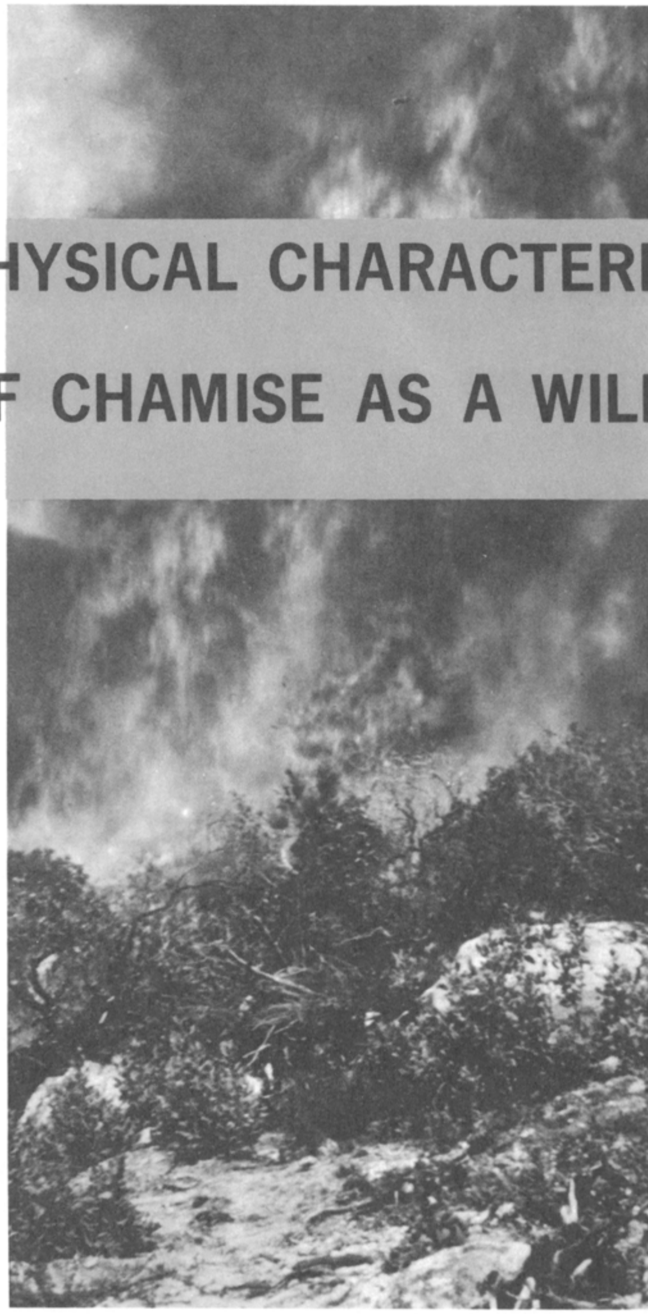
PACIFIC SOUTHWEST Forest and Range Experiment Station

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



PHYSICAL CHARACTERISTICS OF CHAMISE AS A WILDLAND FUEL

Clive M. Countryman

Charles W. Philpot

USDA FOREST SERVICE RESEARCH PAPER PSW- 66 /1970

Countryman, Clive M., and Charles W. Philpot.
1970. **Physical characteristics of chamise as a wildland fuel.** Berkeley, Calif., Pacific SW. Forest & Range Exp. Sta., 16 p., illus. (USDA Forest Serv. Res. Paper PSW-66)

Chamise shrubs in southern California were analyzed for the physical characteristics known to affect fire behavior, such as density, fuel loading, and fuel bed porosity. Considerable variation was found, but results are helpful in developing estimates of chamise fuel characteristics for fire control under field conditions.

OXFORD: 176.1 *Adenostoma fasciculatum:* 431.2.
RETRIEVAL TERMS: Adenostoma fasciculatum; burning characteristics.

Countryman, Clive M., and Charles W. Philpot.
1970. **Physical characteristics of chamise as a wildland fuel.** Berkeley, Calif., Pacific SW. Forest & Range Exp. Sta., 16 p., illus. (USDA Forest Serv. Res. Paper PSW-66)

Chamise shrubs in southern California were analyzed for the physical characteristics known to affect fire behavior, such as density, fuel loading, and fuel bed porosity. Considerable variation was found, but results are helpful in developing estimates of chamise fuel characteristics for fire control under field conditions.

OXFORD: 176.1 *Adenostoma fasciculatum:* 431.2.
RETRIEVAL TERMS: Adenostoma fasciculatum; burning characteristics.

CONTENTS

The Authors

CLIVE M. COUNTRYMAN heads fire behavior studies, with headquarters at the Station's Forest Fire Laboratory, Riverside, Calif. He earned B.S. degree in forestry at the University of Washington (1940), and joined the Forest Service the following year. **CHARLES W. PHILPOT** is studying fuel science problems, with headquarters at the Northern Forest Fire Laboratory, Missoula, Montana. He joined the Pacific Southwest Station staff in 1960, and later transferred to his present assignment with the Intermountain Forest and Range Experiment Station. He earned bachelor's (1961) and master's (1962) degrees in forestry at the University of California, and a doctorate (1970) in Plant Science at the University of Montana.

Energy from burning fuel is the primary driving force for the fire behavior phenomena observed in wildland fires. Physical characteristics of the fuel elements and their arrangement in the fuel bed are important determinants of the amount of energy available and the rate at which it is released. For example, finely divided fuels, such as pine needles or excelsior, release their energy quickly. Large timbers or logs usually burn slowly and may require hours to release all of their potential energy. Quantitative evaluations of the fuel complex are essential to progress in the control and use of wildland fire.

Physical characteristics of fuels and fuel beds now recognized as influencing fire behavior include:

1. Distribution of fuel in the fuel bed, by size and condition (live or dead).
2. Fuel loading (W_a): fuel weight per unit of fuel bed area.
3. Fuel density (d): fuel weight per unit of fuel volume.
4. Fuel surface-to-volume ratio (σ).
5. Fuel bed porosity (γ): ratio of fuel bed volume to fuel volume. The *packing ratio* (β), the converse of fuel bed porosity, is the ratio of fuel volume to fuel bed volume.
6. Moisture content of fuel.
7. Heat content of fuel.
8. Chemical composition of fuel.

At present, many of these characteristics can be determined only by direct physical measurement and calculations made from such measurements. Others can be determined by laboratory procedures. In varying degree, all influence such fire phenomena as ignition time, rate of spread, burning time, and intensity. Procedures for estimating physical characteristics of fuels are not well developed. In an operational situation, such as a going fire, the fire manager needs a quick way of estimating fuel characteristics so that he can forecast probable fire behavior.

In southern California, one of the most hazardous wildland fuels is chamise *(Adenostoma fasciculatum).* This common, aggressive shrub grows in pure stands or in mixture with other chaparral species in the mountains of southern California, throughout the Coast Ranges, and in the lower Sierra Nevada foothills *(fig. 1).* Chamise probably has a wider range and produces more volume of growth than any other shrub in California (Sampson and Jesperson 1963).

Chamise is a medium-sized, evergreen shrub usually 2 to 8 feet tall when mature, but occasionally taller. The shrub has many slender, rigid branches covered with clusters of needlelike leaves ¼ to ½ inch long *(fig. 2).* The leaves are often resinous. The bark is gray or dark-colored, and usually shreddy. Generally, little leaf litter is produced, but under severe drought stress, chamise may shed much of its foliage.

At low elevations new growth usually starts in January, increases rapidly in April and May, and slows or stops in June (Hanes 1965). The beginning of the growth cycle is often delayed at high elevations. After a fire, there is abundant sprouting from the root crowns, and seedlings are numerous. There are few seedlings in dense mature stands, however, and little other vegetative growth.

Besides studying the physical characteristics of chamise, we were interested in the interrelationships of various shrub characteristics. We wanted to find some means of estimating these characteristics in the field with a minimum of measurements. How fuel characteristics affect fire behavior is known in a general way. But explicit relationships for the most part have not been established, particularly for the combinations of fuel factors as they occur naturally. Thus, the precise amount of change needed to produce a significant change in fire behavior is not known. Nevertheless, available information suggests the relative importance of the various fuel characteristics, and the accuracy of the estimates needed. But before standards for accuracy can be set, we need to establish explicit relationships between fuel characteristics and fire behavior.

This paper reports a study of the physical characteristics of chamise as a wildland fuel. It considers their effects on fire behavior and the quantitative values found in a study of chamise. It describes methods of estimating some of the less easily measured characteristics of this shrub, and evaluates the reliability of these techniques.

Most of the quantitative data reported for chamise are from an analysis of 16 shrubs from the North Mountain Experimental Area, 30 miles east of Riverside, California. But where appropriate, we have included data obtained by other investigators.

Figure 1—*Chamise, a highly flammable shrub species, grows throughout the Coast Ranges and lower Sierra Nevada foothills of California.*

Figure 2—*Chamise foliage consists of slender branches covered with needlelike, often resinous leaves in fascicles of 10 to 15.*

PROCEDURES

Collection and Dissection

The 16 shrubs analyzed were selected by a systematic random-sample method at 4,000 feet elevation. Chamise made up about half the vegetation on the site, the rest consisting of other common chaparral species.

The shrubs were collected two or three at a time from June 1964 through May 1965. The shrub height and average crown diameter at its greatest development were measured with the shrub in place. It was then cut off at ground level and wrapped in canvas to prevent loss of any material during transport to the laboratory. There the shrubs were immediately hung in individual sheet-plastic-lined stalls. Dead portions were tagged so that they could be identified when the shrubs became dry.

The material in each shrub was removed in five groups representing the following size classes:

1. Foliage
2. Woody material less than ¼ inch in diameter
3. Woody material ¼ to ½ inch in diameter
4. Woody material greater than ½ inch to 1 inch in diameter
5. Woody material greater than 1 inch in diameter.

Measurement of Leaves

The shrubs were allowed to dry for about 2 weeks at 70°F. before dissection was started. Leaves were then removed with a jet of compressed air, and collected from the bottom of the stall with a vacuum cleaner. Extraneous material was removed with an air-blower-type seed cleaner. The leaves were then weighed and samples were removed for moisture-content determination. On the basis of the average moisture content of these samples, the leaf weight was adjusted to dry weight.

The needlelike leaves of chamise are in fascicles of 10 to 15. The surface area and volume of broad-leaved species can be determined readily by direct measurement, but needlelike leaves present a problem and some geometric shape must usually be assumed (Kozlowski and Schumacher 1943; Kumagi 1962; Madgwick 1964). The surface area and volume of chamise leaves was estimated by assuming a circular cross section and combined shape of three frustrums and a cone. This geometric simulation is shown against a photographic outline of a leaf in *figure 3.* Three one-quarter diameters, the end diameter, and total length were determined by a measuring magnifier. Three samples of 25 leaves each were used to obtain average values for chamise leaves.

Measurement of Woody Material

As material each size class was clipped from the shrub, it was separated into live and dead groups and measured for length. All of the shrubs contained a large amount of material in the smallest size class, so length measurements were made on a 30 percent (by weight) subsample. For the larger size classes all of the material was measured.

The live and dead material was weighed separately and samples of each were withdrawn for moisture-content determination, so that the dry weight of the material could be calculated.

On the assumption that all of the woody material was cylindrical in shape, the surface area and volume were calculated from dry weight, total length, and average density of the material in each size class by use of the equations:

$$V = W/d$$

$$A = 2\pi L\sqrt{(W)/(d\pi L)}$$

in which

V = volume
A = Area
d = Density
W = Dry Weight
L = Length.

The average wood densities used in the calculations were derived from samples taken from five shrubs. Five samples from each size class of live and dead material were taken from each shrub. Symmet-

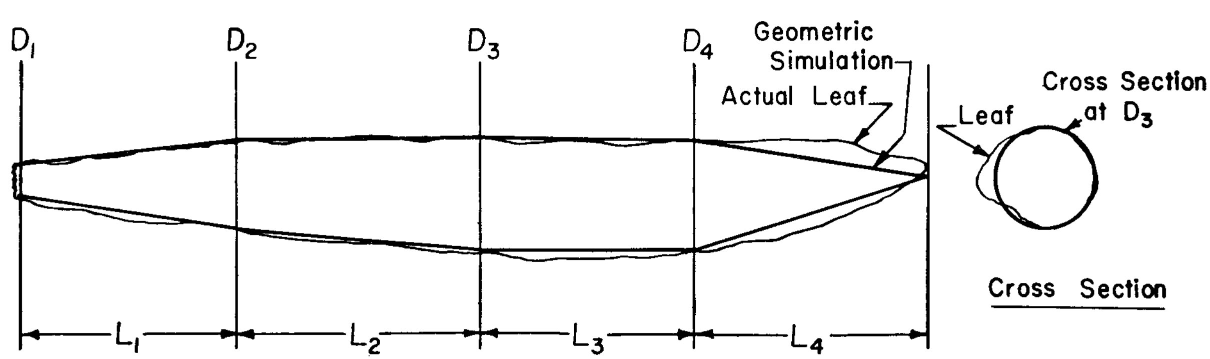


Figure 3—*Geometric simulation of a chamise leaf, shown in comparison with its actual shape, was used to determine surface area and volume.*

rical pieces of wood varying in length from 1 to 2 inches were chosen. Each sample was carefully measured for length and diameter and the volume calculated. Volume of the samples was also determined by the water displacement method. Average volumes as determined by both methods agreed closely; however, the displacement method appeared to give more consistent results, and these were used in the density calculations.

The fuel samples were ovendried to obtain their dry weight. The density of live material was calculated for both the green wood and dry wood volumes. However, to conform to the usual practice for wildland fuels, the density based on green wood volume and dry weight was used in the equations for volume and area determination. The wood density for the live material increased as the wood diameter increased. However, density for a given size class of material differed only slightly between shrubs.

The density of the dead material for each size class varied greatly, not only among shrubs but within a shrub as well. Examination of the samples indicated that they were in different stages of decomposition. The density of dead wood in a good state of preservation was close to that of living material calculated from its dry volume. The density of weathered samples was less–the amount apparently depending upon the degree of decomposition. Unfortunately, no attempt was made to segregate the dead wood by condition when the shrubs were dissected. Average density of the dead material was hence estimated from the material available, and these values were used for calculation of the dead wood volume and surface area.

The results of the chamise shrub measurements and calculation of volume and surface area are summarized in *table 1*.

Table 1–*Dimensions of 16 chamise shrubs analyzed*

Shrub number	Height	Crown diameter	Fuel weight	Fuel surface area	Fuel volume
	Feet	*Feet*	*Pounds*	*Sq. ft.*	*Cubic ft.*
1	6.0	4.1	9.32	133.7	0.2299
2	5.8	3.4	5.02	42.3	.1130
3	8.0	5.0	21.98	234.1	.5144
4	4.2	3.2	4.06	81.5	.1018
5	6.5	4.5	4.83	67.2	.1161
6	5.0	3.9	4.41	68.0	.1076
7	7.0	5.2	9.44	165.1	.2325
8	8.5	8.0	12.63	142.0	.2888
9	7.3	7.0	10.79	111.0	.2462
10	4.5	4.2	2.44	40.1	.0566
11	4.4	3.5	2.77	31.3	.0629
12	6.3	3.0	5.66	75.5	.1329
13	3.4	2.2	1.54	66.7	.0466
14	3.0	3.0	3.07	110.5	.0895
15	3.0	3.0	2.06	37.9	.0515
16	6.3	3.0	2.34	53.2	.0597

FUEL CHARACTERISTICS

Using the procedures described earlier, quantitative values for the characteristics of the 16 chamise shrubs were tabulated. The necessary calculations, as well as the results themselves, are described in the following sections.

Size-Class Distribution

Tabulation of the weight, volume, and surface area of the material showed that the proportion of small material was not consistent among the shrubs *(table 2)*. The percentage of weight, and hence volume and surface area also, represented by the small material varied widely. For example, the weight of the foliage ranged from a low of 5.6 percent to a high of 36.5 percent. These tabulations also show the influence of the smaller material on the total surface area of a fuel bed. About 13 percent of the weight and 23 percent of the volume on the average was in the foliage. However, the average for surface area of the foliage was more than 67 percent of the total.

Observations have indicated that wildfires in chamise usually do not consume material larger than one-half inch in diameter. Thus the proportion of smaller fuels is highly important in determining the behavior of chamise fires. About 61 percent of the fuel weight and 65 percent of the fuel volume of the shrubs was in the fuel one-half inch or less in diameter. Nearly all of the surface area (96 percent) in these fuel sizes.

Amount and Distribution of Dead Fuel

Living fuels usually contain large amounts of moisture and hence do not burn well by themselves. However, in most wildland fuels dead fuel is intermixed with the living fuel. Under appropriate

Table 2–*Distribution of fuel weight, volume and surface area in chamise, by size classes*

Material size (inch)	Shrub number																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Average
	WEIGHT (PERCENT)																
Foliage	12.5	5.7	8.7	15.1	10.9	12.2	13.2	6.8	6.4	7.3	5.6	9.2	36.5	30.2	13.7	16.5	13.2
<1/4	19.8	16.6	19.3	32.8	22.4	20.2	23.7	18.3	19.7	32.7	30.0	23.5	31.1	40.4	33.9	32.0	26.0
1/4 - 1/2	16.2	18.6	21.8	24.9	17.6	35.7	20.0	22.5	22.6	19.8	26.9	13.6	23.3	13.7	28.4	19.3	21.6
1/2 - 1	35.5	41.5	30.6	16.9	46.8	31.9	43.1	35.2	28.2	40.2	18.8	25.0	9.1	15.7	24.0	30.0	29.5
1 - 3	16.0	17.6	19.6	10.3	2.3	0	0	17.2	23.1	0	18.7	28.7	0	0	0	2.2	9.7
	VOLUME (PERCENT)																
Foliage	23.4	11.5	17.0	27.4	20.7	22.6	24.4	13.5	12.8	14.2	11.2	17.9	54.8	47.2	24.8	29.3	23.3
<1/4	17.9	16.2	18.2	28.5	20.5	18.2	21.1	17.6	19.0	30.4	28.9	21.9	22.4	31.2	30.2	27.7	23.2
1/4 - 1/2	14.3	17.6	19.9	21.4	15.6	31.4	17.4	21.1	21.1	18.3	25.4	12.5	16.5	10.2	24.6	16.1	18.9
1/2 - 1	30.8	38.7	27.5	14.3	41.1	27.8	37.1	32.2	26.0	37.1	17.4	22.2	6.3	11.4	20.4	25.1	26.0
1 - 3	13.6	16.0	17.4	8.4	2.1	0	0	15.6	21.1	0	17.1	25.5	0	0	0	1.8	8.6
	AREA (PERCENT)																
Foliage	61.9	61.5	65.2	68.6	68.4	65.6	69.0	61.9	62.5	57.3	51.0	67.2	88.6	79.6	67.7	72.6	67.4
<1/4	20.0	23.0	23.4	26.4	21.3	20.6	22.4	25.g	25.0	35.1	37.8	24.6	9.5	18.4	25.6	22.3	23.8
1/4 - 1/2	3.4	6.2	5.6	3.3	4.3	10.0	4.2	6.2	6.7	4.0	7.6	3.4	1.6	1.3	4.9	2.8	4.7
1/2 - 1	3.9	7.6	4.3	1.3	5.8	3.8	4.4	4.7	4.0	3.6	2.3	3.0	.3	.7	1.7	2.2	3.4
1 - 3	.8	1.7	1.5	.4	.2	0	0	1.3	1.8	0	1.3	1.8	0	0	0	.1	.7

Table 3–*Distribution of dead fuel in chamise by weight, volume, and area, as a percent of total fuel in each size class*

Material size (inch)	Shrub number																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Average
	WEIGHT (PERCENT)																
<1/4	4.6	6.5	7.1	18.3	7.8	7.2	9.7	5.2	7.0	14.2	13.6	9.5	14.3	1.1	3.5	8.1	8.6
1/4 - 1/2	4.0	8.5	9.3	7.5	9.3	15.7	9.7	11.0	12.2	10.0	12.2	4.2	12.1	1.9	6.2	9.7	9.0
1/2 - 1	4.2	13.8	6.9	2.5	10.1	2.9	6.6	14.5	7.6	0	3.3	10.4	3.6	2.1	0	0	5.1
1- 3	1.8	8.9	1.7	4.3	0	0	0	4.2	0	0	0	0	0	0	0	0	12.1
Total	14.6	37.7	25.0	32.6	27.2	25.8	26.0	34.9	26.8	24.2	29.1	24.1	30.0	5.1	9.7	17.8	24.4
	VOLUME (PERCENT)																
<1/4	4.0	6.1	6.4	15.4	6.8	6.2	8.2	4.8	6.5	12.4	12.6	8.5	9.9	0.8	2.9	6.6	7.0
1/4 - 1/2	3.4	7.9	8.3	6.2	8.1	13.3	8.2	10.0	11.1	9.0	11.1	3.8	8.3	1.4	5.2	7.9	7.7
1/2 - 1	3.5	2.4	6.0	2.0	8.5	2.4	5.4	12.8	6.7	0	3.0	9.0	2.4	1.4	0	0	4.1
1 - 3	1.5	7.9	1.5	3.4	0	0	0	3.7	0	0	0	0	0	0	0	0	11.8
Total	12.4	24.3	22.2	27.0	23.4	21.9	21.8	31.3	24.3	21.4	26.7	21.3	20.6	3.6	8.1	14.5	20.3
	AREA (PERCENT)																
< 1/4	4.2	7.2	6.4	12.4	7.7	7.8	8.8	6.8	8.4	14.5	19.4	10.5	4.1	.4	2.0	5.3	7.9
1/4 - 1/2	.9	2.5	2.4	1.0	2.1	5.4	2.0	3.1	3.5	2.0	3.6	1.1	.8	.2	1.0	1.4	2.1
1/2 - 1	.5	2.8	1.0	.2	1.4	.3	.7	1.9	1.2	0	.4	1.1	.1	.1	0	0	.7
1 - 3	.2	.8	.1	.2	0	0	0	.4	0	0	0	0	0	0	0	0	[1].2
Total	5.8	13.3	9.9	13.8	11.2	13.5	11.5	12.2	13.1	16.5	23.4	12.7	5.0	.7	3.0	6.7	10.8

[1]Based on shrubs with any material in this size class.

weather conditions the dead fuels can become dry enough to burn readily. The burning dead fuel can provide the heat necessary to dry the living fuel to a point where it will ignite and add to the total energy release from a fire. The amount and distribution of dead fuel in a fuel array can thus greatly affect its flammability.

In the chamise shrubs analyzed, the weights, volumes, and surface areas of the dead woody fuels were tabulated by size classes *(table 3).* However, there was so little dead foliage that no attempt was made to separate it from the live foliage.

The weight of dead fuel for the 16 shrubs averaged 24.4 percent, which was close to the value found for most of the shrubs. Except for shrubs 14 and 15, which were probably young plants, there was no significant tendency for the amount of dead fuel to vary with the size of the shrub. The distribution of dead fuel volume and surface area followed the same pattern as that for weight, as might be expected. The low average percentage of surface area in dead fuel (10.8 percent) is a reflection of the large proportion of total surface area that is in the foliage *(table 3).*

The dead material tended to fall in the smaller size classes rather than the large *(table 4).* On the average more than one-third of the weight of the two smallest classes was made up of dead material, but for some individual shrubs, more than half the weight was dead material. The distribution pattern for the volume and area was similar to that for fuel weight. Chamise shrubs thus have a high proportion of their dead fuel in the easily ignited and fast-burning size classes.

Fuel Loading

Other conditions being equal, the amount of heat produced by a burning fuel bed will be strongly influenced by the amount of fuel available to burn. Fuel loading (weight per unit of fuel bed area) was determined by assuming each shrub occupied a ground area equivalent to a circle with the diameter of the average crown diameter. Average fuel loading

Table 4–*Proportion of dead fuel in each size class, by weight, volume, and area*

Material size (inch)	Shrub number																Average
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15.	16	
	WEIGHT (PERCENT)																
<1/4	23.4	39.5	36.8	55.7	34.7	35.4	40.8	28.3	35.6	43.5	45.2	40.4	45.9	2.8	10.3	25.2	34.0
1/4 - 1/2	24.7	45.9	42.9	30.2	53.1	43.8	48.4	48.7	54.0	50.4	45.2	31.2	52.0	13.9	22.0	50.6	41.1
1/2 - 1	11.8	33.1	22.6	14.7	21.5	9.0	15.2	41.1	26.9	0	17.7	41.5	39.3	13.9	0	0	19.2
1 - 3	11.4	50.5	8.8	41.9	0	0	0	24.2	0	0	0	0	0	0	0	0	13.6
Total[1]	14.6	37.7	25.0	32.6	27.2	25.8	25.8	34.9	26.8	24.2	29.1	24.1	30.0	5.1	9.7	17.8	24.4
	VOLUME (PERCENT)																
<1/4	22.2	37.8	35.2	54.0	33.1	33.8	39.0	26.9	34.0	41.0	43.5	38.7	44.2	2.6	9.7	23.9	32.5
1/4 - 1/2	23.8	44.6	41.6	29.1	51.7	42.5	47.1	47.4	52.7	49.1	43.8	30.1	50.6	13.3	21.1	49.3	39.9
1/2 - 1	11.3	32.0	21.8	14.0	20.6	8.6	14.5	40.0	25.9	0	17.0	40.3	38.0	12.7	0	0	18.5
1 - 3	11.0	49.6	8.5	41.0	0	0	0	23.5	0	0	0	0	0	0	0	0	13.4
Total[1]	12.4	24.3	22.2	27.0	23.4	21.9	21.8	31.3	24.3	21.4	26.7	21.3	20.6	3.6	8.1	14.5	20.9
	AREA (PERCENT)																
<1/4	21.2	31.3	27.5	47.1	36.2	37.2	39.2	26.5	33.7	41.4	51.3	42.7	43.0	2.3	7.7	23.6	32.0
1/4 - 1/2	26.5	40.2	43.4	30.6	48.4	54.6	47.5	49.7	53.0	49.7	47.1	31.5	49.7	12.5	20.2	50.4	40.9
1/2 - 1	12.0	37.4	22.6	15.3	25.1	6.6	16.5	39.7	30.9	0	19.3	38.3	38.1	13.4	0	0	19.7
1 - 3	21.2	47.9	5.4	39.9	0	0	0	26.6	0	0	0	0	0	0	0	0	14.1
Total[1]	5.8	13.3	9.9	13.8	11.2	13.5	11.5	12.2	13.1	16.5	23.4	12.7	5.0	1.0	3.0	6.7	10.8

[1]Percent of all fuel.

for the 16 shrubs was 0.45 lb./sq. ft. (equivalent to about 10 tons per acre). There was wide variation in the fuel loading between shrubs:

Shrub number	Fuel loading	Shrub number	Fuel loading
	Lb./sq.ft.		*Lb./sq.ft.*
1	0.72	9	.28
2	.55	10	.18
3	1.12	11	.29
4	.51	12	.80
5	.30	13	.38
6	.37	14	.43
7	.44	15	.29
8	.25	16	.33
		Average	.45

Fuel Density

Fuel density (weight per unit volume of the fuel) is an important characteristic. Fons (1946) found that rate of spread in small experimental fires decreased as the fuel density increased. Fons, *et al.* (1960) also found this same effect for laboratory crib fires burning rectangular sticks of white fir. The density of wildland fuels can have a wide variation among species.

The density of woody material in chamise was found to vary with the size of material and its condition (alive or dead), but over a relatively narrow range *(fig. 4).* We have seen that the distribution of weight and volume of the woody material by size classes varied considerably among shrubs *(table 2).* However, the average density of the woody material by shrubs did not show much variation, probably because the shrubs with a larger amount of large material also tended to have a relatively larger proportion of smaller material. The average density for all shrubs was 46.7 lbs./cu. ft. However, because of the large difference in density between foliage and wood, and the wide variation in the amount of foliage among shrubs, the average density of fuel can be expected to vary greatly among shrubs.

Surface-to-Volume Ratio

The ratio, σ, of the fuel surface area to the fuel volume strongly influences flammability. For dead fuels, the moisture that is gained or lost must all go through the surface, so that the rate at which a fuel changes in moisture content is affected greatly by the amount of surface area in relation to the fuel volume. In combustion σ is also of major importance. If an unburned piece of fuel is put into a fire, heat is transferred to the fuel surface by all three methods of heat transfer–radiation, convection, and conduction. But the heat received by the surface is transferred to the interior of the fuel by conduction, and it all must go through the surface. Thus, the greater the surface area in relation to the fuel volume, the faster the fuel will be heated and burn.

For cylindrical fuels, σ (sq. ft./cu. ft.) can be determined from the equation:

$$\sigma = 2/r$$

in which r = fuel radius in feet.

Fons (1946) found that the rate of fire spread increased linearly with increase in σ for small experimental fires over a range of from 1.3 to 12 sq. ft./cu. ft. Fons, *et al.* (1960) also found rate of spread to be directly proportional to a for small crib fires of rectangular sticks.

Fons (1950), in investigating the effect of various fuel factors on ignition time with a muffle furnace, found that ignition time decreased with decreasing fuel size (increasing σ) over a range of furnace temperatures of 850° to 1,300°F. However, his data indicated fuel size had less effect on ignition time as the furnace temperature was increased.

The variation in σ is pronounced. Fuel one-eighth inch in diameter has a σ of 384, whereas for one-inch diameter fuel, σ is only 48. There is little information on σ values for most wildland fuels. Rothermel and Anderson (1960) obtained σ values of 2,700 sq. ft./cu. ft. and 1,741 sq. ft./cu. ft. for white pine and ponderosa pine needles respectively. Cheat grass has a

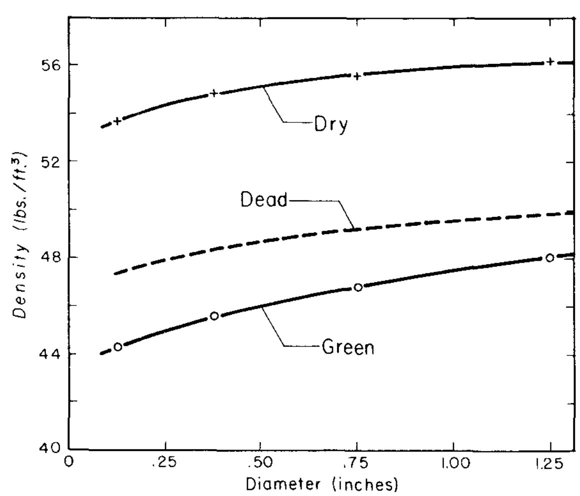


Figure 4–*Density of chamise wood varies with the size of material and its condition (alive or dead).*

σ in the order of 4,390 sq. ft./cu. ft.[1] Spruce-Douglas-fir slash fuels in the northern Rocky Mountain area have been estimated to have values ranging from 305 sq. ft./cu. ft. to 2,134 sq. ft./ cu. ft.

Average surface-to-volume ratio for the shrubs was 690 reflecting the predominance of very small fuel:

Shrub number	σ	Shrub number	σ
	Sq. ft./cu. ft.		*Sq. ft./cu. ft.*
1	581	9	444
2	385	10	668
3	459	11	522
4	815	12	581
5	560	13	1.334
6	618	14	1,228
7	718	15	758
8	490	16	887
		Average	690

Fuel Bed Porosity

The spacing of individual fuel elements in the fuel bed, or how crowded they are together may be referred to in terms of porosity, or its converse, compactness. In a highly compact fuel bed the fuel elements are closely packed together, whereas in a less compact fuel bed the individual fuel elements are spaced far apart. A highly compact fuel bed has a low porosity value and a less compact bed is more porous.

Fuel bed compactness or porosity can be expressed in several ways. Fons (1946) used the ratio (λ) of the volume of voids in the fuel bed to the surface area of the fuel to measure porosity. He correlated rate of spread of small experimental fires with the reciprocal of this ratio (compactness). His work showed that rate of spread increased rapidly with decreasing compactness (increasing porosity).

Rothermel and Anderson (1966) correlated rate of spread of small laboratory fires with the product of σ and λ. They found the spread rate increased rapidly as this product increased. By definition, the product of σ and λ is the ratio of fuel bed void volume to fuel volume—another means of expressing fuel bed porosity. However, in the data used in the correlation, σ as well as λ varied. Since rate of spread varies with both parameters, it is not clear from their published work how much of the change in spread rate was due to the surface-to-volume ratio of the fuel and how much to fuel bed porosity.

There seems to be little information on the effect of fuel bed porosity on burning rate of wildland fuels. One would expect the burning rate to be slow for fuel beds with low porosity since air flow into the fuel bed would be restricted and the oxygen supply deficient. The burning rate should increase rapidly as the porosity is increased and reach a maximum at some optimum fuel element spacing. Beyond this point, further increases in porosity should lead to a decreasing burning rate because of a reduction in the efficiency of heat transfer among the fuel elements as they become further and further apart.

A convenient way to express fuel bed compactness is by the packing ratio (β). This is defined as the ratio of fuel volume to fuel bed volume. The reciprocal (γ) of this ratio is the fuel bed porosity. Packing ratios and fuel bed porosities were determined for each of the shrubs analyzed in this study. Fuel bed volume was obtained by assuming the shrub occupied a cylinder having the height of the shrub and a diameter equal to the average crown diameter. Packing ratios calculated in this manner showed a wide variation, ranging from a low of 0.00068 to a high of 0.00374:

Shrub number	β	γ
1	0.00291	344
2	.00214	467
3	.00327	305
4	.00310	323
5	.00112	893
6	.00179	558
7	.00153	653
8	.00068	1,471
9	.00087	1,149
10	.00092	1,087
11	.00148	676
12	.00297	337
13	.00343	292
14	.00422	237
15	.00243	412
16	.00133	752

There are few data on the packing ratios for natural wildland fuels. Ponderosa pine needle fuel beds may have a packing ratio of about 0.06250, whereas standing cheat grass has a packing ratio in the order of 0.00004. The relatively high porosity values for chamise indicate that very little of the fuel bed volume is occupied by fuel. For fuel bed with a packing ratio of 0.00068, less than 0.07 percent of the fuel bed volume is occupied by fuel, and for a packing ratio of 0.00374 only about 0.37 percent.

Much of the material of a chamise shrub is small sized, as we have seen; these fuels contribute most to the energy peak that exerts a major control on fire behavior (Countryman 1969). The larger-sized fuel

[1]Brown, J. K. *Physical fuel properties and their vertical variation in spruce-fir logging slash.* (MS in preparation)

elements can be considered simply as a supporting framework for the small fuels. This framework permits a fuel element distribution conducive to a high fuel bed porosity and rapid burning. The fuel distribution pattern and high porosity of chamise is shown in *figure 5.*

Fuel Moisture Content

The moisture content of wildland fuel has long been recognized as having a major influence on the ignition, development, and spread of fires (Hawley 1926). Studies have been made of moisture content

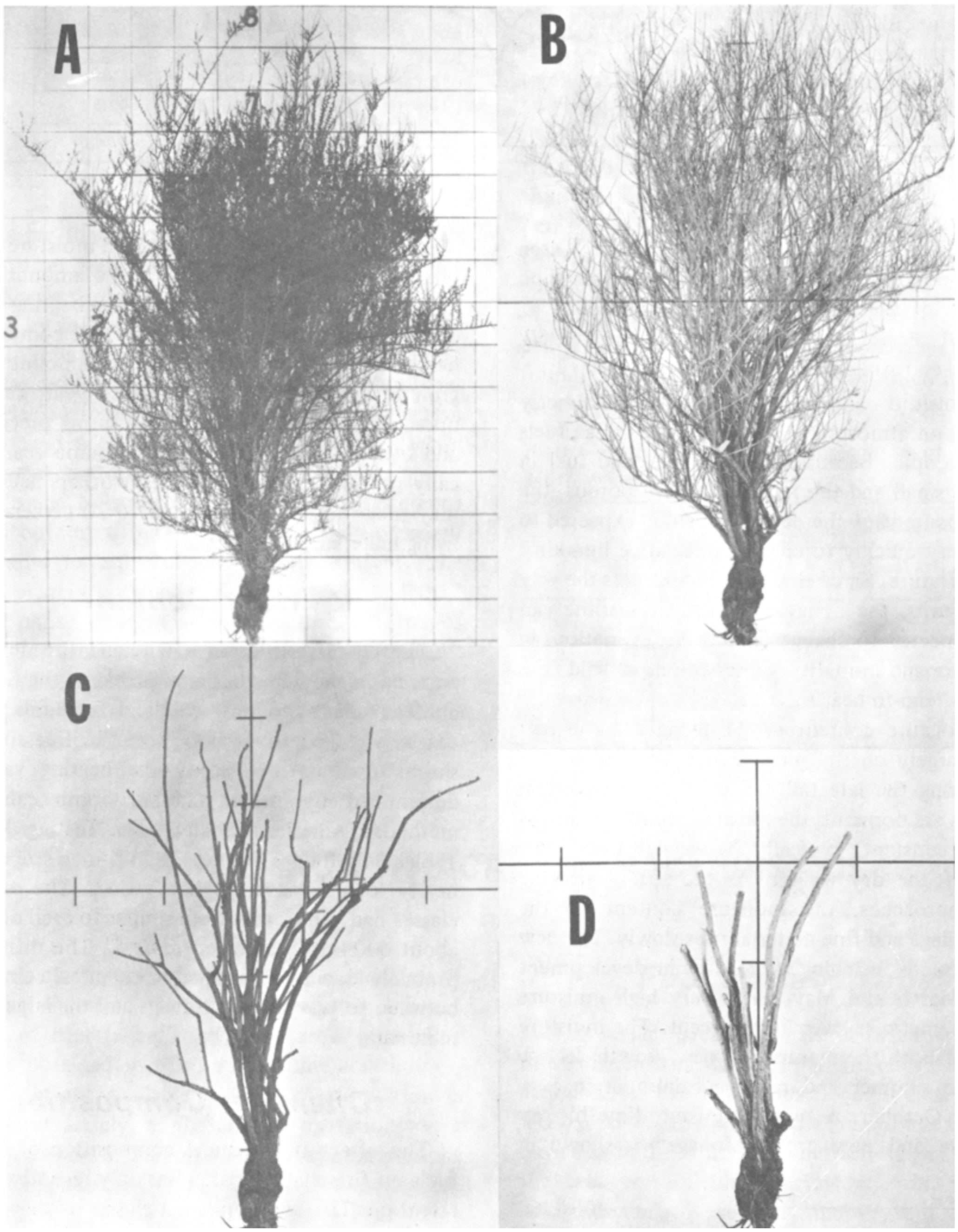


Figure 5–*Distribution of chamise fuel:* A, *Chamise shrub with foliage;* B, *Foliage removed;* C, *Material ¼ inch and less removed; and* D, *Material ½ inch and less removed.*

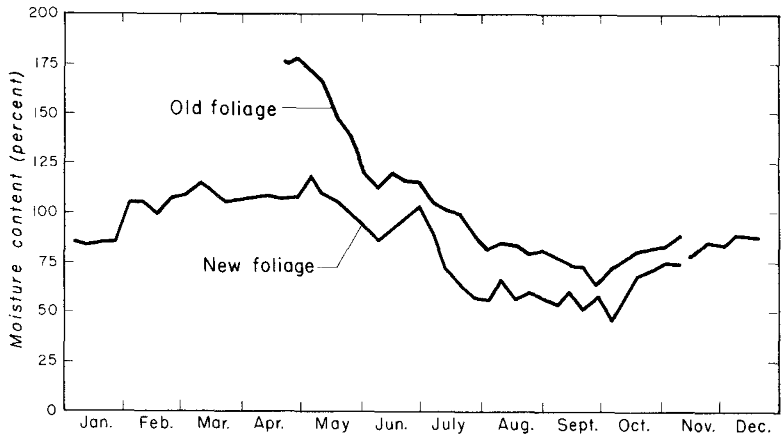


Figure 6–*A typical moisture-time history for chamise foliage shows rise and decline in moisture content.*

variations (e.g., Fielding 1952; Firestop 1955; Olsen 1960; Philpot 1963). Studies have also been made on the effect of fuel moisture on fire behavior (e.g., Curry and Fons 1938; Fons 1946; Fons 1950; Rothermel and Anderson 1966).

The moisture content of dead chamise is directly dependent on atmospheric moisture, since dead fuels are hygroscopic. Because much of the dead fuel in chamise is small and the fuel bed is very porous, the moisture content of the dead fuel can be expected to respond very quickly to changes in relative humidity and temperature. Since the dead fuel effects the way chamise burns, the behavior of fire in chamise can also be expected to change quickly with variations in temperature and humidity. Observations of wild fires in chamise tend to bear this out.

The moisture content of the living chamise fuel depends largely on the physiological activity of the plant. During the late fall and winter months when the shrubs are dormant, the moisture content remains relatively constant, typically between 80 and 110 percent of the dry weight. As the spring growing season approaches, the moisture content of the mature foliage and fine material rises slowly. The new growth, usually reaching its maximum development between March and May, has a very high moisture content–sometimes over 200 percent. The moisture content of both the mature and new growth decline during the summer and reach a minimum in September or October. A typical moisture-time history for mature and new growth foliage[2] is shown in *figure 6.*

[2]Fons, Wallace L. *Progress report on seasonal variation of moisture content of chaparral foliage on the San Dimas Experimental Forest during 1942.* (Unpublished rep. on file at Forest Fire Laboratory, Pacific SW. Forest & Range Exp. Sta., Riverside, Calif.)

Since the new growth has a high moisture content relative to the mature growth, the amount of new growth present has an important bearing on the average moisture content of the fuel complex, and hence on the way it burns. The amount of new growth varies widely from year to year, dependent upon the amount of winter and spring precipitation and other weather conditions. In some years practically no new growth appears; in others new growth may make up an estimated 15 to 20 percent of fine living material.

Heat Content

The characteristics of a wildland fire depend, in part, upon the heat that is available in the fuel. Heat content values for most wildland fuels fall within a range of 7,500 to 10,000 B.t.u./lb. For six of the shrubs used in this study the heating value was determined by using standard bomb calorimetry methods (American Society for Testing Materials 1966). The foliage and less than ¼-inch size class had nearly identical average heat values. The other size classes had values that were similar to each other, but about 600 B.t.u./lb. lower *(table 5).* This difference is probably due to a variance in chemical composition between foliage and small twigs and the larger woody material.

Chemical Composition

The effect of chemical composition of wildland fuels on fire characteristics has only recently received attention. The two important classes of chemicals are (a) the high-energy ether extractives (waxes, oils, terpenes, and fats) and (b) the minerals which affect the pyrolysis of carbohydrates. Mutch (1964) found the ignition time for ponderosa pine powder to be

Table 5– *Heat content of chamise, by size of material*

Shrub number	Foliage	Material (inch) . . .		
		<1/4	1/4 - 1/2	1/2-1
	B.t.u./lb.			
6	8,983	9,085	8,436	8,360
7	8,570	8,779	7,869	8,449
10	8,938	8,783	8,344	8,156
14	9,341	9,072	8,297	8,320
15	8,964	9,144	8,665	8,585
16	9,014	9,106	8,352	8,486
Average	8,968	8,995	8,327	8,393

much longer than for sphagnum moss powder. The pine had over four times more extractives than the moss. However, pilot ignition time for both fuels was increased by the removal of the extractives. Recently, Philpot (1969a) found that the burning rate of aspen leaves was reduced by solvent extraction. Philpot and Mutch (1968) found a similar relationship for guava leaves treated with herbicides, which had extractive contents different from those of the controls.

Broido and Nelson (1964) attribute the difference between burning of naturally leached and unleached corn plants to ash and phosphorus content. The leached plants contained 3.7 percent ash and 0.17 percent phosphorus. The ash and phosphorus of nonleached plants was 11.4 percent and 0.53 percent. The leached plants burned readily, but the non-leached would not sustain flaming. Philpot (1968) found a direct relationship between pyrolysis rate, volatile production, and other thermal characteristics and the effective mineral contents of several species of plant material.

We determined the ash, potassium, and phosphorus content of chamise from samples of different sized materials. All of these chemical components decreased as the size of material increased *(table 6).*

The ether extractives generally have a much higher heat value than other wood constituents. Thus, if they are present in sizeable amounts they can significantly affect the heat value of a fuel.

Philpot (1969a) analyzed samples from the shrubs used in this study along with additional samples from the same area. He found that ether extractives from the foliage varied from about 8 percent to nearly 12 percent of the foliage weight. The amount of extractives in the woody material was less–ranging from 3.4 percent to 8.8 percent. Heat values for the extracted materials as high as 17,378 B.t.u./lb. for the foliage and 24,533 B.t.u./lb. for the woody material were found. These heat values are very much higher than for the plant parts as a whole *(table 5).*

Table 6– *Variation in chemical components of chamise, by size classes*

Item	Foliage	Material (inch) . . .		
		<1/4	1/4 -1/2	1/2 - 1
	Percent			
Ash	4.31	2.47	2.09	1.76
Potassium	.39	.22	.17	.16
Phosphorus	.089	.078	.047	.042

ESTIMATING PHYSICAL CHARACTERISTICS

Reliable estimates of the physical characteristics of fuels can be derived from direct measurements and analyses of fuel taken from small areal plots. But estimates obtained in this way are time consuming–and time is not available when the information is needed immediately, as for control operations on a going fire. Then means of obtaining approximations of the fuel characteristics quickly are much needed.

Some techniques for estimating the physical characteristics of chamise have been worked out, and will be described here. It must be kept in mind, however, that the data given here were drawn from the shrubs analyzed in this study.

Fuel Surface Area

The surface area of a natural fuel is perhaps the most difficult of the fuel parameters to measure or estimate. As previously described, in this study the woody material as well as the foliage was assumed to have a smooth-surfaced geometrical shape from which the area was calculated. However, the surface of wildland fuels is seldom smooth, but is usually fissured and has numerous protuberances. Also different fuel particles vary considerably in conformation. Therefore the assumption tends to result in under-estimation of the actual surface area. Hence the fuel surface area determined for chamise must be considered only an approximation of the actual area.

A large part of the fuel surface area in chamise was found to be in the smaller fuel size classes—most of it in the foliage. Since the foliage grows chiefly on the small twigs, the amount of material in the smallest size class also tended to increase with increasing amounts of foliage. For these reasons the surface area (sq. ft.) per pound of fuel, A_f, was correlated with the proportion of the shrub in foliage to provide a means for estimating the fuel surface area. This gave a prediction equation of the form:

$$A_f = 64.96\ P_f^{.8945}$$

in which P_f is the proportion of the shrub volume in foliage *(fig.* 7).

Use of either the curve or equation permits an approximation of the total fuel surface area from the proportion of foliage and the fuel loading. The surface-to-volume ratio can then be calculated from the equation:

$$\sigma = A_f d$$

in which d is the average density of the shrub.

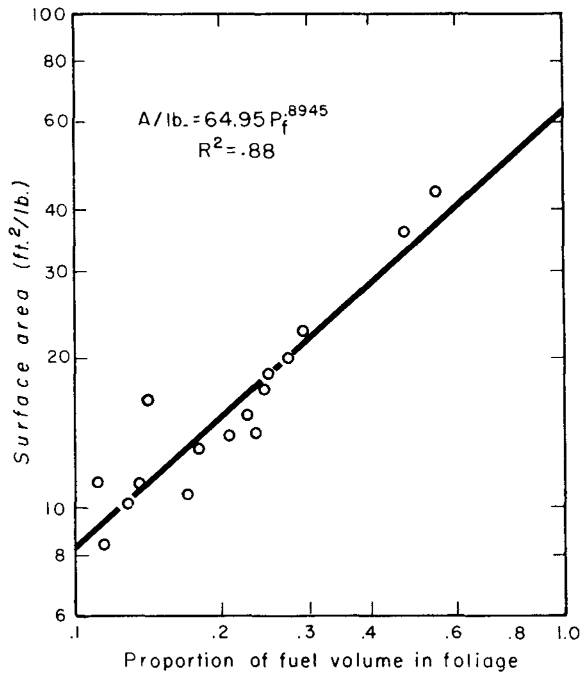


Figure 7–*Total fuel surface area of chamise is correlated with proportion of the shrub in foliage*

Fuel Loading, Packing Ratio, Density

Estimation of any one of these parameters is possible if the others are known, along with the fuel bed height. As we have seen, fuel loading (W_a) is the fuel weight per unit of fuel bed area; fuel density (d) is the weight of a unit volume of fuel, and the packing ratio (β) is the volume of fuel per unit volume of fuel bed. These definitions can be expressed algebraically as follows:

$$W_a = W/A$$
$$d = W/V_f$$
$$\beta = V_f/V_b$$

in which A = fuel bed area, V_f fuel volume, V_b = fuel bed volume, and W = fuel weight.

Fuel loading is dependent upon both fuel density and the packing ratio. If we divide fuel loading (W_a) by the fuel bed height (h), then we can write the equation:

$$W_a/h = d\beta$$

or more simply

$$W_a = hd\beta.$$

Thus, if any three of these fuel parameters are known, the fourth can be calculated. Fuel bed height can generally be obtained with little difficulty by direct field measurement. The other parameters are more difficult to measure directly, and sampling, estimating, or some other means of approximation are usually necessary.

The chief causes of variation in the average density of the fuel material in chamise were found to be the relative amount of dead material and the proportion of the shrub in foliage. Average fuel densities for the different proportions of these fuel components have been calculated *(table 7).* Estimates may be made from the table for the variations likely to be encountered.

To obtain the packing ratio, we must know the fuel loading and fuel density, or the fuel volume. Since it is impractical to measure either fuel weight or fuel volume on a full-scale basis, sampling is necessary. The samples may be individual shrubs as in the present study, or plots of known area.

Where an estimate of the packing ratio or fuel loading is needed immediately, as for fire behavior prediction on a going fire, the sampling procedure is not feasible. Skill in visually estimating fuel loading can be developed with practice and observation of fuel beds of known loading, and this method of estimating fuel loading is frequently used. From such estimates, the fuel density, and the fuel bed height, calculations of the packing ratio is then possible.

For the 16 shrubs analyzed, the packing ratio

Table 7–*Average fuel density for chamise, by percent of volume dead*

Percent foliage (vol.)	Percent dead (volume) ...										
	0	10	20	30	40	50	60	70	80	90	[1]100
	Lb./cubic ft.										
0	46.0	46.2	46.5	46.8	47.0	47.2	47.5	47.8	48.0	48.2	48.5
10	43.6	43.8	44.0	44.3	44.5	44.7	45.0	45.2	45.4	45.6	46.0
20	41.2	41.4	41.6	41.8	42.0	42.2	42.4	42.6	42.8	43.0	43.4
30	38.8	38.9	39.2	39.4	39.5	39.6	39.8	40.1	40.2	40.3	40.9
40	36.4	36.5	36.7	36.9	37.0	37.1	37.3	37.5	37.6	37.7	38.4
50	34.0	34.1	34.2	34.4	34.5	34.6	34.8	34.9	35.0	35.1	35.9
60	31.6	31.7	31.8	31.9	32.0	32.1	32.1	32.3	32.4	32.5	33.3
70	29.2	29.3	29.4	29.4	29.5	29.6	29.6	29.7	29.8	29.9	30.8

[1] Foliage density adjusted to dry volume.

varied widely, ranging from 0.00422 to 0.00068. Differences in packing ratios among the shrubs were visually apparent, suggesting that ocular estimates of the packing ratio might be practical. If the packing ratio can be estimated, then fuel loading can be calculated.

Techniques for estimating the packing ratio have not been developed or tested. Photographs of chamise of known packing ratios would aid the estimator in determining appropriate values. Whether estimates of packing ratios or fuel loading would produce the most accurate result also is not known. However, since fire behavior is sensitive to both fuel loading and packing ratio, both parameters are essential to fire behavior prediction and evaluation and must be obtained in some way.

Critical Fuels

Earlier it was indicated that in most chaparral fires only the fuel less than one-half inch in diameter usually burns. Estimates of the characteristics of these "critical" fuels are thus likely to be of more importance for many purposes than is the total amount of fuel. To obtain the loading of critical fuels, the same equation may be used as for total fuel loading. However, both the average fuel element density (d) and the packing ratio (β) will be different. In the study, average fuel densities for different proportions of dead material and foliage were calculated in the same manner as for the total fuel, except that only woody material one-half inch or less in diameter was included in the calculations *(table 8).*

Packing ratios for the fuel up to one-half inch in diameter (including foliage) were also determined. In making visual estimates of packing ratios, the estimator will probably be influenced strongly by the critical fuels. Most of the foliage and fine material in chamise is on the exterior of the shrub and it is this fuel that gives the shrub the appearance of being dense or sparse. Thus visual estimates of packing

Table 8–Average *fuel density for critical fuel in chamise, by percent of volume dead*

Percent foliage (vol.)	Percent dead (volume) . . .										
	0	10	20	30	40	50	60	70	80	90	[1]100
	Lb./cubic ft.										
0	44.0	45.2	45.5	45.9	46.2	46.5	46.8	47.1	47.5	47.8	48.1
10	42.6	42.9	43.2	43.5	43.8	44.0	44.3	44.6	45.0	45.2	45.6
20	40.3	40.6	40.8	41.1	41.4	41.6	41.8	42.1	42.4	42.6	43.1
30	38.0	38.2	38.4	38.7	38.9	39.2	39.4	39.6	39.9	40.1	40.6
40	35.7	35.9	36.1	36.3	36.5	36.7	36.9	37.1	37.3	37.5	38.1
50	33.4	33.6	33.8	34.0	34.1	34.2	3.44	34.6	34.8	34.9	35.6
60	31.2	31.3	31.4	31.6	31.7	31.8	31.9	32.0	32.2	32.3	33.2
70	28.9	29.0	29.0	29.2	29.3	29.4	29.4	29.5	29.7	29.7	30.7

[1] Foliage density adjusted to dry volume.

ratios are likely to be more accurate for the critical fuels than for total fuel for shrubs like chamise. Packing ratios for the critical fuels were considerably smaller than for the total fuel as might be expected:

Shrub (No.):	Packing ratio	Fuel bed porosity
1	0.00163	613
2	.00020	1,031
3	.00180	556
4	.00240	417
5	.00064	1,562
6	.00129	775
7	.00097	1,031
8	.00035	2,857
9	.00046	2,174
10	.00058	1,724
11	.00097	1,031
12	.00155	645
13	.00321	312
14	.00374	267
15	.00193	518
16	.00098	1,020
Average	.00142	1,033

Fuel surface area for the critical fuel was correlated with the proportion of the shrub volume in foliage. This gave a curve similar in form to that obtained for the total fuel area *(fig. 8)*. For calculation of the surface-to-volume ratio, the same equation as for total fuel may be used.

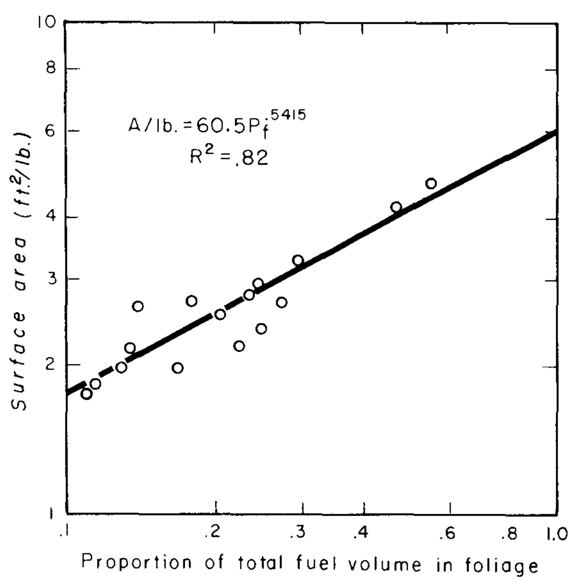


Figure 8–*Surface area of critical fuels in chamise is correlated with the proportion of the shrub volume in foliage.*

The preceding techniques for estimating fuel surface area and fuel loading for both total and critical fuels assume full coverage of the ground area by fuel. If clear spaces exist in the area of interest, then the estimates must be reduced in proportion to the area that is not fuel covered.

Dead Fuel

The amount of dead fuel in chamise can be expected to vary with the age of the plants and with the environmental stresses to which it has been subjected. In southern California, drought and air pollution have been observed to have a marked effect in killing all or parts of chaparral shrubs. Insects and disease also take their toll.

The chamise stand sampled was essentially even-aged. Although the amount of dead fuel varied considerably, the proportion of dead fuel did not show any strong relationship with other fuel parameters. Thus estimates of the proportion of dead fuel must be made from direct measurements or visual observations.

Moisture Content

Live and dead fuels occur naturally in a mixture for many of our wildland fuels, and each has a separate pattern of variation. The effect of the moisture content of dead fuels on fire has been studied extensively. But little is known of the effect of moisture content of living fuel, and even less about that of mixtures of live and dead fuel.

Direct fuel-moisture determination is a time-consuming laboratory procedure. Since moisture content can change quickly, particularly in dead fuels, laboratory moisture determinations are not practical for predicting probable fire behavior for an immediate situation, and indirect means are required. For dead fuels moisture content is estimated from observations of relative humidity, temperature, precipitation, etc., or by some analog device such as the fuel moisture sticks used in many danger rating systems. For reliable estimates, the relationships between actual fuel moisture and environmental conditions or the analog device must be known. Unfortunately, these relationships have been determined for only a few wildland fuels, and chamise is not one of these.

Estimation of moisture in living fuels is largely an unsolved problem. For chaparral fuels in California an approximation of moisture content for fire danger rating purposes is obtained through use of the normal seasonal variation curve *(fig. 6)*. The approximation is crude, however, and not very well suited for fire behavior prediction.

In general, present means of estimating fuel moisture are not satisfactory for evaluating the fire potential for a given fuel situation. Since fuel moisture is known to have a pronounced effect on fire, more precise means of estimating it are badly needed.

Chemical Composition

Although chemical composition is very difficult to estimate, this fuel characteristic cannot be neglected. Research has indicated that for chamise, at least, the chemical composition may change significantly during the year.

There is likely to be some variation from place to place, depending upon soil and climatic conditions, but chemical composition and its seasonal variations are probably highly species dependent. The variation between species is likely to be much more important than the variation within a species. Determination of the chemical composition of a fuel requires complicated laboratory procedures, and hence cannot be accomplished in the field. However, once the chemical composition and seasonal variation for a representative sample of a given species are established, this information can usually be applied generally to the species.

Heat Content

The heat content does not vary much within a given species, and the variation between species is not great for most wildland fuels. The heat content of chamise does vary with the season of the year as a result of the change in chemical composition. If this effect is found to be important, then it must be included in evaluating the fuel in terms of its fire potential. Like chemical composition, the measurement of heat value is a laboratory procedure. But since areal variations are likely to be small, values found for the species can be applied generally.

It is no revelation that chamise will burn hot and fast. Firefighters have been aware of this for many years. The relatively large amount of small material–much of it dead–loosely arranged in the fuel bed gives chamise a large surface-to-volume ratio and a low packing ratio. These factors are conducive to a rapid rate of energy release. The seasonal pattern of living fuel moisture and amount of ether extractive materials with their high heat content makes chamise most flammable in late fall. Traditionally, in southern California where chamise predominates, the worst fire weather also occurs at the same time. Thus the physical characteristics of chamise and the weather combine to make the reputation of chamise as one of the most hazardous fuels a well deserved one.

SUMMARY

Countryman, Clive M., and Charles W. Philpot.
1970. **Physical characteristics of chamise as a wildland fuel.** Berkeley, Calif., Pacific SW. Forest & Range Exp. Sta., 16 p., illus. (USDA Forest Serv. Res. Paper PSW-66)

Oxford: 176.1 *Adenostoma fasciculatum:* 431.2.
Retrieval Terms: Adenostoma fasciculatum; burning characteristics.

Predicting fire behavior is highly dependent upon knowledge of fuel characteristics. Chamise *(Adenostoma fasciculatum),* one of the most hazardous wildland fuels in southern California, is well known to burn hot and fast. Why it does so was determined in an analysis of 16 shrubs from the North Mountain Experimental Area, 30 miles east of Riverside, California.

Chamise has physical characteristics that are conducive to a rapid rate of energy release. The relatively large amount of small material–much of it dead–loosely arranged in the fuel bed gives this shrub a large fuel surface area compared to fuel volume, and an openly arranged fuel bed. The seasonal pattern of moisture in living fuel and amount of ether extractives with their high heat content makes chamise most flammable in late fall, when fire weather in southern California becomes the most hazardous.

Reliable estimates of the physical characteristics of fuels can be derived from direct measurements and analyses of fuel taken from sample plots. But estimates obtained in this way are time consuming, and means of approximating fuel characteristic values are needed. Techniques for estimating some of the characteristics of chamise have been worked out.

The fuel surface area for both the total fuel array

or the critical fuels (fuels one-half inch in diameter or less) is correlated with the volume of foliage. Square feet of surface area per pound of fuel (A/lb.) can be obtained from the equations:

Total fuel

$$A/lb. = 64.95\ P_f^{.8945}$$

Critical fuel

$$A/lb. = 60.50\ P_f^{.5415}$$

in which P_f is the proportion of the fuel volume in foliage.

Fuel loading per unit area (W_a) and packing ratio (β), or fuel bed compactness, can be obtained from the basic equation:

$$W_a = hd\beta,$$

The fuel height (h) can be obtained readily by direct measurement. Fuel density (d) is dependent upon the proportion of foliage and amount of dead fuel in the array. Tables of average values of fuel density have been worked out for the range of amounts of foliage and dead fuel likely to be encountered in chamise. For approximations, visual estimates of fuel loading or packing ratio appear to be feasible.

LITERATURE CITED

American Society for Testing Materials.
1966. **Method of test for gross calorific value of solid fuel by adiabatic bomb calorimetry.** D 2015-66. Philadelphia, Pa.

Broido, A., and Maxine A. Nelson.
1964. **Ash content: its effect on combustion of corn plants.** Science 146(3644): 652-653.

Countryman, Clive M.
1969. **Project Flambeau...an investigation of mass fire (1964-1967).** Final Report--Volume I. U.S. Forest Serv. Pacific SW. Forest & Range Exp. Sta., Berkeley, Calif. 68 p., illus.

Curry, John R., and Wallace L. Fons.
1938. **Rate of spread of surface fires in the ponderosa pine type of California.** J. Agr. Res. 57:239-268.

Fielding, J. M.
1952. **Moisture content of trunks of Monterey pine trees.** Australian Forestry 16(1):3-21.

Firestop.
1955. **Seasonal variation in green foliage moisture content for four southern California chaparral species.** Firestop Progress Rep. 6 U.S. Forest Serv. Calif. Forest & Range Exp. Sta., Berkeley, Calif. 7 p., illus.

Fons, Wallace L., H. D. Bruce, W. Y. Fong, and S. S. Richards.
1960. **Project fire model-summary progress report.** U.S. Forest Serv. Pacific SW. Forest & Range Exp. Sta., Berkeley, Calif. 56 p., 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. & Chem 42:10, 2130-2133, illus.

Hanes, Ted L.
1965. **Ecological studies on two closely related chaparral shrubs in southern California.** Ecol. Monogr. 35: 213-235.

Hawley, L. F.
1926. **Theoretical considerations regarding factors which influence forest fires.** J. Forestry 24(7): 756-763.

Kozlowski, T. T., and F. X. Schumacher.
1943. **Estimation of stomated foliar surface of pines.** Plant Physiol. 18: 122-127.

Kumagai, S.
1962. **Estimation of surface area of akamatsu foliage.** Repub. of Kyshu Univ. of Forestry, Mo. 16, 1-8.

Madgwich, H. A. 1.
1964. **Estimation of surface area of pine needles with special reference to *Pines resinosa.*** J. Forestry 62: 626.

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

Olsen, J. M.
1960. **1959 green fuel moisture and soil moisture trends in southern California.** U.S. Forest Serv. Pacific SW. Forest & Range Exp. Sta. Res. Note 161, 8 p., illus.

Philpot, Charles W.
1963. **The moisture content of ponderosa pine and whiteleaf manzanita foliage in the central Sierra Nevada.** U.S. Forest Serv., Pacific SW. Forest & Range Exp. Sta., Res. Note PSW-39, 7 p., illus.

Philpot, Charles W.
1968. **Mineral content and pyrolysis of selected plant material.** USDA Forest Serv., Intermountain Forest & Range Exp. Sta. Res. Note INT-84, 4 p.

Philpot, Charles W.
1969a. **The effect of reduced extractive content on the burning rate of aspen leaves.** USDA Forest Serv., Intermountain Forest & Range Exp. Sta. Res. Note INT-91, 2 p.

Philpot, Charles W.
1969b. **Seasonal change in heat content and amount of ether extractives in chamise.** USDA Forest Serv., Intermountain Forest & Range Exp. Sta. Res. Paper INT-61, 10 p.

Rothermel, Richard C., and Hal E. Anderson.
1966. **Fire spread characteristics determined in the laboratory.** U.S. Forest Serv., Intermountain Forest & Range Exp. Sta. Res. Paper INT-30, 34 p., illus.

Sampson, Arthur W., and Beryl S. Jespersen.
1963. **California range brushlands and browse plants.** Univ. of Calif., Div. Agr. Sci. Manual 33, 162 p., illus.

GPO 980-635

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

. . . Conducts forest and range research at more than 75 locations from Puerto Rico to Alaska and Hawaii.

. . . Participates with all State forestry agencies in cooperative programs to protect and improve the Nation's 395 million acres of State, local, and private forest lands.

. . . Manages and protects the 187-million-acre National Forest System for sustained yield of its many products and services.

The Pacific Southwest Forest and Range Experiment Station

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

Countryman, Clive M., and Charles W. Philpot.

1970. **Physical characteristics of chamise as a wildland fuel.** Berkeley, Calif., Pacific SW. Forest & Range Exp. Sta., 16 p., illus. (USDA Forest Serv. Res. Paper PSW-66)

Chamise shrubs in southern California were analyzed for the physical characteristics known to affect fire behavior, such as density, fuel loading, and fuel bed porosity. Considerable variation was found, but results are helpful in developing estimates of chamise fuel characteristics for fire control under field conditions.

OXFORD: 176.1 *Adenostoma fasciculatum:* 431.2.

RETRIEVAL TERMS: Adenostoma fasciculatum; burning characteristics.

Countryman, Clive M., and Charles W. Philpot.

1970. **Physical characteristics of chamise as a wildland fuel.** Berkeley, Calif., Pacific SW. Forest & Range Exp. Sta., 16 p., illus. (USDA Forest Serv. Res. Paper PSW-66)

Chamise shrubs in southern California were analyzed for the physical characteristics known to affect fire behavior, such as density, fuel loading, and fuel bed porosity. Considerable variation was found, but results are helpful in developing estimates of chamise fuel characteristics for fire control under field conditions.

OXFORD: 176.1 *Adenostoma fasciculatum:* 431.2.

RETRIEVAL TERMS: Adenostoma fasciculatum; burning characteristics.