soil system. Agron. J. 60: 408-413.

Kramer, P.J., E.B. Knipling, and L.N. Miller.
1966. Terminology of cell-water relations. Science 153: 889-890.

Lang, A.R.G.
1968. Psychrometric measurement of soil water potential in situ under cotton plants. Soil Sci. 106: 460-464.

Letey, J.
1968. Movement of water through soil as influenced by osmotic pressure and temperature gradients. Hilgardia 39: 405-418.

Lopushinsky, W., and G. Klock.
1970. Construction details of ceramic bulb thermocouple psychrometers. Northwest Sci. Soc. Proc.

Merrill. S.D., F.N. Dalton, W.N. Herkelrath, G.J. Hoffman, R.D. Igvalson, J.D. Oster, and S.L. Rawlins.
1968. Details of construction of a multipurpose thermocouple psychrometer. U.S. Dep. Agr., U.S. Salinity Lab. Res. Rep. 115, 9 p.

Peck, A.J.
1968. Theory of the Spanner psychrometer. 1. The thermocouple. Agr. Meteorol. 5: 433-447.

__________.
1969. Theory of the Spanner psychrometer. 2. Sample effects and equilibrium. Agr. Meteorol. 6: 111-124.

Rawlins, S.L.
1966. Theory for thermocouple psychrometers used to measure water potential in soil and plant samples. Agr. Meteorol. 3: 293-310.

__________, and F.N. Dalton.
1967. Psychrometric measurement of soil water potential without precise temperature control. Soil Sci. Soc. Amer. Proc. 1967: 297-301.

__________, W.R. Gardner, and F.N. Dalton.
1968. *In situ* measurement of soil and plant leaf water potential. Soil Sci. Soc. Amer. Proc. 32: 468-470.

Richards, L.A., and G. Ogata.
1958. Thermocouple for vapor pressure measurements in biological and soil systems at high humidity. Science 128: 1089-1090.

Robinson, R.A., and R.H. Stokes.
1959. Electrolyte Solutions. 559 p. London: Butterworth.

Salisbury, F.B., and C. Ross.
1969. Plant Physiology. 747 p. Belmont, Calif.: Wadsworth.

Slatyer, R.O.
1967. Plant-Water Relationships. 366 p. New York: Academic.

__________, and S.A. Taylor.
1960. Terminology in plant- and soil-water relations. Nature 187: 922-924.

Spanner, D.C.
1951. The Peltier effect and its use in the measurement of suction pressure. J. Exp. Bot. 11: 145-168.

__________.
1964. Introduction to Thermodynamics. 278 p. New York: Academic.

Taylor, S.A.
1964. Physics of irrigated soils: soil-plant water relations. Utah State Univ.

__________.
1965. Measuring soil-water potential. P. 149-157 in: Methodology of Plant Eco-physiology. Montpellier Symp. UNESCO Proc.

__________, and J.W. Cary.
1965. Soil-water movement in vapour and liquid phases. P. 159-165 in: Methodology of Plant Eco-physiology. Montpellier Symp. UNESCO Proc.

__________, D.D. Evans, and W.D. Kemper.
1961. Evaluating soil water. Utah Agr. Exp. Sta. Bull. 426, 67 p.

__________, and R.O. Slatyer.
1962. Proposals for a unified terminology in studies of plant-soil-water relations UNESCO. Arid Zone Res. 16: 339-349.

__________ and G.L. Stewart
1960. Some thermodynamic properties of soil water. Soil Sci. Soc. Amer. Proc. 24: 243-247.

Wiebe, H.H.
1966. Matric potential of several plant tissues and biocolloids. Plant Physiol. 41:1439-1442.

__________. (ed.)
Measurement of plant and soil water status. Utah State Univ. Agr. Exp. Sta. Bull. (in press).

__________, R.W. Brown, T.W. Daniel, and E. Campbell.
1970. Water potential measurements in trees. BioScience 20: 225-226.

Wilson, W.J.
1967. The components of leaf water potential. Aust. J. Biol. Sci. 20: 329-367.

Zollinger, W.D., G.S. Campbell, and S.A. Taylor.
1966. A comparison of water-potential measurements made using two types of thermocouple psychrometer. Soil Sci. 102: 231-239.

APPENDIX

Appendix 1

Conversion of energy units to pressure units. The expression of chemical potential in energy units (ergs $mole^{-1}$) is inconvenient for discussions of soil-plant water relations. Therefore, we ordinarily deal with pressure units; the units of equation (2) are:

$$\frac{\text{erg mole}^{-1}}{\text{cm.}^{3}\ \text{mole}^{-1}} = \text{erg cm.}^{-3} = \text{dyne cm. cm.}^{-3} = \text{dyne cm.}^{-2}$$

and:

$$1 \text{ bar} = 0.987 \text{ atm.} = 10^{6} \text{ dyne cm.}^{-2} = 10^{6} \text{ erg cm.}^{-3}$$

Appendix 2

Definition of terms commonly used in water relations:

- e - The vapor pressure of water in the system under consideration at temperature T, in mm. Hg
- e_o - The saturated vapor pressure of pure free water at temperature T, in mm. Hg
- A_w - Relative water activity at temperature T
- R - Universal gas constant, expressed as:
  pressure units = 0.08205 liter atm. $mole^{-1}$ $°K^{-1}$
  energy units = 8.3143 X 10^7 erg $mole^{-1}$ $°K^{-1}$
  = 8.3143 joules $mole^{-1}$ $°K^{-1}$
  = 1.987 cal. $mole^{-1}$ $°K^{-1}$
- T - Absolute temperature °K (0°C. = 273.16 °K)
- $\overline{V}$ - The partial molal volume of water (18.015 $cm.^3$ $mole^{-1}$)
- ψ - Total water potential, defined as the capability of the water in the system to do work compared with pure free water at the same temperature. Since the soil (or plant) water has a lower free energy (ability to do work) than pure water, it will be designated as a negative energy or pressure.
- ψ_π - Osmotic or solute potential, resulting from the presence of dissolved solutes which lower the free energy of water. This quantity will be designated as a negative pressure.
- ψ_m - Matric potential, resulting from the presence of colloids and adhesive surfaces of the soil matrix, and is a negative pressure.
- ψ_p - Pressure on turgor potential, resulting from the effects of positive pressure greater than atmospheric pressure, and is designated as a positive pressure.

Appendix 3

Relative activities (A_w) and water potentials of KCℓ and NaCℓ solutions at 25°C.

Molal (m)	KCℓ A_w [1]	KCℓ ln A_w	KCℓ Bars [2, 3]	NaCℓ A_w	NaCℓ ln A_w	NaCℓ Bars
0.1	0.996668	-0.0033375	- 4.59	0.996646	-0.0033596	- 4.62
.3	.99025	- .0097978	-13.48	.99009	- .0099594	-13.70
.5	.98394	- .016190	-22.28	.98355	- .16587	-22.82
.7	.97763	- .022624	-31.13	.97692	- .023351	-32.13
1.0	.96818	- .032337	-44.49	.96686	- .033702	-46.37
1.2	.9619	- .038845	-53.45	.9601	- .0407178	-56.03
1.4	.9556	- .045416	-62.49	.9532	- .047931	-65.95
1.6	.9492	- .052136	-71.74	.9461	- .0554070	-76.24

[1]Data for A_w taken from Robinson and Stokes (1959).

[2]Under normal atmospheric conditions the ψ of a solution is equal to $\psi\pi$ because there are no other components affecting the free energy status of water in solution other than the solutes.

[3]The calculations of water potential were made using equation (2):

$$-\psi = \frac{RT}{\bar{V}} \ln \frac{e}{e_o}$$

$$= \frac{(8.3143 \times 10^7 \text{ ergs mole}^{-1}\ {}^\circ\text{K}^{-1})\ (298.16\ {}^\circ\text{K})}{18.016 \text{ cm.}^3 \text{ mole}^{-1}} (\ln 0.996668)$$

$$= (137.5994 \times 10^7 \text{ ergs cm.}^{-3})\ \ (-0.0033375)$$

$$= -4.59 \times 10^6 \text{ ergs cm.}^{-3} = -4.59 \text{ bars.}$$

Appendix 4

Some of the manufacturers supplying instrumentation and equipment for application in constructing and using thermocouple psychrometers:

Thermocouple wire

Omega Engineering Inc.
Box 4047, Springdale Station
Stamford, Conn. 06907

Thermo-Electric Co., Inc.
Saddle Brook
New Jersey 07662

Leeds and Northrup Co.
4907 Stenton Avenue
Philadelphia, Pa. 19144

Thermocouples (chromel-constantan, 0.001 inch diameter)

Omega Engineering, Inc.
Box 4047, Springdale Station
Stamford, Conn. 06907

Lepco[3]
459 South Main Street
Logan, Utah 84321

Voltmeters

Hewlett-Packard Co.
P.O. Box 301
Loveland, Colorado 80537

Keithley Instruments, Inc.
28775 Aurora Road
Cleveland, Ohio 44139

Electronic Components

Allied Electronics
5475 Leetsdale St.
Denver, Colorado 80222

Newark-Denver Electronics
Supply Co.
2170 S. Grape Street
Denver, Colorado 80222

Wire Screen

Star Wire Screen
4333 W. Clayton Avenue
St. Louis, Mo. 63110

Teflon

Plastic Products of Utah
2340 S.W. Temple
Salt Lake City, Utah 84115

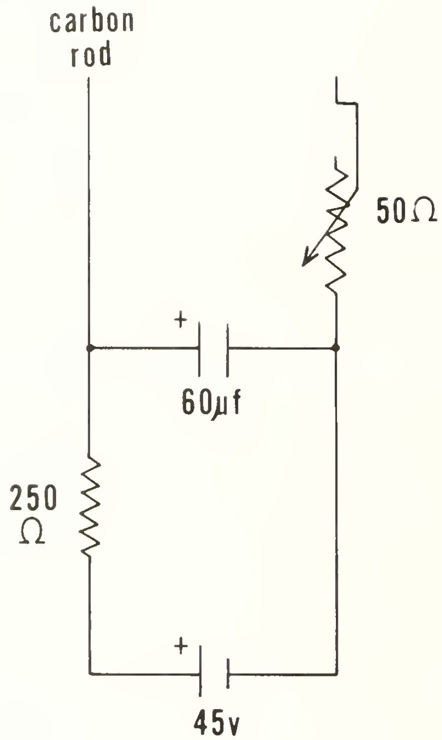
[3]Lepco supplies the entire thermocouple psychrometer with an attached ceramic cup, together with a cooling circuit and voltmeter.

Appendix 5

Circuit diagram and list of components required to construct the arc-welder unit for welding thermocouple psychrometers.

		Quantity
1.	Battery, 45 volt (i.e., Eveready No. 762-S)	1
2.	Resistors	
	a. 250 ohm, 5%	1
	b. 50 ohm, 1 turn, potentiometer	1
3.	Capacitor, 60 uf.	1

(For convenience the unit can be housed in an aluminum box.)

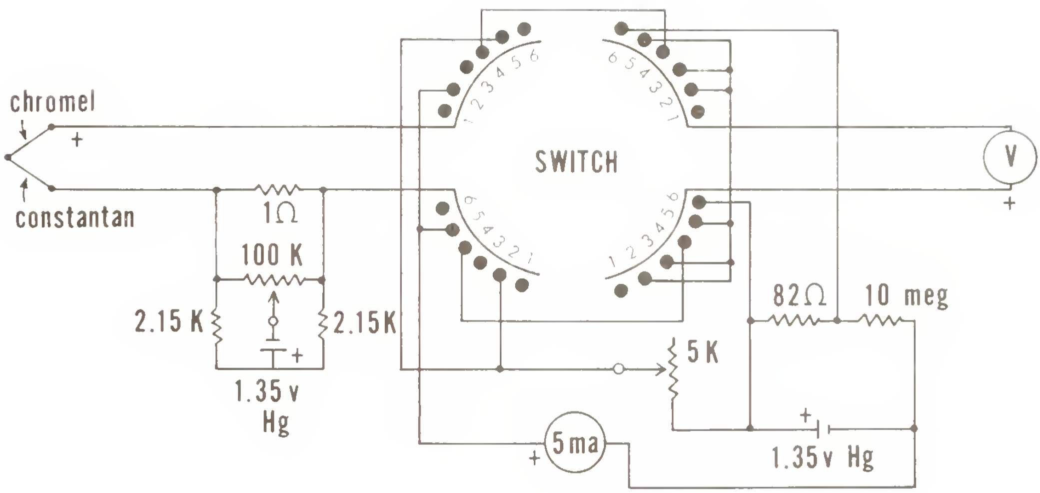


Appendix 6

Circuit diagram and list of components required to construct the "switchbox" cooling circuit for thermocouple psychrometers.

1.	Resistors (all resistors are 1%)	
	a. 82 ohms	1
	b. 10 megohms	1
	c. 2.15K ohms	2
	d. 1.0 ohm	1
2.	Trimmer potentiometer, 5K ohms	1
3.	Battery, 1.35 volt mercury	2
4.	Potentiometer, 100K ohms, 10 turn	1
5.	Milliameter, DC	1
6.	Switch, shorting rotary, 4 poles, 2-6 positions, 2 sections	1

(Note: This assembly should be mounted in an insulated aluminum box similar to that shown in figure 7.)



AFLC/HAFB, Ogden

Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field Research Work Units are maintained in:

- Boise, Idaho
- Bozeman, Montana (in cooperation with Montana State University)
- Logan, Utah (in cooperation with Utah State University)
- Missoula, Montana (in cooperation with University of Montana)
- Moscow, Idaho (in cooperation with the University of Idaho)
- Provo, Utah (in cooperation with Brigham Young University)

AFLC/HAFB/OGDEN / 20