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Burning by Prescription in Chaparral

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CHAPARRAL

In 1977, the Forest Service, U.S. Department of Agriculture, established a research and development program at this Station titled "Vegetation Management Alternatives for Chaparral and Related Ecosystems." This 5-year program, with headquarters at Riverside, California, is an intensive effort to develop, test, and demonstrate a wide range of operations for maintaining or increasing the productivity of chaparral and related ecosystems in southern California.

Cover: Pictured, upper left and continuing clockwise, is chaparral—the fuel for wild and prescribed fires. The photos on the right show ignition; across the bottom, prescribed burns are underway; and at left, the burn along a fuelbreak is complete. The center photo shows maintenance burning.

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PREFACE

This paper is an attempt to put together what is known about prescribed burning in the chaparral ecosystems. It also draws upon experience from related ecosystems. Work done over a period of 20 years by members of the Fuel-break Project and the more recent Chaparral Management Research and Development Program, both under the Pacific Southwest Forest and Range Experiment Station, is summarized, and other pertinent findings reported in the literature are also included.

The first part of this paper gives a general overview of the procedures necessary to plan, carry out, and evaluate a prescribed burning project. The second part discusses in considerable detail the information that has been gathered from research and experience to guide decisionmaking at each step of the procedure. At appropriate points, specific recommendations are made. Future practice and research in this field will fill in some of the gaps in the information we have—many such gaps are indicated in the discussion—and allow additional recommendations to be made.

Although all planning considerations are discussed at least briefly, emphasis is on the burn prescription. Most fuel managers and fire management officers who have adopted or been assigned prescribed burning projects have had more problems with prescription development than with all of the other phases of prescribed burning. They have been generally comfortable with equipment, suppression of escapes, mopup, and other fire management tasks that relate to suppression. They have not been equally comfortable with the tasks called for in planning to burn and lighting the fire. I believe that much more prescribed burning would be done if managers felt better able to predict what the fire might do under the existing or forecast weather and fuel conditions.

There has been a considerable lack of understanding of the effects of fuel and weather elements on fire. Most burning plans submitted to the Station's Forest Fire Laboratory, Riverside, Calif., have quoted prescription indexes from the California (now Pacific Southwest) Region's Supplement to the Forest Service Manual without attention to specific fuels and weather elements. This paper addresses that problem by discussing the various elements that affect fire behavior, then fitting them together into a list—a prescription—with which the prescribed burn manager can be comfortable. Much less space has been devoted to those areas where most fire management officers feel proficient.

Prescribed fire is a wildland management tool whose time has come. The National Park Service, U.S. Department of Interior, committed itself to prescribed burning several years ago. The present fire policy of the Forest Service makes provision for allowing prescribed fires to burn beyond 10:00 a.m. The California Department of Forestry is newly committed to prescribed burning projects covering more than 100,000 acres per year. This publication is intended to reinforce the increased emphasis on prescribed burning.

ACKNOWLEDGMENTS:

Many knowledgeable people in research and in fire management agencies have reviewed this paper. Reviews by representatives of the California Department of Forestry and the Forest Service, U.S. Department of Agriculture, were particularly valuable. For all these, I am deeply grateful.

IN BRIEF

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Retrieval Terms: prescribed burning, brushland burning, chaparral, fuel moisture content

Prescribed burning is the application of fire to wildland fuels under such conditions of weather, fuels, and topography that specific objectives are accomplished safely. Prescribed burn objectives in chaparral usually include hazard reduction and wildlife habitat improvement.

Environmental statements, reports, and burn plans are part of burn preparation and must be completed and approved well ahead of the anticipated burn date. The prescription is a prominent part of the burn plan. Fixed prescription elements such as the proportion of dead fuel in the stand and the slope percent should also be estimated or determined before the burn day. Then, ranges of those factors that change rapidly—the dead fuel moisture, relative humidity, windspeed and direction, and air temperature—can be established.

Test burns are a useful check on all the burn preplanning. The test burn is made on a small area where the fire can be observed before the main burn is ignited. With the test burn completed satisfactorily, the main burn can be ignited with greater confidence that all will go well.

When burn preparations are complete and fuel and weather are within prescription, highest priority should be given to getting the burning job done. If unexpected unfavorable burn conditions develop, the burn boss must modify or postpone the firing; otherwise, he will proceed to completion. Careful mopup and patrol of the perimeter are essential.

Burn evaluation is a final step that should improve prescribed burn performance. Weather and fuel conditions during the fire should be correlated with fire behavior and burn results as a check on the prescription and as a guide to future burning.

The elements of the burn prescription are drawn from a range of values for influences on fire behavior. Fuel conditions affect fire behavior as follows:

- The dead fuel moisture determines whether dead fuels will burn, or how intensely. Brush that is 20 to 30 percent dead should be burned at about 6 to 9 percent dead fuel moisture. This moisture percentage should increase as the proportion of dead fuel increases; brush stands about 50 percent dead should be burned with a dead fuel moisture of 10 to 15 percent. Fuel moisture of twigs ¼ to 1 inch (0.6 to 2.5 cm) in diameter is frequently estimated with fuel moisture sticks.
- Live fuel moisture can also be important, because considerable energy is required to drive off moisture before the live fuel will burn. For prescribed burning of mature brush, live fuel moisture should be 60 to 75 percent. As the fuel moisture drops below 60, the chaparral burns more and more violently. If the live fuel moisture is above 85 percent, little burning can be accomplished.
- Because dead fuel carries the fire in chaparral and live fuel absorbs energy as it is dried, the ratio of dead-to-live fuel in the stand is obviously important. Chaparral less than 20 percent dead seldom burns under prescribed fire conditions, and chaparral less than 25 years old is usually less than 20 percent dead. Brush 35 to 50 years old and 30 to 45 percent dead is ready for prescribed burning. Decadent or treated brush that is 45 to 100 percent dead can be expected to burn with intense fire unless other factors, such as moisture content, limit the rate of combustion. Fire behavior studies indicate that fire is more and more intense as the amount of available fuel increases, and as the depth of the fuel bed increases. About 70 to 80 percent of small-stemmed shrubs such as chamise and *Salvia*, and only about half the volume of shrub species with stems of larger diameter, is available fuel.
- Chemical content of fuels is not usually considered in most planning for a prescribed burn, but species whose dry weight contains more than 7 percent ether extractive products tend to burn more fiercely than those containing less than 7 percent. Inorganic or mineral constituents tend to slow down combustion.

Weather elements are as important as fuel conditions in prescribed burning. Most relevant weather elements are measurable at the burn site or can be obtained from National Weather Service forecasters.

- Wind is the factor most difficult to forecast accurately and the local element causing fire bosses the most problems. Winds should not be more than 10 mi/h (16 km/h) for burning chaparral, and 4 to 8 mi/h (6.4 to 12.8 km/h) is usually about right. Some wind is needed or fire will not spread unless terrain is steep.
- Relative humidity must be considered in prescribed burning because of its effect on moisture content of small dead fuels. If relative humidity is less than 50 percent for one to several hours, fine fuel moisture will be less than 10 percent and the fuel will probably burn readily or intensely. Fine fuel moistures of 10 to 20 percent occur when the relative humidity has been 60 to 100 percent, particularly when temperatures are low. Relative humidity changes rapidly as temperature rises or falls. The effects of changes in elevation are important if the differences are 2000 ft (610 m) or more. Mature or decadent stands of chaparral that are one-third dead should be burned at 25 to 35 percent relative humidity.
- Air temperature affects relative humidity, and warm fuels burn more readily than cool, damp fuels. The likelihood of

spotting increases above 75° or 80° F (24° or 27° C). Damage to tree canopies is greater if the temperature is higher than 70° F (21° C). A temperature range of 60° to 80° F (15° to 27° C) is best for burning standing chaparral.

Several other factors should be considered in the burn prescription:

• *Topography*—Irregular terrain affects wind patterns, usually making fire control more difficult. Elevation influences time of year when growth starts and herbaceous vegetation matures. Fuels on southerly aspects are drier than those on northerly exposures; fires set on south-facing slopes can often be counted on to go out at the ridgetop during the winter and spring. Slope affects fire spread much as wind does; fire spread will roughly double for each 25-percent slope increase.

• *Time of burn*—Any time of year is suitable for prescribed burning, although prescription conditions exist only infrequently during summer and fall. Probably the safest time of day to burn, if conditions are within prescription limits, is midday to late afternoon.

In addition to the burn prescription, planning addresses other concerns. Brush that is less than 20 percent dead, including most chaparral less than 25 years old, can seldom be burned satisfactorily without a crushing or chemical spray treatment. Any method of crushing that breaks off branches and compacts shrubs is satisfactory. Spraying with 2,4-D or other herbicide can be done during late spring, with burning to follow during fall or winter.

Most prescribed burns in chaparral use the perimeter method of firing. Firing starts at the upper elevations and upwind, and proceeds across the top, down the sides, and across the bottom of the burn area. Strip headfiring, center perimeter firing, and area ignition may be used at times. The helitorch promises to be a useful new tool for igniting brush burns.

The Clean Air Act and subsequent State legislative response place restrictions on prescribed burning, such as the requirement that smoke dispersion be away from sensitive areas. The burn planner should be familiar with these laws. Combustion is most nearly complete and there is less smoke when dry or nearly dry fuels are burned. Backing fires produce less smoke than headfires. Smoke released above an inversion will generally disperse, but smoke released under an inversion accumulates and fills the atmosphere close to the ground.

Inexperienced prescribed burn managers tend to use more manpower and equipment, and build wider control lines than experienced managers. Several National Forests have burned south slope vegetation during the winter without control lines.

The prescribed burn manager must take advantage of National Weather Service forecasts, and he must supplement this with weather data collected at the burn site during 2 weeks prior to the burn.

The National Fire Danger Rating System was not designed for prescribed burning, but it does give indication of ignition hazard and fire spread. Methods of interpreting the NFDRS for prescribed burning are being developed.

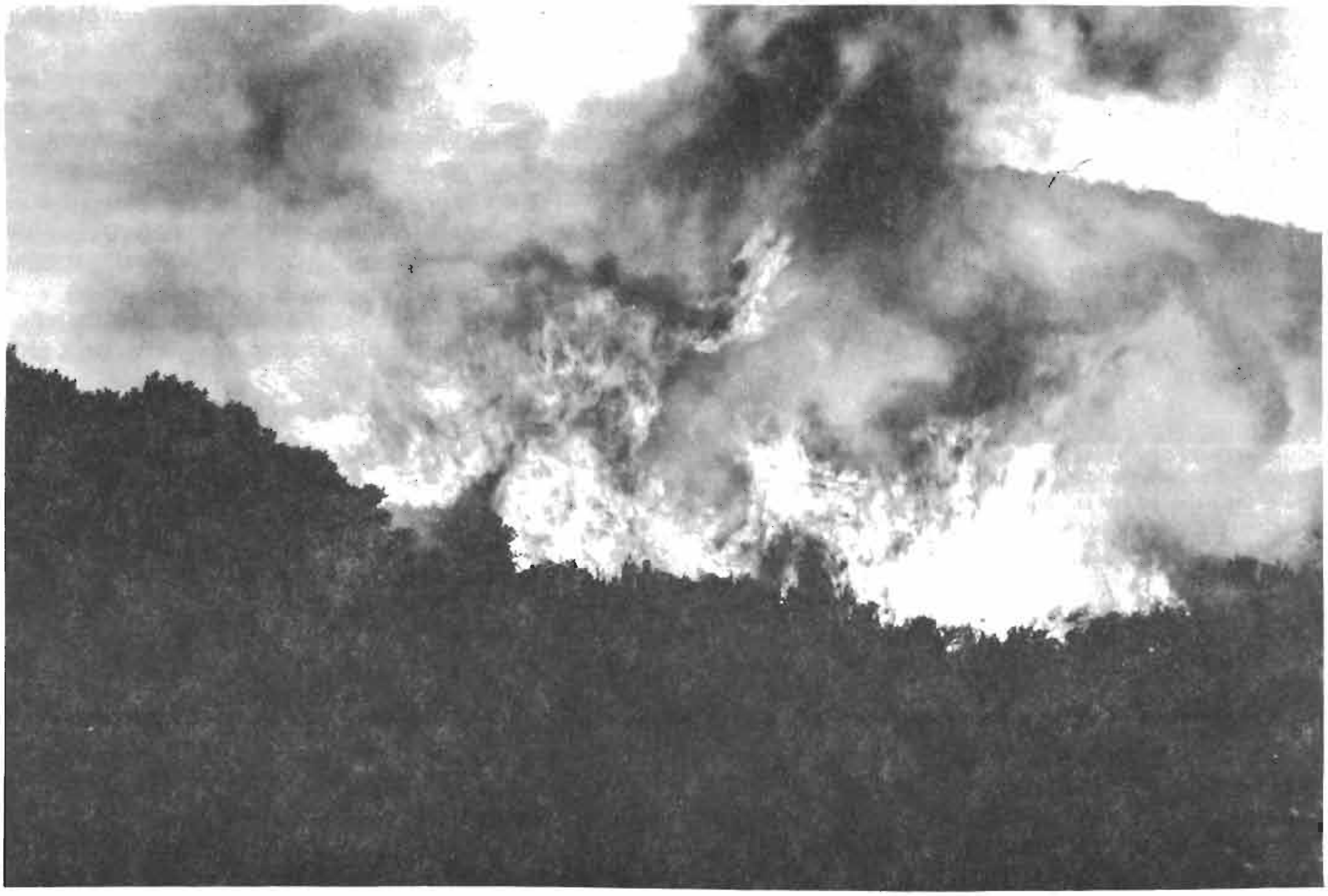

Figure 1—The most damaging wildland fires occur when fuels are very dry, temperature and windspeed are high, and relative humidity is low.

The concept of burning chaparral as a deliberate management action is not new, but it still carries some uncomfortable associations. Some of these may be removed by considering the difference between wildfire and prescribed burning. Damaging wildfires in chaparral usually occur during periods when fuels are very dry, relative humidity is very low, and air temperature and windspeeds are high (*fig. 1*). Such wildfires are frequently disastrous for soil as well as vegetation; they remove plant litter, and are followed by soil erosion over extensive areas (*fig. 2*). The site is degraded as fine soil particles, humus, and nutrients are removed. Prescribed burns, on the other hand, are conducted under more moderate burning conditions. The manager is generally satisfied with removal of a small amount of fuel, less heat is generated, and there is less site disturbance, over a more limited area, than during wildfires.

Planned burning of chaparral fuels for range improvement has been practiced by California ranchers under permit from the California Department of Forestry since 1945. In 1977, this controlled burning covered more than 2 million acres (810,000 ha) (Calif. Dep. Forestry 1978). Burns were planned at winter meetings of county range improvement organizations, and summer burn dates were assigned to ranchers who requested them. The rancher completed preparations for controlled burning, and with the help of other ranchers and friends, conducted the burn. Results were variable and some fires escaped control, but burning costs were minimal.

Research and administrative personnel of State and Federal agencies frequently advocated more preparation for burning, and more follow-up seeding, than was usually done on rancher burns. They advised more attention to fuel preparation and to confining burns to conditions of weather and fuel moisture that would allow safe burning, the accomplishment of burning objectives, and minimum site damage at reasonable cost. This more exacting or scientific employment of fire as a management tool has become known as "prescribed" burning.

Figure 2—Following wildfire in mountainous terrain, the exposed soil is frequently carried down into urban areas below.

PROCEDURES IN PRESCRIBED BURNING

Prescribed burning is the application of fire to wildland fuels under such conditions of weather, fuels, and topography that specific objectives are accomplished safely. Those who have conducted a prescribed burning project know that it begins long before the fire is lit, and does not end until long after the fire is out. In the following sections, the main concerns of the burn manager are described.

The preparations for a prescribed burn may include procedures not specifically discussed here, because they are part of broader management responsibilities. It is important to note, however, that such duties as writing environmental analysis reports and impact statements pertaining to the burn area, getting the necessary approval at higher levels of authority, and coordinating with other disciplines are all essential to success of a prescribed burning project on public lands. These jobs should be completed well in advance of the burn date. Many times, fire and fuels management personnel have watched in frustration as good burn opportunities went by, sometimes for an entire year, because the required paperwork was not completed and approved.

Preparing the Burn Plan

A written burning plan, prepared by knowledgeable people, is needed for each prescribed burn. The plan can be a simple document if burn personnel are experienced and competent; otherwise it may need to be complex so that important points will not be overlooked. The burning plan should be clearly stated and should include the following items:

Burn objectives—Objectives influence the size of the burn, preparation of the burn prescription, and the general planning and conduct of the burn.

Area map—This should include boundaries; generalized topography; roads and directions of travel; location of water supplies; burn compartments if used; problem areas; sector assignments for firing, and for suppression crews; and any areas to be protected.

Description of the burn unit and surrounding area—This should cover the items shown on the map, and also the vegetation.

Burn prescription—This should be an appraisal of the influences on fire behavior (fuels, weather, topography, etc.), giving acceptable ranges for each.

Approximate date and time of burn—These cannot be established precisely more than a day or two before the burn.

Ignition procedure—This depends on the topography, the prevailing winds, and the burn objectives.

Manpower and equipment estimate—These must be planned for, so they will be available when needed.

Burn publicity plan—This should indicate the audience for public statements and news releases—including supervisors, interested staff, cooperators, any individuals or organizations that may be affected by the burn, and the news media.

Line of authority—This should be clearly established, so that qualified people are in charge of all aspects of the burn.

Some of the items in the burn plan are discussed in greater detail in later sections of this paper. Others are briefly covered here.

Setting Objectives

A manager planning a prescribed burn should have in mind some desired accomplishments, some objectives to be attained by the project. For chaparral burning, the objectives are frequently wildfire hazard (fuel) reduction and wildlife habitat improvement (*fig. 3*). Vegetation may also be manipulated by fire to encourage palatable shrubs such as wedgeleaf ceanothus (*Ceanothus cuneatus* [Hook] Nutt.), to retard brush succession, to reduce undesirable herbaceous plants such as medusa-head grass (*Elymus caput-medusae* L.), or to prepare the site for planting trees or perennial grasses. Other prescribed burning objectives in chaparral might be to protect structures or valuable trees, ease access into brushfields for recreation or for livestock management, or increase water yield.

Only if the prescribed burn objective is clearly expressed, can a burning prescription to accomplish it be written. Here are some possible objectives:

- Run fire through two-thirds to three-fourths of the area within control lines, eliminating existing dead fuel in the 0- to 3-inch (0- to 7.6-cm) diameter class, removing the loose litter and part but not all of the compacted litter, and burning green twigs up to ¼ inch (0.6 cm) in diameter. Leave islands of unburned brush.

• Reduce the hazard to black oak and pine trees in the area so they can be expected to survive a wildfire.

• In a 100-acre (40-ha) area dominated by canyon live oak, remove the dead fuels up to ¾ inch (0.2 cm) in diameter, remove part of the leaf litter without exposing mineral soil, but kill no more than 30 percent of the canopy of the standing trees whose stems are greater than 3 inches (7.6 cm) basal diameter.

• Improve deer habitat by inducing new sprouts and encouraging ceanothus, and by temporarily increasing forb production, on burn areas of 5 to 20 acres (2 to 8 ha).

• Reduce brush fuels sufficiently to allow the area to be seeded with the rangeland drill.

Establishing Size of Burn

Prescribed burn acreage in chaparral depends on management objectives, and on such considerations as exposure, topography, need to complete the burn during one burning period, need for acreage accomplishment, location of existing fire barriers that can be used as firelines, and method of firing.

In general, the larger the burn area, the larger the ratio of burn area to perimeter, and the easier fire control tends to be. The cost per unit area burned is considered to be inversely proportional to the area of the burn, with costs rising steeply on small areas (Cheney 1978). Costs per unit area of rancher-controlled burns monitored by the California Department of Forestry tend to increase, however, when burn size exceeds 450 to 500 acres (180 to 200 ha) (Sampson and Burcham 1954).

Small burns are usually completed during one burning period; otherwise there is excessive expense for patrolling and the danger of unfavorable weather. If blocks are laid out so they can be ignited and the boundaries mopped up within 1 day, the burn size is usually limited to a range of 40 to 150 acres (16 to 60 ha), although, if terrain is suitable and holding lines are not a problem, several hundred acres can sometimes be burned. When the helitorch is used, much larger blocks can be planned, particularly in remote areas.

Writing the Prescription

The elements of a burn prescription are drawn from a range of values for various influences on fire behavior. These values can be expected to produce fire response at a given level of intensity, broadly estimated. That is, the fire may be of high, medium, or low intensity, depending on the values chosen for the prescription. The summary of values presented in *table 1* is appropriate for standing chaparral, and is based on the detailed discussion provided in a separate section. The values given should not be used for a prescription without preliminary review of the discussion, which includes both basic theory and practical advice drawn from research and experience. Important qualifications of the judgments represented in the table are provided, as well as a definition of the three levels of fire intensity.

Burning in Chaparral

Some of the values required for the burn prescription table are "fixed" and should be determined in advance. The proportion of dead fuel can be estimated from the stand age, but a much better approach is to estimate it carefully onsite. Live

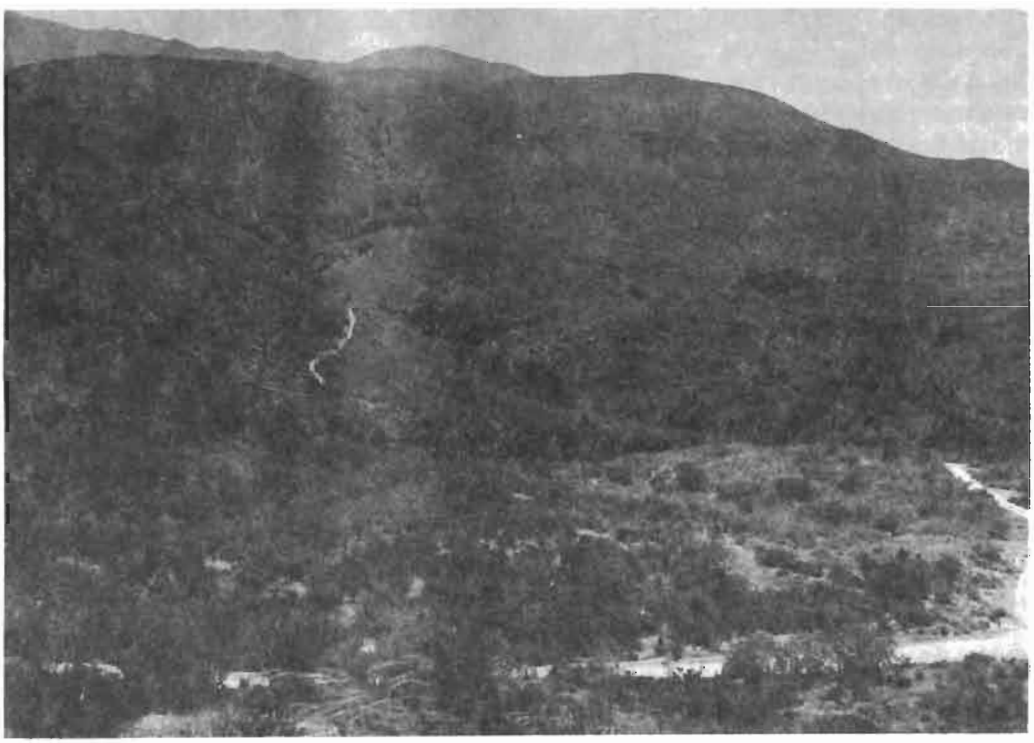

Figure 3—Burning objectives for this area might include creation of a mosaic pattern of uneven-aged stands, improvement of wildlife habitat, and protection of the oaks against wildfire.

fuel moisture trends can be estimated from the report titled "California Chaparral Live Fuel Moisture Conditions" (formerly "California Fire Weather Severity"), published every 2 weeks during the fire season by the Forest Service's Pacific Southwest Region (R-5). The live fuel moisture should be determined more precisely onsite during the weeks just before the burn, so that adjustments can be made, if necessary, in the prescription of acceptable humidity, temperature, and windspeed. Topographic features and available fuel quantity and continuity can be noted in advance. Important topographic features include aspect, slope, and canyons or other significant features that would affect fire behavior.

Once the fixed elements have been covered, acceptable values for the variable elements—the dead fuel moisture, relative humidity, windspeed and direction, air temperature, and time of day—can be selected as needed to safely accomplish the burn objectives. For example, assume that the burning objective is similar to the first objective described in Setting Objectives, "Run fire through two-thirds to three-fourths of the area within control lines. . . . Leave islands of unburned brush." This objective is likely to be accomplished if most prescription items are in the medium range or the low end of the high range of fire intensity, and if the brush is more than 30 years old. The additional qualifications, to burn only the 3-inch (7.6-cm) diameter or smaller dead material, if larger sizes are present, and only part of the litter, requires that the burn be made during the winter or early spring, after considerable rain or snow, but after a few days of dry weather so that the smaller fuels and upper duff will burn.

Let us further assume that the area to be burned is 90 acres (36 ha) of 30-year-old chaparral dominated by chamise. The aspect is predominantly southerly, although drainages create some east and west exposure. Slope is 10 to 25 percent (6° to 14°) on the lower slope, increasing to 45 percent (24°) just below the ridgetop firebreak. About 25 to 30 percent of the stand is dead. Brush stems in the chamise chaparral are mostly less than 3 inches (7.6 cm) in diameter, so burning is not restricted to a time when the larger fuels are wet through.

In *table 1*, we find prescription suggestions for our burn as follows:

Dead fuel (fuel stick) moisture	6 to 8 percent
Live fuel moisture	60 to 75 percent
Relative humidity	18 to 25 percent
Air temperature	60° to 80° F (15° to 27° C)
Windspeed	5 to 8 mi/h (8 to 13 km/h)

Table 1—*Influences on fire intensity as elements of a burn prescription for standing chaparral*

Indicators	Units	Values that produce given fire intensity response		
		Low	Medium	High
Fixed				
Total biomass	tons/acre	3 to 10	11 to 30	31 to 45
Available fuel	tons/acre	3 to 6	6 to 10	10 or more
Dead fuel	pct. of total	20 to 30	31 to 45	46 or more
Live fuel moisture	percent	90 to 76	75 to 60	59 to 45
Continuity of fuel	pct. cover	< 40	41 to 70	71 to 90
Slope	percent	0 to 19	20 to 40	41 to 70
Aspect		N, NE	E, SE, NW, W	SW, S
Season		Spring	Winter, early spring	Late summer, fall, early winter
Flammable chemical content		Low	Medium	High
Variable				
Dead fuel moisture when fuel is	pct. fuel stick			
20 to 30 percent dead		12 to 9	8 to 6	5 to 3
31 to 45 percent dead		18 to 12	11 to 7	6 to 5
46 to 65 percent dead		20 to 15	14 to 9	8 to 6
66 to 100 percent dead		30 to 19	18 to 11	10 to 8
Relative humidity when fuel is	percent			
20 to 30 percent dead		35 to 26	25 to 18	17 to 15
31 to 45 percent dead		45 to 36	35 to 24	23 to 18
46 to 65 percent dead		60 to 41	40 to 31	30 to 25
66 to 100 percent dead		75 to 41	40 to 36	35 to 20
Windspeed	mi/h	0 to 4	5 to 8	9 to 12
Air temperature	°F	20 to 59	60 to 80	81 to 95
Time of day		Early morning	Late morning, late afternoon	Early to mid-afternoon

The values for medium fire intensity in *table 1* will generally be adequate to accomplish objectives, but trade-offs can be made. For example, if slopes are gentle or brush is not continuous, higher windspeeds are needed to spread the fire. If the proportion of dead fuel is on the low side of the appropriate dead-live range, the dead fuel moisture and relative humidity prescription items might include the upper part of the high intensity range in compensation. If the live fuel moisture is above or below the desirable range, other prescription items can be adjusted.

It is important that the prescription not be extremely narrow, or the burning conditions will seldom be realized. It should be flexible enough to allow the fire boss to make adjustments if conditions change.

A desirable practice is to select several areas for prescribed burning, at different elevations, and, if possible, on different exposures. Then, if one area does not fit the prescription at a given time, another may do so. One location may be in fog while another at higher elevation is in bright sunlight, or one may be below an inversion layer while another is above it. (The Mendocino National Forest has found this procedure useful in their prescribed burning of wildlife habitat.)

A second approach to arriving at prescription elements for standing chaparral is the "alignment" method illustrated in *table 2*. A prescription number assigned on the basis of stand age, proportion of dead fuel, and fuel reduction objective is "aligned" with a corresponding number for a specified set of values for fuel moisture, windspeed, etc. Again, the proportion of dead material in the stand is dominant in determining the prescription. Brush stands with less than 20 percent dead fuel will not burn under moderate burning conditions. They must be treated with chemicals, or crushed. There is a rough correlation between age of stand and proportion of dead material, and this can be used as a guide, but the dead proportion should be directly estimated by careful examination in the field.

Table 2—*Examples of the alignment of brush stand and fuel objective with the burning prescription.* Method: To arrive at an approximate prescription, use the proportion of dead fuel and the fuel reduction objective of the burn to determine the prescription number, then find the column for the corresponding prescription number in the lowest table. The prescription will be a small range on either side of the values given (Prescription 3 would fall between 2 and 4, etc.)

Age of stand (years)	Proportion of dead fuel (percent)	Prescription number, by fuel reduction (percent)		
		75 or greater	50 to 75	Less than 50
7 to 20	5 to 20	1	1	1
20 to 35	20 to 30	2	3	4
35 or more	30 to 45	5	6	7
50 or more	45 to 65	8	9	10

	Prescription					
	2	4	5	7	8	10
Windspeed, mi/h	10	6	8	3	6	0
Relative humidity, percent	17	28	25	40	35	70
Air temperature, °F	90	65	85	60	75	40
Fuel stick moisture, percent	5	8	7	10	9	16
Live fuel moisture, percent	60	65	65	75	65	85

Note: Prescription 1 should include crushing, or spraying with herbicide. This brush is too green for successful prescribed burning. It may also be too flexible for successful crushing. Prescriptions 2 and 3 will also need treatment if the dead fuel is in the lower part of the range.

Burning Under Canopies

Underburning—the use of fire to remove fuels under trees—is sometimes necessary. Many fuel managers have learned to use fire under ponderosa pine and other trees in the mixed-conifer forest. Pine needles or bear clover (*Chamaebatia foliolosa* Benth.) or both, are the dominant fuels, and flames 1 to 2 ft (0.3 to 0.6 m) high can usually be maintained without damage to trees 6 inches (15 cm) in diameter or larger.

Underburning in the California oaks presents greater problems. California oaks, with the exception of coast live oak (*Quercus agrifolia* Née.) are thin-barked and sensitive (Plumb 1980). Their branches frequently sweep the ground, and chaparral grows around and under them. Consequently, using fire to remove fuels, without serious damage to oak tree canopies or stems, is a difficult task (*fig. 4*). Hand or mechanical removal of brush fuels in proximity to the oak groves, and pruning of the oaks themselves, are frequently needed before burning (Green 1980). If an area dominated by oak or tanoak (*Lithocarpus densiflora* Rehd.) has not burned for 40 years or longer, it is likely to contain dead fuel more than 3 inches (7.6 cm) in diameter that will burn with great intensity. Unless these fuels can be reduced manually or mechanically, burning should be done when the large fuels are thoroughly wet and will not burn; that is, in winter or early spring.

The following prescription for underburning can be used in the ponderosa pine forest. It is also suitable for oak, if some fuel reduction is done in dense stands by other methods:

	Values that produce a given fire intensity response		
Indicator:	*Low*	*Medium*	*High*
Dead fuel moisture, pct.	18 to 16	15 to 10	9 to 7
Live fuel moisture, pct.	90 to 76	75 to 60	59 to 45
Relative humidity, pct.	60 to 41	40 to 31	30 to 25
Air temperature, °F	20 to 39	40 to 70	71 to 80
Windspeed, mi/h	1 to 3	4 to 8	9 to 10

Making a Test Burn

When all preparations are complete, high priority can be given to accomplishing the burn on any date that meets the prescription requirements. This date is identified from National Weather Service forecasts and from monitoring of fuel and weather conditions onsite.

The number of days during a year when precise burn prescription requirements exist are relatively few, generally

Figure 4—To make the oak trees, and the house near them, relatively safe from wildfire would require pruning of the lower tree branches, hand cutting or tractor removal of brush from under and around the trees and house, crushing or disking a buffer strip, and prescribed burning of the treated fuel during late winter or early spring.

not more than 25 or 30 in the chaparral, because of prescription limitations and smoke management regulations. The number is further reduced because manpower is not available on weekends.

Johnson and Main (1978) tabulated 10 years of relative humidity, temperature, windspeed, and precipitation data from the Mark Twain National Forest in Missouri, and found that there were about 18 working days (Monday-Friday) per year with satisfactory burning conditions. Similar calculations can be made using data from any fire danger rating station. In Lake County, California, Biswell (1960) could broadcast burn from 47 to 53 days in the pine forest, and Schimke and Green (1970) reported an average of 25 days during the spring and 18 days during the fall when good broadcast burning conditions existed in the central California mixed-conifer zone.

Because suitable burn days are so few, anyone wanting to conduct a burn should have all environmental statements, burning plans, and other needed approvals well in advance of the suggested burn date. When the prescription conditions exist, the prescribed burn should have highest priority for personnel and equipment. Establishing alternate sites that have different prescription requirements or different prevailing conditions, and planning for possible night burning can increase the opportunities.

Before any fire is ignited, the burn boss should assemble and organize the crew early enough to allow a thorough orientation and briefing (Martin and Dell 1978[1]). Each crew member should understand his job, and also know what others will be doing. He should be aware of contingency plans and safety procedures. The fire boss should be aware of local weather, and should have a crew member or observer taking periodic observations. These are valuable for keeping everyone informed and also for evaluating the burn and sharpening the prescription for future burning.

A test burn will add to the confidence of the burn boss and the safety of the prescribed burn. The test should be made close to the main burn date, in a small area where fire behavior can be observed before the main fire is ignited, and where the fire can be extinguished readily if necessary. If the fuels, weather, and topography have been evaluated properly, and combined properly in the prescription, the test burn will confirm that the burn boss can go ahead with the main burn. If, however, all the fire behavior elements have not been properly evaluated, or if these elements have changed, then excessive flame length or lack of fire intensity and spread will tell the burn boss to postpone the main burn.

Test burns should generally be made during the time of day when the most severe burning conditions are expected, usually early afternoon. If the main prescribed burn is small enough, it can be completed in the same afternoon. If it is large, the test burn may have to be a day before the scheduled main burn.

If a test burn is ignited during the morning hours, it will reveal how the fire will burn at that time, but not necessarily how fire will behave later in the day. Grasses and small twigs, the 1-hour and 10-hour timelag fuels that become cooler and more moist during the night, may not burn well until they are warmed and dried by rising daytime temperatures and lower

[1]This reference includes detailed checklists for the burning plan and its execution.

humidities. Conversely, if the air is warm through the night, and relative humidity does not exceed 30 or 40 percent for long nighttime periods, a morning test fire might indicate that fuels would burn intensely immediately.

Conducting the Project Burn

When the test burn has been completed satisfactorily, the burn boss can order firing of the project burn, following the written plan prepared earlier. The dispatcher and other interested parties are notified. If weather conditions remain as predicted, the burn will be completed as scheduled. If unexpected, unfavorable burning conditions are encountered, the burn boss must decide whether to stop or modify the firing. Good communication between the burn boss, supporting supervisors, backup forces, and the dispatcher are essential.

Careful mopup and patrol of the perimeter are essential final steps of the prescribed burn process (*fig. 5*). Wildfires—some small and a few very large—have developed several days after prescribed burns. Usually, strong winds, accompanied by low humidities and high temperatures, fan pockets of smoldering fire in deep duff or punky logs, and without fire suppression, wildfire develops. These events may occur after several days of a warming trend following prescribed burning. Infrared detection scanners are useful for locating such smoldering fire.

Evaluating the Burn

If all participants in a prescribed burn are to improve their performances and if new people are to learn from those more experienced, a burn appraisal and summary are required. Burning prescriptions can be improved by correlation of records and observations during and after the burn with the associated weather and fuel conditions.

A good first step in observation is to have hygrothermograph charts made for a few days and nights before the burn, and to appoint someone with a belt weather kit to take temperature, humidity, and speed and direction of wind, and to measure fuel stick moisture before and during the burn. A continuously recording portable weather station is useful, and replaces some of the spot observation.

Ignition time and the time of other significant events during the fire should be recorded. Fire behavior should be observed, and notes taken on flame length and height, and scorch height if tree canopies are present. Fire spread rates can frequently be estimated or recorded as the fire moves between two points. The relation of any spot fires observed to conditions affecting fire behavior should be noted.

Answers to certain questions should help explain why the burn did or did not do what was expected.

Fuel consumption is an important concern. What twig size class of each important shrub species was removed? What percent of the area within control lines was burned? Were islands left unburned? Was all the ground litter consumed?

The success of the planning should be evaluated. Did the results achieved match those expressed in the burning objectives? Was adequate manpower and equipment on hand, or was there more than needed? Were the ignition tools adequate for the job and was the firing system adequate?

Prescribed burning in chaparral releases visible columns of smoke into the air. Did the smoke rise as a column into the upper air, or did it drift close to the ground surface? Did the smoke drift toward cities or other sensitive areas?

Figure 5—Mopup and patrol are part of every prescribed burn.

ELEMENTS OF THE BURN PRESCRIPTION

The experienced fire boss knows that many influences determine fire behavior during prescribed burns. Some of these influences are obvious, others are not. Fuel characteristics, weather conditions, and topography are primary considerations. Time of year and even time of day may determine whether the burn is a success or a disaster. Some understanding of all these influences can give the fire boss on a prescribed burn the confidence and knowledge needed for success.

The following discussions present information leading to general suggestions for burn prescriptions, and to some specific recommendations. The influences described primarily affect fire intensity and rate of spread.

Fuel Moisture

Lack of knowledge about fuel moisture conditions can mean time and effort wasted on unsuccessful burns. For example, attempts are sometimes made to burn brush with a low dead-to-live ratio and high green fuel moisture content—brush less than 20 years old. These attempts are seldom successful.

Moisture content is highly important in determining whether fuels will ignite and burn, and it strongly influences fire behavior. Heat from a fire or other ignition source must vaporize excess moisture and drive it off before sufficient heating for ignition and combustion can take place. Also, water vapor greatly reduces the radiation of heat from a flame and thus reduces the burning rate (King 1973, Countryman 1977b).

A fuel moisture content of 25 percent of ovendry weight is an approximation of the value above which fuels will not burn (Rothermel 1972), but this "moisture of extinction" varies with the type of fuel, fuel loading, size of firebrand, windspeed, and other factors.

Dead Fuel Moisture

Effect on Flammability—Several studies have dealt with the effects of moisture content on flammability of various dead fuels. Dead chaparral fuels in Arizona did not burn vigorously when fuel moisture was above 15 percent, and ceased to burn when fuel moisture reached 25 to 30 percent (Lindenmuth and Davis 1973). Dense mature southern California chaparral burned fiercely when dead twigs and litter contained 10 percent moisture, leading Green (1970) to suggest that dead fuel moisture content might be up to 15 percent at the time of a burn. Bentley and others (1971) specified not less than 7 percent dead fuel moisture for safe burning of manzanita chaparral in northern California. When they burned ground litter and standing brush that was more than 50 percent dead, with dead fuel moisture content at 14 percent, individual fire sets spread slowly and islands of unburned brush covered one-fourth the burn plot after the fire was out. During a prescribed burn on the Monterey Ranger District, Los Padres National Forest, dead branchwood under coast live oak burned well, but fires did not spread laterally, with 16 percent fuel moisture and no wind.

Fire did not burn eucalyptus litter when the moisture content was above 20 percent (Foster 1976). When underburning Douglas-fir forest in Oregon, Swanson (1974) found that a fuel moisture of 20 percent was maximum for fire spread and that 17 to 19 percent was borderline.

Mutch (1967) found that cheatgrass brome (*Bromus tectorum* L.) would ignite with a match, starting at about 30 percent moisture, but that it burned more and more readily with lower fuel moisture. Tobosa grass (*Hilaria mutica* [Buckl.] Benth.) and associated southwestern grasses burned satisfactorily at moisture contents between 12 and 25 percent (Britton and Wright 1971, Stinson and Wright 1969, Heirman and Wright 1973), but windspeeds were usually greater than 10 mi/h (16 km/h). During the burning of 41 test fires in grasslands, Sneeuwjagt (1974) found that if moisture content was greater than 15 percent, fire would not spread on level terrain with less than 3 mi/h (4.8 km/h) of wind.

Effect on Fire Spread—As fuel moisture goes up or down, burning intensity and fire spread rate change proportionately. In a laboratory test, matchsticks containing 10 percent moisture burned at just half the rate of ovendry matchsticks (King 1973). In ponderosa pine needle fuel beds, the rate of spread decreased by 4.23 percent for each 1-percent increase in fuel moisture (Rothermel and Anderson 1966). If we extend this relation beyond the limits of the experimental data, we find that fire in ponderosa pine needles apparently will not spread when the moisture content reaches 24 percent.

The Fireline Handbook (U.S. Dep. Agric., Forest Serv. 1975) indicates that fire spread will be slow in a fuel bed where moisture content is greater than 15 percent, but that fire spread rate increases rapidly as fuel moisture drops below 15 percent. Between 15 and 10 percent, the spread rate doubles; between 10 and 5 percent, the spread rate triples. The most rapid change in spread rate is in the 7- to 10-percent moisture range (U.S. Dep. Agric., Forest Serv. 1975).

When fuel moisture content is below 7 percent, a lowering of the fuel moisture by 2 percent will double the rate of fire spread in eucalyptus litter at a given wind velocity. A reduction of fuel moisture from 7 to 5 percent is equivalent to a rise in air temperature of around 30° F (17° C) if relative humidity remains constant, and a drop of around 15 to 20 percent in humidity if air temperature is held constant (McArthur 1967).

Ignition potential is determined more by fuel moisture content than by other fuel bed characteristics. During northern California tests, a shower of firebrands did not ignite windrowed brush with a 12 percent moisture content (Bentley and others 1971). At fuel moisture contents around 4 percent, even the smallest of burning embers has a high probability of starting new fires (McArthur 1967).

Fuel Stick Measurements—Fuel moisture can be determined by gathering samples of dead or live fuel, weighing them before and after drying in an oven, and expressing weight (moisture) loss as a percent of ovendry weight (Countryman and Dean 1979). This is an excellent procedure and should be used wherever possible for field work. A faster method is available, however, for estimating moisture in dead twigs about ¼ to 1 inch (0.6 to 2.5 cm) diameter; this is the fuel stick method (*fig. 6*).

Fuel moisture indicator sticks, as used in most Western forests, are a set of four ½-inch (1.3-cm) diameter ponderosa pine sapwood dowels spaced ¼ inch (0.6 cm) apart on two hardwood pins. The resultant "stick" is 2¾ inches (7 cm) wide and 20 inches (51 cm) long, and has an ovendry weight of 100 grams. After exposure in the field for 1 to 2 weeks until equilibrium is reached, the stick is weighed, and the weight in grams in excess of the ovendry weight is the percent fuel moisture (Fischer and Hardy 1976).

In a survey (Beaufait 1966) made in the northern Intermountain area, three-fourths of the experts questioned would burn dry slash when fuel sticks in slash blocks showed between 6 and 15 percent moisture content. Only a few would try to burn when 4 or 5 percent or over 16 percent moisture was indicated. Using experience from the Mark Twain National Forest in Missouri, Haug (1977) determined that for a successful general-purpose prescribed burn to remove brush, herbicide-killed shrubs, slash, or any dead light vegetation, fuel stick moisture should be between 6.5 and 9 percent. At fuel stick moistures of 4, 5, or 6 percent, there was spotting and spread rates were excessive. Fuel stick moistures of 1 to 4 percent have been reported during wildfires in California.

Considerable caution is essential in using fuel sticks. They can predict the moisture content of dead fuels about ½ inch (1.3 cm) in diameter, but not that of grasses, pine needles, or other "1-hour timelag" fuels. Moisture content of these fine fuels may respond to temperature and humidity changes within minutes, whereas the fuel sticks usually require hours. Fuel sticks are not used to estimate moisture content of fuels larger than 1 inch (2.5 cm) in diameter, nor of green fuels. The response characteristics of the fuel stick dowels may be slightly different from that of dead wildland fuels, and aging or soiling of a fuel stick will affect its response to humidity changes. The "standard" installation of an indicator stick requires that it be horizontal on a wire frame, 10 inches (25 cm) above a 2-inch (5-cm) thick bed of dead twigs, leaves, needles, or other predominant litter. The stick should be oriented north-south and should be in full sun. After equilibrium moisture content is reached, the fuel stick readings from the standard installation are slightly lower, about 2 or 3 percent, than they are from nearby sticks that are shaded, and slightly higher, up to 5 percent, than they are from sticks close to the ground in full sun (Countryman 1971, McArthur 1967).

Figure 6—Fire behavior is strongly influenced by the moisture content of small, dead fuels. Here, moisture content is being estimated by weighing fuel moisture sticks.

In southern California (Dell and Philpot 1965), fuel stick moisture determinations were compared with results of xylene distillation, as follows:

Air temperature (°F)	*Relative humidity (pct.)*	*Fuel moisture (pct.)*	
		Xylene	*Fuel stick*
85	27	7.0 to 8.3	6
83	11	5.7 to 7.8	4
60	9	6.3 to 8.9	5

Fuel stick moisture readings in Montana differed from oven-determined readings by as much as 5 percent (Norum 1977). If a burn prescription is based on an error of 5 percent fuel moisture, particularly if moisture content is less than 10 percent, actual fire behavior could be markedly different from that expected.

Experience of Forest Fire Laboratory personnel in burning chaparral, and that reported in the literature, suggest that moisture content of dead fuel, as measured by laboratory procedures or (except for 1-hour timelag fuels) by properly installed and maintained fuel moisture sticks, should be about as shown below to produce the indicated fire intensity response. Cured grass is estimated to contain 5 to 10 percent moisture when summer daytime temperatures are 70° to 90° F (21° to 32° C) and relative humidity is 20 to 30 percent. If relative humidity is 60 percent and the temperature about 60° F (15° C), moisture content of fine fuels is about 15 percent; at 80 percent relative humidity and 50° F (10° C), it is about 20 percent (Luke and McArthur 1978).

	Dead fuel moisture content (pct.) for given fire intensity		
Type of fuel:	*Low*	*Moderate*	*High*
Standing mature brush			
20 to 30 pct. dead	15 to 10	9 to 6	5 to 4
30 to 45 pct. dead	18 to 13	12 to 7	6 to 5
45 to 100 pct. dead—sprayed, crushed, or piled	30 to 15	14 to 9	8 to 6
Dry grass, weeds, and other 1-hour timelag fuels	25 to 15	14 to 8	7 to 5
Tree canopy underburning	18 to 16	15 to 10	9 to 7

The fire intensity levels are defined as follows:

• Under low fire intensity, there is some difficulty igniting the brush, except in small concentrations of dead fuel. If shrub canopies are not continuous, considerable effort by the firing team is needed to get fire in contact with most brush plants. Fire envelops shrubs that have dead fuels throughout the crowns, but burning is patchy, so that some individual shrubs or groups of shrubs are burned, but others are not. Results obtained under low-intensity burning in chaparral do not ordinarily remove enough fuel to satisfy management objectives.

• When chaparral burns with moderate intensity, it ignites readily with a drip torch, and fire envelops most of the crowns. Volatile components distilled from the green twigs frequently burn 5 or 10 ft (1.5 or 3.0 m) above the brush crowns. Hot embers may be capable of igniting fine dry fuels 10 to 20 ft (3 to 6 m) downwind from their source. Nearly all dead fuel is consumed, and most green twigs less than ⅛ inch (0.3 cm) in diameter. Most green twigs greater than ¼ inch (0.6 cm) in diameter do not burn.

Figure 7—Live fuel moisture is calculated using fresh and ovendry weights of twigs clipped to ⅛ inch diameter.

• In a high-intensity prescribed fire in chaparral, there is immediate flaming from drip torch ignition, and the heat forces observers away from the fire front. Flames envelop the shrubs and burn volatiles 10 to 30 ft (3 to 9 m), or higher, in the air above the shrubs. Spotting begins to be a problem, especially when wind gusts are greater than 10 mi/h (16 km/h). Green twigs up to ½ inch (1.3 cm) in diameter are consumed. Whirlwind activity during the latter part of the burn is common.

Fire intensity on the floor of a mixed-conifer forest, or in annual grasses and weeds, is somewhat different than in thick brush. Low-to-moderate-intensity fire then has 1- to 3-foot (0.3- to 0.9-m) flame lengths and releases 20 to 50 Btu/s/ft. Firefighters can work right up to these flames. In a high-intensity burn, flame lengths are greater than 4 ft (1.2 m), and release more than 100 Btu/s/ft of fire front.

Live Fuel Moisture

"Live" or "green" fuel moisture is the moisture content of twigs up to ⅛ inch (0.3 cm) in diameter and the attached leaves (*fig. 7*), unless some other size class is specified. This definition is agreed upon by California agencies concerned with wildland fire, and has been in use for two decades (Olsen 1960).

The importance of live fuel moisture in fire behavior has long been recognized by some fuels experts, but is still ignored by some who do prescribed burning in chaparral. Fire spreads through chaparral largely through the crowns, and where dead material is scattered, moisture in the live twigs largely determines how the fire will burn, or sometimes if it will burn at all (Countryman 1974). In the Southwest, moisture content of juniper foliage was found to be the determining variable in ignition and burning (Bunting and Wright 1976).

Moisture content of living fuel is so high that it will not burn unless subjected to continuous heat, except when ether extractables in the fuel are very high (see "Chemical Content of Fuel"), or under extreme Santa Ana wind conditions. If a hot fire is to develop and move through the brushfield, heat released from burning dead fuel must dry out the live fuel until the small green twigs ignite.

Moisture in live fuels acts as a sink for energy from burning dry fuels. The greater the live fuel moisture content, the more dry fuel must be consumed before the green will burn. Most forest fuels have a heating value near 8500 Btu/lb when ovendry. A moisture content of 20 percent will reduce this value to 6881 Btu/lb; 80 percent, to 4183; 100 percent, to 3643; and 160 percent to 2522 (Countryman 1977a).

Moisture content of live fuel varies from year to year but typically is highest during the spring. It is higher in new than in old growth, and higher in some shrub species than others. In spring, moisture content of new growth in chaparral rises rapidly to a peak. In chamise in southern California, this peak is about April or May; farther north and at higher elevations, it is later. Peak moisture in manzanita on the Stanislaus National Forest is not reached until late June or early July. Fuel moisture of new growth may be 150 to 200 percent, or 1.5 to 2 times the ovendry weight. Peak for old growth may be 90 to 150 percent.

Once the peak is reached, there is a fairly regular decline in live chaparral fuel moisture through the spring, summer, and fall (*fig. 8*). Moisture in new chamise growth in southern California approaches to within 10 percent of old growth moisture in July, and thereafter is either slightly higher or about the same as moisture in the old growth. Minimum moisture in live chamise is reached between September and early November, and readings may be near minimum almost continuously during these months. If rainfall during fall and early winter is minimal, there may not be much moisture recovery until spring, but several inches of rainfall during October, November, or December, along with cool weather, initiates an upward fuel

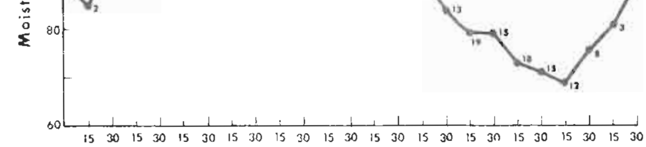

Figure 8—Decline in live fuel moisture of chamise is evident from data gathered on Glendora Ridge, Angeles National Forest. New and old growth are averaged. (Years of data averaged for each data point are shown.)

moisture trend. Data[2] (Dell and Philpot 1965) suggest that live desert ceanothus and chamise regain 10 to 30 percent fuel moisture and reach 70 to 90 percent by December 31. Thus, to take advantage of low live fuel moisture, chaparral should be burned during early winter. This may not be necessary at high elevations, however, since whiteleaf manzanita (*Arctostaphylos viscida* Parry) at 3000 to 5000 ft (915 to 1524 m) in the central Sierra Nevada retained its lowest moisture content through the winter months (Philpot 1963). Shrubs evidently are more physiologically active under the less severe winter conditions present at lower elevations in southern California.

Species differences are more pronounced in spring. Thus chamise, hoaryleaf ceanothus (*C. crassifolius* Torr.), and black sage (*Salvia mellifera* Greene) differ widely in live fuel moisture during the period from February to June, but are similar during the summer and fall (Olsen 1960). Live fuel moisture in black sage follows surface moisture availability, but live fuel moisture in the deeper rooted chamise more closely reflects the moisture availability at a depth of 42 inches (1.1 m).

Live fuel moistures less than 60 percent are hazardous during prescribed burning of standing brushfields unless compensated for by low windspeed, gentle slope, high humidity, low temperature, firing pattern, or adequate suppression forces. Live fuel moisture less than 50 percent is typical of Santa Ana winds and severe wildfires. The lowest fuel moisture percentages ever recorded by the Riverside Forest Fire Laboratory personnel occurred in southern California during a drought year following dry years. Chamise live fuel moisture was only 74 percent in May 1961, 45 percent in mid-July, and during a Santa Ana wind in October, 26 percent. The low point recorded in scrub oak was 36 percent (Pirsko and Green 1967).

As live fuel moisture levels rise from about 75 percent, brushfields are harder and harder to burn. Above 85 or 90 percent, the brush can be burned only under extreme burning conditions, and crushing or spraying with herbicides may be necessary.

Live fuel moistures should be determined on the site two or three times during the few weeks just before a prescribed burn. The data will help managers decide whether or not the burn will proceed as scheduled, or whether adjustments in other parts of the prescription will be needed to compensate for high or low live fuel moisture. Procedures are explained in *Measuring Moisture Content in Living Chaparral* (Countryman and Dean 1979).

Experience has shown that for mature chaparral 30 to 50 years old and 25 to 40 percent dead, fire intensity response to live fuel moisture is (approximately) low at 90 to 76 percent, moderate at 75 to 60 percent, and high at 59 to 45 percent.

Stem size affects live fuel moisture. During the early spring months, twigs less than ⅛ inch (0.3 cm) in diameter have double the moisture content of stems ½ inch (1.3 cm), or more, but the difference becomes smaller through the summer and fall, when it may be only 5 to 10 percent. The live fuel moisture in leaves and ⅛-inch-diameter twigs of most chaparral species is about 150 percent at the time of flowering, and 50 to 65 percent during September or October. Moisture in the stems ½ inch or more is generally 60 to 65 percent during the spring and 45 to 50 percent during September, and that of intermediate-sized twigs lies between these ranges. The relation between moisture content and stem size is illustrated by chamise (Dell and Philpot 1965) and by desert ceanothus (*Ceanothus greggii* Gray) collected by Forest Fire Laboratory personnel in the San Bernardino Mountains in 1974:

	Moisture content (pct.) of desert ceanothus twigs		
Date:	*0 to ⅛ in. diam.*	*¼ to ½ in. diam.*	*½+ in. diam.*
June 6	121	65	54
July 2	98	67	59
Aug. 6	71	61	57
Sept. 3	58	55	51
Oct. 1	55	56	47
Nov. 4	78	64	55
Dec. 10	82	63	55

In spite of their relatively low moisture content, stems ½ inch or more burn only infrequently, even during hot wildfires. Their low surface-to-volume ratio, low content of volatiles, and position in the plant all make them less susceptible to burning than twigs of smaller diameter.

Dead-to-Live-Fuel Ratio

During the first 2 to 5 years after brush removal, annual grasses and forbs grow among the sprouting shrubs and shrub seedlings. These herbaceous plants die each year, and if they are thick and continuous enough, can support intense fire, which kills brush seedlings and topgrowth of sprouting shrubs. Similarly, if the brush grows in a scattered stand, annuals may form a continuous ground cover that will carry fire.

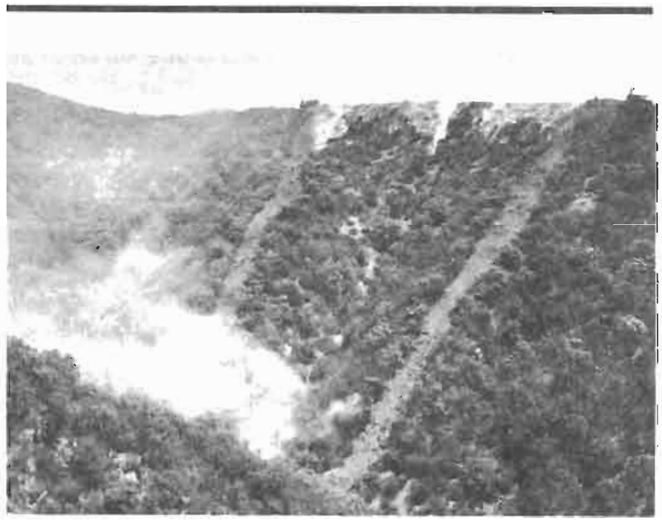

Figure 9—Fire would not run upslope in this 16-year-old brush because the percent dead fuel was too low and the relative humidity (35 percent) was too high. Crushed brush at the top of the slope did burn.

[2]Data on file in Chaparral Management Work Unit, Forest Fire Laboratory, Riverside, Calif.

Figure 10—Dead branches and twigs frequently make up one-third to one-half the fuel volume in chaparral stands more than 30 years old.

If the proportion of dead brush in a chaparral stand is less than 20 or 25 percent, as it is if the stand is less than 20 years old, getting fire to burn through the stand is difficult under all but extreme burning conditions (*fig. 9*). Brush stands less than 20 years old seldom burn well, although chamise on south slopes or soft chaparral species may sometimes be exceptions. Brush 5 to 20 years old includes dry remnants of plants such as deerweed (*Lotus scoparius* [Nutt.] Ottley), some brush skeletons if the stand was destroyed earlier by fire, and scattered dry twigs under the green canopies. Prescribed burning of such brush can be done successfully only if the brush is prepared by mechanical treatment (Roby and Green 1976), or with herbicides (Green 1977). Generally, it is advantageous to confine prescribed burning to older stands with a greater proportion of dry fuel.

After brush reaches 16 to 25 years of age, the proportion of dead brush in the stand increases. To estimate by a rough rule of thumb, consider the stand 1 percent dead for each year since the brush canopy closed following the last major fire or other clearing. As closure generally occurs about 5 years after a fire, brush 30 years old will probably be no more than 25 percent dead unless there have been several years of drought. A 50-year-old stand might be 35 to 50 percent dead (*fig. 10*). The proportion of dead and live brush can also be estimated directly, which entails crawling under the green canopies, noting dead plants, examining shrubs to see how many main stems or branches are dead, and noting whether many dead dry twigs are present. The most accurate method, but also by far the most time-consuming one, is to cut and weigh the fractions on representative plots. Brush on north slopes usually contains a smaller proportion of dead fuel than indicated here; brush on south slopes dominated by chamise, or *Salvia* and other soft chaparral plants, may contain more (Calif. For. and Range Exp. Stn. 1955). The proportion of dead fuel will increase following very dry years (*fig. 11*).

Fire intensity responses to the proportion of dead fuel in a stand of brush is (approximately) low at 20 to 30 percent, moderate at 31 to 45 percent, and high at 46 to 100 percent. This relation was recognized by a southern California fire management officer who said, "After approximately 20 years, deterioration of the plant is evident through a general increase of the dead-to-live ratio of plant material. Brushfields over 30 years old are often made up of 35 percent or more dead material. Fire intensity nearly doubles from a 20-year-old brushfield to a 40-year age-class" (Bates 1978).

Fuel Volume

The term "fuel volume" describes quantity and is expressed in pounds or tons dry weight per unit area. Fuel loading is a comparable term. Both terms are used in two senses: (1) to mean the total weight of vegetative matter—the biomass—on an area; or (2) less frequently, to mean only the available fuel—that which burns during passage of a fire. The distinction is important in prescribed burning.

Available Fuel

When chaparral burns under severe or extreme conditions, nearly all of the dead material burns, but live stems larger than ½ inch (1.3 cm) in diameter usually remain unburned. In small-stemmed plants such as chamise and *Salvia*, wildfire consumes 70 to 85 percent of the plant biomass, with only the larger, basal stems remaining. Large shrubs, with stems 2 to 5 inches (5 to 12 cm) in diameter near the ground, lose no more than half their weight (*fig. 12*). In one high-intensity prescribed burn where total biomass was about 35 tons (32 t) per acre, 20 percent of which was dead, and where the brush had been treated with a contact desiccant to dry out the foliage, 85 percent of live chamise biomass was consumed, 75 percent of manzanita, 45 percent of mountain mahogany, and 40 percent of scrub oak (Green 1970).

During Operation Firestop in coastal California, fires burned 96 percent of sage (*Salvia*), 66 percent of chamise, but almost no scrub oak. Relative humidity was above 30 percent and winds less than 10 mi/h (16 km/h) (Chandler 1957). In northern California, about 30 percent by weight of chamise and other brush, mostly in the larger stems, was not consumed during wildfires (Sampson 1944).

Figure 11—Coastal sage species die back during drought periods. Note the white sage (*Salvia apiana*) above the hand, and the mass of dead twigs below.

The available or burnable fuel is somewhat less during prescribed burns than during wildfires, and more stems remain after the burn. In the prescribed burn, weather is cooler and fuel moisture is higher, so that less fuel burns. Shortly after several inches of rain or melting snow have thoroughly wet all dead fuels, practically none will burn, but with each passing day of drying weather, more and larger twigs and branches will burn. After two or more warm days, fine fuel becomes available and prescribed burning should be considered.

Burning permits, to satisfy air pollution requirements, may soon require an estimate of tons of fuel per acre that will be consumed. This is already a requirement in the Pacific Northwest. Such a requirement in the chaparral would at once make the burnable fraction an important statistic.

Volumes of total and available chaparral fuel to be expected during prescribed burning may be estimated as follows:

	Fuel volume (tons/acre)	
Fuel:	*Total*	*Available*
Dry grass	½ to 2	½ to 2
Light chamise, sage, or sagebrush	3 to 10	2 to 8
Medium chamise	12 to 15	8 to 10
Tall, dense, mixed chaparral	15 to 30	10 to 20
Chaparral common on north exposures	20 to 40	12 to 24

Effect on Intensity and Rate of Spread

Studies of fire behavior have indicated that the amount of available fuel in the small size classes affects the rate of fire spread and the fire intensity (the rate of energy or heat release per unit of time and length of fire front) (Rothermel 1972).

Both experience and research indicate that as fuel quantity increases beyond 1 to 2 tons of available fuel per acre (2.2 to 4.5 t/ha), fire burns more intensely and takes longer to control. Two tons of available fuel per acre was suggested by experienced firefighters as the maximum that should be allowed on fuelbreaks (Pacific Southwest Forest and Range Exp. Stn. 1963). Available fuel accumulations of 2 to 3 tons/acre (4.5 to 6.7 t/ha) burned with relatively low intensity in Australian tests, even under severe meteorological conditions. When available fuel quantities were about 10 tons/acre (22.4 t/ha), suppression was much more difficult (McArthur 1962).

If we assume that 2 to 5 tons/acre (4.5 to 11.2 t/ha) of standing dead chaparral fuel will burn with low intensity, that 5 to 8 tons/acre (11.2 to 18 t/ha) will burn with medium intensity, and that available fuel greater than about 8 tons will burn with higher intensity than generally desired, then nearly every chaparral burn is potentially a high intensity burn. Fuel moisture and other influences may moderate the fire intensity, however. Norum (1977) used the same principle when making recommendations for forest fuels. He recommended that a fuel loading of less than 4 tons/acre (9 t/ha) of 0- to 3-inch (0- to 7.6-cm) diameter forest fuel be burned at a moisture content of 10 to 12 percent, that a loading of 4 to 8 tons/acre (9 to 18 t/ha) of available fuel be burned at a moisture content of 12 to 15 percent, and that a fuel loading of 8 to 10 tons/acre (18 to 22

Figure 12—Fire is sometimes responsible for creating available fuel. The scrub oak skeletons shown (*A*) weighed 13 tons per acre, whereas there were 3.2 tons of stems per acre in the chamise stand (*B*).

t/ha) should contain 15 to 17 percent moisture. Higher moisture content serves to offset the effect of greater fuel quantities. Similarly, decadent chaparral stands with large quantities of available fuel should be burned under cool burning conditions.

In west Texas, fire was not intense enough to kill standing mesquite (*Prosopis*) shrubs when fine (1-hour timelag) fuel was ½ to 2 tons/acre (1.1 to 4.5 t/ha), but did kill them when there was 2 to 3½ tons/acre (4.5 to 7.8 t/ha). Most chain-crushed, dead mesquite was consumed where fine fuel totaled 1 ton/acre, but the fire was not intense enough to ignite them at 1200 lbs/acre (1.6 t/ha) (Heirman and Wright 1973).

A study in the tall grass prairie of Nebraska is of interest. Fire was introduced into two areas that were similar except that one had been grazed with 0.6 animal months of grazing per acre, the other only 0.3. The frontal advance of the fire was 1.56 ft/s (0.47 m/s) in the lightly grazed area, and only 0.53 ft/s (0.16 m/s) in the more heavily grazed range. Comparable flame heights were 5 and 1 ft (1.5 and 0.3 m), respectively (Davis 1949). When tobosa grass (*Hilaria mutica*) was burned in west Texas, maximum temperatures at ground level increased proportionally from 182° F (83° C) when ¾ ton/acre (1.7 t/ha) of fuel was burned to about 1260° F (682° C) when 3½ tons (7.8 t/ha) were burned (Wright 1968).

A study of wildfires in chaparral on three southern California National Forests showed a strong tendency for the size of the fire to be correlated with the age of the brush and, indirectly, the quantity of available fuel. Fire starts could occur in any chaparral, but in young brush these were usually extinguished with ease. Fires of ¼ to 10 acres (0.1 to 4 ha) tended to occur in brush at least 3 years old; fires of 10 to 40 acres (4 to 16 ha) and over required at least 13-year-old cover (Rogers 1942). Most large chaparral fires, those covering 10,000 acres (4050

Table 3—*Selected fuel loadings (total biomass) in chaparral*

Chaparral type	Average height	Live	Dead	Duff and litter	Total	Source and location
	ft		*Tons per acre, ovendry*			
Scrub oak	6.1	23.5	3.7	8.8	36.0	USDA, FS 1955, coastal
Laurel sumac	6.5	19.6	2.0	15.8	37.4	USDA, FS 1955, coastal
Coyote brush	5.0	8.4	0.4	6.1	14.9	USDA, FS 1955, coastal
Chamise	—	8.6	3.3	3.4	15.3	USDA, FS 1955, coastal
Soft chaparral	—	4.6	3.0	6.2	13.8	USDA, FS 1955, coastal
Grass	—	0.9	—	1.2	2.1	USDA, FS 1955, coastal
Chamise, ceanothus, and deerweed	4.0	3.8	4.6	5.3	13.7	USDA, FS 1955, coastal
Chamise	5.7	13.0	1.8	—	14.8	Kay and others 1958, Mariposa
Chamise	6.0	23.5	6.0	—	29.5	Green 1970, interior
Manzanita	7.0	27.5	5.0	—	32.5	Green 1970, interior
Scrub oak	10.0	48.0	5.0	—	53.0	Green 1970, interior
Greenleaf manzanita	4.0	10.0	6.0	8.0	24.0	Bentley and others 1971, Mt. Shasta

Figure 13—The ground surface under chamise is usually lacking in herbaceous growth and litter (top of photo). Popcorn flower (*Plagiobothrys* sp.) dominates the foreground, where there is an opening in the chamise stand.

ha) or more, burn in brush that has accumulated volume and dead material for 30 years or more.

The beneficial effect of reducing the available fuel volume has often been observed. Many wildfires in California have been stopped when they ran into areas burned a few years earlier (Philpot 1973). For example, in mid-September 1979, sections of the Monte and Sage Fires, burning in chaparral on the Angeles National Forest, burned into the Mill and Pacoima Fires of 1975 and stopped. In numerous instances, prescribed burning in pine forests is credited with reducing damage from later wildfires (Davis and Cooper 1963, Little and others 1948, Moore and others 1955).

Aboveground Biomass

The average ovendry weight of all brush in California has been estimated by Riverside Forest Fire Laboratory personnel to be 18 to 20 tons/acre (40 to 45 t/ha). Biomass extremes vary from about 5 tons/acre (11 t/ha) for grass mixed with soft chaparral to 40 or 45 tons/acre (90 or 100 t/ha) of dense tall chaparral on northerly exposures. Some selected biomass fuel loadings are presented in *table 3*.

Volume of dense chamise will seldom be greater than 30 tons/acre (67 t/ha), and 15 tons/acre (33 t/ha) may be about

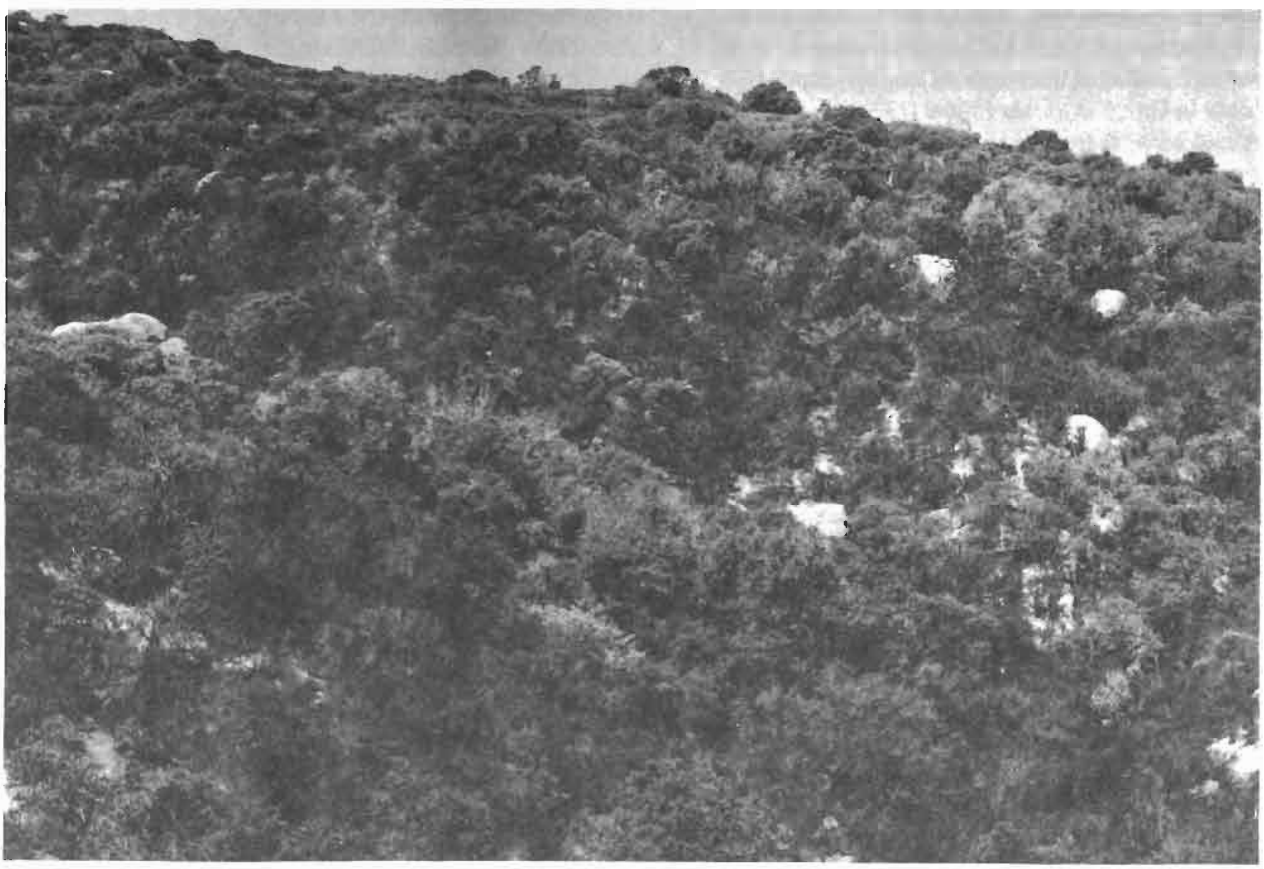

Figure 14—For fire to move through this brush, open enough for relatively easy walking, would require higher windspeeds than are generally specified in the prescription.

average. Thick chamise stands generally contain between 3500 and 4600 plants/acre (8650 and 11,400/ha) (Green, unpublished data). Countryman and Philpot (1970) found the average ovendry chamise shrub weight to be 6.4 pounds (2.9 kg) per plant, or a volume of about 12 tons/acre (27 t/ha). Green (1970) found 23.5 tons/acre (53 t/ha) of live aerial plant material in a dense chamise stand where plants were 5 to 6 ft (1.5 to 1.8 m) high, and 6 tons/acre (13 t/ha) of dead fuel.

In Mariposa County, California, Kay and others (1958) studied a chamise brushfield that was at least 25 years old. They found that the dry weight of live chamise varied from 8½ to 17½ tons/acre (19 to 39 t/ha), or an average of about 13 tons (29 t). Dead material added 1¾ tons/acre (3.9 t/ha). The average height was 5 ft 9 inches (1.75 m), there were 5500 plants/acre (13,600/ha), and crown closure was 95 percent. Only 4 percent of the ground surface had any herbaceous cover. Sampson (1944) found that chamise in northern California grew rapidly to 5.7 tons/acre (13 t/ha) in 8 years, after which the growth rate slowed. Dense old stands contained about 14 tons/acre (31 t/ha).

Litter

Duff and litter under chaparral may vary from a few hundred pounds per acre under some chamise stands (*fig. 13*) to 15 tons/acre (33 t/ha) or more under large thick brush and small trees growing on favorable site. A stand of 14-year-old chamise and *Ceanothus crassifolius* Torr. in the Bell Watersheds at the San Dimas Experimental Forest had accumulated an average of 5.8 tons/acre (13 t/ha) of litter with an average depth of ¼ inch (0.63 cm). In Fern Canyon, at 4500 ft (1372 m) elevation, where there had been no fire for 55 years, the dry weight of litter under chaparral dominated by canyon live oak (*Quercus chrysolepis* Liebm.), big berry manzanita (*Arctostaphylos glauca* Lindl.), and whitethorn ceanothus (*Ceanothus leucodermis* Greene) was 16.6 tons/acre (35 t/ha). The average depth was 0.6 inch (1.5 cm) (Kittredge 1939).

At the North Mountain Experimental Area, south of Banning, California, Green (unpublished data) found 3.3 tons/acre (7.4 t/ha) of duff and litter under old chamise about 5 ft (1.5 m) tall, and 25 tons/acre (56 t/ha) under both manzanita 7 ft (2.1 m) tall and scrub oak up to 10 ft (3 m) tall. This was on productive lower slope site. In Arizona (Pase 1972), there were 4.1 tons/acre (9 t/ha) under shrub live oak (*Quercus turbinella* Greene) on north exposure and 7.3 tons/acre (16.3 t/ha) on south exposure. Under some dense oak and manzanita stands on east exposure, there were 11 to 12 tons/acre (25 to 27 t/ha) of litter and duff. These data for oak and manzanita in California and Arizona represent near-maximum accumulations of chaparral floor litter.

Fuel Continuity

For successful prescribed burning, there must always be fine, dead fuel, more or less uniformly distributed, to carry the fire. This can be dry grass, or a litter layer of loose twigs and leaves or pine needles, or dead twigs or stems within the brush crowns, or some combination of these. If there are breaks in the fuel, the fire spread is interrupted, although this can be nullified in part by steep slopes or winds higher than usually recommended (*fig. 14*). To maintain fires through shrub or tree crowns, some wind is necessary or the crown fire collapses, even in dense chaparral. Without considerable air movement, ground surface fire is needed to supply part of the heat needed for lateral spread through the shrub crowns.

Thick, dense brush has a canopy or crown cover of 60 to 90 percent; branches are intertwined, and fire can travel through the canopies without interruption. As crown cover drops below 60 percent, fire spreads through the canopies only under severe or extreme burning conditions. A similar proportion of crown cover is needed to burn small trees. For example, to get good kill of standing piñon-juniper in Arizona, 200 to 400 trees/acre (500 to 1000 trees/ha) with nearly continuous canopies were required. Even so, low humidity and windspeed of 10 to 20 mi/h (16 to 32 km/h) were required to move fire through the trees (Pase and Granfelt 1977).

Chemical Content of Fuel

The chemical content of wildland fuels is generally ignored during planning for prescribed burning, partly because other conditions may be overriding (Bunting and Wright 1976, Montgomery and Cheo 1969, Friedman and Waisel 1966), but also because chemical information is seldom available. Research data are steadily increasing, however, to demonstrate that the presence of various materials affects the burning

Figure 15—High above the shrubs, volatile components distilled from chaparral burn fiercely.

characteristics of forest fuels. Chemical content may partially account for the combustion of living chaparral, coniferous forest, and palmetto-gallberry of the Southeast (Rothermel 1976), and bear clover (*Chamaebatia foliolosa* Benth.) in the mixed-conifer forest of California, at moisture content levels above those at which dead fuels burn.

Ether Extractives

Among chemicals readily identified in woody fuels are the ether extractives—the waxes, oils, fats, and terpenes. These materials have about twice the heat value of cellulose (Philpot 1969), which makes up about half of the woody framework of plants (Mobley and others 1976). Ether extractives are sometimes a substantial part of the dry weight of wildland fuels (*table 4*) and may affect the total heat yield significantly (*fig. 15*). Shrub species with high proportions of ether extractives, above 8 percent dry weight, tend to be quite flammable; species with low proportions tend to be less so.

Eucalyptus leaves that were free of volatile oils would scarcely burn in an Australian laboratory test, but when they contained 3 percent oils by weight, the same leaves burned readily with pronounced flaming, especially during the early stages of combustion (King and Vines 1969). Ignition time for powdered ponderosa pine and sphagnum moss samples was increased by removal of the ether extractives (Mutch 1964). Ignition time was found to be closely related to extractive content in numerous southern California chaparral species (Montgomery 1976). Dry chaparral leaves lost 14 percent of their weight during a 5-minute heating period which simulated heating by an approaching fire (Trujillo 1976). Philpot (1969) found that the extractive content of chamise leaves was highest, 12 percent, during the fall and early winter fire season, and lowest during the spring.

Inorganic Chemicals

A second class of extractable chemicals are inorganic or mineral in nature. Studies of pyrolysis of cellulose treated with inorganic compounds have indicated that flammability of plant material is lowered by the presence of inorganic materials (Shafizadeh 1968). Field-dried and leached corn leaves were found to be more flammable than unleached leaves because leaching reduced mineral content (Broido and Nelson 1964). Philpot (1970) found that wildland fuels which differed in mineral content also differed in their burning characteristics. In plant materials with higher ash content, the volatilization rate decreased, active pyrolysis, but not flaming combustion, began at a lower temperature, and amount of residue was greater compared with plant materials with lower mineral contents.

Silica, sodium, and perhaps other minerals may be less important than phosphorus (Lindenmuth and Davis 1973, Mutch and Philpot 1970, Philpot 1970). The efficacy of phosphate in reducing flammability was demonstrated in a Forest Products Laboratory test in which plywood panels were treated with solutions of 11 chemicals; the most effective in retarding flaming was monammonium phosphate (Eickner and Schaffer 1967). In Arizona chaparral, the rate of spread decreased as phosphate

Table 4—*The ether extractive proportion of leaf samples of chaparral species, as percent of ovendry weight*

Species	Ether extractives
	Percent
Black sage (*Salvia mellifera*)[1]	19.1
Dwarf rosemary (*Rosmarinus officinalis*)[1]	18.4
White sage (*S. apiana*)[1]	18.0
California sagebrush (*Artemisia californica*)[1]	15.6
Pointleaf manzanita (*Arctostaphylos pungens*)[2]	14.3
Aspen (*Populus tremuloides*)[3]	11.2
Bigberry manzanita (*Arctostaphylos glauca*)[1]	10.7
Creeping sage (*S. sonomensis*)[3]	10.1
Chamise (*Adenostoma fasciculatum*)[1]	8.8
Ponderosa pine (needles) (*Pinus ponderosa*)[3]	8.2
Toyon (*Heteromeles arbutifolia*)[1]	6.9
Laurel sumac (*Rhus laurina*)[1]	6.4
Shrub live oak (*Quercus turbinella*)[2]	6.2
Hoaryleaf ceanothus (*Ceanothus crassifolius*)[1]	5.3
Mountain mahogany (*Cercocarpus betuloides*)[1]	5.2
Scrub oak (*Quercus dumosa*)[1]	3.7
Fourwing saltbush (*Atriplex canescens*)[3]	1.0
Castlevalley saltbush (*A. cuneata*)[3]	2.3

[1] Montgomery 1976.
[2] U.S. Dep. Agric., Forest Service 1964.
[3] Rothermel 1976.

(PO_4) content increased to about 0.235 percent, where rate of spread leveled out (Lindenmuth and Davis 1973).

King and Vines (1969), in Australia, also found low flammability of leaves of forest species to be associated with high mineral content; but they related the effect to the total concentration of mineral elements rather than to the concentration of any one element.

Slow-Burning Plants

Researchers often receive requests for lists of "fire resistant" or "low flammability" plants, or they are asked to rate the "fire resistance" of plants on a list. Answering such requests to the satisfaction of those requesting help is usually not possible, although some general statements concerning fire resistance can be made.

Moisture content is generally considered the most important influence on flammability. Unirrigated woody plant growth has its highest moisture content during the early spring, and is most fire resistant at that time. Young brush stands are higher in moisture content than older growth, and young brush free of dead fuel is almost fireproof.

Coniferous plants—the pines, firs, cedars, junipers, etc.—as a group, are more flammable than broadleaved trees, which are sometimes planted in strips through pine plantations to act as firebreaks. Conifers contain more of the ether extractives than do most broadleaved trees, and their moisture content tends to be lower than that of deciduous trees. The eucalypts growing in Mediterranean-type climate in Australia are very flammable because of volatile oils in their leaves (King and Vines 1969) and because considerable bark sloughed from the trunk accumulates as ground litter. Among these species, the blue gum eucalyptus (*Eucalyptus globulus* Labill.), widely planted in California, is particularly flammable.

All native California shrubs will burn under extreme conditions; although some are observed to be more or less flammable than most, the reasons are not always obvious (Ching and Stewart 1962). Chamise, California buckwheat, members of the *Salvia* genus, and other members of the soft chaparral community are flammable because of high content of extractables, low moisture content, large proportion of dead material, small size of stems, and the presence of dry grass among the shrubs (Countryman and Philpot 1970, Philpot 1969, Tyson 1974). Shrubs in the chaparral community, particularly those common on north slopes such as scrub oak and mountain mahogany, are less flammable. More wildfires occur in soft chaparral than in chaparral.

Fire resistant plant research at the Riverside Forest Fire Laboratory was directed more at finding low-volume than slow-burning vegetation. Many promising plants were tested (Nord and Green 1977), but because of chaparral ecosystem complexity, no shrubs were found that were widely adapted.

Weather

Fire weather is the state of the atmosphere surrounding a prescribed fire location and as far away as it may affect fire behavior on a burn date (Schroeder and Buck 1970). Most weather elements important in prescribed burning are readily measurable. Some can be measured directly, others can be estimated from professional weather forecasts. Interpretation and application of weather data can be difficult.

Wind

Predicting the speed and direction of the wind is the most difficult task in local fire weather forecasting. Wind, more than any other fire danger factor, makes fire behavior erratic, and windspeeds in excess of acceptable limits cause most prescribed burn escapes (*fig. 16*). Winds of 20 to 70 mi/h (32 to

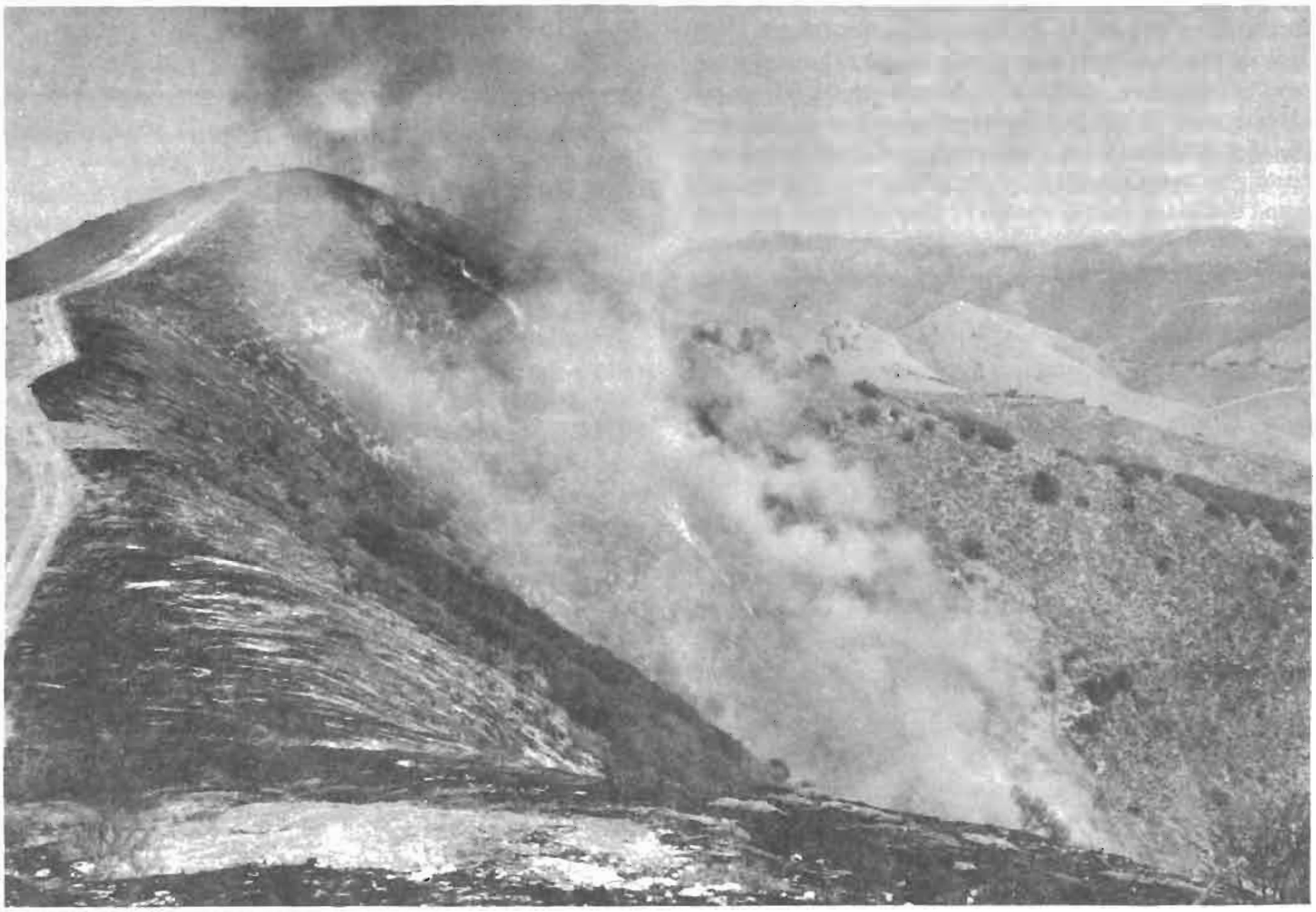

Figure 16—A combination of steep slope and wind gusts of about 24 mi/h took fire up a previously backfired slope and across a fireline.

113 km/h) have been primarily responsible for the spread of large wildfires.

Winds accelerate the oxygen supply to the burning fuel zone, thereby boosting the rate of combustion. They carry heated air to the fuel on the downwind or lee side of burning material, thus raising the fuel temperature, and driving off moisture. The result is faster ignition and greater burning intensity. Winds also carry away water vapor, which otherwise dampens fire, and accelerate evaporation from fuels. Finally, winds encourage firebrand formation and move the brands ahead of the fire front.

On the other hand, wind near the upper limits of a burning prescription may permit burning of fuels with relatively high moisture content. If windspeeds are near zero and terrain is flat, fire in chaparral does not spread. Thick brush, especially chamise chaparral, usually does not have enough ground litter (1 ton/acre [2.2 t/ha] or more) to allow fire spread. Winds must be strong enough, at least 3 or 4 mi/h (4.8 or 6.4 km/h), to move fire through brush crowns on level or gently sloping terrain, and to dissipate heat under tree canopies. Wind is especially important in spreading fire where fuels are sparse.

Data in the *Fireline Handbook* (U.S. Dep. Agric., Forest Serv. 1975) indicate that increases in windspeed are accompanied by roughly corresponding increases in rates of fire spread. As wind velocity goes from about 1 to 10 mi/h (1.6 to 16 km/h), the rate of spread increases about five times. As wind velocity increases from 1 to 22 mi/h (1.6 to 35.4 km/h), the rate increases about 10 times. In very fine fuels such as dry grass, rate of spread seems to increase faster than wind velocity. For slightly heavier fuels, such as small twigs, the rate is proportionate to changes in windspeed. In larger fuels, those about ¼ inch (0.63 cm) in diameter, an increase in windspeed does not cause an ever-increasing rate of spread (pers. commun. Richard C. Rothermel).

The maximum safe windspeed for prescribed burning of standing chaparral is generally accepted to be 10 mi/h (16 km/h) (Southwest Interagency Fire Counc. 1968; Northern Region, Forest Serv. n.d.). Exceptions to the maximum 10 mi/h (16 km/h) windspeed recommendation for prescribed burning have been made for grasslands in Texas and for piñon-juniper. In Texas, winds between 8 and 16 mi/h (13 and 26 km/h) may be necessary to burn standing herbicide-treated brush on level terrain where the fire spread is in grass (Wright and Bunting 1976). Lindenmuth and Davis (1973) thought winds of at least 7 to 8 mi/h (11.2 to 13 km/h) necessary for good burning of brush under prescribed conditions. To kill scattered or clumpy juniper with sagebrush and rabbitbrush understory but not much grass, winds of 8 to 15 mi/h (12.8 to 24 km/h) were prescribed in eastern Washington and Oregon (Pacific Northwest Region, Forest Serv. 1973). Fuels in juniper types are frequently sparse, and higher windspeeds and lower humidities are needed for burning than in more closely spaced fuel types (Martin 1978, Pase and Granfelt 1977).

For burning in chaparral, winds of 4 to 8 mi/h (6 to 13 km/h) are generally about right, except possibly where wind is blowing up a steep slope. Windspeed may then be too great, and a range of 2 to 6 mi/h (3 to 10 km/h) is recommended. With 8 to 10 mi/h (13 to 16 km/h) winds, there will be gusts of 12 to 15 mi/h (19 to 24 km/h). These do not usually cause serious control problems, but gusts of 15 to 20 mi/h (24 to 32 km/h) commonly carry firebrands 100 or 200 ft (30 or 60 m), and spot fires may result. During one prescribed burn in southern California, gusts of 20 mi/h (32 km/h) carried firebrands 300 ft (91.5 m), and "smokes" resulted in three dead fuel accumulations (Green 1970).

Wind direction, especially changes in direction, may be as important as windspeed during a prescribed burn. Usually, a prevailing surface wind can be identified and kept in mind in burn planning. A firebreak is frequently prepared before the burn, or burned out as a first phase of the burn, so the prevailing wind will not carry firebrands beyond the planned burn limits.

Local topographic features frequently cause unstable and erratic winds, particularly during the afternoon when windspeed may increase. Winds tend to change direction and vary in velocity as the airstream flows around and over ridges and through saddles, and otherwise adapts itself to the topography. Near the ocean, a sea breeze may develop, and controlling fire is then a difficult job.

During daylight hours, after the air near the ground has warmed, air movement tends to be upcanyon and upslope, sometimes strongly so. The effects of wind and slope are then mutually reinforcing, and fire spread rates may be doubled. About sundown, or a little later, air movement is normally downcanyon and downslope, and this continues until shortly after sunrise.

The classic pattern of local daytime upcanyon and nighttime downcanyon winds can be upset by overriding ambient (synoptic scale) winds. Such upsets occur when high air pressure systems occupy the Intermountain States, and pressure is lower off coastal California or Oregon. Sometimes, very strong foehn winds result. In southern California, the Santa Anas blow from the north or northeast and in central California, the Monos blow from the east. If the ambient northeast Santa Ana winds are of low to moderate intensity and are blowing aloft but not along the ground, upcanyon south or southwest daytime winds may be measured at a burn site when official forecasts call for northeast winds. This apparent contradiction can be confusing if the relation between surface and ambient winds is not understood.

Firefighters have also observed wind shifts from upcanyon to downcanyon during the early afternoon in east-facing canyons. Fires burn erratically during a change in wind direction. In the historic Decker wildfire in the Santa Ana Mountains of southern California, the prevailing winds stopped suddenly in late afternoon. The fire then responded to topographic influences and ran uphill, where it trapped and burned firefighters, six of whom died.

An intense downslope wind—the Sundowner—has been experienced on the western slopes of coastal mountains during evening hours, especially in the Santa Barbara area. The conditions responsible have not been precisely determined.

Knowledge of windspeed and direction is important not only for maintaining the security of the burn, but also in satisfying current air quality regulations which limit prescribed burning. (See discussion of "Smoke Management.")

For measuring and reporting windspeed, the standard height used by the Weather Service and Fire Danger Rating and other stations collecting weather data is 20 ft (6 m) above open ground or above vegetation. Wind velocity measurements on prescribed burns in chaparral are not generally taken at 20 ft, however. Most portable automatic recording weather stations have anemometer masts 6 to 10 ft (2 to 3 m) high, which means that they record windspeed only a few feet above the brush canopies. Similarly, measurements with a hand-held windspeed meter are usually made at about 5 ft (1.5 m), near the midflame zone for chaparral; this midflame wind determines the rate of fire spread.

Because of surface irregularities, wind velocities at 20 ft aboveground are greater than those closer to the ground or within stands of vegetation. Midflame windspeeds are about half those at 20 ft in fuels such as grass or brush that are directly exposed to the windflow.[3] An even greater reduction in windspeed exists between the 20-foot and the standard 4½-foot (1.4-m) midflame height of fuels sheltered by dense tree canopies. The nomograms published by Albini (1976) have a built-in correction to reduce the windspeed measured at 20 ft to the midflame windspeed for each fuel type; the TI-59 Calculator Fire Behavior Program does also.[3]

The windspeeds quoted and recommended in this paper should be considered as midflame measurements.

Relative Humidity

Moisture in the atmosphere—the humidity—is important in planning prescribed burns because small dead fuels take moisture from the atmosphere, or give up moisture to the atmosphere, depending on the relative humidity. Otherwise, humidity has little direct effect on fire.

Relative humidity expresses the amount of moisture in the air compared with the water vapor capacity if the air were saturated at the existing temperature and pressure. At 20 percent relative humidity, the air has considerable capacity to dry out damp fuels. Relative humidity of 100 percent is frequent at night, when moisture condenses as dew or fog, and occurs at any time if rain is falling. Relative humidity tends to be lowest during the part of the day when temperatures are highest.

Dry fuel exposed to the atmosphere absorbs moisture until it reaches equilibrium; that is, the fuel absorbs all the moisture it can at a given relative humidity. If the fuel is exposed long enough to saturated air (relative humidity = 100 percent), its moisture content reaches about 30 percent. Increases in moisture content of dead fuel beyond 30 percent require the addition of liquid water such as dew, rain, or melted snow. Because relative humidity is usually less than 100 percent, and exposure of woody fuels to high humidities is restricted by diurnal fluctuations, moisture content of wildland fuels is generally less than 20 percent (*table 5*).

Not all wildland fuels have the same absorption characteristics; twigs from one species may contain slightly more or less moisture than twigs from another species exposed to the same relative humidity (Mobley and others 1973; Northern Region, Forest Serv. n.d.).

Effect of Temperature—Relative humidity is the proportion of water vapor capacity of the air that is actually occupied by water vapor. If the air temperature rises, the capacity of the atmosphere to take on moisture increases, and the proportion of this capacity actually occupied by moisture decreases. At 20° F (−6.6° C), a block of air weighing 1 kg would be saturated by about 2.3 g of water; at 40° F (4° C), just over 5 g; at 60° F (15° C), 10.5 g; at 80° F (27° C), about 20.3 g; and at 100° F (38° C), 40.3 g (Brown and Davis 1973). Thus, the capacity of air to hold water approximately doubles with each 20° F (11° C) temperature increase, and is halved by a reduction of 20° F.

An average of many humidity readings taken with a sling psychrometer during prescribed fire operations in southern

[3]Data from the TI-59 Fire Danger/Fire Behavior Calculator Training Test Course, Northern Forest Fire Laboratory, Missoula, Montana, August 1979.

Table 5—*Approximate moisture content of small dead fuels (1- and 10-hour timelag) at equilibrium with temperature and humidity*[1]

Relative humidity (pct.)	Moisture content, by temperature (degrees F)								
	40	50	60	70	80	90	100	110	120
10	2.5	2.5	2.5	2.5	2.4	2.3	2.3	2.2	2.1
20	4.6	4.6	4.6	4.5	4.4	4.3	4.2	4.0	3.8
30	6.3	6.3	6.2	6.1	5.9	5.8	5.6	5.4	5.2
40	7.9	7.8	7.7	7.6	7.4	7.2	7.0	6.8	6.5
50	9.6	9.3	9.2	9.1	8.9	8.8	8.6	8.3	8.0
60	11.3	11.2	11.1	10.9	10.7	10.5	10.2	9.9	9.6
70	13.4	13.3	13.2	13.0	12.8	12.5	12.2	11.9	11.6
80	16.3	16.3	16.2	16.0	15.8	15.5	15.1	14.7	14.3
90	21.4	21.3	21.1	20.8	20.5	20.1	19.6	19.1	18.5

[1] Adapted from Countryman (1971) and from Green (unpublished data).

California showed that between 60° and 90° F, relative humidity was approximately doubled or halved by 20° F temperature changes, but that between 60° and 40° F, the corresponding changes tended to be less than double. Relative humidity fluctuated widely, however, at any temperature, reflecting the varying water content of the airmass during a day, or from one day to another. Assuming that on a given day the moisture content of the air in the inland Northwest may be relatively stable, Martin and Dell (1978) suggest that for prescribed burning, rough predictions of relative humidity may be made early in the day from air temperature forecasts or measurements.

Effect of Air Pressure—The effect of atmospheric pressure on relative humidity is much less dramatic than that of air temperature, and is frequently ignored. Wide elevational differences produce effects great enough to be important, however, in some prescribed burning operations. Selected values from relative humidity tables show this:

	Relative humidity, by temperature (°F)		
Elevation (ft):	*Dry bulb 60°, wet bulb 40°*	*Dry bulb 80°, wet bulb 60°*	*Dry bulb 100°, wet bulb 70°*
		Percent	
0 to 500	5	29	21
500 to 2000	6	30	21
2000 to 4000	9	31	22
4000 to 6000	12	32	23
6000+	15	34	25

It is evident that substantial errors in relative humidity readings can result if charts or scales designed for low elevations are used at high elevations.

General Recommendations—When dry slash from lumbering operations is burned, a relative humidity of 30 to 40 percent is recommended (Beaufait 1966; Buck 1971; Donoghue and Johnson 1975; Northern Region, Forest Serv. n.d.). Levels above 40 percent resulted in slow burning conditions, and below 20 or 25 percent in dangerous burning. These data apply to piled or windrowed brush, or other dead fuel accumulations.

Preferred relative humidity for forest underburning in the southern United States where prescribed burns are conducted on several million acres each year was in the 30- to 50-percent range (Mobley and others 1973). Relative humidity between 26 and 64 percent was suggested for underburning on fuelbreaks in the Sierra Nevada mixed-conifer type (Schimke and Green 1970).

Experience in chaparral indicates that to burn standing, untreated chaparral 25 to 40 years old, with 25 to 40 percent of the biomass dead, a relative humidity of about 25 to 35 percent is about right. If the humidity is above 40 percent, and particularly if it has recently been higher, as is usual during the night or morning hours, fire will not spread without excessive wind or steep slope (*fig. 17*). If the fuel biomass is less than 20 percent dead, it may not burn at all under prescribed burning conditions, unless relative humidity is about 15 to 20 percent and there are brisk winds, or the area has steep slopes. Conversely, if the brush is very old and 40 to 60 percent dead, or if it has been crushed or sprayed to increase the dead-to-live ratio, a humidity of 35 to 60 percent is needed to keep fire intensity within acceptable limits.

Figure 17—At relative humidity of 42 percent, some litter accumulations were burned from beneath this stand, but the fire did not spread, nor did it burn green brush.

Slopes covered with chamise or soft chaparral generally burn at about 25 to 35 percent humidity, if the brush is mature. Chandler (1957) found that scrub oak brush would not carry fire at 65 percent relative humidity, even with 8 mi/h (13 km/h) of wind, but 93 percent of sage (*Salvia*) burned at 38 percent relative humidity, and two-thirds of chamise fuel was consumed at 33 percent relative humidity. Bentley and others (1971) regarded 40 to 45 percent humidity as too high to burn old manzanita brushfields around Mount Shasta, California, unless wind was greater than 5 mi/h (8 km/h). About 30 percent is recommended by Mendocino National Forest personnel for burning without firelines.

Fuel accumulations where dead stems 1 to 6 inches (2.5 to 15 cm) in diameter predominate can be burned at any humidity range provided stem interiors are dry. Brush piles or other slash containing large-diameter dry material should be burned with 40 to 70 percent relative humidity.

Relative humidity for prescribed burning of various fuels is summarized as follows:

	Relative humidity (pct.) for given fire intensity response		
Type of fuel:	*Low*	*Moderate*	*High*
Dry grass, weeds, other 1-hour timelag fuels	50 to 41	40 to 30	29 to 20
Standing mature brush			
20 to 30 pct. dead	35 to 26	25 to 18	17 to 15
31 to 45 pct. dead	45 to 36	35 to 24	23 to 18
Brush sprayed, crushed or decadent, 45 to 65 pct. dead	60 to 41	40 to 31	30 to 25
Piled brush or slash	70 to 41	40 to 36	35 to 20
Woodland or forest			
Thinning slash	70 to 41	40 to 36	35 to 30
Underburning mixed conifer or oak in California	60 to 41	40 to 31	30 to 25

Air Temperature

During the day, high air temperatures warm fuels so that less preheating by fire is required for combustion. Evaporation is more rapid, and less heat energy is required to reduce fuel moisture. As air temperature rises and relative humidity decreases, fire intensity increases and spotting becomes more likely. High air temperatures can cause unstable air. Heating near the ground results in convection currents that may act like chimneys for the fire, or firewhirls can develop. High air temperatures cause strong upslope daytime winds, but strong inversions or ambient winds may override this effect and prevent the upslope winds from developing.

In chaparral, spotting incidence increases noticeably as temperatures rise above 80° to 85° F (27° to 29° C). During summer and fall in northern California, when small dead manzanita brush fuels were dry, danger of spotting was minimal when air temperature was 80° F and relative humidity was 60 percent (Bentley 1967). In later burning trials in manzanita brushfields near Mount Shasta, California, there was no trouble with spot fires when air temperature was 63° to 70° F (17° to 21° C), and relative humidity was 35 to 42 percent (Bentley and others 1971). During a southern California burn where chamise chaparral had been treated to desiccate leaves and fine twigs, wind gusts of about 20 mi/h (32 km/h) carried live firebrands as much as 300 ft (91.5 m) when air temperature was 80° F and humidity 28 percent (Green 1970).

Field data from 32 prescribed fires in Texas grass-brushland indicated that air temperature was the best predictor for maximum fire spotting distance. No firebrands ignited grasses beyond 100 ft (30 m) when air temperature was less than 60° F (15° C), nor beyond 400 ft (122 m) when air temperature was 75° F (24° C), relative humidity was at least 25 percent, and wind was no more than 15 mi/h (24 km/h) (Bunting and Wright 1976).

In one chaparral incident in southern California, crews tried to burn dense, 45-year-old brush at 9:15 a.m. without success. By 10:30, the brush smoldered, and at about 11:15 it burned with flames up to 30 ft (9 m) high, a reflection of the warmer temperatures and lower humidity. The temperature of the fuel, as influenced by ambient air temperature and direct sunlight, had a profound effect on the ignition and combustion.

High air temperatures contribute to crown scorch in burning under trees. Cambium is damaged at 140° F (60° C) or less, depending on duration of exposure (Hare 1961). The higher the air temperature, the sooner this critical temperature is reached. A tree crown above a fire when the air temperature is 95° F (35° C) would suffer about twice as much damage as it would if the temperature were only 40° F (4° C). Air temperatures of 80° to 95° F (27° to 35° C) are recommended for summer burns when the objective is to kill undesirable trees, but less than 50° F (10° C) for winter burning aimed at cleaning up the forest floor (Mobley and others 1973).

For fuelbreak maintenance in the central Sierra Nevada, Schimke and Green (1970) suggested air temperatures of 30° to 80° F (−1° to 27° C). For underburning in Sierra Nevada ponderosa pine forest, Biswell and Schultz (1956) recommended 65° F (18° C) or below. During burns conducted under Arizona ponderosa pine forest, Gaines and others (1958) concluded that the 59° to 67° F (15° to 19° C) range they experienced was near the ideal, but that 73° to 75° F (23° to 24° C) was too hot. Where singeing tree crowns is not a danger, as in chaparral burning or on open fuelbreaks, somewhat higher air temperatures can be tolerated.

Air temperature recommendations during prescribed burning are as follows:

	Air temperatures (°F) for given fire intensity response		
Fuel:	*Low*	*Moderate*	*High*
Standing chaparral	20 to 59	60 to 80	81 to 95
Burning under tree canopies	20 to 39	40 to 70	71 to 85

Topography

Prescribed burning in chaparral is almost always in, or near, rough topography that directly or indirectly affects burning decisions. The terrain may determine the ignition pattern to be used, and may also create difficulties in forecasting speed and direction of wind.

Local Terrain

Air close to the ground is warmed during hours of bright sunlight, and because warm air rises, upslope or upcanyon surface winds are common during the day. At sunset, cooling near the ground begins. The cooled air, heavier than the warmer air above, flows downhill or downcanyon and into the valleys. General surface airflow is also channeled through canyons and saddles, moving more rapidly as passages become narrow. (Fuelbreaks are therefore widened at such places.) Upslope or downslope winds may influence a fire burning low on the slope more than a fire burning high on the slope. Conversely, a fire high on the slope is usually more affected by ambient winds (Northern Region, Forest Serv. n.d.).

Gusty, turbulent flows and directional changes occur particularly at canyon intersections and wherever canyons change direction. Narrow or shallow canyons act as "chimneys" up which fire rushes, making control difficult and increasing danger to fire crews. Eddies are frequently created as wind crosses a ridgetop or flows through a saddle, and these cause erratic winds on the lee side of ridges (Brown and Davis 1973, Schroeder and Buck 1970, Southwest Interagency Fire Counc. 1968).

Chaparral at low elevations is ordinarily, but not always, ready for burning earlier in the year than brush at higher elevations. Normally, air temperature decreases at least 3.5° F/1000 ft (2° C/305 m) of elevation, and plant development is delayed about 10 days for each 1000 ft. Effects of temperature inversions, however, may alter this pattern. Air that is cooled after nightfall by contact with cool ground surfaces flows downcanyon, forcing the warm air to rise and forming a "thermal belt" partway up a mountain canyon slope. There, vegetation can be burned when similar vegetation below, or sometimes above, will not burn. (This effect has been reported from the Mendocino and Angeles National Forests.) Along coastal areas, cold marine air hundreds or even thousands of feet thick (Schroeder and Buck 1970) may push inland. Again, brush in the warmer air above may be burned while burning of brush in the zone of marine air must wait until conditions change.

Aspect

Aspect (exposure) influences air temperature, winds, fuel temperature, fuel moisture, and fuel types (*fig. 18*). The relative fire danger increases from northern to southern exposures (Northern Region, Forest Serv. n.d.; Southwest Interagency Fire Counc. 1968). Most severe fire microclimates are on southern or southwestern exposures.

Sunlight strikes southern exposures more directly and for longer periods each day than northern exposures. Consequently, south-facing slopes are hotter and drier. Evaporation and transpiration stresses are greater on southern exposures, and both dead and live fuel moistures are lower than on northerly or easterly exposures. South-facing slopes in the chaparral are generally dominated by chamise and burn when north-facing slopes do not. Thus, personnel of the Grindstone Canyon Brushland Management Project, Mendocino National Forest, report that they can conduct prescribed burns at times with no fireline construction. Within certain prescribed conditions, fires simply go out when the ridgetop is reached and the exposure changes.

A study in the Pacific Northwest (Morris 1966) showed that during drying periods following rains, with lower duff still wet, fire would spread in clearcut slash on northern slopes only if fuel stick moisture was 10.6 percent or below, but it would spread in slash on southern exposures with fuel stick moisture up to 18.5 percent. Where lower duff had dried, fire would spread with fuel stick moisture below 17.7 percent on north slopes and 25.6 percent or below on southern slopes.

Southern exposures might call for burning during early morning or evening so that fire intensity could be controlled.

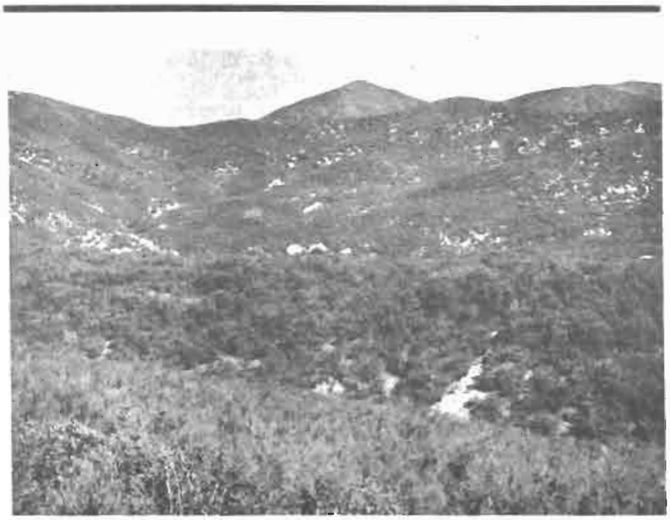

Figure 18—Ceanothus and chamise dominate the south-facing slope in the foreground, and manzanita and scrub oak dominate the north-facing slope beyond.

North slopes and moist canyon bottoms might best be burned during the hot part of the day and after adjacent south slopes have been burned.

Slope

Slope has an effect on fire similar to windspeed—the steeper the slope, the more rapidly fire spreads uphill and the more slowly it spreads downhill (*fig. 19*). The heat rising from burning fuel dries and preheats fuel located uphill from the heat source. The rising heat has much less effect on downslope fuels. Fire consequently moves much more rapidly upslope than downslope. Frequently the fire cannot be stopped until it reaches the top of a hill where terrain flattens out.

A tabulation derived from analysis of fire reports in California (U.S. Dep. Agric., Forest Serv. 1975; Southwest Interagency Fire Counc. 1968) suggests that relative slope effects are as follows:

Fire movement:	*Slope (pct.)*	*Relative rate of forward spread of flame front*
Downslope	−40 to −70	1.0
	−20 to −39	1.5
	−5 to −19	2.5
Nearly level	−4 to +4	5.0
	+5 to +19	7.5
	+20 to +39	10.0
Upslope	+40 to +70	22.5

From this tabulation, we can estimate that a fire burning up a slope of +20 to +39 percent will spread two times faster than a fire on a nearly level slope (10.0 ÷ 5.0 = 2.0); that a fire burning down a 40- to 70-percent slope will travel about one-fifth as fast as on nearly level ground, and that rate of spread will

Figure 19—When moving up a slope such as this, fire will spread three to five times faster than on level ground.

roughly double for each 25- to 30-percent increase in slope percentage.

The California Department of Forestry (Helm and others 1973) determined that fire spread on slopes of 41 to 60 percent would have windspeed equivalents in miles per hour one to four times as great as on 0- to 40-percent slopes, and that slopes greater than 60 percent would have windspeed equivalents two to seven times greater than 0- to 40-percent slopes. In Australia, a 10-degree (about 18 percent) increase in slope was credited with doubling the rate of fire spread up the slope; a similar decrease in downslope halved the rate of fire spread. Fire on a 17- to 18-percent slope spread upslope twice as fast as on level ground; on a 35-percent slope, fire spread upslope about four times as fast (Foster 1976, McArthur 1962).

In the estimates of forward spread given above, the effects of fire spotting are not allowed for. An additional slope effect that increases fire spread is that burning material may roll downslope and across a control line and start new fire. Also, as the slope increases, movement of personnel and equipment becomes more difficult.

Other slope effects appear to be small. In Canada, maximum temperatures on steep slopes were only about 4° F (−16° C) higher than on level terrain, and steepness of slope had little effect on fuel moisture (Muraro 1964).

Season and Time of Day

The timing of a prescribed burning project is an important planning element. Both time of year and time of day affect burning conditions.

Figure 20—Summer burns are apt to be intense because values for prescription elements tend to be high. This research burn took place July 19, 1977. Air temperature was 87° to 90°F, relative humidity was 28 to 36 percent, windspeeds were 0 to 12 mi/h, and 35 to 45 percent of the stand was dead.

Seasonal Considerations

The season for prescribed burning can be any time that burning can be accomplished within prescribed limits of weather, fuel, and manpower, and when burn objectives can be met. The months of July through October offer fewer opportunities than other months, although with proper planning or at high elevations, chaparral can be safely burned even then. Since 1945, California ranchers have conducted burns regularly under permit from the California Department of Forestry during summer months; there were occasional escapes and some burn shutdowns during weather extremes.

Fire escape hazard is greatest during the late summer and fall because of weather extremes, dry fuel, and high chemical content of the brush (*fig. 20*). At that time, there has been little or no rainfall for 4 or more months, and both soil and brush foliage are dry. To make matters worse, late summer to early winter are the seasons when the frequency of foehn winds—the Santa Anas of southern California, and the Monos and east winds farther north—is greatest. The ether extractable components—the fats, waxes, oils, etc.—of chaparral shrubs are at their highest during the autumn months, bringing about a considerable increase in heat value. In one study, chamise leaves increased in extractive content from 8.5 percent in the spring to 12 percent in the fall. Stem extractive content increased from 4.3 to 8.9 percent during the same period (Philpot 1969).

In October, November, and December there are days suitable for burning, even before significant amounts of rain have fallen. Days are short and nights are cool, so that with proper preparation, burns can be accomplished safely. During these early winter months, there is only a modest recovery in moisture content of green brush, and prescribed burns are hotter and cleaner than they are later in the year. If mineral soil should be exposed, as for conifer reproduction or grass seeding, fall or early winter is a better time for burning than late winter or spring.

The late fall or early winter months, before considerable rain has fallen, is not the best time to burn where litter is deep, or where there are large-diameter fuel accumulations. Where concentrations of 100- to 1000-hour timelag fuels—those greater than an inch in diameter—are present, burning is particularly risky during this period. These fuels will contain only minimal moisture, and will burn intensely, with maximum damage to soil and to oak or conifer stems and canopies.

After several inches of rain have fallen, burning must of course be suspended. However, 1-hour timelag fuels—grasses, weeds, or pine needles—can be burned a few hours following soaking rain, or within a day or two, provided there is drying weather. After 2 to 5 days of drying weather following rain, small brush fuels can usually be burned. Unfortunately, once the rainy season has started, a succession of storms may prevent burning.

Growth starts in the spring during periods when there is available soil moisture, and when air temperatures are at least 40° F (4° C) (Bentley and Talbot 1951). Then, moisture content of the shrubs increases rapidly, and the risk of escape is more nearly eliminated than at any other time of year. Spring is an

Figure 21—Late winter or spring is a good time to burn crushed brush or brush piles. Surrounding brushfields are more fire resistant than at any other time of the year.

excellent time to burn crushed brush, sprayed brush, brush piles or windrows, or other concentrations of dead fuel (*fig. 21*).

Summer burning in perennial grass may result in considerable mortality, depressed yield, or both (Cable 1965, 1967; Dwyer and Pieper 1967; Humphry and Everson 1951; Reynolds and Bohning 1956). On the other hand, burning after heavy rains during the dormant season will probably not damage the stand. Perennial grasses have been burned in Arizona (Pase 1971, Pase and Knipe 1977) and on the Mendocino National Forest during December and January following soaking rains without damage to the stand. Burning of stands of tall fescue (*Festuca arundinacea* Schreb.) in the Ozarks during the late winter dormant stage did not reduce yield (Probasco and Bjugstad 1977).

Time of Day

Within any 24-hour period, fuel and weather conditions vary and prescribed fire planning must allow for this or take advantage of it. For example, in the central Sierra Nevada, whiteleaf manzanita averaged 159 percent leaf moisture content during the cool hours before dawn and 121 percent during early afternoon hours (Philpot 1965). Fluctuation in flow of springs reflects, among other things, the transpiration demands of the plants above the spring. In summer at the San Joaquin Experimental Range, Madera County, California, flow varied from a pencil-sized stream to a drip between early morning and hot afternoon.

Probably the safest time of day for prescribed burning is from midday to midafternoon. During this period, fuels are as dry as they will be, air temperatures are at a maximum or are cooling, and winds are frequently at or past peak velocity. As burning is extended into late afternoon, control problems become minimal. The recommended timing requires more night patrolling, and perhaps overtime pay or adjusted workdays for crews would be necessary. If the objective is a high-intensity burn that removes a maximum of brush, the operation would need to start at about 1300 hours.

During prescribed burning studies near Mount Shasta, California, personnel of the Fuel-Break Research Project found that prescription conditions that ensured a relatively safe burn frequently did not occur until evening (*fig. 22*). Values for one or more prescription elements were excessive throughout the day, and evening and night burns were therefore carried out. The limited visibility at night required special communication arrangements, night patrol, and mopup. Igniting fires during

Figure 22—Late evening or nighttime burning is necessary if prescription conditions do not occur earlier. Hazardous fuels along a fireline are sometimes burned at night.

evening hours required careful attention to the likelihood of wind shifts from upcanyon or calm to downcanyon.

Night burning has been used successfully by California ranchers to clear wide firelines in grass and scattered brush, but is used less frequently in dense, mature brush. Riverside Forest Fire Laboratory personnel have burned brush at night on fuelbreak locations following ball and chain crushing. At one site, the fire did not burn into 18-year-old brush at all, and on other sites, older but untreated brush and dry grass did not ignite or burn readily because the fine, dry fuel had absorbed moisture as the humidity percentage increased.

Sometimes a burn is begun as early in the morning as fuels will burn, so that it can be completed before the heat of the day. If the area to be burned is extensive, or terrain is a problem, the immediate objective may be to have a safe line burned out before the hot part of the day. Early morning burns are facilitated by nighttime relative humidity of not more than 50 percent. If nighttime humidity approaches 100 percent, moist fine fuels and low temperatures may make successful burning impossible during the morning hours. Fuels are cool and damp, and fuel sticks located in full sunlight may not reflect the actual resistance to ignition and fire spread of shaded fuels within the burn unit. Relative humidity readings taken during the morning similarly may not reflect actual burning conditions. Slow ignition and spotty fuel consumption may result. There may be flare-ups later in the day. Slopes exposed to early morning sunlight can be ignited earlier than shaded slopes or gullies.

OTHER PLANNING CONCERNS

The topics discussed here, though important to success of a prescribed burning project, do not normally make a part of the prescription. They are considerations in the planning process.

Fuel Preparation

Prescribed fire for reduction of chaparral is most useful in mature or decadent stands with a high dead-to-live-fuel ratio. These are the stands most subject to dangerous wildfire if fuel reduction is not achieved. When brush stands are young—less than 20 or 25 years old—the dead-to-live-fuel ratio is usually less than 1:5; the brush is less than 20 percent dead. The green fuel moisture in young brush tends to be high and contributes to low flammability of the brush stand. *Brush that is less than 20 percent dead can seldom be burned satisfactorily,* and large wildfires seldom occur in such youthful brushfields (Rogers 1942). Brush that is about one-fourth dead is marginal for prescribed burning, and only when the dead-to-live-fuel ratio is between 1:3 and 1:2 does a prescribed fire burn readily, or a 10,000- or 30,000-acre (4050- or 12,150-ha) conflagration become a threat.

If young dense brush is to be burned, it must be treated to increase the proportion dead, and to reduce the average moisture content. This can be accomplished by spraying with herbicide, or by mechanical crushing (Green 1977, Roby and Green 1976).

Spraying of standing brush for burning is generally more economical than crushing, but because the desiccants are usually broadcast from aircraft, their use is restricted to locations remote from towns or farmlands.

Figure 23—New twigs are produced from undamaged stems following spraying with contact herbicides, and sometimes following 2,4-D spray.

Systemic herbicides such as 2,4-D should be applied during the late spring. Leaves and twigs dry slowly during the following weeks and months. A single treatment usually kills about one-third of top growth of brush species that sprout from a root crown, such as oak or chamise, but may kill more sensitive species such as *Ceanothus* and *Salvia* (sage). The stand can then be burned during the winter or spring following treatment, frequently with almost complete removal of the brush.

Quick-acting contact herbicides—fortified weed oils and other products—damage only the plant tissue touched by the herbicide (Green 1977). Leaves and very small twigs lose moisture within hours, and the effect is complete within 1 or 2 weeks if daily maximum temperatures are above 70° F (21° C). Prescribed burning should follow soon; if it does not, the effect is nullified as the small branches put out new twigs and leaves (*fig. 23*). Removal of branchwood by treatment with contact herbicides is minimal.

Crushing as a brush treatment is generally more effective than spraying with herbicides, unless the brush is very limber and cannot be broken and compacted. Crushing can be done by a bulldozer with the blade 12 to 14 inches (30.5 to 36 cm) above the soil surface, by a chain between two tractors, or by a chain between a tractor and a large steel ball (Roby and Green 1976) (*fig. 24*). One or two passes of a crushing instrument will usually convert fire-resistant brush to fuel that will be consumed by fire a few days later.

If complete brush removal is needed for drill seeding or other range improvement, 100 percent of the area should be crushed. If brush is mature and dense, crushing strips amounting to as little as one-fourth to one-third of the area will be enough to accomplish most prescribed burn objectives.

Ignition Methods

The ignition or firing pattern is determined primarily by the speed and direction of prevailing winds, and by the slope. Other considerations are size of burn, accessibility of the burn interior to personnel, and fuel loading. In the following discussion, several "standard" firing patterns are described. Schimke and Green (1970) discuss variations of these ignition methods to use when burning fuelbreaks. These hand-firing methods are rapidly being modified as the helitorch comes into wide-scale use.

Backfiring Versus Headfiring

The direction of fire progress in relation to slope and wind is important in discussion of ignition methods. A backing fire is any fire burning into or against the wind or down a slope without the aid of wind. During Santa Ana conditions, fire is sometimes driven downslope by strong winds, and it then acts as a headfire—one that burns with the wind, or upslope. A flanking fire spreads at right angles to the wind or slope direction.

Headfires move faster and burn more area with greater flame height and intensity than backing fires. In burning tests on pine-hardwood plots in Texas, headfires burned over plots five times as fast and flames were three times as high, as with backing fires (Ferguson 1957). Because of the greater flame length, headfires have a more damaging effect on stems and canopies than backing fires (Hough 1968, Palmer and Devet 1966). Headfires can be used when backfires won't burn satisfactorily, because they will spread through somewhat sparser fuels and fuels with slightly higher moisture content.

Backing fires need continuous and uniform fine fuels to spread the fire. Because the rate of fire spread, flame height, and energy release are so much less than for headfires, backing fires do less damage to canopies and should be used when oaks or conifers are to be protected during prescribed burning. However, if there are fuel accumulations around bases of trees, backing fires may burn deeply for a long period with a higher heat release rate than during a headfire, and kill or damage the trees. To prevent this, burning must be done when subsurface litter is wet.

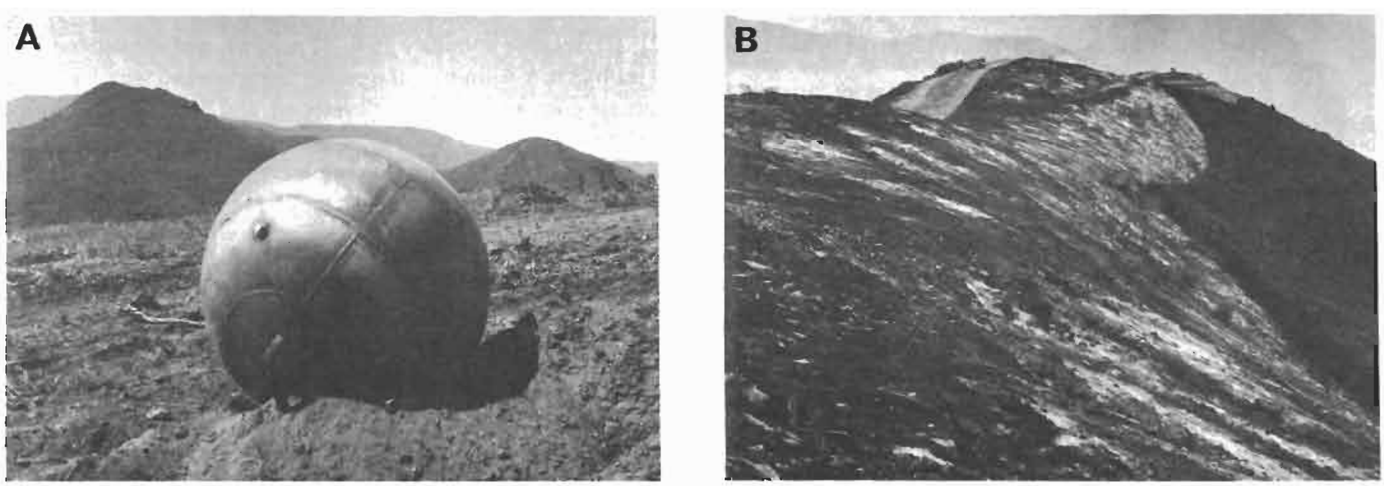

Figure 24—To crush chaparral shrubs, a Navy buoy, or ball (*A*) is filled with water, attached to a tractor by a chain, and dragged along a hillside. Treated brush may burn completely (*B*) when untreated brush will not burn at all.

Perimeter Firing

Most chaparral burns are on mildly sloping to steep terrain; almost none are on level ground. In daytime burning, winds tend to be upcanyon and upslope. Because both slope and wind encourage rapid uphill fire runs, safe daytime prescribed burns in chaparral must usually be started near the highest elevation along the fireline surrounding the burn site. Two teams start back to back and ignite the brush as they move away from each other along the ridgetop firebreak. This procedure causes the fire to back slowly into the wind and down the slope. The two firing teams work across the upper boundary of the burn, and the "backing" fire creates a wide burned firebreak as it burns downslope. As the firing teams pass the upper corners of the burn area, they turn downslope, usually on lateral ridges, and ignite the brush along the sides or flanks of the burn. As they approach the lower elevation fireline, the two teams start working toward each other across the bottom of the burn area to close the ring around the fire. The headfire, burning with the wind and up the slope, then burns until it meets the backing and flanking fires.

The procedure described is known as the perimeter or ring firing technique (Mobley and others 1973, Martin 1976, Martin and Dell 1978). It is the easiest firing technique to use safely in chaparral. A possible disadvantage of perimeter firing is that once begun, it must be completed—the ring must be closed to prevent escape. There is usually no provision for stopping the burn short of completion. In coniferous forest, perimeter firing may result in too much crown scorch in the center of the burn.

Strip Headfiring

Where the terrain and fuel allow crews carrying firing equipment to cross the slope safely, they can ignite the backfire along the ridgetop fireline, then drop downslope—50 ft (15 m), more or less, depending on slope steepness and burning conditions—and fire a line parallel to the first one. From there, the fire burns as a headfire up to the backfire. The firing teams then burn out successive strips downslope until they reach the bottom fireline. This is the strip headfire method of firing. It is not practical in tall, dense brush unless trails are prepared for the firing crews before the actual burn, or unless the helitorch is used (see discussion below).

The strip headfire method was used for some small (5-acre [2-ha]) experimental prescribed burns in southern California (Green 1970). Strips about a chain apart were crushed to allow access through brush 6 to 8 ft (2 to 2.5 m) high. Two men with drip torches went to the center of each crushed strip and fired as they proceeded toward opposite edges of the burn. The same firing team burned out all the strips, thus ensuring that a strip below them on the slope would not be inadvertently ignited prematurely. The partially dry crushed brush burned fiercely, contributing to greater consumption of brush in strips above.

Stopping a strip burn before completion is difficult unless the fuel is light and can be readily extinguished. For a large burn, firelines may be prepared to allow for better control in the event that the fire needs to be stopped. But the strip firing process can be stopped at any time, and fire spread downslope would then be slow.

Flank Firing

A system called flank firing can be used where crews can walk safely and easily downslope through the fuels. Backfiring from the ridgetop establishes a burned line across the top of the burn. Then, several men fire from this line parallel to one another into the wind or downslope. The lines of fire spread out in an irregular V behind the fire setters and burn together. Where two lines of fire merge, a line of greater fire intensity exists until the fuels are consumed. Flank firing is useful in grass or in open stands of low-growing brush, but not in dense brush.

Center Perimeter Firing

When a high-intensity fire is needed that will override effects of low-intensity surface winds, reduce heat near the perimeter, and put smoke high in the air, center firing may be the answer (Martin and Dell 1978). Center firing is commonly used in clearcut slash burning and has been used in chaparral. The procedure calls for lighting a fire or a small ring of fires near the center of the prescribed burn. When flames are 6 ft (1.8 m) high or more, additional fires are lit in a ring around the center fires. After these are burning and flames are being pulled toward the center, another ring of fires—or more likely, in small burns, the burn perimeter—is fired. Inrushing air pulls flames into the burn and toward the center convection column.

The center perimeter firing system is most useful on level or gentle terrain and should not be attempted if slope is greater than 30 percent.

Center perimeter firing was used in manzanita-dominated chaparral near Mount Shasta, California, where prescribed burning on plots of 4 and 18 acres (1.6 and 5.7 ha) was being studied (Bentley and others 1971). Because the brush was dense and movement on foot too difficult and slow for manual firing, the plots were center-ignited with electrical squibs attached to diesel-gel fuel boosters wired in a series circuit and fired with a blasting machine (Schimke and others 1969). On plots that had been sprayed to desiccate the brush, and under cool burning conditions—air temperature 63° to 70° F (17° to 21° C), relative humidity 35 to 42 percent, and windspeed 2 to 4 mi/h (3 to 6.4 km/h)—the center firing worked very well. An intense convection column developed, and flame along the plot perimeters "leaned inward" toward the plot centers (*fig. 25*). A swarm of flaming or glowing leaves and twigs was drawn into the convection column, but they were cool when they came down in adjoining plots and no spot fires resulted.

Area Ignition

In area ignition, a number of spots or lines through the burn area are fired as nearly simultaneously as possible. Sometimes, patterns are laid out over the area in a center-ring firing configuration. The fire sets must be close enough—1 to 2 chains apart—to influence and support each other. Fuels between the fires are preheated by radiation, and thus burn more rapidly than from a single fire front. The small burns pull or draw on each other so that fire intensity is magnified, particularly at the junction zones (Mobley and others 1973, Sackett 1968, Fenner

Figure 25—During prescribed burn studies in chaparral on the Shasta-Trinity National Forest, plots were center-fired, then the perimeter was fired (*A*). A few minutes later, a well-developed center convection column pulled the perimeter fire inward (*B*).

and others 1955). The numerous fire sets finally burn as one intense fire with a strong indraft. Firewhirls—small fire storms—frequently develop.

Area ignition can be a useful firing technique when burning conditions are such that other ignition methods spread fire too slowly, or not at all, or if a clean burn is desired. This type of firing can be scheduled for late winter or spring when moisture content of green fuel is high and there is little escape hazard.

Area ignition techniques were developed to burn heavy brush fuels. Although the system requires that readily ignitable fuel be available through the brushfield, there is no point in using area ignition on light flashy fuels which burn readily with other firing systems.

To keep control over the mass fire created by area ignition, the burn area should be kept small—no more than 5 or 6 acres (2 or 2.4 ha) (Fenner and others 1955). If a larger area is to be burned by this method, the firing must be timed so that some acreage is in the individual ignition point stage, some is in the buildup stage where fires are beginning to affect each other, some is in the mass fire stage, and some is cooling down.

Area ignition should be used when winds are less than 5 mi/h (8 km/h). One area ignition test fire went "over the hill" because of too much wind at the time of maximum fire activity. Other prescription conditions should also tend to low fire intensity—relative humidity should be 30 percent or higher, and air temperature less than 85° F (29° C). A test fire from a single ignition point should spread slowly and be readily extinguishable.

Use of the Helitorch

The helitorch is a device for igniting wildland fuels; it is suspended under and controlled from a helicopter. A frame supports a 55-gallon drum containing alumagel (a jellied aluminum-gasoline mixture), a small electric motor which drives a pump, and an igniter. As the helicopter flies along a ridge at 40 mi/h (64 km/h), or hovers, or flies a grid pattern, the jellied gasoline is pumped out of the drum and ignited, and falls to the ground as globules burning with high-intensity flame.

Research and experience have shown that large firebrands, because they emit greater amounts of heat over a greater length of time, dry out and ignite fuels with higher moisture contents than do smaller firebrands. We also know that the distance between spot fire sets strongly influences fire intensity under a given set of weather and fuel conditions. High-intensity burns can result from many sets close together.

The helitorch capitalizes on these principles. It ignites fuels that cannot be readily ignited with hand-held drip torches. It is speeding a trend toward less dependence on extensive perimeter firelines and large ignition crews. The helitorch can ignite fuel in extensive and remote areas where control lines are not easy to install, but where they may not be truly required. The Mendocino National Forest in northern California used the helitorch to burn brush areas not surrounded by firelines, where the fire self-extinguished at the ridgetop. Much is yet to be learned about use of the helitorch, however; costs in relation to results, for example, have not been clearly determined.

Smoke Management

After the prescribed burn planning is complete, the prescription written, and fire control lines constructed, and even when manpower and equipment are on the burn site, the prescribed burn can be canceled because it is a "no-burn" day. This designation is applied by an agency representing citizenry concerned with the contribution of smoke to air pollution. Many otherwise good prescribed burn opportunities are unavailable because of limitations imposed by air pollution regulations.

The Clean Air Act, Public Law 88-206, passed by Congress in 1963 and amended thereafter (1965-77), requires (Paulson and others 1978) that

- The U.S. Environmental Protection Agency (EPA) shall prepare lists of air pollutants that have an adverse effect on public health and welfare. Listed pollutants resulting from burning include carbon monoxide, sulfur dioxide, hydrocarbons, nitrogen oxides, suspended particulate matter, and ozone.
- The Environmental Protection Agency shall establish national ambient air quality standards for each major air pollutant.
- Each State shall establish air quality regions covering the State, and assure that air quality will meet national standards.
- Each State shall ensure against the significant deterioration of air quality. This means that the presently clean air over national parks, wilderness areas, other federally owned lands, desert areas, etc., must not suffer significant deterioration, including deterioration of visibility. This requirement could affect prescribed burning adversely.

The California Legislature established the Air Resources Board, which operates under provisions of several sections of the California Health and Safety Code. The Board has established 14 air basins (Air Pollution Control Districts) for California, and has also adopted regulations on burning of agricultural wastes, including rangeland and forest burning. Meteorological criteria have been established in each of the basins, and are the bases for the burning regulations. Regulations and other actions of the Board which affect prescribed burning are given below.

- By 1500 h daily, and usually before noon, for each of the Air Pollution Control Districts, the Board determines whether the following day is a permissive burn day or a no-burn day. If the decision cannot be made that day, it is announced by 0745 h on the following day. The decision is based on meteorological data, and the probable effect of burning on ambient air quality within the air basins.
- The Board has defined agricultural burning to include open fires used in forest management, range improvement, or improvement of land for wildlife and game habitat, or disease or pest prevention. Range improvement burning means the use of open fires to remove vegetation for a wildlife, game, or livestock habitat, or for the initial establishment of an agricultural pasture on previously uncultivated land. Forest management burning means the use of open fires as part of a forest management practice, to remove forest debris.
- The Board has designated the Forest Service, the California Department of Forestry, and certain other fire departments as agencies with authority to issue burning permits in their respective areas of jurisdiction. The permits are to be issued jointly with the Air Pollution Control District.
- The Board has exempted agricultural burning at altitudes above 6000 ft (1830 m) from the agricultural burning guidelines, except in the Tahoe Basin.
- Upon request through a designated agency, 7 days in advance of a proposed range or forest burn, an air resources meteorologist will give 48-hour burn or no-burn forecasts, and these will be continued each day until a permissive burn notice can be issued up to 48 hours before the scheduled burn date. The State Board has the power to cancel permissive burn notices that were issued more than 24 hours in advance, and a local (county) board can cancel any burn within its area of responsibility.
- The Air Pollution Control District may designate a period between January 1 and May 31, during which time range improvement burning may be conducted under permit on a no-burn day, provided that more than 50 percent of the land has been treated to modify brush (brush has been felled, crushed, or sprayed).

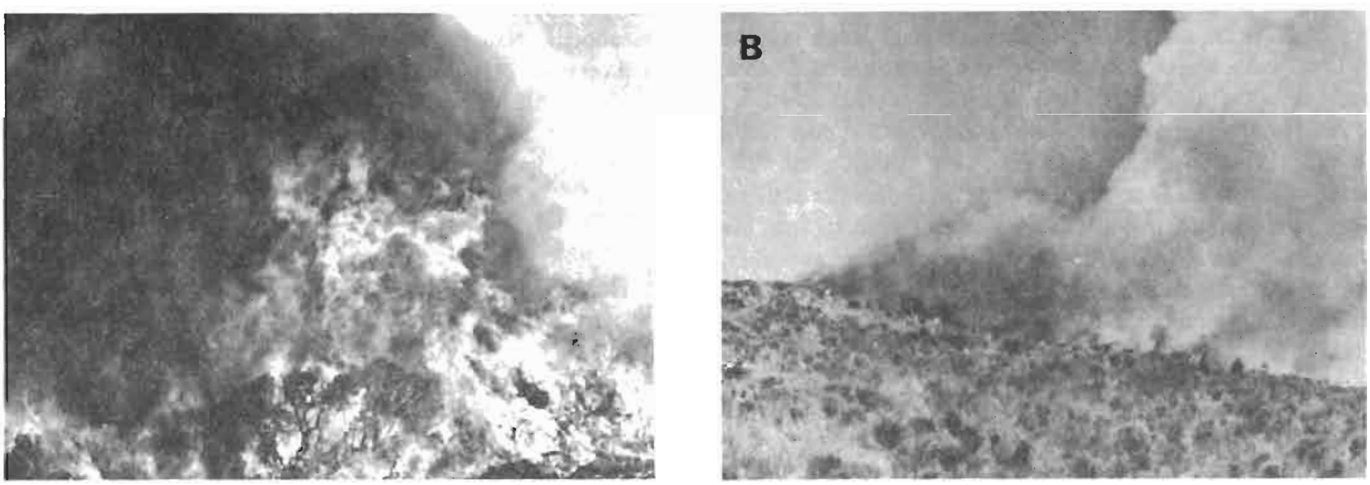

Figure 26—Smoke from fires burning green brush (*A*) contains more suspended particles, carbon monoxide, nitrogen oxides, and hydrocarbons than smoke created (*B*) when cured grass and spray-killed brush that is mostly dry is burned.

Each Air Pollution Control District is required by law to take the following actions:

- Adopt, in cooperation with the fire protection agencies having jurisdiction within the Air Pollution Control District, an implementation plan for agricultural burning consistent with the agricultural burning guidelines.
- Require material that is to be burned to be sufficiently dry, and free of material, such as tires, that is not produced in the agricultural operation, to burn with minimum smoke.
- Regulate burning when wind direction is toward a nearby populated area.
- Regulate the total amount of waste that may be burned each day.
- Give consideration to modification of the burn day criteria for specific sites where the location is favorable with reference to populous areas, where the amount of material to be burned is not excessive, and where expected impact on air quality is not expected to be excessive.

Air Pollution Control Districts or local government entities within the Districts may establish rules that are more stringent than the California Air Resources Board rules. San Diego County, for example, has established minimum days of drying for various agricultural fuels (including forest and range fuels).

Emissions from forestry burning are highly complex, consisting of hundreds of gaseous chemical compounds and particulates which vary greatly in composition and physical properties (*fig. 26*). If burning could be done at temperatures around 1800° F (1000° C) with adequate oxygen, essentially all the products of combustion would be converted to carbon dioxide and water. But such conditions are seldom experienced in the field, and leading experts in forest burning estimate emissions from forest prescribed burning of predominantly dry fuel as follows (Geomet, Inc. 1978; Sandberg and others 1979):

Emission:	*Pounds per ton of fuel*
Carbon dioxide	2000 to 3500
Water	500 to 1500
Carbon monoxide	20 to 500
Particulates	17 to 67
Hydrocarbons	10 to 40
Nitrogen oxides	2 to 6

Emissions from wildfires, and from prescribed fires burning considerable amounts of green fuel, would be greater, or at least would fall near the upper end of the ranges indicated.

In planning for prescribed burns, the following points should be considered:

- Combustion is more nearly complete when dry or dead fuels, rather than wet or live fuels, are burned. There is less production of carbon monoxide, hydrocarbons, and particulate per unit of material consumed (Darley and others 1966). Dry or partly dry fuel is a result of spraying, crushing, and aging of the brush. Mature crushed brush in southern California has been observed to burn with so little smoke that the column was scarcely visible a mile away.
- Backing fires appear to produce less smoke than headfires (Pharo 1976)—35 percent less in laboratory studies (Ward and Lamb 1970). Backfire burning in rice straw reduced emissions by up to 50 percent when straw moisture content was no greater than 10 to 12 percent (Nelson and others 1980). Headfires may produce up to three times as much particulate material as do backing fires (Tangren 1976, Ryan and McMahon 1976).
- Smoke dispersion is better in an unstable than a stable atmosphere. Caution is necessary, however, because excessive instability may result in escaped fires. Signs of a stable air condition are clouds in layers, smoke columns drifting apart after a short rise, and poor visibility due to smoke, haze, or smog. An unstable air condition is signaled by gusty winds, dust devils or other surface whirlwinds, cumulus-type clouds which indicate rising air currents, smoke rising to great heights, and good visibility. When the temperature increases with height, creating a temperature inversion, the air below the top of the inversion layer is very stable. When there is considerable decrease in temperature with height, about 5.5° F/1000 ft (3° C/305 m) elevation, the air is unstable (Davis 1969, Schroeder and Buck 1970, Brown and Davis 1973).
- Air pollution is minimized in a high-energy fire that produces a tall convection column. This vents the smoke through the stable air of inversion layers, provided the burning is within a few hundred feet from the top. Smoke released above the inversion will be picked up by moving air and dispersed. If the burning is a thousand feet or more below the top of the inversion, burning should be delayed, because smoke will be trapped below or in the layer. Without a convection column, the smoke drifts in local air currents (Cramer and Graham 1971) (*fig. 27*).
- Burning at high elevations, 3000 to 4000 ft (915 to 1220 m), may be possible when smoke from lower elevations might be trapped by a temperature inversion. Alternate sites should be planned.

Figure 27—A stable atmosphere, perhaps with an inversion layer, results in weak convective columns and drifting of smoke along the ground.

• Burning should be done at times when air movement is away from sensitive areas (*fig. 28*), so that smoke will be less likely to drift toward such areas.

Manpower, Equipment, and Control Lines

When an organization or fire boss takes on a prescribed burn project for the first time, manpower and equipment are usually assembled as though to combat a wildfire. Wide lines are constructed and equipment is stationed at strategic locations. This may sometimes be necessary during summer and fall, but the need is much less in winter and spring, when the danger of widespread escape is small. As burning experience accumulates and trust in burning prescriptions and good weather forecasts is acquired, the need for elaborate lines and so much manpower and equipment lessens. Burn crews become smaller, and the cost of burning drops. This learning process has been repeated many times.

Many low-intensity burns of 1 to 10 acres (0.4 to 4 ha) were carried out by researchers during early spring in the mixed-conifer type of the Stanislaus National Forest, using a crew of only four men. Two did the lighting, one acted as boss and observer, and one managed a pickup truck with a slip-on pumper unit. The ranger district could have been called on for help had any of the burns escaped, but this was never necessary. For fall burns, a suppression force was kept more immediately accessible.

Because prescribed burns in chaparral are seldom low intensity as compared with those under a coniferous forest canopy, more precautions—wider lines and more manpower and equipment—are normally taken for chaparral burns. Even so, crushed brush has been burned in southern California during the spring with the green brush serving as fireline, and five or six men on hand. There have also been limited trials in southern California, and more extensive experience on the Mendocino National Forest, in which standing brush has been burned without firelines. Early summer and fall prescribed burns of 50 to 150 acres (20 to 61 ha) have been successfully accomplished using control lines 20 or 30 ft (6 or 9 m) wide, several pieces of firefighting equipment, and 20 to 30 men.

Figure 28—Because sensitive areas must be kept free of smoke, a burn such as this must be made only under suitable conditions.

Most prescribed burns have definite perimeter control lines determined and constructed in advance, but for some winter and spring burns, the firelines may not actually be constructed. If fire reaches the perimeter of such a planned burn and crosses it, a decision can then be made to let the fire burn to another planned perimeter for reasons which should be recorded, or action can be taken to suppress the escape. In the past, prescription fires that crossed a perimeter line were immediately suppressed. This is costly and not always necessary. If the burn prescription, including National Weather Service forecasts, is still being met, the fire might be allowed to burn to the secondary perimeter at nominal cost for additional benefits.

Weather Information

Whether or not the prescribed burn objectives are accomplished safely depends in large part on elements of the weather. The planner of the burn must make a considerable effort to acquire the needed weather data.

Fire Weather Forecasts

When preparation for the prescribed burn is nearly complete, and the tentative burn date is approaching, the help of the National Weather Service should be enlisted. If available, a special fire weather forecaster should be consulted; otherwise, the forecaster on duty should be asked for a spot weather forecast.[4] One person should be appointed for this purpose, and should introduce himself in person or by telephone to the forecaster a few days before the anticipated burn date, explain his mission, and promise that the forecaster will be contacted daily for 2- to 5-day spot forecasts until the burn is completed. These calls should generally be after 0800 and 1700, when updated general forecasts become available. The forecaster will need to know the prescribed burn location, the elevation, and the terrain, and probably will want local weather data collected at the site. Fire weather information can also be obtained through the local forest dispatcher, from continuous radio broadcasts on 162.55 MHz, and from commercial television and radio.

Weather Data at the Burn Site

Weather readings should be taken at the burn site, rather than at a distant ranger station or National Fire Danger Rating Station (see below). Otherwise, there is danger that data may not be relevant. Readings may not indicate local temperature or wind features, for example, and these might seriously affect fire behavior or smoke distribution.

[4]The Weather Service has a request form for special "spot" weather forecasts, "Fire Weather Special Forecast Request."

One or two locations should be selected where representative onsite weather observations will be taken. Preferably, locations should be about midslope or on a flat within the burn, provided brush or trees do not interfere with airflow past the weather-measuring equipment. A suitable location may be a low ridge near or within the burn site. Midslope locations are most representative but may not be accessible to personnel because of dense brush.

A weather station should be set up 1 to 2 weeks before the expected burn on one or both of the sites selected for gathering weather data. The station can be a standard National Weather Service instrument shelter with louvered sides, slatted bottom, and fixed or removable legs (Fisher and Hardy 1976). Instruments normally included are a battery-operated or hand fan psychrometer for accurately determining relative humidity, a hygrothermograph to give continuous temperature and humidity records, and a scale for weighing fuel sticks. Fuel sticks should be located near the other instruments, over a litter bed in full sun. Other fuel sticks can be located within the brush stand. A rain gauge can also be installed in a nearby exposed spot if rain might possibly create a problem. With this equipment, windspeed must be determined with a hand-held wind meter, and direction with a compass. Mechanical weather stations are available that record windspeed and direction, plus temperature and humidity, at a cost of at least $3000. Belt weather kits and portable fuel stick balances can also be used. Equipment cost will be lower, but less data will be collected.

The pattern of diurnal wind direction and speed variation should be observed at the burn site well in advance of the burn, and should be considered when selecting the ignition plan. One main value in National Weather Service forecasts is the advance warning about changes in synoptic weather that would disrupt the prevailing winds, and cause problems during the burn.

Optimum and Hazardous Weather

When temperatures aloft decrease with increase in elevation at about 3.5° F/1000 ft (2° C/305 m), the air is considered stable and good for prescribed burning. If the temperature decrease with increased altitude is 5.4° to 5.5° F/1000 ft (3° C/305 m), the air is definitely unstable (Davis 1969) and hazardous for burning. A period of high pressure 1 or 2 days after the passage of a low pressure system is often a good time to burn. As the high pressure system moves into the area, air tends to become stable and the daytime upcanyon, nighttime downcanyon weather prevails.

Hazardous weather for prescribed burning occurs when weather fronts with their unstable air are approaching, when scattered thunderstorms are expected, and when temperatures above 90° F (32° C) and humidities below 25 percent coincide with winds in excess of 10 mi/h (16 km/h). When cold fronts approach, clouds and strong erratic gusty winds from any direction may be expected. Updrafts, downdrafts, and surface gusty winds occur during thunderstorm development and dissipation (Schroeder and Buck 1970). When successive days of high temperatures and low humidities occur, the hazard becomes greater with each day.

Fire Danger Rating

The National Fire Danger Rating System (NFDRS) is designed to give an indication of ignition hazard, tendency for fire spread, and potential for fire intensity (Deeming and others 1977). Fuel and weather elements are measured at the time of day when fire danger is normally highest, at key fire danger rating locations which represent areas of 10,000 acres (4050 ha) or more. Fire danger rating is used by forest managers as a guide to fire occurrence and manpower needs, to warn the public of fire danger, to issue or lift forest closures, and for other fire prevention measures. Because NFDRS predictions have application to broad geographic areas rather than to a specific prescribed burn location, and because they estimate "worst case" fire potential, the NFDRS has not been directly useful for prescribed burning. However, methods of interpreting the danger rating system for application to prescribed burning are being developed.

Fire danger rating and fire behavior programs have been written for the programmable, hand-held TI-59 calculator; these programs make the calculator useful for estimating the probable spread rate and flame lengths if a fire burns as a line fire and reaches a steady burning state. Fuels, weather, and slope information from a prescribed burn site can be entered into the calculator and outputs calculated (Burgan 1979, Cohen and Burgan 1979). Graphic procedures (nomograms) are also available (Albini 1976) to help estimate these fire characteristics.

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Prescribed burning is frequently suggested for reducing conflagration costs in chaparral. Preparation for a prescribed burn includes environmental impact reports, approval by higher levels of authority, and a burn plan. After objectives are stated, the prescription can be written. Elements of the burn prescription reflect fuel, weather, and other factors that determine fire behavior. Proportion of dead fuel, quantity of available fuel, live fuel moisture, topographic features, and chemical content can all be considered prior to the burn date. Then the desired ranges of dead fuel moisture, relative humidity, windspeed and direction, air temperature, and time of day can be selected. Perimeter firing is commonly employed, after weather forecasts and locally collected weather data indicate prescription elements are acceptable and smoke management is not a problem. An important final step is burn evaluation.

Retrieval Terms: prescribed burning, brushland burning, chaparral, fuel moisture content