Refined Burning Prescriptions for Yosemite National Park

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ABSTRACT

Overprotection from natural surface fires in the mixed conifer forest of Yosemite National Park has caused unnatural vegetation changes and increased fire hazards. Fire is being reintroduced as a management tool to rectify these conditions. This report presents results of a study on the effects of prescribed fires burning in four fuel types and over a range of weather conditions on fuel, fire, and vegetation characteristics.

Fuel moisture level, fuel type, and direction of burning were found to have significant effects on fire characteristics, fuel reduction, and vegetative composition. Information gained from the study was used to refine burning prescriptions.

The application of the results of this study will allow the resource manager to simulate natural fires with prescribed fires and to plan and implement burning programs.

Contents

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INTRODUCTION

Early travelers and photographers in the mid-1800s recorded the forests of the Yosemite region as being parklike with little undergrowth and wide expanses of meadows. These forests were part of a mixed conifer zone dominated by ponderosa pine (*Pinus ponderosa* Laws.)[1] with some incense-cedar (*Libocedrus decurrens* Endl.) and California black oak (*Quercus kelloggii* Newb.) at the lower elevations, and increasing numbers of sugar pine (*Pinus lambertiana* Dougl.) and white fir [*Abies concolor* (Gord. and Glend) Lindl.] at the upper end of the zone. Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] was more prevalent in the northern portion of the region.

Beneath the larger trees the forest floor was carpeted with needles, bear clover (*Chamaebatia foliolosa* Benth.), or various grasses and forbs.

The understory, where present, consisted of tree reproduction, ceanothus (*Ceanothus* spp. L.), and manzanita (*Arctostaphylos* spp. Adans.). These open conditions were attributed to low intensity surface fires set by Indians and lightning. If fires were frequent enough, fuel accumulations and undergrowth were kept at a minimum (Fig. 1).

Subsequently, in 1890 an era of protection began when the area was set aside as Yosemite National Park. Cessation of Indian burning and subsequent park management under a philosophy of preservation caused many changes. Overprotection from natural surface fires permitted the forest floor to become a tangle of understory vegetation and accumulated debris. Shade-tolerant incense-cedar and white fir thickets increased and caused an unnatural ecological succession away from the less

[1]Tree nomenclature is from Little (1953). All other taxonomic references are from Munz and Keck (1968).

FIG. 1. An open mixed conifer forest in Yosemite National Park. Ponderosa pine, sugar pine, and incense-cedar are in the overstory. The sparse understory consists of manzanita plants and coniferous reproduction. This area has been managed with periodic prescribed fires.

shade-tolerant ponderosa and sugar pines. Pines are better adapted to a regime of periodic surface fires and would be favored.

As undergrowth increases, fuel volumes expand and a continuous fuel layer extends from the ground to the forest canopy. Currently, the total fuel layer, including dead trees, branches, needles, and other debris, is so thick that a wildfire would soon reach catastrophic proportions.

The early management decision to extinguish all natural fires has led to conditions which not only threaten to destroy those park values which were intended to be preserved but also modify the forest to an unnatural state. Recent changes in National Park Service policy, in part due to recommendations of the Leopold Committee (1963), direct that each park be restored as nearly as possible to the conditions that existed when Europeans first visited the area. A management philosophy of perpetuating natural processes rather than preserving and protecting objects has evolved.

Prescribed fire is now being introduced into the mixed conifer forests of Yosemite National Park as the most natural method of manipulating the vegetation to recreate and perpetuate what are thought to be pristine conditions and also to reduce fire hazards. In order to use fire effectively and judiciously, burning prescriptions need to be developed and refined. A prescription specifies the weather and fuel conditions under which a fire could be ignited to meet specific management objectives.

Objective

The objective of this study was to develop refined burning prescriptions for environmental restoration and fire hazard reduction fires in the mixed conifer forests of Yosemite National Park. This was done by evaluating the effects of prescribed spring fires burning in different understory fuel types, within a specific range of fuel and weather conditions, on fire characteristics, fuel reduction, and understory plant composition.

Previous Work

That fire played an important role in Yosemite's forest can be surmised from historical accounts. John Muir (1894) not only described the open nature of the original forest in his book *The Mountains of California* but also wrote about periodic fires which occurred in the forest. Reynolds (1959) and Vankat (1970) have both attempted to determine the exact nature of the pristine Sierra Nevada forests. There is general agreement that the forests were quite open compared to present conditions and that fire was important in maintaining the openness.

Changes in Yosemite's vegetation subsequent to fire suppression activities have been chronicled by Ernst (1949, 1961). He noticed the forest encroaching on the meadows of Yosemite Valley and the increase of undergrowth throughout the forest. Using a sequence of historical and modern photographs, Gibbens and Heady (1964) showed the dynamic nature of the vegetation increases.

Fire ecology studies in California have included fuel reduction and modification investigations in giant sequoia-mixed conifer forests (Biswell 1967), fuel conditions in similar forests (Agee 1968), and the restoration of fire to various ecosystems of Sequoia and Kings Canyon National Parks (Kilgore 1970, 1971). No specific studies relating fire behavior to weather variables and fuel consumption have been made for this region. Data from a study of this type have been published for the southern coastal plains in Georgia (Hough 1968), although burning was restricted to one fuel type and no attempt was made to burn at specific moisture levels.

Prescriptions for burning to maintain fuel breaks in the central Sierra Nevada have been established by Schimke and Green (1970). To obtain safe, satisfactory fires, the prescriptions specify upper and lower limits for air temperature, relative humidity, wind speed, and fuel moisture content. These prescriptions must be further refined, however, if prescribed fires are to be used for environmental restoration and fuel reduction in a mosaic of understory fuel types.

Considerable research concerned with fire characteristics has been done by using fire models in laboratories. At the U.S. Forest Service Missoula Fire Laboratory, Beaufait (1965) characterized backfires and headfires in prepared fuel beds. Rothermel and Anderson (1966) developed equations to relate fire spread characteristics to fuel moisture and wind speed, and Anderson (1969) used mathematical models to describe heat transfers and fire spread. Project Fire Model conducted at the Macon Laboratory used model fires to characterize fire behavior (Byrum et al, 1966). Field studies under natural conditions, however, have been limited (Mount 1969). Van Wagner (1971) suggests that field research is essential if fire behavior knowledge is to receive practical application.

METHODS

Rationale

The effects of overprotection from fire in the mixed conifer forests are most pronounced between 4000 ft and 5000 ft in elevation. There the overstory is predominately ponderosa pine with incense-cedar. The forest has understory fuel types consisting of bear clover, pine needles, or incense-cedar reproduction. On the floor of Yosemite Valley, the pines stand above an understory of large and small incense-cedars. Investigations were made in each of these four types.

Fire behavior and subsequent effects are influenced by the direction that a fire is burning. Fires burning with the wind or upslope, called headfires, spread more rapidly and are hotter. Backfires spread against the wind or downslope and are slower and less intense than headfires. Both methods of burning were evaluated.

Prescribed burning can be accomplished only within certain ranges of fuel moisture, wind speed, relative humidity, and air temperature. Considerable variation exists within these ranges, however, and burning under various combinations of these variables will produce fires with different characteristics and effects. Closer examination of the variables shows that they are somewhat related. Air temperature and, to a lesser extent, wind speed affect relative humidity. Fuel moisture content is closely related to relative humidity and is one of the most important factors affecting fire behavior. Fuel moisture content serves as an indicator of the combined effects of both air temperature and relative humidity and is easily measured with fuel sticks that are commonly used for the California Fire Ranger Rating. The safe, effective range for fuel stick moisture content is from 6 to 20%. Four levels of fuel moisture within this range were chosen to study.

The fire characteristics considered in this study were rate of spread, fuel energy, intensity, and scorch height. To calculate the amount and rate of energy released, it was necessary to measure the amount of fuel consumed and the caloric values of the fuel.

Prescribed fires decrease fire hazards primarily by reducing the amount or weight of ground fuels. Fuel weight is distributed between fine fuels (duff, litter, small branches), heavy fuels (large limbs, logs, stumps), and vegetative fuels (grasses, forbs, low brush, tree reproduction). A direct measure of the reduction of fire hazard is provided by changes in the weight of the various kinds of fuel after a fire. Fuel weight reduction was used as a measure of fire hazard reduction.

Changes in plant composition were evaluated by measuring density by size class and basal area for each species in the understory before and after burning.

FIG. 2. The mixed conifer zone in Yosemite National Park is represented by the hatched area. The two study areas were in Yosemite Valley and near Wawona.

Study Areas

Ideally, the study plots should have been distributed throughout the mixed conifer zone of Yosemite National Park. Practical and administrative considerations dictated that burning be confined to areas southeast of Wawona and in Yosemite Valley (Fig. 2).

WAWONA. The Wawona area is typical of the mixed conifer zone in the park. It is characterized by an overstory of ponderosa pine, with some incense-cedar and an occasional California black oak.

The elevation is 4600 ft and the slopes are primarily southwest-facing. The understory on these slopes consists of a mosaic of fuel types. The pattern of the mosaic is about 0.1 to 0.25 ha in size. Patches of bear clover are interspersed with clumps of incense-cedar reproduction and areas with only pine needles. Heavy fuel was sparsely scattered over the area although there were some concentrations of downed "insect" trees. Figures 3, 4, and 5 show the three fuel types at Wawona.

YOSEMITE VALLEY. The valley floor presents a unique situation within the mixed conifer zone. The floor is practically flat and is surrounded by steep canyon walls. Because of the high walls, the south side of the valley is more moist than the north side and the character of the vegetation manifests this fact. Ponderosa pine and canyon live oak (*Quercus chrysolepis* Liebm.) dominate the northern stands. The designated burning area was on the south side of the valley near Sentinel Creek.

The understory is sparse consisting primarily of larger incense-cedar trees, with an occasional white fir or Douglas-fir. In the early summer there is also some

FIG. 3. The bear clover fuel type has an overstory of ponderosa pine and incense-cedar. The understory vegetation is primarily bear clover with scattered incense-cedar trees.

FIG. 4. Ponderosa pine and incense-cedar make up the overstory of the pine needle fuel type. The surface fuels are pine needles and an occasional small tree.

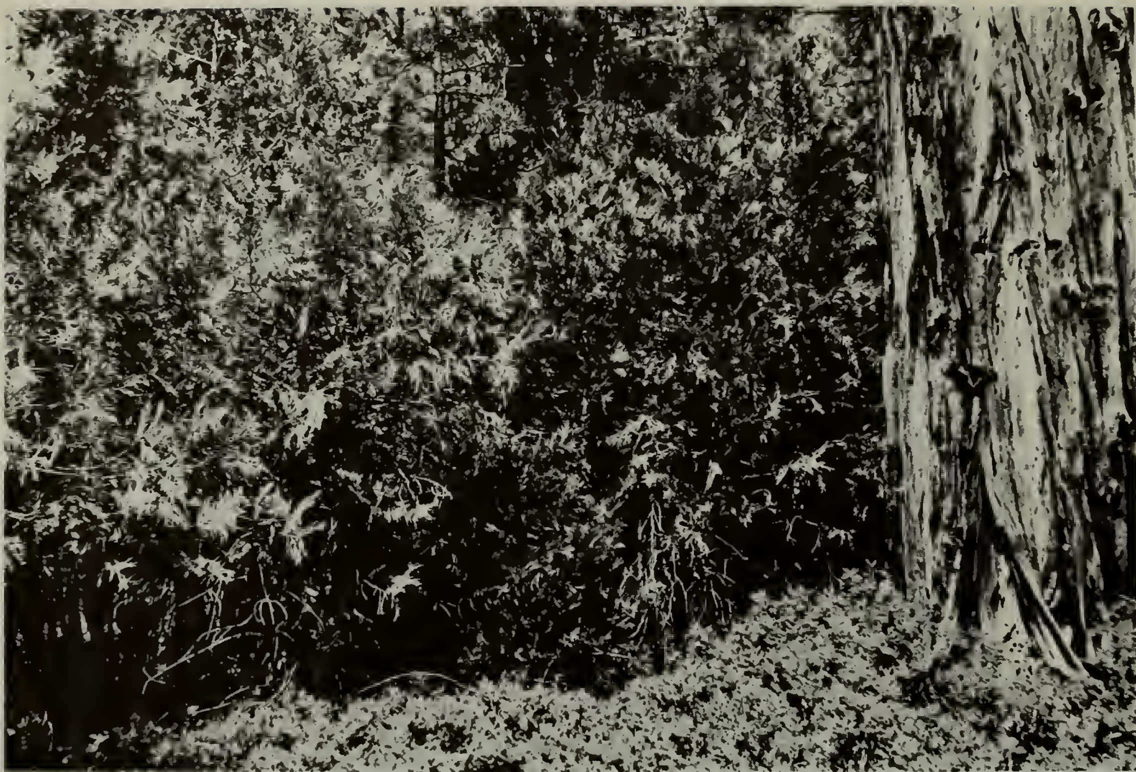

FIG. 5. Dense thickets of incense-cedar reproduction predominate in the understory of the incense-cedar fuel type. Large ponderosa pine and incense-cedar trees are in the overstory.

FIG. 6. The valley fuel type is characterized by large accumulations of heavy fuel. Both large and small incense-cedar trees are in the understory and the overstory consists of ponderosa pine and incense-cedar.

herbaceous cover. In general, the nature of the Yosemite Valley area is most similar to the areas at Wawona that have only pine needles (Fig. 6).

There is considerable heavy fuel in the valley because of the number of trees that have been cut due to insect damage or *Fomes annosus* root rot. The heavy fuel, flat terrain, and cooler local climate contribute to a different fire behavior environment than at Wawona.

Analytical Model

The models used for analysis were the analysis of variance model for the prefire and postfire fuel and vegetation measurements and for the caloric values, and the analysis of covariance model for the fire characteristics.

A three-way factorial design was used to analyze the effects of fuel type, fuel moisture level, and direction of burning on the fire, fuel, and vegetation variables. The covariance design, in addition, included wind speed. This increased the sensitivity of the model by removing wind speed effects from the other effects. F-tests were used to test the significance of the main effects, the interaction effects, and the covariate effects. Details of the models have been discussed by van Wagtendonk (1972).

Plot Selection

Units of 5-10 ha were selected for study in each of the two areas. The Wawona unit was first stratified into understory fuel types by running parallel line transects through it at 20-m intervals and recording the fuel types on a map. The valley unit was also transected to locate a relatively homogeneous area.

The number of plots needed for the project was dictated by the experimental design. Burning at four fuel moisture levels with two methods of burning at each level necessitated 10 plots per stratum, including 2 control plots, or a total of 40 plots.

The plot size was determined by the minimum area necessary for an adequate fire to burn without being influenced by "edge effects." Experience with previous fires indicated that 100 m^2 plots would give reliable results.

A 10 X 10-m grid was superimposed on each unit, and 10 plots were randomly selected in each stratum. When adjacent plots were selected, one was randomly rejected and an additional plot selected. This was necessary to create a 5-m wide buffer zone around each plot. The total area burned for each plot was 400 m^2, including the 100 m^2 plot itself and the buffer zone. For the low intensity fires used, a 5-m strip was sufficient for the fire to reach an energy output equilibrium before reaching the plot, thereby eliminating edge effects and preventing unnatural burning conditions as the fire stopped. Additional rejection criteria were established for plots falling in two fuel types, or with excessive rock outcrops or heavy fuel.

Plot Sampling

VEGETATION. Overstory basal area by species was determined by measuring every tree over 3 m high standing within the plot. Every second tree standing exactly half way in a plot was not included in the determination. Overstory basal area was not remeasured after the fires since there was no change.

Understory vegetation was measured on four 1 m^2 subplots distributed randomly within each 100 m^2 plot. Subplots containing large overstory trees or excessive heavy fuel were rejected. Basal area was recorded for each species for all the trees in the 1-m to 3-m height class. Understory density by species was measured on each subplot by counting stems in three height classes: 0-0.3 m, 0.3-1 m, and 1-3 m. The same subplots were remeasured 1 month after burning to determine mortality.

FUEL. Heavy fuels, defined as having a diameter greater than 2.5 cm, were sampled for an entire plot by the line intercept method of Van Wagner (1968). Absolute and percent reduction in heavy fuel was calculated from the before and after burning measurements.

Sampling for fine fuel weight was done on randomly distributed, paired 20 X 50 cm subplots. After the first of each pair was located, the second one was established in conditions as nearly identical as possible to the first. For each pair, one subplot was randomly selected for prefire measurements, the other for postfire measurements. Paired subplots reduce variance by decreasing the difference between before and after burning measurements due to variations within the larger plot. Prefire measurements were made immediately prior to burning.

Since sampling for fine fuel weight is destructive, the "before" subplots were reconstituted so as not to affect the fire. Each fuel sample was divided into fresh, weathered, and decomposed needle layers which were then placed in plastic bags and sealed. Figure 7 shows a 20 X 50-cm subplot with the surrounding fuel removed. In part (a) the fresh and weathered layers were removed to show the decomposed layer. The fresh layer was removed in part (b) to show the weathered layer. Part

FIG. 7. A 20 × 50 cm subplot is shown with the surrounding fuels removed. In (a) the decomposed layer is exposed; in (b) the weathered layer is exposed; and in (c) the fresh layer remains intact.

(c) shows all layers intact with the fresh layer on top. Vegetative fuels were sampled similarly above each 20 X 50-cm subplot to a height of 3 m.

The accuracy desired, the variance of the variables, and the design of the experiment determined the number of fuel subplots. Type I and type II errors were chosen to be 0.05 and 0.10, respectively. Data from a pilot study in 1970 gave an estimate of the variance of fuel weight reduction. Using these values, the total number of subplots was determined to be 320 or eight pairs of subplots per plot. Figure 8 shows a typical plot with its subplots.

Burning Procedure

PLOT PREPARATION. After each plot and its subplots had been marked by steel stakes and sampled for heavy fuel and vegetation, a fire line was constructed around the plot and its buffer zone. The fire line consisted of a strip 0.5 m wide dug to mineral soil. Understory vegetation was cut away 1 m on each side of the strip and any logs which crossed the line were cut.

As an additional precautionary measure, a trail was constructed to each plot, which enabled a standby truck with a slip-on tanker to reach it.

FIRING DETERMINATION. The selection of the plot to be burned, the method of burning, and the order of their burning were random. As soon as the areas were clear of snow in the spring, fuel sticks were placed 12 inches above ground at each plot. These were monitored for at least 48 hours to determine when a plot would be burned. The four fuel moisture levels were the following intervals: 9-11%, 12-14%, 15-17%, and 18-20%. An effort was made to burn at the interval midpoints.

Once the fuel moisture was at the proper level and a decision was made to burn, the other weather variables were measured to determine if they were within the prescribed ranges as established by Schimke and Green (1970). Wind speed was measured with a hand-held anemometer. If the wind speed exceeded 10 mph, burning was postponed. Wind speeds were adjusted for differences in slope. Air temperature was required to be within the range from 20 to 84°F. The acceptable range for relative humidity as measured by a sling psychrometer was from 29 to 65%. If all these values were acceptable, the plot was ignited with a single pass of a backfiring torch using a 4:1 diesel to gasoline mixture. Backfires were ignited at the side away from the wind or at the upper side of the plot. Headfires were ignited from the windward or bottom side.

FIRE VARIABLES OF INTEREST. If a single pass did not ignite the fuels or the fire went out before it left the buffer zone, ignition was said not to have occurred.

Rate of spread was determined by measuring the time necessary for the fire to burn between two pairs of plot corner stakes in line with the fire direction. If a fire went out within a plot, the rate of spread was said to be 0. These values were averaged and converted to a rate of spread in meters per second.

The available fuel energy is the amount of energy released by the fuel volume which is burned. The total available energy for each fire was calculated by multiplying the heat yield in kilocalories per gram for each fuel layer by the weight in grams lost in that layer and adding the products for the four layers. Heat yield is determined by adjusting the various heats of combustion for losses due to radiation, heat of vaporization of the initial moisture and the water of reactions, and incomplete combustion (Byram 1959).

Fire intensity I is calculated from the equation:

$$I = Er$$

where E is the available fuel energy and r, the rate of spread. This is a measure of the energy release per unit of fire front and time and is expressed in kilocalories per second per meter. Scorch height was determined one month after a plot was burned by measuring the height to which randomly selected trees on the plots were scorched and then averaging these values. Scorch could be seen within a month by a color change of the needles which were killed. The temperature necessary to cause needle death is approximately 60°C (Davis 1959).

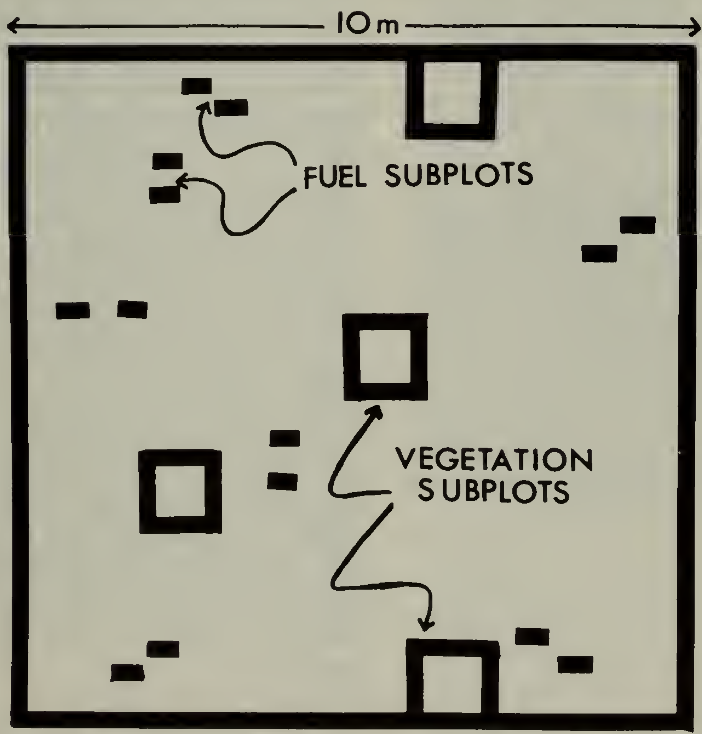

FIG. 8. Each plot was 10 m^2 with a 5 m buffer strip around each edge. Fuels were sampled on 20 X 50 cm subplots and vegetation on 1 m^2 subplots.

Laboratory Work

All "before" fuel samples were taken to the laboratory in sealed plastic bags and weighed before being oven-dried. Oven temperature was 65°C and a sample remained in the oven until there was no additional weight loss. The moisture content for the before fuel samples was obtained by subtracting the before and after oven-drying measurements. Percent and absolute reduction in fuel weight were determined by comparing the oven-dried weights for each sample pair.

After drying, the before fuels were saved for caloric determinations. Fuels from the same fuel type and fuel layer were shredded and mixed into 16 type-layer combinations. Random grab samples were taken for grinding through a 20-mesh Wiley Mill. Six pellets were made from each fuel using 2000 psi pressure and were then oven-dried. Standard procedures were followed using a Paar model 1242 bomb calorimeter (Paar 1971). Adjustments were made for the heat of combustion of the fuse wire and for the energy remaining in the free acids formed by combustion of the fuels.

The heat of combustion for each fuel was then determined with and without inorganic ash. The inorganic ash content was determined from sampled fine fuels. The samples were weighed before and after placement in a muffle furnace at 600°C for 24 hours.

Statistical Analysis

Computer programs were used to compile raw data for statistical analysis. The DANIEL multiple regression program (Daniel and Wood 1971) was then used for the analysis of variance and covariance runs. Orthogonal contrasts were also run on the program by altering the X matrix to include the contrast coefficients.

The results from the F-tests for each dependent variable and the results from the orthogonal contrasts for each dependent variable were given in van Wagtendonk (1972). All tests for significance were at the 0.95 level.

RESULTS

Fire characteristics, fuel reduction, and vegetative changes were all affected by fuel type, method of burning, and fuel moisture level. Prefire fuel and vegetation measurements and caloric values differed by understory fuel types.

Fire Characteristics

The fire characteristics differed variously by fuel type, method of burning, and fuel moisture level. In general, the fires became hotter as they burned under drier fuel conditions (Table 1).

IGNITION. For a fire to ignite and to continue to burn, sufficient heat must be present to raise the temperature of the water in the fuel, to release bound water from the fuel, to vaporize the water in the fuel, and to heat the water vapor to flame temperature. At the higher fuel moisture levels, insufficient heat was produced to accomplish the above; consequently, no new fuel was ignited and the fires went out.

The method of burning also affects ignition. For low intensity backfires, the primary heat-transfer mechanism for preheating and drying fuels is radiation. A fire with the flames bending away from the unburned fuels radiates heat to those fuels and begins to dry them. A headfire, on the other hand, in addition to transferring heat by radiation, preheats fuels by convection. The flames bend toward the unburned fuels, thereby increasing the drying rate. This explains why some of the headfires were able to ignite while backfires at the same fuel moisture level were not.

Differences in the fuel-bed characteristics for the four fuel types resulted in different rates of ignition success. The bear clover plots had fuel beds consisting of ponderosa pine needles draped over the low bear clover plants. Such an arrangement not only allowed considerable drying of the fuel to occur but also provided adequate oxygen for combustion to continue. These plots ignited with a backfire when the fuel sticks indicated a moisture content of 19%, while plots in the other fuel types did not ignite with moisture contents above 13 or 16%. The fuel beds of the needle and valley plots did not differ in their general nature, although the needle plots tended to have more fuel present and a somewhat more porous arrangement. Ignition did not occur for backfires at 19% for the needle plots and at 19 and 16% for the valley plots. Beneath the incense-cedar understory, the fuel bed was more compact and had a higher ratio of incense-cedar to ponderosa pine needles. The incense-cedar needles are much smaller and form a tight fuel bed allowing little aeration. This characteristic affected drying and combustion and, consequently, ignition.

RATE OF SPREAD. Once a plot was ignited, its rate of spread was influenced by some of the same factors as ignition. The analysis of covariance of the differences in rates of spread of the various fires showed that they were significantly affected by fuel moisture level and

Table 1. *Rate of spread, available fuel energy, and intensity are shown for 32 prescribed fires. Fires which did not ignite show no rate of spread while fires which ignited and subsequently went out have a rate of spread of 0.0 m/sec. Available fuel energy was not affected by fuel type or method of burning, and intensity was not affected by fuel type.*

Fuel Moisture Level	RATE OF SPREAD meters/second								AFE kcal/m²	INTENSITY kcal/sec/m	
	Bear Clover		Needle		Valley		Incense-cedar				
	Head	Back	Head	Back	Head	Back	Head	Back		Head	Back
19%	.3	.0	.0		.0		.0		411.8	3.5	0.0
16%	.5	.1	.3	.1	.0		.0		793.4	14.2	2.2
13%	1.5	.2	3.3	.1	.4	.1	.0	.0	1246.7	63.1	5.6
10%	1.2	.8	2.5	.2	1.3	.1	.5	.1	1657.2	60.8	14.1

method of burning. Fuel type and the covariate effect of wind speed were not significant. The rates of spread for the various fires are shown in Table 1. Some of the fires which ignited show no rate of spread because they went out before burning the entire plot.

As less energy was required to drive off the water in the fuel at lower moisture levels, more was available for preheating and drying new fuel. This sped the combustion process and increased the rate of spread. For the four fuel types there appeared to be a threshold between the 16% and 13% fuel moisture levels. On the moist side of this threshold, the fires did not spread at all or, at best, spread slowly. Rates of spread were considerably higher on the dry side of the threshold.

Headfire rates of spread in all types exceeded backfire rates. The higher rates for headfires were due to the preheating effect of the convection of hot gases and to new ignitions ahead of the fire by the tilted flames. All fires seemed to spread well once ignition occurred and there was sufficient dry fuel to carry the fire. The arrangement of the topmost needles, which were the driest, did not appreciably differ from type to type. Even on the incense-cedar plots, there were enough loose needles above the compact fuel bed to carry the fire well. The two fastest fires could not be explained within the design of the experiment. A possibility is that since both fires had some bear clover in the buffer strip in front of the plots, these fires were hotter when they reached the plots.

Of the 32 fires, only two had wind speeds in excess of 3 mph. Wind speeds were within the acceptable range of 0-10 mph for all fires. Since the wind speeds were so low, they did not affect rate of spread. The three two-way interactions between fuel type, fuel moisture level, and burning method were not significant.

AVAILABLE FUEL ENERGY. The available fuel energy of a fire is the amount of energy actually released by the fire. This value was determined by multiplying the amount of fuel consumed by its caloric value. Available energy is therefore related to fuel loss.

When each fuel layer was analyzed separately, significant differences in available energy between the fuel moisture levels were recognized (Table 1). No significant differences were found between the weathered or decomposed needle layers.

INTENSITY. Fire intensity, the product of available fuel energy and rate of spread, was influenced most by those factors affecting rate of spread. The rate of energy released is directly related to the speed of the fire and, consequently, the method of burning. Fuel moisture, acting through available fuel energy, also affects intensity. The more fuel which is available and the faster it burns, the higher the intensity. A significant contrast was present between fires which burned at 19 and 16% fuel moisture, and those which burned at 13 and 10%. The former fires burned slowly if at all, while the latter fires spread well.

As additional moisture is lost below the 10% level, fuel moisture becomes less important. At that point, so little water is left in the fuel that the total amount of fuel available becomes more important. Fire intensity increased as fuel moisture decreased and was greater for headfires than for backfires (Table 1).

SCORCH HEIGHT. The scorch height of the fires differed significantly between the fuel moisture levels and the methods of burning (Table 2). However, neither wind speed nor the two-way interactions showed significance.

Since rate of spread is an indicator of the rate of energy release, the effects on scorch height were related

Table 2. *Scorch height in meters is shown for 32 prescribed fires.*

Fuel Moisture Level	FUEL TYPE: Bear Clover		Needle		Valley		Incense-cedar	
	Head	Back	Head	Back	Head	Back	Head	Back
19%	1.7	.9	.0		.6		.0	
16%	1.6	1.2	1.1	.6	.6		.0	
13%	2.4	1.9	6.9	1.1	1.3	1.0	1.4	.0
10%	3.0	2.6	9.9	2.1	2.4	1.2	2.2	1.8

to rate of spread. As a fire spreads faster, it releases heat energy at an increasing rate. A high rate of energy release has high temperatures associated with it. If the temperature in the crown reached the lethal level of 60°C, scorch occurred. Since the headfires and the backfires burning at the lower moisture levels had greater rates of spread, scorch height was also greater. Some of the fires scorched crowns before they went out.

Fuel Measurements

HEAVY FUEL. The amount of heavy fuel on each plot differed significantly by fuel type (Table 3). The valley plots, which had large concentrations of downed trees, had larger accumulations of heavy fuels.

In general, the heavy fuels were not affected by the fires. In the spring these fuels are wet internally, not drying until mid-summer. The greatest amount of reduction occurred in the needle plots where the heavy fuels were relatively small in size. The valley plots, which had concentrations of large heavy fuels, had no reduction of those fuels.

Table 3. *Prefire measurements for fine and heavy fuels are shown in grams per meter.*[2]

Layer	FUEL TYPE: Bear Clover	Needle	Valley	Incense-cedar
Vegetative	166.4	22.6	28.2	18.0
Fresh	318.0	422.3	383.8	292.0
Weathered	565.7	604.5	532.5	431.5
Decomposed	4127.4	3565.7	2971.0	2830.9
Total Fine	5177.5	4615.1	3915.5	3572.4
Heavy Fuel	508.6	1726.5	5062.4	1261.3
Total	5686.1	6341.6	8977.9	4833.7

[2]California Wildland Danger Rating System (USFS 1962).

FINE FUEL. The amount of fine fuel (Table 3) differed by fuel type. There were significantly more fine vegetative fuels on the bear clover plots due to the bear clover ground cover. The incense-cedar plots had less fuel in each layer than the others because there were fewer ponderosa pine trees and hence fewer pine needles on these plots. Other comparisons showed that the bear clover plots differed in the amount of fuel in the fresh, weathered, and decomposed layers from the needle and valley plots, and that the valley and needle plots did not differ in the amount of vegetative fuel present.

The average amount of vegetative and fresh needle fuel reduction is shown in Table 4. Prescribed fires within the range of intensities produced in this study had little effect on the reduction of fuels in the weathered and decomposed needle layers. The inability to show significance was due to the small quantities of fuel consumed in these layers and the large variance between before and after subplots in the decomposed layer. The amount of fuel burned in the lower layers is small when burning is done during the spring. These layers have high moisture contents and dry slowly in comparison to the fresh needle layer. As the season progresses, differences in moisture content become smaller and more of the weathered and decomposed layers are consumed.

The amount of vegetative fuel reduction was affected by fuel type and fuel moisture level, but not by the method of burning. The bear clover and incense-cedar plots, which had distinct vegetative fuel layers, had greater losses than the valley and needle plots. The latter two types had practically no vegetative layer and did not differ from each other.

Fuel moisture effects interacted with fuel type to produce differences between fuel moisture levels. The bear clover plots burned at higher moisture levels due to aerated fuel-bed characteristics which were influenced by the plants. As a consequence, the bear clover plants were also consumed at those levels. Beneath the incense-cedar understory, the compact fuel bed did not carry a fire until the fuel moisture level reached 10%. Since the bear clover plots burned at all moisture levels, the effect due to moisture level was produced by the incense-cedar plots. These combined effects also made the fuel type-moisture level interaction significant.

Practically all the vegetative fuels on the bear clover plots were burned by headfires and backfires alike. Incense-cedar fuel reduction was also not affected by the method of burning since the small amounts consumed were almost equal. The strong influence of the type effect made the type-method interaction significant.

Table 4. *Fuel losses in grams per meter² are shown for the vegetative and fresh needle layers. Losses in the weathered and decomposed needle layers were not significant.*

Fuel Moisture Level	Layer	Bear Clover Loss	Bear Clover %	Needle Loss	Needle %	Valley Loss	Valley %	Incense-cedar Loss	Incense-cedar %
19%	Vegetative	167.0	88.2	0.0	0.0	0.0	0.0	79.0	44.1
	Fresh	158.5	76.2	118.0	25.7	98.5	31.0	49.5	18.8
16%	Vegetative	140.5	100.0	41.5	100.0	0.0	0.0	60.0	28.1
	Fresh	234.0	88.0	378.0	87.4	101.5	25.6	55.0	22.1
13%	Vegetative	186.5	100.0	31.5	100.0	101.5	98.1	115.5	51.3
	Fresh	341.5	100.0	500.5	98.9	299.5	68.2	88.5	42.6
10%	Vegetative	106.5	100.0	40.0	100.0	0.0	0.0	169.5	78.9
	Fresh	470.5	92.2	385.5	98.6	329.0	83.7	440.0	97.4

The loss of fresh needle fuels was significant for fuel type and fuel moisture level. Method of burning did not affect the amount of loss. The incense-cedar plots differed significantly from the rest, and there was a significant contrast between the valley and needle plots. Each fuel moisture level contrast was also significant.

Differences in fuel reduction due to fuel type are a result of the fuel-bed characteristics of the various types. The incense-cedar plots, with their compact fuel beds, did not burn over much of the fuel moisture range and, consequently, had little reduction in the fresh needle layer. Although the bear clover plots had fuel beds which were quite porous, there was no significant difference between them and the combined valley and needle plots. This could be attributed to the fact that the needle plot fuel beds, while not quite as open, were of such a nature that most of the fresh needle layer was consumed at all moisture levels except the 19% level. The contrast between the needle and valley plots, on the other hand, was significant, indicating some difference in fuel beds. One obvious difference was the presence of some herbaceous material on the valley plots. Their added moisture content could have been enough to cause differences in fresh needle reduction.

The fresh needle layer was most sensitive to changes in fuel moisture content. Consequently, as more water was present in the fuel layer, more energy was required to heat and drive out the water. This energy could not combust new fuel until the energy requirements of the water had been met.

Method of burning was not significant because, if a fire burned, both headfires and backfires consumed all the available fuel at any particular moisture level. The strengths of the type and moisture effects combined to make that interaction significant.

FUEL CALORIC VALUES. There were significant differences in fuel caloric values due to fuel type, fuel layer, and the type-layer interaction (Table 5). Orthogonal contrasts for fuels with ash showed that the bear clover fuels differed from the needle and incense-cedar fuels combined and the needle fuels singularly. Fuel-layer contrasts were significant between the decomposed layer and the rest, between the vegetative layer and the fresh and weathered layers, and between the fresh layer and the weathered layers. The drop in caloric value with ash is primarily due to increasing incorporated inorganic matter in the lower litter layers.

Table 5. *Caloric values for the various fuels layers are shown in kilocalories per gram with and without inorganic ash.*

LAYER	Bear Clover w/ash	Bear Clover w/o ash	Needle w/ash	Needle w/o ash	Valley w/ash	Valley w/o ash	Incense-cedar w/ash	Incense-cedar w/o ash
Vegetative	5.098	4.309	5.145	5.548	4.893	5.339	4.905	5.370
Fresh	5.024	5.221	5.028	5.237	5.033	5.309	4.996	5.268
Weathered	5.019	5.274	4.864	5.175	4.859	5.240	4.802	5.137
Decomposed	3.572	5.157	3.830	5.197	3.674	5.002	3.274	5.252

With the inorganic ash removed, fuel type, fuel layer, and interaction effects were still significant. The contrast between the valley fuels and the rest was also significant. The caloric values for the bear clover fuels and the needle and incense-cedar fuels did not differ although all the other contrasts remained significant.

Vegetation Measurements

OVERSTORY BASAL AREA. The overstory basal area did not differ significantly between fuel types since the areas were selected to minimize overstory differences. The average total basal area on all plots was 80.01 m^2/ha. Ponderosa pine dominated the stands with 61.2% of the total basal area, consisting primarily of trees with diameters greater than 20 inches. Scattered, larger incense-cedar trees and numerous smaller trees made up 33.9% of the overstory. The remainder of the basal area was distributed over California black oak, Douglas-fir, and white fir trees.

UNDERSTORY BASAL AREA. Prefire understory basal area varied between types. This was expected since the understory was the criterion for selection of fuel types. The incense-cedar plots had 90% of the total basal area of 39.36 m^2/ha. Incense-cedar reproduction made up 95% of the basal area on the incense-cedar plots, the remainder being ponderosa pine. The sparse understory on the bear clover, needle, and valley plots consisted of scattered incense-cedar trees.

The change in understory basal area after burning was 2.34 m^2/ha (100%) for the bear clover plots and 7.17 m^2/ha (21.4%) for the incense-cedar plots. Ponderosa pine understory basal area was reduced 0.29 m^2/acre (14.8%) on the incense-cedar plots. There was no significant reduction on valley and needle plots.

UNDERSTORY DENSITY. The understory density prior to burning differed significantly between fuel types. Table 6 shows the number of stems per hectare of the various species by height class for the four fuel types. Fuel type and fuel moisture level, as well as their interactions, significantly affected density losses in the 0-0.3 m height class for bear clover, ponderosa pine, and all species combined.

Density losses in the 0.3-1 m height class were not significant. To a large extent, this size class was absent on all plots except the incense-cedar plots on which the losses were confined to some incense-cedar trees on the 10% plots.

A greater number of trees were in the 1-3 m height class, primarily on the incense-cedar plots. Density losses for incense-cedar and all species combined were attributed to fuel type and moisture level, and to the

Table 6. *Prefire understory density in stems per 0.1 ha is shown for each species. Losses in stems per 0.1 ha and percent loss are also shown.*

Species	Size class	Bear Clover Bef.	Bear Clover Loss	Bear Clover %	Needle Bef.	Needle Loss	Needle %	Valley Bef.	Valley Loss	Valley %	Incense-cedar Bef.	Incense-cedar Loss	Incense-cedar %
Bear Clover	0-.3	9780	7900	80.7	300	283	94.0	0	0	0.0	1148	42	3.7
Incense-cedar	0-.3	8	0	0.0	20	0	0.0	20	0	0.0	40	0	0.0
	.3-1	0	0	0.0	13	0	0.0	0	0	0.0	90	0	0.0
	1-3	3	3	100.0	10	0	0.0	3	0	0.0	178	48	26.9
	Tot	11	3	27.2	43	0	0.0	23	0	0.0	308	48	15.6
Ponderosa Pine	0-.3	0	0	0.0	0	0	0.0	98	57	58.2	2	0	0.0
	.3-1	0	0	0.0	3	0	0.0	0	0	0.0	3	0	0.0
	1-3	0	0	0.0	0	0	0.0	0	0	0.0	27	3	11.1
	Tot	0	0	0.0	3	0	0.0	98	57	58.2	32	3	9.4
All Species	0-.3	9788	7900	80.7	320	283	88.4	118	57	48.3	1190	42	3.5
	.3-1	0	0	0.0	16	0	0.0	0	0	0.0	93	0	0.0
	1-3	3	3	100.0	10	0	0.0	3	0	0.0	205	51	24.9
	Tot	9791	7903	80.7	346	283	81.8	121	57	47.1	1488	93	6.3

type-moisture interaction. The incense-cedar plots differed from the plots in the other type and the 10% plots differed from those which did not burn.

DISCUSSION

The experimental fires burning under varying conditions of fuel and weather reduced fire hazards and changed vegetative composition in the mixed conifer ecosystems studies. Using the results of the experimental fires, an ecologically sound burning program for the mixed conifer forests of Yosemite is proposed.

Prescribed Fire Effects

Fuel moisture content was the principal factor influencing fire characteristics and subsequent effects on fuel and vegetation. Fuel moisture appeared to integrate the effects of air temperature and relative humidity and combined with fuel type to produce considerable variation in fire behavior within the range of conditions prescribed by Schimke and Green (1970).

The inverse relationship of fuel moisture on fire characteristics and fuel consumption has been studied under laboratory conditions (Byrum et al. 1966; Beaufait 1965). This study defined this relationship for field conditions in the mixed conifer type. Similar studies by Hough (1968) in the southern pine type and Kilgore (1971) in the red fir type did not burn over a specified range of moisture conditions, but rather only measured fuel moisture content at the time of burning. Both investigators reported 50% reductions of the litter layers and considerable change in the density of the understory vegetation. This corresponds to the fuel reduction for the 10 and 13% moisture level fires of this study.

Changes in the understory tree composition were caused by the 10% fires. Density was reduced by 50% with most of the loss being incense-cedar trees. The loss of bear clover stems, while not important from a composition standpoint since the plants resprout after burning, is an important part of fire hazard reduction. The new sprouts are not as flammable as the older, larger, mature plants because they contain less dead material and have higher moisture contents.

The effect of direction of burning was not significant for fuel reduction. Hough (1968) and Beaufait (1965) found that backfires consumed more fuel in the litter layer than headfires. They attributed this difference to the fact that the backfires spread slowly and burned deeper into the litter layer while the headfires spread rapidly, often burning only the upper litter layer. In this study both head- and backfires burned primarily in the upper or fresh needle layer since the lower layers were too wet to burn. The amount of fuel consumption was therefore independent of the rate of consumption since both methods of burning consumed equal amounts of fuel.

Rate of spread and intensity were affected by the burning direction as explained previously. Scorch height, which is dependent on the rate of energy release, was also affected. These results are in agreement with those of other investigators (Hough 1968; Beaufait 1965; Byram et al. 1966).

The insignificance of low wind speeds concurs with the conclusion reached by Hough (1968) and Byrum et al. (1966) that the rate of spread did not change for wind speeds between 0 and 8 mph. At higher speeds, wind does become important and assumes a nonlinear effect (Beaufait 1965). These speeds, however, are beyond the range considered for this study.

Management Applications

The results from the experimental fires can be used by the resources manager. Refined burning prescriptions will enable the manager to plan and implement ecologically sound burning programs which will meet specific management objectives.

REFINED PRESCRIPTIONS. It was found that fire behavior was very sensitive to changes in fuel moisture, and that the behavior varied between fuel types. Fuel moisture provides the key to prescription refinement. Not only is it easy to measure in the field but also it is a reliable predictor of fire characteristics and subsequent effects.

The prescriptions developed here refine fuel moisture ranges. Although these refinements would be applicable to most of the central and southern Sierra, they are specifically designed for the lower portion of the mixed conifer zone in Yosemite National Park. Fuel moisture prescriptions are given for the bear clover, pine needles, and incense-cedar understory fuel types, and, in addition, for the unique condition in Yosemite Valley.

The bear clover fuel type burned throughout the range of moisture levels with variable results. At the 19% level, the fires did not burn satisfactorily. Fires burning at less than 9% would have been too hot for control. The range for safe, effective burns in the bear clover type should be from 9 to 17% fuel moisture. Within this range, fuel reduction will vary, but practically all of the fresh needle layer and the bear clover stems will be consumed. At the drier moisture levels, the weathered needle layer will be reduced and scattered understory trees killed. In many instances a fuel moisture of 17% will be reached within days after snow has melted in the spring.

The pine needle fuel type would not burn at the 19% moisture level. The same range from 9 to 17% is recommended for the needle type. Consumption at the 16% level was limited to the fresh needle layer, while the weathered layer was reduced at the 13% level. Some of the decomposed layer was reduced by the 10% fires. Reduction in the lowest layer is more dependent on the seasonal drying trend than on the fuel stick readings. At the lower two moisture levels, scattered understory trees were killed.

Fires burned satisfactorily in the incense-cedar fuel types only at the 10% level. Although the 7% level would probably still be safe, it was not tested since that level was never reached during the period of experimentation. The recommended range for the incense-cedar type is from 9 to 11% fuel moisture. Within this range incense-cedar trees up to 5 cm in diameter can be killed. Fuel reduction was primarily in the fresh needle layer although some weathered needles were consumed.

In Yosemite Valley, two refinements are suggested. For the shaded and cooler southern side, the fuel moisture range should be from 9 to 14%. Burning could be accomplished from 9 to 17% on the northern side of the valley. The northern side is similar to the needle type at Wawona, while the southern side is intermediate between the needle and incense-cedar types.

The following prescriptions are recommended for burning within the lower portion of the mixed conifer zone in Yosemite National Park. All but the fuel moisture ranges are from Schimke and Green (1970).

Wind Speed:	0 - 10 mph
Air Temperature:	20 - 84°F
Relative Humidity:	20 - 64%
Fuel Stick M.C.:	
Bear Clover	9 - 17%
Needle	9 - 17%
North Side	9 - 17%
South Side	9 - 14%
Incense-cedar	9 - 11%
Timber Burning Index:[2]	2 - 6
Ignition Index:[2]	5 - 52

[2]California Wildland Danger Rating System (USFS 1962).

BURNING TECHNIQUES. Even within the refined ranges the manager can exert considerable influence on fire behavior. By waiting to burn when a specific fuel moisture level is reached, he can control the amount of fuel consumption. In conjunction with time of burning, the method of burning controls the rate of spread and intensity of the fire. The manager can control scorch height and understory mortality through control of intensity.

Method of burning is also important at the moist end of the fuel moisture range, where a headfire is often effective while a backfire is not. Conversely, at the drier moisture levels, a headfire is often exceedingly destructive while a backfire is safe.

Specific objectives will dictate which combination of fuel moisture and fire direction to use. In general, however, the following prescriptions will give desirable results. Backfires and headfires burning within the 9-14% range in the bear clover type are satisfactory. Only headfires are effective between 15 and 17% fuel moisture. The headfires spread rapidly and should be used only with extra caution. Figure 9 shows a headfire in bear clover burning at the 13% fuel moisture level. This fire produced sufficient heat to kill the incense-cedar in the right center of the picture.

In the needle fuel type, headfires again were the only ones which were effective within the range from 15 to 17% moisture. The backfires did consume fuels, however, but were very slow.

Between 9 and 14%, the headfires were excessively hot, while the backfires were satisfactory. The intensity of the 10% and 13% headfires in the needle type were beyond acceptable levels. Extreme caution must be exercised when these fires are used. Figure 10 shows the 10% fire which produced scorch up to 10 m and killed several 3-m tall trees. On the other hand, the backfires at these levels were easy to control and consumed satisfactory amounts of fuel without doing excessive damage such as scorching the crowns of large trees.

Headfires are recommended in the incense-cedar fuel type since satisfactory kills could be accomplished only with higher intensity fires. Backfires were equally effective, however, in reducing fuels within the 9-11% moisture range. Figure 11 shows a headfire in this type.

Either headfires or backfires can be used on the south side of the valley. On the north side, the prescription for the needle fuel type should be used. A backfire on the south side of the valley is shown in Figure 12.

In general, it must be remembered that spring fires burning at moisture levels above 10% are effective primarily in reducing flashy fuels such as bear clover and fresh needles. Some reduction of understory density can be accomplished in the incense-cedar type. The manager can determine the extent of the reduction and mortality by controlling the time and method of burning.

In addition, in many sensitive areas, such as roadsides and picnic areas, scorch height can be easily controlled.

FIG. 9. This fire was burning uphill with a headfire in the bear clover fuel type at the 13% fuel moisture level. Sufficient heat was produced to kill the small incense-cedar tree.

By using a backfire in such areas, the manager can avoid excessive scorch and resultant public criticism.

BURNING PROGRAMS. The manager can use the refined prescriptions and techniques to plan an integrated burning program. As a first step, an inventory of areas to be burned must be made. Fuel types and natural or man-made fuel breaks should be recorded.

The objectives of the burning program must also be examined. The manager must decide how much fuel reduction and understory density reduction is desirable. By using fuel type and fuel moisture level controls, he has considerable flexibility in planning his program. Several possible programs are discussed below.

If, for instance, the objective is to burn off the flashy fuels in the bear clover type, the bear clover patches could be burned with a headfire at 19% fuel moisture when the other types would not burn. Such a fire could burn up slope without the danger of escape. As soon as the snow leaves an area, fuel sticks are placed in representative bear clover patches. Burning commences when the 19% level is reached. Two- or three-man teams could cover a wide area by going from patch to patch with fuel torches. No fire lines would be needed since the patches would be surrounded by other fuel types which would not burn or fuels still wet from the receding snow. The burned areas can serve as fuel breaks for later spring fires burning at lower moisture levels, or as a means of breaking up continuous ground fuels to ease wildfire control.

Another program would be to burn all the flashy fuels in the bear clover and needle types but not in the incense-cedar type. Backfires set at the tops of ridges or other natural fire breaks, when the fuel moisture is between 12 and 17% would accomplish such an objective. These fires would burn down hill to a natural or man-made break. In this case, the incense-cedar patches could be burned at 10% or lower later in the season without the danger of fire escape since they would be surrounded by previously burned areas. Fuel sticks placed in each fuel type would enable the manager to predict the effects of fire in each type.

Since fuel moisture varies with local topography, south-facing slopes could be burned when north-facing slopes are too wet. When the north slopes dry sufficiently, they would be ignited using the previous burn as a fuel break.

FIG. 10. Trees up to 3 m tall were killed by this headfire in the pine needle type burning at the 10% fuel moisture level. Fires of this intensity are not recommended for application by management.

FIG. 11. In the incense-cedar fuel type, only this headfire burning at the 10% fuel moisture level was effective in killing understory trees.

FIG. 12. This fire was burning against the wind with a backfire in the valley fuel type at the 13% fuel moisture level.

In Yosemite Valley, grass-filled meadows are interspersed with the forests. Although not specifically studied in this project, it is known that the previous year's herbaceous growth will burn early in the spring before the forest fuel types will ignite. The meadows could be burned at this time, providing fuel breaks for later forest burning.

The reduction of heavy fuel is a primary concern in a hazard reduction program. This can be done with fall burning, although extreme caution is necessary since the fuels are very dry. Alternatively, the heavy fuel left by a spring fire could be burned in the fall with a great reduction in risk. Since the flashy fuels have been removed, the danger of escape is reduced. Individual logs or accumulations of heavy fuels can be burned by teams going from one to the other.

In each of the above programs the sensitivity of fire behavior to fuel moisture is used by the manager. He can design his program to meet his needs by using a good survey and the fuel sticks.

SUMMARY

Fire is a natural element of the mixed conifer ecosystems of the Sierra Nevada. Historical records have indicated the prevalence of fires in the past. The present study shows that prescribed fires can be used to simulate natural fires.

The key to using prescribed fire is the recognition of the fact that fires behave differently under varying fuel type and fuel moisture conditions. Fire characteristics and fire effects on fuel and vegetation can be controlled by the resources manager by using the refined prescriptions developed in this study. Aided by an inventory map of understory fuel types, the manager can decide when and how to burn to meet his specific objectives. It is felt that the prescriptions would be generally applicable to the lower portion of the mixed conifer zone in the central and southern Sierra for hazard reduction and vegetative manipulation work.

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Occasional Paper No. 2

As the Nation's principal conservation agency, the Department of the Interior has basic responsibilities for water, fish, wildlife, mineral, land, park, and recreational resources. Indian and Territorial affairs are other major concerns of America's "Department of Natural Resources." The Department works to assure the wisest choice in managing all our resources so each will make its full contribution to a better United States—now and in the future.

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