(NASA-CR-138399) WILDLAND FIRE MANAGEMENT. VOLUME 1: PREVENTION METHODS AND ANALYSIS Final Report (Stanford Univ.) ~~218~~ 219 p HC $14.00 CSCL 08F G3/13

N74-22969

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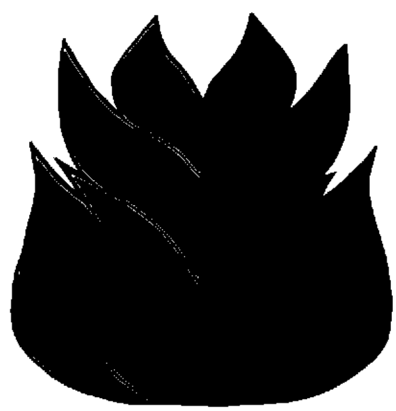

WILDLAND FIRE MANAGEMENT

VOLUME I: Prevention Methods and Analysis

Results of the 1973 NASA/ASEE
Summer Faculty Fellowship Program
In Engineering Systems Design
At Stanford University and Ames Research Center

NASA Contract NGT-05-020-409 School of Engineering, Stanford University, 1973

TO THE READER:

This report is the product of an eleven-week summer workshop on systems design sponsored jointly by the National Aeronautics and Space Administration and the American Society for Engineering Education. The participants were nineteen faculty members from across the nation, representing various engineering disciplines plus law, economics, and computer science. Stanford University and Ames Research Center were the host institutions. The purpose was both to give the participants experience in systems engineering and to produce a useful study.

The problem considered was how to reduce the number and severity of California's wildland fires. The report is in two volumes.

Volume I presents a review of prevention methodologies and the development of cost-benefit models for making preignition decisions. Early in the study, it became clear that prevention as opposed to suppression was the most fruitful area for current efforts. Although the study is not complete or comprehensive, it is believed that the basic, systematic approach to the problem is not only valuable but crucial to obtaining further improvements in wildland fire management.

Volume II presents the preliminary design of a satellite-plus-computer earth-resources information system with potential uses in fire prevention and control. It is recommended that the "wildland fire community" as one potential user, take an active part in promoting and justifying the needs for such peaceful surveillance services. In addition, some suggestions are made for new organization and hardware.

We would like to acknowledge the invaluable information, advice, and encouragement that we received from the agencies responsible for wildland fire management: primarily, the U.S. Forest Service and the California Division of Forestry. In particular we thank Robert Weaver of the California Division of Forestry for tours and documents, enthusiasm and photography.

Some of our most valuable sources were the people who lectured during the first two weeks. They are listed here with their topics.

NATURAL RESOURCES AND FIRE IN CALIFORNIA	Dewitt Nelson, Chairman Natural Resources Management Corp.
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APPLICATIONS OF DECISION ANALYSIS TO WILDLAND FIRE CONTROL	D. Warner North, Decision Analysis Group Stanford Research Institute

Finally, as director of the Stanford portion of the program, I would like to thank Dr. John Billingham, my co-director for his hospitality and the good services of Ames Research Center. Also, Linda Ploeg must be cited by all of us for continuing good cheer and good work as coordinating secretary.

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Final Report

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VOLUME I: Prevention Methods and Analysis

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NASA Contract NGR-05-020-409
School of Engineering
Stanford University

February 1974

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Chapter I

INTRODUCTION*

A. The Problem Setting

California's wildland fire problem is the product of an unusual combination of physical and human factors. Physically, California's wildland vegetation, climate, weather, topography, and geography produce a natural setting for wildland fires. And society has intensified the dangers of the natural setting through the multiple uses it has made of wildlands and through the creation of complex artificial governmental boundaries drawn without respect to the nature of the wildland resources.

Wildland fires in California feed on fuels produced by vegetation ranging from timber conifers, through pines and junipers, and on to sagebrush, chaparral, and grasslands. Approximately 61 percent of the State's some 100 million acres is covered with wildland timber, woodland, brush or grass (Task Force, 1972). All of these fuels reach varying degrees of flammability during the dry months--from May through November, the so-called "fire period." Depending on the weather and location, they may be in a flammable state during much of the remainder of the year. The degree of dryness of these fuels determines the readiness with which fires ignite and spread. And the quantity of accumulated dead fuels, in proportion to the living fuels, determines the degree of a fire's intensity.

The Mediterranean-like climate of California provides cool, wet winters, and long, warm, dry summers. Geographically, rainfall decreases latitudinally from northern to southern California. The "fire period" is characterized by little or no precipitation, relatively high temperatures, and progressively lowering humidities away from the coast. During this period, moisture is drawn out of the accumulations of dead fuels and the moisture content of the living vegetation is likewise reduced. Paradoxically, a longer wet winter and spring may increase the danger of the subsequent fire season. In the wet season of 1973, heavier than usual rainfall turned the brush covered areas into virtual jungles and provided normally more arid regions with a thick grass cover. Then, an earlier and drier than usual spring sapped the moisture from the heavy vegetative growth, leaving what was described as "a multimillion-acre fire trap."

The single most important weather factor in wildland forest-fire management is wind. It provides fresh supplies of oxygen for the ready fuels, so that two sides of the "fire triangle" are then present, with only the third side, ignition, being required to complete the pattern. Wind spreads fire into new fuels and carries fire brands far ahead of

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*Section A was prepared by R. Sennett and H. Young, Section B by R. Sennett, Section C by M. Jischke and J. Shamblin, and Section D by S. Weissenberger.

the main fire front, producing "spot" fires. Wind direction and flow rate is important. The prevailing California winds blow from west to east and carry cool, moist marine air to the coastal hills and even the interior valleys. On occasion, the pattern is reversed by a high pressure area forming over the inland U.S. with a concurrent low pressure trough lying along the Pacific Coast. Then, the air flow reverses: hot, dry interior air is pushed at speeds of as much as 100 miles per hour from east to west over Southern California and from northeast to southwest over Northern California. As the air descends from the high Sierras to the coast, it becomes warmer and drier. In Southern California, these winds are called "Devil Winds" or "Santa Anas."

Topography poses special problems in California's wildland fire management efforts. It affects fire behavior and the ability of fire fighting personnel to get their equipment to the fire site; it also limits the types of possible suppression actions that may be undertaken. The rough topography of the State channels air flow and creates extremely erratic winds in canyons. Some winds flow up a canyon, some down, and some in ever-changing patterns such as were experienced in the Romero Fire in 1971. Also, rainfall decreases sharply with a drop in elevation from the mountains to the foothills and valleys. This lesser rainfall contributes to the growth of brush in the foothill area of Northern California and throughout most of Southern California.

Aggravating the coalescence of these natural physical factors in high fire hazard periods are the use patterns which man has made of the wildlands. The wildland forested areas of the State, both commercial and noncommercial, cover approximately 40 percent of the total land area (Dana and Krueger, 1958). These forest resource areas are the site of timber and logging operations, railroad and power line sites, grazing and farming activities, and recreational developments and home sites. The chaparral lands of Southern California border on or contain extensive suburban housing development. Many of these uses and activities are inherently fire-prone or increase the probability of ignition or spread of a fire. Furthermore, despite fire safety regulations, wildland residence-users do not always prepare adequately for the fires that sweep through volatile brush and timber and threaten or destroy a wildland home. In fact, not uncommonly a fire fighter finds himself having to protect lives and homes while the wildfire's perimeter spreads out of control, and thus destroys additional structures (Task Force on California's Wildland Fire Problem, 1972).

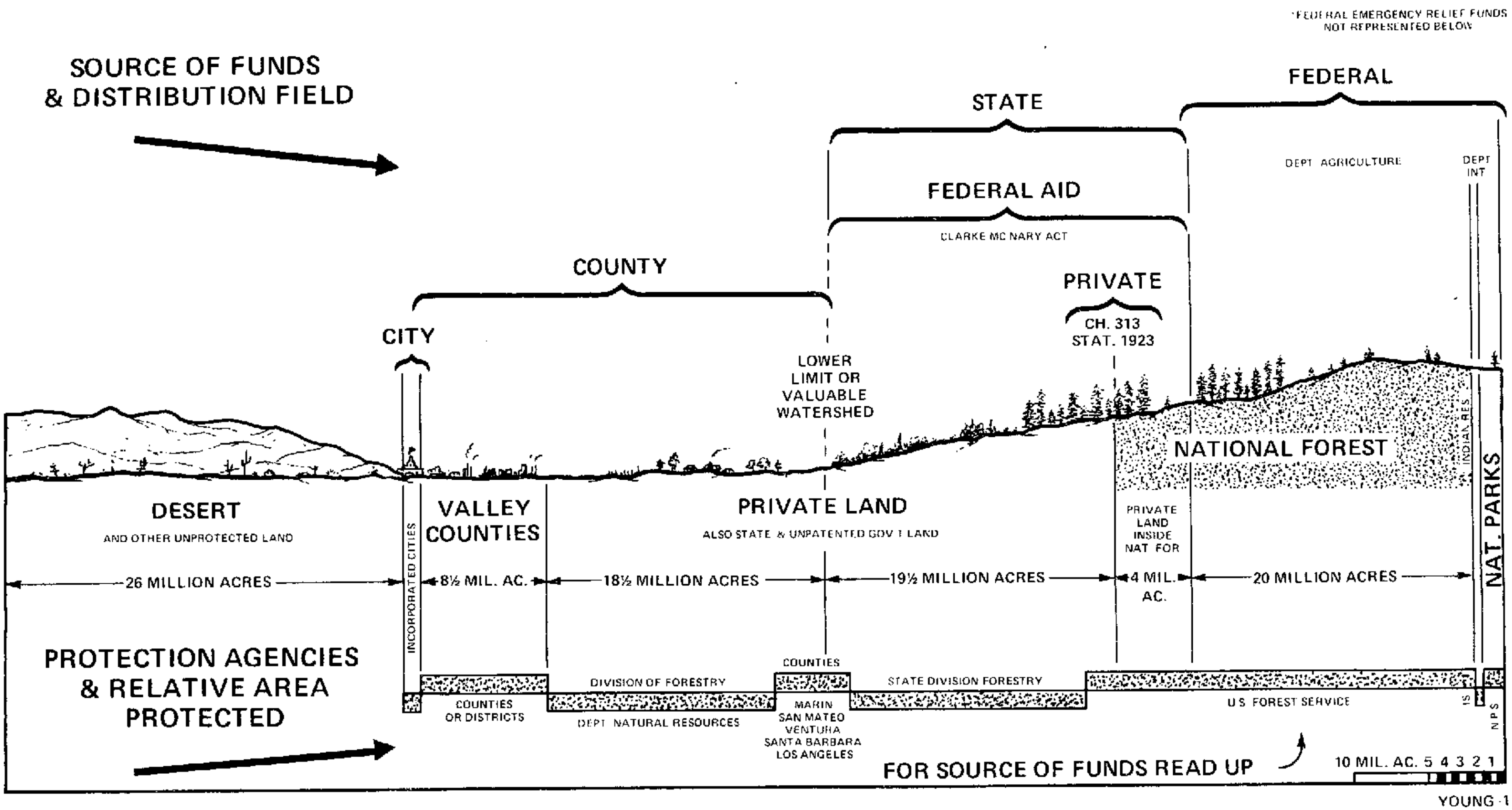
Forests and the lands upon which they stand are not respectors of ownership differences or governmental boundaries. Conversely, society has not respected the location of forest resource areas as it has divided up the forest ownership and drawn its governmental jurisdictional lines. Thus, 50 million acres of California's total 100 million acres, is privately owned, with 30 million acres in farm and ranch usage; 6.5 million in commercial forest type timber, not on farmland; and the remaining 5.5 million acres given to a variety of urban uses. Another 47 million acres is in federal ownership comprised of the unreserved public domain (including grazing districts), national forests, and defense installations. The final 3 million acres is owned by the State in the form of beaches, parks, school-grant lands, and tax-deeded lands (Dana and Krueger, 1958).

Of the State's 33 million acres of forest and watershed lands, some 24 million acres are within the external boundaries of the 22 national forests, wholly or partially situated within California, but only approximately 20 million acres within such boundaries are owned by the national forest system, the remaining 4 million acres being owned primarily privately, or by the State (USDA, 1972). The total commercial forest lands within the State are owned 52 percent by the federal government, 47 percent privately, and 1 percent by the State (Dana and Krueger, 1958). A tree may be standing in a National Park in which event it is owned by the federal government, but administered by the National Park Service of the Department of the Interior. Or the tree may be standing in a national forest, where it may be owned by the federal government, the State government, or privately, but is, for some purposes at least, administered by the U.S. Forest Service of the Department of Agriculture. Or it may be standing on federally owned land outside of a national park or forest and be administered by the Bureau of Land Management of the Department of the Interior. Or it may be standing on State, county, or privately owned land. Who, then, has the wildland fire responsibility in this maze of intermingled ownership and fragmented jurisdictions? (see Fig. 1.1).

Early in its history, California--uniquely among the several states--decided that standing timber is "a resource possessing a particular value for many persons and groups" (Clar, 1969). Among these, in addition to the government, are the actual owner, lumber workers, the local business community, and numerous types of recreation seekers (Ibid.). California declared that there existed an "inextricable collection of interested persons and parties who, whether they are actually aware, have something to lose if the forest is destroyed, and who therefore should pay some share of the cost of its protection" (Ibid.). Actual designation of responsibility levels for statewide fire protection came to be dealt with in terms of governmental levels: Federal, State, County, City, and fire protection districts specifically created to serve politico-geographic communities not adequately served by one of the four common echelons of government.

Basically, the United States Forest Service protects forested lands owned by the federal government within the external boundaries of national forests as its primary fire protection responsibility.

On the other hand, the California Division of Forestry of the Department of Conservation is primarily a fire control organization for the privately owned wildlands of the State and small amounts of State owned lands. The Public Resources Code charges the State with primary financial responsibility for the prevention and suppression of fires on about 37.5 million acres of private lands--slightly over one-third of the land area of California. Included are lands covered wholly or in part by trees capable of producing forest products, lands covered wholly or in part by timber, brush, undergrowth, or grass which protect the soil from excessive erosion and those contiguous lands which are used principally for range or forage purposes. Most mountain and foothill private lands within the State fit this classification. In 1969-1970 over $33,000,000--or about $1 per acre--of General Fund money was expended by the State in discharging its fire protection activities within this designated area of state responsibility (Legislative Analyst, 1972).



Reference: Clar, C. Raymond. 1969. California Government and Forestry - II. Division of Forestry, Dep't of Conservation, State of California, p. 162

Figure 1-1 Fire Protection Agencies and Governmental Responsibility in California

But "the basic state responsibility is to protect only the natural (wildlands) vegetative cover and does not directly include structures or other improvements on the land" (Ibid.). However, during the fire season, the Division of Forestry responds to structural or other improvement fires in its responsibility area because of the danger that these fires might spread to the wildlands and become forest fires, and also because of the possibility of the loss of life and economic values. The Division itself carries out the state function on state responsibility lands, but contracts with other agencies for the remainder of state responsibility lands. For example, the Division pays the United States Forest Service for the protection of state responsibility privately owned lands within the external boundaries of national forests. Also, five counties--Kern, Los Angeles, Marin, Santa Barbara, and Ventura--provide fire protection on state responsibility areas within their respective county boundary lines. And in addition to providing fire protection on state responsibility lands, the Division has rather extensively entered into cooperative agreements with counties, cities, or special fire protection districts for fire protection activities on local responsibility lands. Thus, there is a substantial web of cooperative and mutual aid agreements between the several governmental levels and the special districts with considerable exchanging of fire protection monies for services.

B. Study Objectives

Figure 1.2 is based on an analysis of data collected from California Division of Forestry Fire Activity Statistics reports (CDF 1963-1972). Plotted are:

(1) Fires/Acre Protected

(2) Total Acres Burned

(3) Acres Burned/Fire, by year, 1963-1972

The number of fires/acre protected is clearly increasing, while neither total acres burned/fire nor total acres burned shows a discernable trend. However, high peaks in burned acreage occur throughout the record with some regularity. Since it may be expected that marginal damage costs for many categories of damage (e.g., watershed damages) increase with increasing acres burned, the relative peaks of damage costs (in dollars) may be expected to be even higher than suggested by the acres-burned data.

Figure 1.3 was constructed from the same data for fires greater in size than 1000 acres. Plotted against time are incidence and the percentage of total acreage burned due to fires larger than 1000 acres. Note that the decrease in the incidence rate correlates with the decrease in the percentage of total acreage burned by large fires. This suggests that an effective job in detection and suppression of large fires is being performed by the protection agencies.

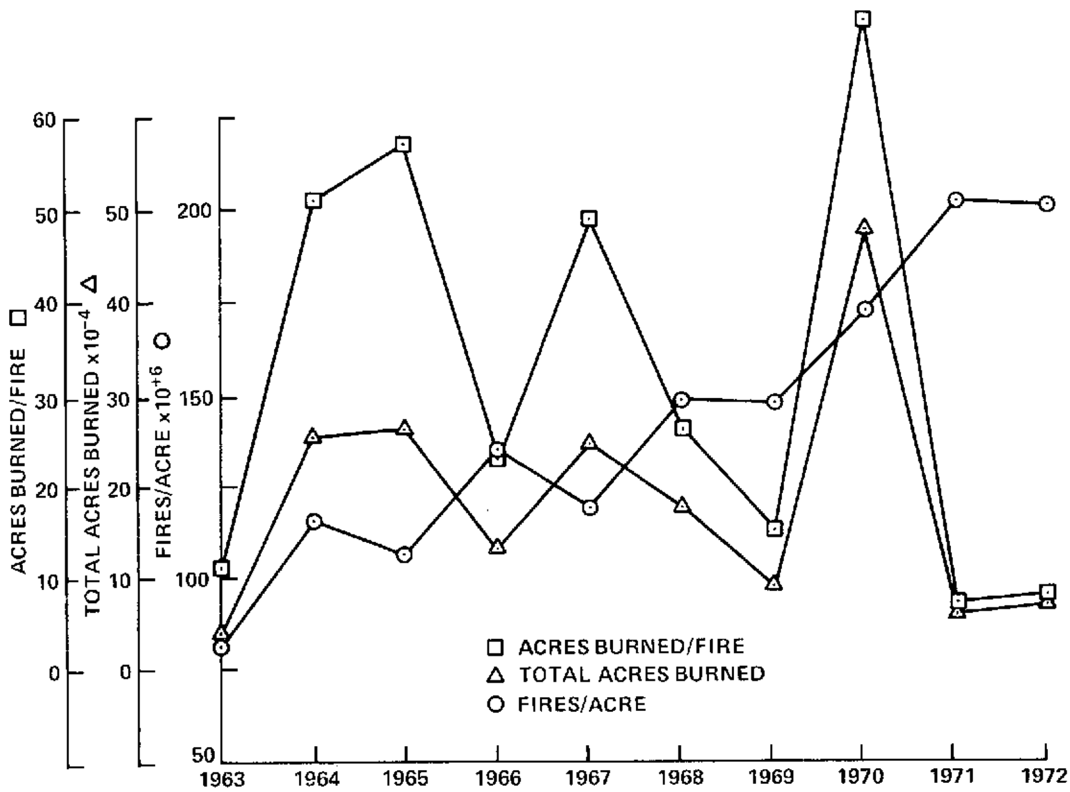


Figure 1-2 California Wildland Fire Statistics, all Fires, 1963–1972

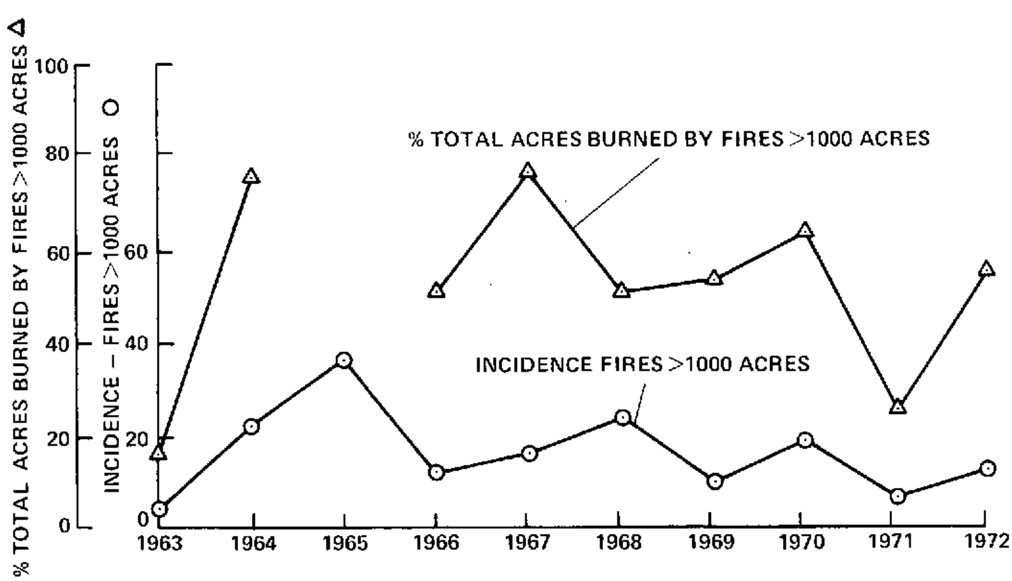


Figure 1-3 California Wildland Fire Statistics, Large Fires, 1963–1972

Several plausible inferences can be made from the data of Figs. 1.2 and 1.3:

(1) Since the incidence of fires is steadily increasing, further efforts in the area of prevention may be well repaid.

(2) In spite of some evidence for advances in fire suppression effectiveness (Fig. 1.3), total acres burned per fire has not clearly decreased, and high peak-damage years occur with apparently undiminished frequency (Fig. 1.2).

There is thus reason to believe that increased emphasis on presuppression activities such as fuel management and structure protection would be effective in reducing wildland fire costs.

The desirability of greater attention to nonsuppression fire control activities is also generally supported by wildland fire control personnel, as attested to by numerous private conversations. It is also of interest to note that in pending legislation in Congress it is stated that "more attention needs to be given by the fire services at the local levels to fire prevention, public education, and fire safety design rather than fire suppression,..." (H. R. 7681 and H. R. 8185).

The above arguments are in part the basis for the selection of our STUDY OBJECTIVES:

(1) to identify and investigate prevention and presuppression policies which might be successful in reducing the cost-plus-loss due to wildland fires;

(2) to use the information from (1) to construct models of the wildland fire process which can be used to calculate and assess the effectiveness of various prefire alternative policy decisions;

(3) to make use of the models from (2) to select policies which minimize the total cost-plus-loss due to wildland fires.

In the last section of this chapter we shall elaborate on these objectives with a detailed description of the contents of the report; we offer first, however, in the next section a discussion of the report's basic approach and underlying point of view: the cost-benefit analysis of wildland fire control.

C. Cost-Benefit Analysis of Wildland Fire Control

We propose to develop and use a cost-benefit model to calculate and assess the effectiveness of various fire management programs. The model will ideally permit policies to be selected to minimize the cost-plus-loss due to wild fires; it will also facilitate conceptualization of the wildland fire control problem. A diagram suggesting the major elements of the cost-benefit model is shown in Fig. 1.4.

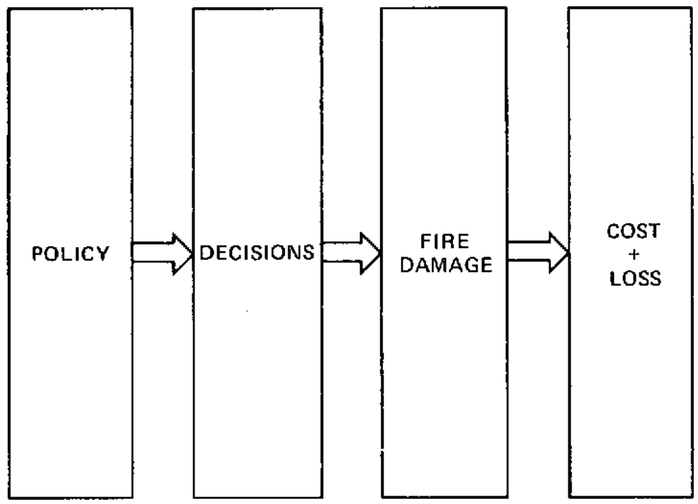


Figure 1-4 Major Elements of Cost-Benefit Model

Policy is here interpreted as providing a set of constraints for decision-making. Roughly speaking, policy provides the context within which the wildland fire problem occurs and has a very long time scale for change--of the order of five to ten years or more. Such questions as jurisdictional authority, intermingled ownership within national forests, zoning, property and building codes, and fire-fighting policy are considered policy questions. Generally, policy is established by agencies external to the specific agency responsible for fire control.

Decisions on the other hand are here taken to be within the aegis of the fire control agency. Decisions have a shorter time scale for change--of the order of one year. In the present cost-benefit analysis, five types of fire control decisions have been identified: suppression resources, fuel modification, entry and use control, structure regulations, and education and penalties. These decision types will be discussed in more detail shortly. For now, it suffices to note that these decisions effectively determine the level at which a particular fire control technique is employed and at what cost--how much suppression resource is available and at what cost, how much fuel modification and at what cost, and so on. The purpose of the cost-benefit analysis is to assess the relative effectiveness of the latter four prefire prevention strategies with the suppression resources held constant at the current level.

Given the fire control decisions, the fire-damage part of the model determines the damages which result from fires that have occurred over a period of time. This determination requires modeling of ignition occurrence, simulation of fire behavior and suppression, and evaluation of physical damage. Also, the cost of suppression must be evaluated.

The cost-plus-loss part of the model takes the determined fire damage and suppression-plus-prevention costs and evaluates the additional losses attendant to fire occurrence in order to obtain a total cost-plus-loss for wildland fires. Recreation, timber, watershed, property, and life represent typical resources whose values are here assessed as part of the total expected cost-plus-loss calculation. That decision or series of decisions which leads to the minimum expected cost-plus-loss is then identified as the optimum strategy.

There is also an influence of the expected cost-plus-loss result on policy, decisions, and fire damage that was not indicated in Fig. 1.4. That is, there is "feedback." In response to the anticipated expected cost-plus-loss of a given decision, the fire control system adjusts in an effort to minimize the expected cost-plus-loss. The time scale for adjustment of the different elements of the system varies. Policy, for example, takes substantially longer to change than do decisions made by the fire control agency.

An expanded, more detailed diagram of the cost-benefit model developed herein is shown in Fig. 1.5. The various decisions have been isolated and the details of the fire damage determination are shown. It is

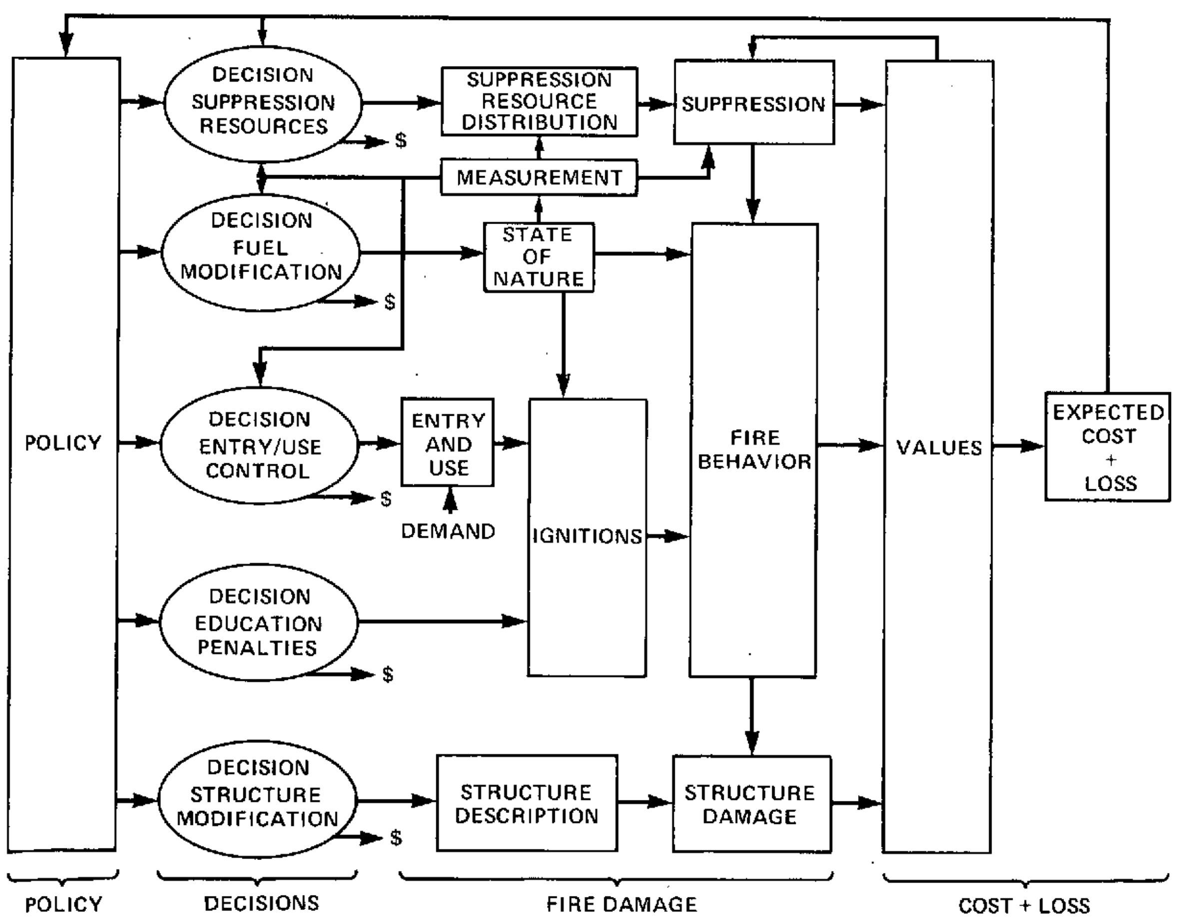


Figure 1-5 Details of Cost-Benefit Model

our purpose here to describe each element of the detailed model in terms of its input and output. While some of the actual methods of calculation of the output from the input will be described elsewhere, this discussion should indicate the conceptual framework within which the analysis has been conducted.

Policy outputs are a set of rules or constraints which govern decisionmaking. These limits on decisionmaking are assumed to be set by agencies external to the fire control agency and represent the environment within which the fire control problem occurs.

The suppression resources decision output gives the total amount of suppression capability of the fire control agency by type of suppression device and the cost of the use of these devices. For example, the output may consist, in part, of fifty D-4 bulldozers with a cost of $50 per hour of use per bulldozer, 200 hand crews with a cost of $500 per day per crew and so on. In addition to these use-costs, there are also fixed costs associated with the purchase, maintenance, and/or rental of the suppression resources. These are costs which would be borne by the fire control agency as a result of having the suppression resources available even if there were no fires. The output from the fuel modification decision is the specification of the type of fuel modification, the extent of the modification, and its cost. Fuel modification can be either of the area type or lineal type. Area-type fuel modification includes treatment with herbicides and/or fire retardants, physical removal, prescribed burning, and replanting with fire resistant species. The extent of area-type fuel modification is a specification of the fuel bed which results after the modification. Lineal-type fuel modification refers to fuel break construction. The extent of lineal-type fuel modification gives the fuel break location and probability of containment as a function of fire intensity and wind speed. The entry and use control decision specifies the maximum number of people by activity allowed in the area under consideration and the costs attendant to such restrictions. Education and penalties decisions refer to educational programs to be employed (e.g., Smoky the Bear) and the structure of penalties to be assessed for various fire-producing activities. The output of such decisions would be the expected reduction in ignitions by people engaging in activities of a given kind and the associated costs. The structure regulations decision specifies the required fire protection for individual structures (e.g., building materials, vegetation clearance, and replanting), zoning restrictions, and insurance regulations.

The state of nature takes the fuel modification decision as input and gives the actual state of the fuel, weather, and topography in contrast to a measured or perceived state. The output gives the ignitability of the fuel to the ignitions computation, the fire spread rate to the fire behavior simulation, and the actual values of the data which are measured as part of the determination of the various indices and ratings of fire danger. Measurement takes the actual state of nature and transforms it into a more or less accurate measure of the state of nature. This measured or perceived state of nature provides a basis for decisions on suppression resources, fuel modification, and entry and use control. That is, as the perceived state of nature changes, resources allocated to suppression will change. A reduction in the fire danger rating would imply a decreased need for suppression capability. Similarly, decisions on fuel modification and entry and use control depend directly upon perceived fire danger

Suppression resource distribution takes the total suppression resources available along with the perceived or measured state of nature as given, for example, by the fire danger rating and determines the distribution of suppression resources both spatially and temporally. This involves locating fire stations and tanker bases, for example, determining the time period when helicopters are leased, as well as establishing the automatic initial dispatch levels. This distribution of resources has been considered by several people as an optimization problem in itself. This aspect of the problem was not pursued but instead the distribution of the existing fire control system was used.

Entry and use takes the decision on entry and use control as modified by the perceived state of nature and the demand for entry and use as given by the number of people by activity seeking entry and use and from these inputs estimates the number of people by activity in the fire control area under consideration. Given the number of people by activity in the fire control area and the fuel ignitability as given by the state of nature, the ignitions computation determines the number of fires started per unit of time and the distribution of locations of fire starts. Educational programs and penalties have an influence on this result.

Structure description takes the decisions on structure regulations and determines the characteristics of the structures in the area being simulated. Specifically, it determines the location of the structures within the area under consideration and the percentage of structures that would be burned in a fire as a function of the fire intensity. The percentage of structures burned, for a given fire intensity and fire suppression capability, varies with the type of structure involved and will depend upon the use of fire retardant paints and building materials, brush clearance, and fire resistant plantings.

The suppression calculation takes the measured state of nature and the distribution of suppression resources and, for a given fire ignition, determines the initial dispatch level, reinforcement rules, and fire suppression strategy to be used in fighting a fire. It also evaluates the cost of suppressing a fire. Given an ignition, a specific state of nature, and the suppression doctrine, the fire behavior part of the model simulates the fire growth and suppression activity. The simulation determines the area burned and the intensity of the fire. The structure damage calculation takes the results of the fire simulation and the structure description and determines the losses due to fire damage of structures.

With the physical damages due to fire and the cost of suppression known, the values calculation determines the losses due to damage of timber, watershed, recreation, and aesthetic resources so that a total cost-plus-loss estimate can be obtained. Having determined the prevention and suppression costs and the losses due to fire damage, the expected cost-plus-loss calculation evaluates, after selection of a discount rate, the total expected cost-plus-loss from fire under the given policy and a set of chosen decisions. This is the desired output of the analysis.

This cost-benefit model is believed to accurately describe the wildland fire control problem. It provides a conceptual framework within which the complete system can be considered. The model allows trade-offs to be made as all decisions can be evaluated on the common basis of expected cost-plus-loss.

In addition, the model illustrates the complexity of the system and provides a means for examining the many interactions between different elements of the system and allows one to begin to understand some of the unexpected effects of a given decision. For example, consider a decision to employ area-wide fuel modification as a prevention technique. The immediate effect of such a decision is to alter the actual state of nature by changing the state of the fuels. This change in the state of nature alters the ignitability of the fuels which changes the number of ignitions per unit time as given by the ignitions part of the model. A changed actual state of nature would also lead to a changed measured state of nature. This measured state of nature is the basis upon which suppression resources are distributed and suppression strategy is developed. Also, the measured or perceived state of nature provides the basis on which decisions regarding allocations for suppression resources and fuel modification are made. The changed actual state of nature affects fire behavior through a reduction in the rate of fire spread and, indirectly through the ignitions model, by reducing the ignitability of the fuels. The altered fire behavior would, in turn, imply a reduced structure damage and, when combined with the reduced suppression costs, reduced fire damage. This cost, together with that of the proposed area-wide fuel modification gives the expected cost-plus-loss of the decision to modify the fuels. If this cost-plus-loss is less than that obtained without the fuel modification, we would infer that area-wide fuel modification is cost-effective.

It is proposed that meaningful evaluations of the effectiveness of different fire-control techniques can only be obtained from a "complete system" point of view. The complexity of the wildland fire-control system requires a model of the sort developed here so that a "complete system" view can be achieved.

D. A Reader's Guide

Because this report covers a wide range of subjects from many different individual perspectives, the reader may be assisted at this point by a descriptive guide to the report's contents. This brief commentary is offered by the editor to provide such guidance: to aid the reader in plotting a course through the report, to choose chapters and sections to satisfy his particular purposes and to fit his particular background.

The report is divided broadly into two parts. The first (Chapters III-VIII) is devoted primarily to the systematic collection and exploration of information on a variety of wildfire management techniques; the second part (Chapters IX-XI) is largely concerned with the development and application of alternative models of the wildfire management process.

This difference in emphasis is reflected in differences in tone and approach between the two parts, the first being predominantly descriptive, the second largely analytical and quantitative.

A survey by subject of the contents of the report follows:

Part 1: Largely Informational

Chapter III: Structure Protection in the main (Sections A-B, D-G) deals with the techniques, costs, and benefits of structure protection through roof and vegetation modification. The treatment is detailed, thorough, and in a number of respects novel. Also included are brief and preliminary discussions of the use of inspection (C), zoning (H), and insurance (I) to obtain improvements in structure protection; these sections outline important problems, but do not obtain conclusive or new results.

Chapters IV and V: Fuel Management present a detailed collection of data on the techniques, costs, and effectiveness of fuel breaks. Chapter V considers prescribed-burning and let-burn policies, with an extensive survey of the literature and an emphasis on the beneficial aspects of these policies; the lack of quantitative data, however, constrains the treatment to be largely descriptive and the conclusions suggestive rather definitive. Important and interesting long-term problems are outlined.

Chapter VI: Education presents an extensive survey of the (largely sociological) literature in the area of the use of education as a fire-prevention technique, where again the lack of conclusive experimental data on effectiveness is apparent. (The reader may be interested in comparing the style and scope of the psycho-sociological modelling of human behavior implicit here with the economic modelling of behavior developed in Chapter IX. It should also be noted that the nature of the management decisions considered differ in the two studies.)

Chapter VII: Land Management discusses wildfire management in the larger context of public wildland management, but with particular emphasis on the problems of intermingled public-private ownership. The treatment is descriptive, with conclusions favoring lessening of intermingled ownership, although nonfire aspects of the problem were given some consideration.

Chapter VIII: Fire-Danger Rating System describes in detail the present National Fire-Danger Rating System. (Chapters X and XI make explicit use of some aspects of this system; recommendations of specific modifications are made in Chapter X.)

Part 2: Modelling

Chapter IX: An Analysis of Prevention provides a detailed analysis of the economic determinants of individual incendiary and precautionary behavior. The analysis is based on a model which employs a mathematical description of the individual's utility function;

the individual is assumed to act in such a way as to maximize the expected value of this function. The analysis results in a number of policy implications regarding the relative importance of imprisonment, fines, and the probability of apprehension. The style of this chapter is distinctly analytical, although the results are qualitative, and there is extensive discussion to amplify and interpret the underlying mathematics.

Chapter X: A Model of Ignitions and Damages develops a model of ignition generation and damage production that is used to obtain decision rules for the regulation of wildland activities (e.g., logging and recreation) to minimize expected total cost-plus-loss. Of particular interest among the conclusions is the recommendation of the adoption of a new definition of "Risk" for the Fire Danger Rating System. Except for a final section on the problem of estimating wildland values for uses where an active market does not exist, the treatment is analytical and detailed: like the preceding chapter, an effort is made to be precise and complete in the development and statement of assumptions and conclusions. However, to aid readers impatient of such detail there is a lengthy introductory description of the chapter in Section A, with a summary of the main results.

Chapter XI: A Simulation Model of Suppression presents a model which simulates wild-fire behavior and existing suppression actions. The model, described in considerable detail, is suitable for programming on a digital computer, although all fire simulations reported in the study were carried out by hand. A detailed description of one particular fire simulation is presented, as well as the interesting results of several simulation studies regarding the effectiveness of various presuppression decisions. The model appears to give good agreement with observed fire-suppression processes, and should find a number of further applications.

A final introductory note is perhaps in order. It should be clear from the foregoing outline that the report does not fully realize the ambitious objective stated in Section C of a completely integrated systems analysis of the wild-fire problem. The effort does, however, constitute a constructive first step toward this goal, and a partial achievement of it: hence, the statement of the original, ultimate objective has been left standing without fear of compromising a report which, if less than completely definitive, is nonetheless a useful beginning.

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Chapter II

SUMMARIES AND RECOMMENDATIONS

Chapter II

SUMMARIES AND RECOMMENDATIONS

A. Chapter III: Structure Protection

1. Summary

Brush clearance and installation of fire-resistant roofing are both important in helping to make a home safe in a wildfire situation. Data shows quite dramatic reductions in expected wildfire damages by these techniques. Noncombustible eaves and enclosed foundations are also desirable. Although these observations are not surprising, a drive through the brush areas outside Los Angeles reveals that such recommendations are frequently not followed.

Brush clearance and roof conversion ordinances are usually passed at the county level since many wildland areas are outside city limits. Few counties have such ordinances, and in those that do, enforcement is obviously lax. Inspection to achieve enforcement may be a cost-effective means of increasing structure protection.

Insurance surcharges are added in certain high wildland fire-danger areas to homes without fire resistant roofs or brush clearance, but these charges do not make it cost-effective for the individual homeowner to convert his roof or clear his brush. Changes in the insurance rate structure could improve this situation. The zoning process may also be used to advantage to obtain better and more uniform structure protection.

Neither the general public nor nurserymen know which plants are fire-resistant, though many are, and the cleared lot is often needlessly pictured as a barren wasteland in prepared brochures.

Alternatives to roof conversion are or will be available to ease the cost of complete conversion. Effectiveness of these alternatives depends heavily on having cleared the brush.

2. Recommendations

(a) State-wide regulations on brush clearance and roof conversion should be established for wildland areas. Further, counties should be required to identify wildland fire-danger areas in which the regulations are applicable.

(b) Information should be disseminated on the availability of fire-resistant plants. Federal and State agencies should expand the Tree Seedling Program to include such plants and nurserymen should understand and communicate their virtues.

(c) Brochures on wildland home fire protection should be made more widely available. They should include suggestions on inexpensive ways to comply with regulations; they should, via graphics, convey the need for compliance with regulations on brush clearance and roof conversion; and, they should, via illustrations, demonstrate that a fire-safe home need not be an unsightly home.

(d) Regular inspection for compliance with fire prevention rules should be considered for all homes in or near fire hazardous areas. Such inspection would probably include all homes at first, but be reduced to written reminders and random inspection after one or two years. Noncompliance would be followed by reinspection and, where appropriate, by citation. Detailed cost-benefit studies in conjunction with experimental programs should precede the state-wide implantation of such a plan.

B. Chapter IV: Fuel Management: Fuel Breaks

1. Summary

A fuel-break model has been developed having two key elements: fuel-break construction and maintenance costs, and fuel-break effectiveness as a function of fuel-break width. These two elements together with inputs from the fire-spread model, fuel type, topography, etc., will determine the direct benefits (savings in suppression costs) and indirect benefits (savings in watershed damage, recreation resources, etc.), thereby providing the wildland resource planners with a more objective means of presuppression planning.

Currently in California, there exists 1,850 miles of maintained fuel breaks and another 900 miles of unmaintained fuel breaks to protect over 100,000 square miles of wildlands. Of the existing maintained fuel breaks, more than 60% are less than 300 feet in width and practically all of the maintained fuel breaks are 400 feet or less in width. Yet, upon considering the effectiveness of manned fuel breaks under severe fire conditions, there is a point in the effectiveness curve for fuel breaks 700-900 feet in width beyond which further widening of the fuel break does not increase the effectiveness substantially. Using this effectiveness data, it has been shown that increasing existing fuel break widths will reduce the expected cost plus loss during a wildland conflagration.

The amount of data available on fuel-break effectiveness is limited to four studies, and some diversity exists between the results of these studies. In addition, it is very difficult to compare the results of one study against another to determine validity since the conditions under which the studies were conducted differ.

In 1957 three principal wildland fire fighting agencies in Southern California, U.S. Forest Service, California Division of Forestry and Los Angeles County Fire Department initiated a program to "develop, test, and evaluate methods for breaking up or otherwise modifying expanses of brush or other wildland fuel." This continuing research program has provided the wildland resource planners with new mechanical and chemical brush control methods, revegetation techniques, fire resistant plants, and other means of fuel modification.

2. Recommendations

(a) Existing fuel breaks should be maintained and/or widened to make them effective as a suppression aid justified on a least cost-plus-loss basis.

(b) New fuel breaks should be justified on a least cost-plus-loss basis.

(c) Better quantitative data should be obtained on fuel-break effectiveness as a function of width through gaming techniques with combinations of parameters such as wind velocity, fuel type, topography, etc., considered and varied.

(d) Continue research for and application of new construction and maintenance methods of fuel breaks.

C. Chapter V: Fuel Management: Prescribed Burning and Let-Burn Policies

1. Summary

Despite increased suppression activity, large fires continue to occur and cause extensive damage to timber, watershed, structures, and recreational facilities. Prescribed burn and let-burn policies have been recognized as effective means of reducing fuel loadings, but have received little use. There are a number of reasons for nonimplementation, such as the lack of knowledge of how, when, and where prescribed burning should be used, the attitude that all fires are bad, and the fear of a prescribed burn escaping. There are widespread ecological implications connected with burning and many effects of controlled burning are beneficial to the forest ecosystem.

2. Recommendations

(a) Detailed mapping of fuel types and fuel loadings by area and population density must be accomplished in order to make decisions with respect to all types of fuel management techniques.

(b) Instruction of forest personnel in techniques of prescribed burning should be initiated.

(c) Consideration should be given to the expansion of let-burn areas.

(d) The public must be instructed with respect to the necessity for a statewide fuel-management program, including prescribed burning.

D. Chapter VI: Prevention through Education

1. Summary

Well over 90% of all the damage caused by wildfires is due to fires caused by people. Carelessness (campers, smokers, debris burners), mechanical equipment (mostly autos and trucks), and arson are the prime causes. Incendiary fires are increasing at a rate even faster than the total number of fires. Many are set by children, usually boys, 5 to 10 years old for whom fire seems to offer a great fascination. Most children will set a fire only once--if at all--and are sufficiently scared by the results not to do it again. In kindergarten and first grade children can be taught to experience fire safely and, psychologists believe, the fascination of playing with fire can be removed.

Some children set fires repeatedly to satisfy some emotional needs. Such children can be detected and distinguished from the one-time fire setters by a relatively simple investigation into the school and family situation of every child found setting a fire. Emotionally disturbed children may require extensive counseling to prevent continuation of their antisocial behavior.

Among adults most fires are started by people who live and work in or near the forest lands. They are also the fire's most immediate victims. Education of adults does not seem to be effective in changing basic attitudes, e.g., it will not deter an incendiarist, but it can change the behavior of those people who, because of ignorance of fire regulations or penalties, have been insufficiently careful; e.g., it may cause people to clear brush around their house.

2. Recommendations

(a) State-wide fire education programs for kindergarten and first-grade students should be continued and expanded to afford children firsthand, safe experiences with fire.

(b) A psychological profile should be obtained on every child who has been found setting a fire. If the profile indicates the likelihood that the child will repeat its action, every effort should be made to obtain psychological counseling for the child.

(c) Thought should be given to initiating a program whereby every householder in or near forest lands is personally contacted, reminded of his stake in preventing fires, of the fire regulations, and of the penalties for violations. This contact could be made in an annual group meeting or in connection with a fire inspection of the property.

E. Chapter VII: Land Management: Intermingled Ownership

1. Summary

Prior to establishment of the national forests, millions of acres of some of the most productive, valuable, and strategically situated public domain passed into private ownership during a long period of a fast-disposal policy. Then, in an abrupt reversal of policy the forest reserves were created with equal haste, resulting in the inclusion of vast areas--sometimes with little or no relevance to forestry--held in private ownership within the external boundaries of the national forests. Today, more than one acre in six of the total ownership within national forest boundaries is nonfederal, not infrequently reflected in a checkerboard pattern of federal and nonfederal ownership.

The forest reserves, while created for the protection of watershed and timber production, became multiple-use reservations and were put to such additional uses as grazing, mining, and recreation of a commercial nature. More recently, priorities have shifted and noncommodity benefits, such as wilderness, wildfire habitat, inspiration, and scientific research have assumed much greater importance. Coordination of these diverse and often conflicting uses, with due regard for biological, physical, social, economic, and esthetic considerations, creates a most difficult problem of rational administration of the national forests.

Intermingled ownership of the lands lying within the external boundaries of the national forests further complicates the increasingly complex problem of wildland forest management, including wildland fire prevention and control. For example, it precludes the application of uniform policies of fire prevention, such as limiting or denying entry and use during periods of high fire danger.

While there are isolated benefits deriving from intermingled ownership within the national forests, such benefits do not pertain to wildland fire control. And these benefits generally derive to private landowners from the coexistence of adjacent federally owned lands.

If realignment were to be accomplished by exchange alone, the total cost would be relatively small, relating primarily to appraisal costs and the costs of transfer of legal title through exchange instruments. Purchase would involve such administrative costs plus purchase price. Purchase prices would be highly variable. For example, 149,088 acres have been acquired within the boundaries of national forests situated in California under the Weeks Act of 1911 at an average cost of $13.89 per acre, but the high and low ranges have been from $3.62 per acre to $621.52 per acre.

2. Recommendations

Further consideration should be given to realignment of the external boundaries of the national forests by exchange and purchase, or a combination of the two, so as to eliminate or ameliorate problems of intermingled ownership in order to ease administrative burdens and to improve wildland fire prevention and control techniques.

F. Chapter VIII: Fire-Danger Rating System

1. Summary

The State of California has adopted the 1972 National Fire-Danger Rating System, NFDRS, for use in wildland fire control. One major improvement of the 1972 NFDRS over previous systems is that it has an analytical base for most of the elements of the system. The purpose of the system is to give an indication of the effort required to contain the fire problem over a given period of time. The system determines three fire behavior components and three fire-danger indexes. The numerical values of all indexes and components are relative and not absolute, and they are all scaled from 0 to 100. The system considers only fires spreading at a steady rate without crowning or spotting taking place.

The intended use of the 1972 NFDRS was as one of several inputs to be used by fire management. The system does not consider the suppression forces available, the condition of the soil, accessibility, location of property, and other factors that must be considered by fire management. Any fire control officer must have a thorough understanding of the philosophy, structure, and limitations in the NFDRS in order to effectively integrate it with the other factors that must be considered during the fire season.

2. Recommendations

(a) The state should have a single agency for collecting and analyzing all fire data.

(b) The sensitivity of the NFDRS to its inputs should be fully understood by all fire management personnel.

(c) The effectiveness of the locations of the fire weather stations should be investigated.

(d) In high fire danger areas it is desirable to have weather history regarding wind speed and direction. Of importance here would be the time of day major changes take place.

(e) All fire reports should contain a fire-danger rating calculated near the fire area.

(f) After validation of the 1972 system in California, all wildland fire control divisions in the state should adopt and operate under the same fire-danger indexes and dispatch nomenclature.

G. Chapter IX: An Analysis of the Effectiveness of Penalties and Enforcement

1. Summary

This portion of the report analyzes the deterrent capabilities of a number of policy changes. The investigation is carried out within the framework of the expected utility theorem, a powerful tool for analyzing individual decisions when the consequences of actions are stochastic. Two problems are addressed: The response of incendiary activity and the response of precautionary activity (with respect to ignitions) to changes in (i) wealth levels, (ii) the severity of punishment, and (iii) enforcement, were derived under several assumptions about the structure of punishments. The major results follow:

Changes in Enforcement: Expenditures which result in increased enforcement (increases in the probability of apprehension) lead to decreased damages resulting from all types of man-caused wildfires. This result holds whether penalties are fines or a mixture of fines and sentences.

Changes in Punishment: As long as penalties for incendiarism are fines only, increases in the size of fines lead to decreased incendiarim and also to increased efforts directed to precautionary activity. Thus, if both criminal and civil penalties are fines, damages from all types of man-caused wildfires decrease with the level of the fine. On the other hand, we are unable to draw any conclusions about incendiarism when penalties include both fines and prison sentences, although fine increases may still deter.

Changes in Wealth: If penalties are only fines, then increasing wealth levels not only increases incendiarism, but also decreases the incentive on the part of other wildland users to take fire precautions. On the other hand, it is shown that in a mixed fine-sentence penalty system, the effects of increasing wealth on incendiarism are ambiguous. However, if prison sentences are the only form of penalty, then increases in wealth will cause incendiarists to "retire."

Relative Effectiveness of Enforcement vs Punishment: We find that in fine-only penalty systems that increases in either enforcement or punishment lead to a reduction in fire damage from all man-caused sources. We then ask which policy change has the greatest effect in reducing damages and find that percentage increases in fines cause a greater reduction in damages than do equal percentage changes in enforcement. This result holds independent of the "existing" level of fines and enforcement. A similar result is not forthcoming for mixed fine-prison sentence penalty systems.

2. Recommendations

(a) The analysis clearly points out that it is not actual enforcement and actual punishment that are important in the results we have reported, but rather the individual's perception of enforcement and punishment levels. The conclusion is obvious: Policy makers must design policies which are easily communicated and understood if they are to be effective. When policies are changed, the chances of being caught and the penalty if caught must be "advertized" if increased deterrence is to be forthcoming.

(b) Since the effects of increasing the severity of punishment depends upon the structure of penalties and could even lead to increased incendiary activity, any such policy changes should be carefully studied after enactment.

(c) Since increasing wealth leads to increased fire losses in all penalty systems based on fines, but decreased fire losses if punishment is based exclusively on prison sentences, thought should be given to programs which emphasize prison sentences for apprehended incendiarists.

H. Chapter X: A Model of Ignitions and Damages, with Applications to Activity Regulation

1. Summary

A probability model is developed which describes the generation of ignitions caused by various activities as a function of a number of variables, including activities, the time period, the ignition index, the number of users engaged in specific activities, and a parameter, the mean number of ignitions per user-day by activity, which may be estimated from fire-history data. This ignition model is conbined with a damage model, yielding a useful representation of expected fire loss as a function of various prevention and suppression decision parameters.

The expected fire-loss expression is taken as the basis for a detailed investigation of optimal activity regulation (minimizing expected cost-plus-loss). Decision rules are derived under a variety of conditions, producing a number of interesting connections with the existing Fire-Danger Rating System. A modification of Fire Load Index to include expected damages and costs and a new precise definition of "risk," produces an index which can be used as the basis of optimal decisions.

The effects of a budget constraint and the sensitivity of cost to measurement errors are investigated. Finally, there is a discussion of the problem of determining the value of wildland areas, for wildland uses where an active market does not exist.

2. Recommendations

(a) The conceptual and analytical framework presented here should be used as the basis of general prevention planning in the design of experimental programs and the interpretation of the results of these programs.

(2) Fire-control agencies should keep fire data in a form that combines the following: number of fires by activity, area, and ignition index, and number of users in the activity. Damages and costs per fire should be computed and compiled by burn index and activity. Opportunity costs (loss of benefits to users resulting from prohibition of an activity) should be tabulated by activity.

(c) The structure of the present Fire Load Index (FLI) is (under certain conditions) correct for activity regulation decisions, provided "risk" is redefined as the product of (i) mean number of fires per user-day per unit ignition index, and (ii) mean total cost-plus-loss per fire per unit burn index (both for a particular activity), divided by the total cost of prohibiting an activity per user day. A similar redefinition of "risk" is appropriate for cases where all activities must be considered together.

Ignition-generating activities should be regulated on the basis of an index F_i (FLI defined for each activity i in the above sense). The resulting decisions (which minimize total expected cost-plus-loss) are either admit all $(F_i < 1)$ or admit none $(F_i > 1)$ for each activity. If policy constraints dictate that all activities be either prohibited or permitted together, then this decision should be made on the basis of an index F which is constructed similarly to the indices F_i.

I. Chapter XI: A Simulation Model of Suppression, with Applications to Presuppression Decisions

1. Summary

The simulation of the suppression and fire behavior part of the general cost-benefit model is described and tentatively verified. The simulation has some original features which are believed to make the simulation of general interest. An illustrative example of the simulation, including the effects of varying weather and topography is given. Uniformly distributed fuel breaks of different widths and separation distances are evaluated. Results obtained show, for the range of conditions considered, that wider fuel breaks with a larger separation distance are more cost-effective than narrow fuel breaks with a smaller separation distance. Errors in measured fire danger lead to errors in the initially dispatched suppression capability. We examine this question by determining the change in the acres burned if, on all high fire-danger days, a medium fire-danger initial dispatch level is used. Similarly, the effect of dispatching a high fire-danger level force on medium fire-danger days was determined. In the first case, which corresponds to a twenty-nine percent decrease in the dispatched force, there was a nineteen percent increase in area burned. The second case, which corresponds to a forty percent increase in the dispatched force, leads to forty percent decrease in the area burned. Area-wide fuel modification is examined by considering the effect of fuel age on the area burned. Simulation chamise fuel shows that the fuel age has a dramatic effect on the burned area. Compared with fifteen-year-old chamise, five-year-old and ten-year-old chamise burned over ninety-nine and ninety percent less area, respectively. The cost-effectiveness of area-wide fuel modification depends critically on the values at risk and the cost of the fuel modification. Area-wide fuel modification such as prescribed burning may be a cost-effective method of constructing fuel breaks.

2. Recommendations

(a) The existing system of fuel breaks should be made more effective by widening the fuel breaks, with the spacing between fuel breaks being determined so as to optimize the expected cost-plus-loss due to fire damage. Our calculations show that for a fixed fuel-break expenditure, there is an optimum combination of spacing and width.

(b) Area-wide fuel modification to reduce average fuel age should be conducted in those areas for which calculation shows it to be cost-effective. The use of prescribed burning to construct wide full breaks should be explored.

(c) The dispatching system should be modified to initially dispatch a suppression force which places more emphasis on the predicted rate of fire spread. Our calculations indicate that there is an optimum initial dispatch which minimizes the expected cost-plus-loss.

(d) Additional data should be gathered to further verify the simulation and substantiate the conclusions derived therefrom. For example, verification of the distributions of wind speeds used in the simulation would be useful.

(e) The cost-benefit model and simulation should be further developed for use as a planning and training device.

(f) A simplified, graphical version of the simulation should be developed for use at large fires by the Plans Boss.

Chapter III

STRUCTURE PROTECTION

LIST OF FIGURES

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Chapter III

STRUCTURE PROTECTION

A. Introduction

This chapter is devoted to the investigation of the prevention of damage to structures in wildland fire areas by means of structural and site modifications. In severe wildland fire situations, the individual structure is threatened either by (i) direct flame contact, or by (ii) firebrands landing near or on the structure. Direct attack on the first mechanism of destruction usually involves removal of combustible fuels from the vicinity of the structure, whereas an attack on the second mechanism involves the prevention of firebrands from igniting the structure. It is current practice in structure protection to recommend brush clearance for the former, and the installation of a fire-resistant roof for the latter.

The Bel Air fire in Los Angeles in 1961 has been extensively analyzed for damage statistics (LAFD, 1962; Wilson, 1962; NBFU, 1962; Howard, 1973). Figure 3.1 presents a dramatic summary of the effect of brush clearance

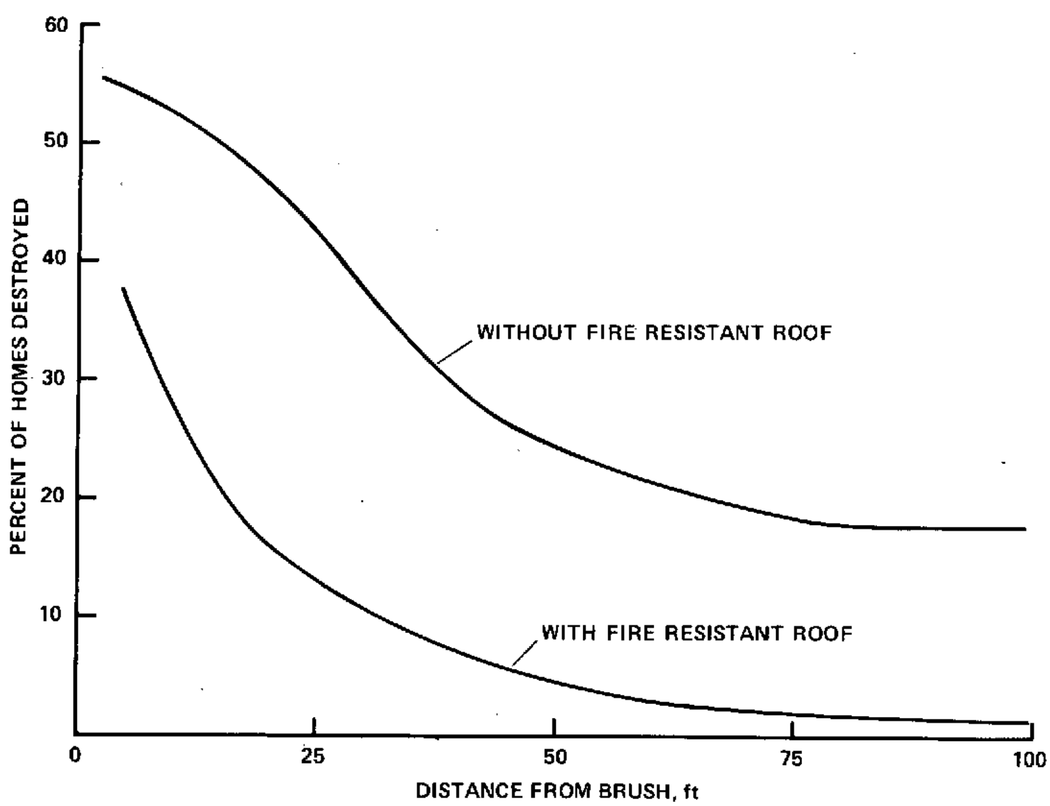


Figure 3-1 Effects of Clearance and Roof Conversion — Bel Air Fire 1961

*Sections A, B, and D through G were prepared by V. Bond, A. Kraft, and W. Feldt; Section C was prepared by E. Chilton and A. Kraft; Sections H and I were prepared by A. Kraft.

and roof type on fire-destruction risk. Homes with little brush clearance and/or with wood shingle or shake roofs were much more likely to be destroyed than those with over 100 feet of clearance and fire retardant roofing. The graph also shows the strong interaction between these two factors, but before considering this point further, we will embark on a detailed discussion of the constituents of the structural protection problem.

B. Economic Arguments for Structure Protection

The economic advantage of structure protection is clear-cut from the viewpoint of society at large (Howard, 1973). For example, if one interpolates graphically from Fig. 3.1, the more useful data of Table 3.1 is obtained.

Table 3.1

PROBABILITY OF A HOME BURNING
IF EXPOSED TO FIRE, $P(B|F)$

	Brush Clearance		
	None	30 Feet	100 Feet
Wood roof	0.54	0.34	0.15
Nonwood	0.38	0.08	0.008

For illustration assume a value of 1/30 as the probability of a home being exposed to fire in a given year. (This value can be viewed as the average portion of wildland in a particular area of interest which burns each year.) The expected or average annual fire damage for a particular home is calculated as the product of (1) the probability of fire exposure $P(F)$, (2) the probability of a home burning if exposed to fire, $P(B|F)$, and (3) the value V of the home. That is,

$$\text{Expected Annual Damage} = P(F)\ P(B|F)\ V$$

A home with an insured value (structure and furnishings) of $50,000 with wood roof and no brush clearance would have expected annual fire damage of 1/30 (0.54) (50,000) or $900; whereas a similar home with fire retardant roof and 100 foot brush clearance would have an expected annual fire damage of 1/30 (0.008) (50,000) or $13. (Similar calculations for other clearance distances are shown in Table 3.2.) Consequently, there is a net savings of $887 per year for roof conversion and 100 feet of brush clearance. However, this savings would immediately accrue to the

Table 3.2

AVERAGE ANNUAL FIRE-DAMAGE COST ($) TO A $50,000 HOME

	Brush Clearance		
	None	30 Feet	100 Feet
Wood roof	900	567	250
Nonwood	633	133	13

insurance company rather than the homeowner. Only later, on the basis of changes in claim history, would the homeowner benefit in terms of lower premiums. This ultimate savings, in fact, would be greater than $887 because insurance systems costs, a fixed percentage of claims, are part of the premiums paid by homeowners. If to these ultimate insurance savings is added the annual savings in suppression costs, one obtains an estimate of the expected annual savings to society resulting from the specified improvements, a figure which would clearly far exceed $887 for this particular home. (Such calculations are carried out in detail in Howard, 1973.)

It is unreasonable to expect the homeowner to carry out a program of roof modification or brush clearance unless he perceives immediate net benefits to himself. To estimate these benefits, assume that the owner of the $50,000 home has on the order of $10,000 worth of intangibles and uninsured valuables subject to destruction by fire (Howard, 1973). On this basis, the average annual uninsured fire damage cost to the homeowner would be as shown in Table 3.3. Thus, the owner of the home in this example can justify an expenditure of no more than $180 per year for brush clearance and roof conversion. If one questions the value estimate of intangibles and uninsured valuables, the argument for brush clearance and roof conversion is even less convincing. Thus, although the figures in Table 3.2 regarding damage to the home suggest a significant savings to <u>society</u> effected by brush clearance and roof conversion,

Table 3.3

AVERAGE ANNUAL UNINSURED FIRE-DAMAGE COST ($) TO HOMEOWNER ($10,000 UNINSURED VALUE)

	Brush Clearance		
	None	30 Feet	100 Feet
Wood roof	180	113	50
Nonwood	127	27	3

the figures in Table 3.3 regarding uninsured losses to the homeowner indicate that very inexpensive means of accomplishing brush clearance and roof modification must be available to the homeowner to make it either cost-effective for him or reasonable of society to require him to carry out clearance and roof modification, unless society absorbs part of the expense.

Further discussion of the effectiveness of inspection programs designed to ensure brush clearance and roof conversion will be presented in the following section. The remainder of the present chapter is devoted to discussing alternatives available to the homeowner for accomplishing these steps (Section D to G) as well as zoning and insurance considerations (H and I).

C. Inspection of Homes

Legal requirements, together with inspections, may be used to induce homeowners to effect structure protection measures. One test of the effectiveness of inspection campaigns was undertaken under the direction of the USFS in Butte County, California (Folkman, 1967 and 1968). A sample population of one thousand homes was selected. Half of the residents in the study area were sent letters prior to inspection informing them of the coming fire season and recommending various preventive measures. This letter had no immediate effect on compliance with the recommendations. In fact, those who received letters had a slightly higher rate of noncompliance than those who had not received such a letter, according to the personal inspection made at every house some two weeks after the letters had been sent. Many "property owners who received only the inspector's notice (said) that they had not bothered to take any corrective action because they had expected no follow up" (Folkman, 1967). Follow-up letters and/or a second inspection to some of those who had been in violation during the first inspection proved particularly effective. Of those who had received both letters and both inspections, only 17% remained in violation compared with an original 67% violators. Inspection centered on the remaining violators and, finally, 12 of them were recommended for prosecution. A letter from the District Attorney got immediate compliance from all but one. Therefore, the study showed that "a high level of compliance can be achieved without coercive action" (Folkman, 1967). As another consequence, debris burning fires which are often caused by faulty incinerators, were appreciably reduced in the sample population during the years following the test. It is also possible that there is a spill-over effect which causes neighbors of the sample population to emulate their peers and adopt safer operating procedures themselves.

A follow-up study (Folkman, 1968) indicates that there is a considerable hold-over effect from one year to the next. This suggests that a thorough inspection procedure be carried out prior to the fire season for one or two years, to be followed by inspection on randomly selected homes in subsequent years.

There appears to be strong support for inspection and other preventive activities among professional foresters. (Sarapata and Folkman,

1970) found that almost two thirds of CDF personnel reported that they felt fire prevention and suppression activities should be given equal importance. More than 3/4 of them recommended that more funds be made available for prevention activities. In reality, however, "Fire prevention is perceived to occupy an importance level much below fire suppression and fire detection..." (Ibid.). CDF personnel did not necessarily recommend a reduction in suppression effort, but felt that the increased prevention action would eventually result in a curtailment of suppression efforts. Such action has a historical basis. During the 1940's when there was a dramatic reduction in acreage burned and fire starts compared to other time periods, USFS expenditures on presuppression efforts exceeded the expenditures on suppression.

Pinkerton (1964) reports the use of young people from the Youth Opportunity Corps in the State of Washington for various fire prevention tasks, including inspection. The program was so effective that it was eventually expanded to a year-round format. Women and other volunteers from the peer community have also been suggested for the inspection task. It is possible that such people will be more readily accepted by the person whose property is to be inspected, and they are also likely to be less costly than foresters. Reinspection and prosecution should, however, be entrusted only to experienced and uniformed personnel.

To calculate the benefits of structure inspection, consider the Butte County studies where it was estimated that the average time per inspection was between 10 and 15 minutes. We shall assume that travel and follow-up will make this one hour per home, and we shall estimate the total cost of the inspector at $10 per hour. Hence, an inspection costs about $10 per home.

It has recently been shown (Howard, 1973) in a thorough and detailed analysis of the Santa Monica Mountains area that brush clearance alone would result in an expected savings to society of approximately $52 per home per year, whereas both brush clearance and roof conversion would result in an expected savings to society of approximately $126 per home per year.* If we assume that homes in the Santa Monica Mountains are worth on an average $50,000 and homes in Butte County are worth on an average $20,000, and that savings are a constant proportion of average home value for both areas (an admittedly bold assumption), we obtain Butte County savings to society of $21 and $50, respectively. If we further assume that only every other house benefits from the inspection, i.e., that half the householders obey the law without inspection,** we obtain annual savings of $10 and $25. Assuming that inspections need be carried out only every three years, we obtain an annual cost per inspection of about $3.

*Total cost plus loss to society included clearance and roof conversion cost, insurance system cost, loss of human life, watershed damage, aesthetics, wildfire and recreational value, marginal suppression costs, and brush fire fighting capability costs.

**Folkman (1967) stated that, on first inspection there were over 67% violations.

Hence, with inspection costs of approximately $10 per home, inspection for brush clearance yields a net benefit of about $7, while inspection for brush clearance and roof conversion together produces a net benefit of about $22 per home.*

This calculation should be viewed only as a very preliminary example of the sort of calculation that should be carried out in much more detail in the future.

D. Techniques and Costs of Vegetation Modification

The effectiveness of brush clearance around structures in reducing losses from fire exposure has been recognized for several years (LAFD, 1972; Wilson, 1962). The Task Force on California's Wildland Fire Problem (TFCWFP, 1972) recommended that clearance of hazardous wildland fuels adjacent to structures be required to a distance of 100 feet even if clearance goes beyond property lines and that greenbelt standards and guidelines be prepared. Others have now shown very convincingly that brush clearance (as well as roof protection) is cost-effective for society at large (Howard, 1973). However, the actual cost of brush clearance must be born by the individual property owner, and the uninitiated homeowner can easily incur expenses far in excess of the minimum clearance cost. In addition, few homeowners will be satisfied with the appearance of their lot after it has only been cleared of brush.

Most people would want to replace the natural brush with green grass, ground cover, shrubs, or trees. While fire damage reduction is effected by establishing and maintaining brush clearance alone, it is only reasonable to expect the homeowner to incur additional expenses associated with establishing and maintaining a greenbelt around the home. It seems essential then to provide the homeowner with not only the clearance requirements, but also guidelines for inexpensively clearing brush and establishing a greenbelt.

1. Brush Clearance

When obtaining estimates of the cost of clearing brush, one is confronted with a confusing array of figures. For example, L. R. Green of the U.S. Forest Service estimates the cost of bulldozing brush into piles or windrows on slopes up to about 30% to be $25 to $60 per acre, and suggests that the commercial rates for hand-cutting chaparral are $300 to $1500 per acre, even when some mechanical tools are used (Green, 1973). In contrast, bulldozer contractors in the San Francisco Bay Area estimate the cost of bulldozing to be $500 for a single acre, and (Howard, 1973)

*Possible benefits not included in the calculation are the reduction of fire starts through simultaneous inspection of incinerators, and generally raising the level of fire consciousness of the family to make them more careful regarding fire.

estimates the cost of hand clearing a single acre to be $75 to $700, depending on terrain. The difference in bulldozer prices is perhaps explained by the fact that the USFS uses its own bulldozers and operators which minimizes their bulldozer clearance cost, whereas the private homeowner pays $40 delivery cost plus $30 per hour for bulldozer operation, making it prohibitively expensive to bulldoze a single acre. The differences in hand rates is not so easily explained. An acre of light to medium chaparral on less than 20% slope can be cleared by hand in 20 to 40 man-hours. Obtaining labor at $2 per hour should be possible in most areas making hand clearance cost $40 to $80 per acre. Landscape firms would undoubtedly charge more than this rate and steep terrain and/or heavy chaparral could easily increase the price by a factor of ten. A method which would be very desirable for the individual homeowner is the use of a farm tractor equipped with a tandem disc plow operated from a power lift. Such equipment can be rented for $40 per day, driven on public streets and roads, and can be used to thoroughly double-disc an acre of light to medium brush on medium slope. This would plow much of the brush into the soil and minimize the amount to be removed or burned in addition to reducing the amount of hand labor. Table 3.4 summarizes what seems to be reasonable estimates of clearance costs by various methods.

Table 3.4

HOMEOWNERS' OUT-OF-POCKET EXPENSE FOR INITIAL CLEARANCE OF ONE ACRE

Method	Medium Slope Light Brush	Steep Slope Heavy Brush
Hand Clearance		
Self	20-40 hrs	200-400 hrs
Common Labor	$40-80	$400-800
Commercial	$200-400	$1000-2000
Farm Tractor Rental	$50	N/A
Bulldozer	$400-600	$600-900

2. Greenbelt

In spite of the refusal of landscapers to estimate costs of establishing a greenbelt and their warnings that no attempt should be made to do so, this section is an effort to estimate that cost. If the typical homeowner would consult a retail nursery to price grass seed, sod, ground cover, shrubs and trees, he would find that indeed these prices are not low. To quote a representative from a retail nursery-landscape firm, "the cost of plantings for an acre of land is typically several hundred dollars and labor commonly runs 80% to 90% of the total price, so for commercial landscaping an acre lot you are talking about several thousand dollars." Table 3.5 summarizes costs of various types of plantings.

Table 3.5

COSTS OF PLANTINGS

Type of Plantings	Cost per 100 Square Feet	Cost per Acre
Grass		
Seed	25¢	$11
Sod	$22	$88
Ground Cover		
Obtain from Neighbor	0	0
Wholesale	$2-$5	$800-$2000
Retail (apprx. 10¢ ea.)	$4-$10	$1600-$4000
Small Shrubs	$2 ea.	
Large Shrubs and Small Trees	$7-$15 ea.	

Observation of several homes in the brushy hillsides south of San Francisco revealed that homeowners who had cleared the brush to a 100 foot distance (approximately an acre) typically had greenery as indicated in Table 3.6.

Table 3.6

TYPICAL EXTENT OF GREENERY AROUND CLEARED HOMESITE

Grass	5,000 sq. ft. per acre
Ground Cover	4,000 sq. ft. per acre
Bare Ground	Remainder
Small Shrubs	40 per acre
Large Shrubs and Small Trees	20 per acre

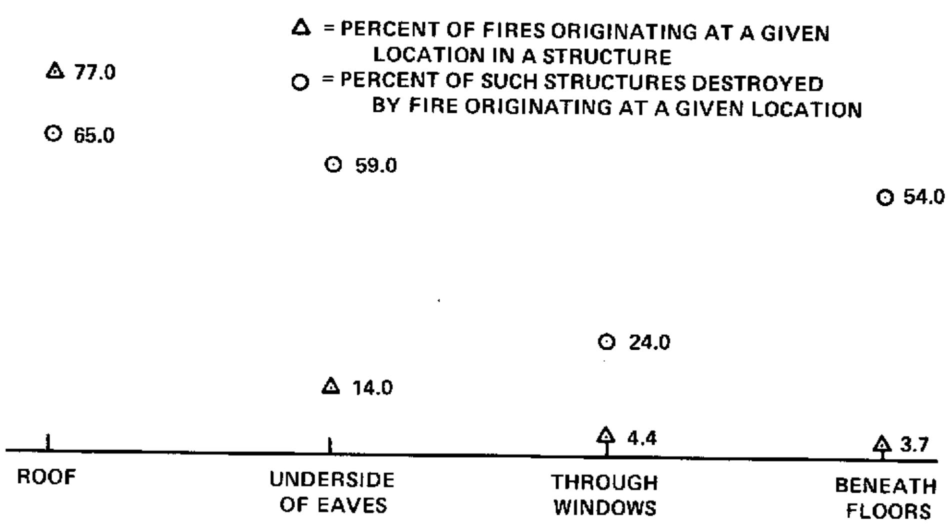
To use a cliche which became a monotonous response from persons asked for estimates, "of course, that varies from home to home." The above figures suggest that the typical homeowner would choose to establish a 30 foot greenbelt even though he may clear brush back 100 feet from his house.

The most valuable advice to the homeowner is that he obtain ground cover starts from a neighbor. In most areas this is possible, effecting an \$80 to \$200 (or more) savings for the typical one acre plot. In this manner he can spend \$12.50 on grass seed, \$80 on small shrubs, and \$200 on small trees, do all the work himself and greenbelt his home for less than \$300. This is viewed as a bare minimum if aesthetics play any role at all. The entire project of clearance of an acre and establishing a 30 foot greenbelt would then involve several hundred man hours of hard work plus an annual maintenance cost of perhaps \$50 (primarily for water and herbicide to clear brush). The equivalent total annual cost of clearance and maintenance of brush clearance for 100 feet and establishing and maintaining a 30 foot greenbelt is on the order of \$80 to \$100 per year in a light-brush area with medium slope.

E. Techniques and Costs of Roof Protection

The problem of firebrands landing on a roof is dealt with most directly by installing a fire-resistant roof. Table 3.7, illustrating statistics from the Bel-Air fire of 1961, indicates that the highest number of fire starts involved roofs.

Table 3-7 Location of Housing Fire Starts



(STATISTICS BASED ON BEL AIR FIRE—NOVEMBER 6-7, 1961)

Some roofs are more fire resistant than others. Underwriters Laboratories classifies fire-resistant roofing as either Class A, B, or C in decreasing order of fire resistance (UL, 1969). The roof is tested for resistance to fire exposure (flame and brands), fire spread, and production of firebrands. The prescription for carrying out the tests is quite detailed. The Class A rating is considerably harder to obtain than is Class C. For example, the burning brand used in the Class A test has almost 200 times the volume of the brand used in the Class C test.* A roof section not passing all of the tests for one of the classifications is not classified fire resistant. Other agencies using similar tests can provide fire-resistance certification in certain jurisdictions.

The most widely used roofing type that does not qualify as fire resistant is wood shingles and shakes. Such roofs ignite easily, by either direct flame or firebrands and themselves produce brands which cause spot fires elsewhere. Firebrands have been observed covering ranges of several miles (Wilson, 1965). This behavior seems well documented with respect to the Bel-Air fire of 1961 (LAFD, 1962), though different analysts reach somewhat differing conclusions (Wilson, 1962, 1965, 1966; NBFU, 1962; RCSHSB, 1961). The Los Angeles Fire Department statistics show that the fire covered an area of about 6090 acres containing 2204 dwellings. 484 of the dwellings were completely destroyed; 28% of the homes with wood shingle or shake roofs were destroyed, whereas 11% of the homes with other classified roof types were destroyed. The destruction rate was more than 2-1/2 times as high for wood roofs as for other roof types.

People living in wildland fire-danger areas evidently select wood shingle or shake roofs for their appearance. Such roofs are particularly attractive in the rustic settings of the forest or brush land. Technology has changed somewhat since Bel-Air, fortunately. It is now possible to obtain a wood shingle or shake roof with a UL Class C (or better) rating, or equivalent (Koppers, 1973; RCSHSB, 1973).

As is indicated in Table 3.8, a fire-resistant roof, even one using wood shingles, need not be considerably more expensive than a nonresistant

Table 3-8 Installation Costs and Lifetimes of Common Roofing Materials

	COST*	LIFE**
FIRE RESISTANT (U.L. CLASS A, B OR C, OR EQUIVALENT)		
COMPOSITION	$ 25- 60	15-25
TILE	$ 75- 100	40
TAR AND GRAVEL	$ 35- 45	15
PRESSURE TREATED WOOD SHINGLE OR SHAKE	$ 125-175	20-25
WOOD SHINGLE OR SHAKE WITH ASBESTOS – FELT UNDERLAY	$ 55- 90	20-25
NOT FIRE RESISTANT		
WOOD SHINGLE OR SHAKE	$ 50- 75	20-25
LIGHT GRADE ASPHALT	$25	15

* PER SQUARE (100 SQUARE FEET) INSTALLED. ADD ~$15 PER SQUARE IF REMOVAL OF OLD ROOF IS NECESSARY

** AVERAGE YEARS TO REPLACEMENT

SOURCE: LOCAL CONTRACTORS AND RED CEDAR SHINGLE AND HANDSPLIT SHAKE BUREAU

*Class A brand measures 12" × 12" × 0.344" while Class C brand is 1.5" × 1.5" × 0.781".

roof. In new construction in wildland areas, there is no excuse for violating local fire codes, paying an insurance surcharge, or ignoring warnings regarding fire-resistant roofing. This stricture also applies when reroofing becomes necessary. The next section will discuss some approaches for the homeowner with a nonresistant wood roof who does not need a new roof at this time.

In a recent survey (Neal, 1973) ten counties in California, of the 55 surveyed, required roofs (and exteriors) of buildings located in wildland areas to be fire resistant. Laxity also exists in enforcement of ordnances currently in effect. Typically, little is budgeted for inspection and education, and penalties are seldom severe.

F. Other Structural Modifications

Assuming that the homeowner has cleared the brush around his home, but does not have a fire-resistant roof, he can still install a water distribution system designed to wet down his roof and create an auxiliary water source independent of the municipal mains (if any).

A water reservoir holding at least 2000 gallons is recommended. This may be a swimming pool or a water tank or redwood or steel. Water then is pumped through piping to the roof to keep it wet. The pump should be gasoline powered since the electricity supply may not be dependable.

An alternative to the pump, when a tank is used, is to pressurize the tank with an air compressor. This requires a larger tank. Should the terrain permit, neither a pump nor compressor may be necessary if it is feasible to elevate the tank. If a tank is employed, a hook-up to the water main is needed for replenishment when the danger has past.

Authorities recommend that those who own swimming pools provide access for fire trucks for draughting water. A secondary hose hook-up would seem a good idea for combatting flare-ups.

The cost of such roof protection systems for a 3000 square foot home could run anywhere from $1000 to over $5000. The systems considered provide good protection for $300-$1025 (Table 3.9) and, in many cases, could prove financially attractive. A roof which is kept wet will not burn. These simple systems do require, however, someone to turn them on before a fire approaches. Automatic sprinklers would be much more expensive and less cost effective versus roof conversion.

The most foolproof and simple system is to convert the roof to a fire-resistant type. The financial costs involved could be relieved by allowing an income tax deduction or a similar subsidy in recognition of the benefit to society involved.

Work is currently being carried out to develop a satisfactory and inexpensive treatment for application to existing shingle and shake roofs to provide some degree of retardance to fire. It is anticipated that such a product will be available fairly shortly (Petrolie, 1973; SRI, 1973).

Table 3-9 Roof Protection Alternatives

SITUATION AND ALTERNATIVES

A	POOL AVAILABLE	
B	NO POOL AVAILABLE	USE OF TANK AND PUMP
C	NO POOL AVAILABLE	USE OF ELEVATED TANK
D	NO POOL AVAILABLE	USE OF PRESSURIZED TANK

EQUIPMENT	APPROXIMATE COSTS			
	A	B	C	D
POOL	**	–	–	–
2000 GAL. TANK	–	$500	$450	–
3000 GAL. TANK AND LID	–	–	–	$725
PUMP*	$200	$200	—	–
COMPRESSOR*	–	–	–	$200
PLUMBING	$100	$100	$100	$100
	$300	$800	$550	$1025

* GASOLINE POWERED, "HIGH" QUALITY
** ASSUMED EXISTING

SOURCE:
LOCAL CONTRACTORS

Some protection is also possible if chemical fire retardants, such as Phos-Chek or Firetrol are mixed and applied to the roof with a wire brush. This solution, while cheap, is quite messy and can be corrosive to flashings and gutters. It thus must be applied soon before fire danger and removed when the danger passes (UCAES, 1971). Depending on the pitch of the roof, great amounts of dexterity may be required when applying or removing the retardant.

Space-program technology has come up with a charring type paint that affords protection by forming an insulating layer of charred material upon exposure to flame (Sawko, 1972). The distributor currently does not recommend its use in inhabited areas since toxic fumes are emitted during the reaction. Costs are also high at this time (Avco, 1973).

Other fire protection measures are recommended by authorities (SBCFD, 1972; CSAC, 1965A). These include use of fire-resistant materials on any surfaces that could come into contact with fire, installing screens and/or plywood shutters over glass windows or doors and installing spark arrestors on chimneys.

G. Public Education Regarding Structure Protection

While a number of brochures providing suggestions for structure protection do exist (CLAFD, 1965, 1968; UCAES, 1967, 1970A, 1970B; CSAC, 1965; SBCFD, 1972; CLADABG, 1970), several comments regarding those brochures seem worthy of mention. First, several important points were almost uniformly absent from the brochures. None of the publications provide any quantitative or economic motivation for structure protection, but only say in some manner that people should protect structures, without appreciable effort to convince them that protection is actually effective. Evidence such as that displayed in Fig. 3.1 or perhaps Tables 3.2 or 3.3 could easily be included and should provide motivation to a large portion of the population. Another point not stressed in proportion to its importance is the effect of roof construction materials. With the exception of two of the leaflets from Los Angeles and Santa Barbara County Fire Departments (CSAC, 1965; SBCFD, 1972), the publications stress roof protection systems and most do not mention the subject of roof materials. Finally, the brochures and booklets are totally devoid of illustration of cleared and greenbelted homes which are attractive. The few examples show skimpy sketches of clearance requirements or a "before and after" comparison showing a lovely home in a wooded setting versus a fire-protected home on a lot scraped bare with no aesthetic value at all. One such comparison went so far as to show pictures comparing a $70,000 home in a wooded hillside fire-hazardous area with a low priced trailer house on a large barren flat lot (CSAC, 1965A).

In addition to the several important points not being stressed in the brochures, the brochures do not seem to be either easily available or complete. Brochures from many sources must be collected, with difficulty, before one obtains good information on all aspects of structure protection.

A very surprising observation is that fire protection information, in particular that pertaining to clearance and fire-retardant plants, is not available at nurseries. The nurserymen are well aware of drought and cold-resistant plants for erosion control, but have almost no information on plants for fire control. In fact, there is strong indication that fire control agencies could get much free publicity of fire hazard reduction by allowing the nurseryman to exploit the fire-retardant nature of some plants. At least, good information including brochures regarding fire-retardant plants should be available at nurseries (UCAES, 1961; CLADABG, 1970). Conversation with USFS personnel regarding this subject revealed that fire control people are not confident that the right plants are known yet. Some plants are only fire retardant in their early years or when watered regularly. As long as these limitations are stated and the fire retardance not overstated, the above reservations about pushing fire-retardant plants do not seem justified. Guidelines and suggestions with limitations are far better than no guidelines at all.

H. Zoning

With ever more people living in the wildlands, there are increasingly compelling reasons for regulating land use there. Not the least of these reasons is the high cost, public and private, of wildland fire damage. This section considers the problem of regulating wildland home construction through zoning to reduce fire costs. It begins with a general description of the zoning process for regulating land use.

It is desirable that in any system for resolving disputes over the use of privately owned land, the local municipality retains its role as the initial decision maker (Babcock, 1966). The state government has the authority to "influence" decisions concerning private land use when major public services are affected. The only restriction is that the criteria for these land-use restrictions should be consistent with the interests of the region.

Current land-use policy requires state acts to follow three generalized guidelines:

(1) There should be a detailed statutory prescription of the required administrative procedures governing zoning at the local level.

(2) There should be a statutory statement of the major criteria under which local decision making is measured.

(3) There should be a statewide administrative agency to review the decisions of local authorities in regard to land-use matters. In addition to this agency the final appeal rests with the appellate court (Babcock, 1966).

In the end it is up to the courts or the state administrative agency to determine the applicability of the zoning criteria in particular cases. They must decide whether or not the local procedure is consistent with statutory mandate.

The statewide administrative agency is charged with the authority to:

(1) Enforce uniform rules of procedures and standards of evidence for hearings before local zoning boards, commissions, and legislative committees.

(2) Hear, under the policy criteria set out in the statutes, all appeals from rulings of those local bodies. The local bodies have the authority to grant or deny variances, regulations of zoning, and special land uses.

(3) Grant cash awards as a condition of sustaining local zoning policy when such awards are deemed necessary to carry out such policy (Babcock, 1966).

The state's major contribution is to set up generalized standards for local governments and have them recognize that the public interest is greater than that of the immediate community (Whyte, 1968).

The problem facing county and city planners is a complex one. There are some areas where limitation of private development is desirable because of high watershed values and the difficulty of wildland fire suppression. Yet, some of these same lands have a high potential value for urban development. Thus, comprehensive land use criteria must be established so that orderly development can occur and the land will realize its full economic and social potential. It is at this point that local zoning and planning ordinances come into play. The lands can only be properly developed if the planning organizations recognize the need for adequate fire-safety measures.

"Planning for wildland use designed to meet the pressures of California's growth is mandatory if these lands are to be used and developed without great risk and the creation of irreparably hazardous situations. Fire protection is a fundamental need--a common denominator--to man's habitation and use of these mountainous lands" (CSAC, 1965).

Development in certain areas should be regulated because of topography and high watershed values. Slope has an important bearing on fire behavior through its effect on wind conditions and heat radiation contributing to the spread of fire. Extremely steep slopes also increase the difficulty of fire suppression: fire trucks and bulldozers cannot effectively navigate on steep slopes; and men with hand tools have difficulty in clearing lines. Development in areas of high watershed value should be regulated because of the high costs to the public of soil errosion and losses due to floods that eventually occur on burned land.

It would not be unreasonable for some lands in the state to be zoned as open space. The Williams Act provides for open space zoning whereby agricultural land is left open with a subsidy paid to the owner for not developing his land except for agricultural purposes. In addition, the land owner may deduct any difference between the subsidy and potential income from the land if it were not left open from his Federal Income Tax as a charitable contribution (Whyte, 1968).

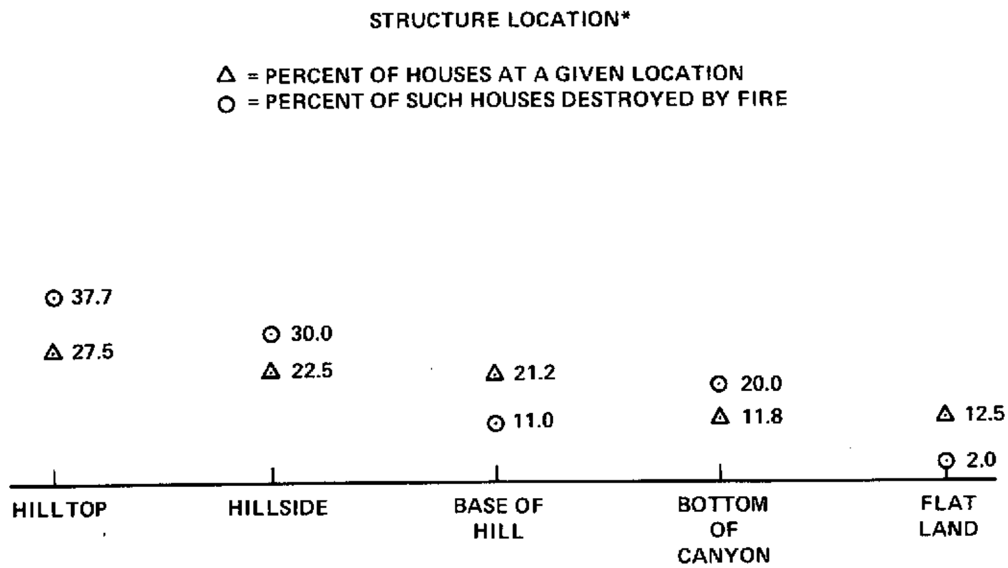
Some such efforts at restricting residential and commercial development on certain tracts of land could well begin immediately. To start with, lands within the state of California should be subjected to study to determine what zoning classification they fall within on the basis of watershed values and the fire-safety hazard existing on them; then, a priority list can be prepared on the basis of which open-space zoning actions may be begun. In actual procedures, an easement must be secured from the owner that the land will remain open and undeveloped. In most cases involving flood-plain zoning, the court will uphold the ruling if it has been applied fairly based upon existing criteria. This is, of course, subject to the condition that little residential construction has previously occurred on surrounding lands. If this is not the case, property values could be greatly affected by such a zoning ruling and consequently extensive cash remuneration would have to be made to the owner.

As an example of the influence of land-use patterns on wildland fire damage, consider Table 3.10. The data shows clearly that fire damage is greatest on the tops and sides of hills and least on a flat land area.

I. Insurance Regulation

This section considers the role insurance companies play in encouraging behavior which reduces fire damage.

Table 3-10 Land Use and Fire Damage



*STATISTICS BASED ON BEL AIR FIRE—NOVEMBER 6-7, 1961

Insurance companies follow rates which must meet the general regulations of existing laws on rate structure. The rates may not be excessive or discriminatory. The basic rating of each insurance policy depends on the fire grade rating of the local fire district (Insurance Services Office, 1972). This grading is dependent upon a fire-rating classification system that is established for the local district based upon a number of factors: equipment available, number of fire stations in the district and their proximity to the structures in their protection area, manpower in the fire protection agency and their level of training, water supply, etc. The grading uses from one to ten with a one signifying the best fire protection classification. Aside from the grading of the local protection agency, the only other factor coming into play is the material the house is constructed of. Masonry or brick houses are considered to be safer than wood frame houses. For this reason, wood frame houses are charged a higher rate for fire insurance. These houses are not, however, inspected, except for a drive-by look of the entire area when the local protection agency is graded.

There are certain instances where insurance companies can deviate from these rates. This occurs in the high risk area of Southern California where there is intense brush cover. There, all of the insurance companies selling property insurance have banded together to form the "California Fair Plan Association." The insurance policies are underwritten by all of the companies together, and the companies jointly share in the premiums and losses.

Since the companies in Southern California are sharing in a higher risk situation, their rates are different from those of the rest of the state for similar structures and local fire protection area grading.

The policy premium is based on the normal base rates for the entire region plus an additional "brush surcharge" which takes into account the added risk of writing such a policy. The surcharge varies according to the material structure of the roof and the brush clearance around the building. The more extensive is brush clearance around the house, the lower is the brush surcharge. Similarly, an approved fire-retardant roof will also cause the surcharge to decrease.

Property owners with approved roofs pay 20 percent less in premium surcharge rates than do property owners with unapproved roofs for the same degree of brush clearance. However, in an extensive study of insurance surcharge premiums (Howard, 1973) it was found that the premium reduction does not reflect the differences in the expected loss, and hence there is insufficient economic incentive for the property owner to spend his money putting on an approved fire retardant roof. On the basis of economic incentives using a least-cost-plus-loss criterion, property owners with an unapproved roof and one hundred feet of brush clearance are considered to be in the best situation. Economic incentives for fire-retardant roofs would arise if the overall level of the brush surcharge were raised for unapproved roofs and the existing rates for approved roofs were fixed.

In addition to their role in providing economic incentives for structure protection (although as pointed out above, these incentives may be imperfect), the insurance companies offer another useful service, in that they make annual inspections of their insured property in the brush regions to see if the rates charged a policy holder should change. Such inspections could also be coordinated with those of the local fire protection agency to eliminate duplication and save costs.

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Chapter IV

FUEL MANAGEMENT: FUEL BREAKS*

A. Introduction

The term "fuel management" refers to a class of techniques for reducing wildland fire damage through the modification of vegetative fuels. The potential effectiveness of a fuel management program can be illustrated by considering the rate of spread of fire in mixed chapparal; the data of Fig. 4.1 (Rothermel and Philpot, 1973), shows that any method of significantly reducing the average fuel age ("fuel loading" or "fuel build-up") on a given area of land will enable a suppression force to more easily control wildland fires. (Compare, for example, the rates of fire spread for 15 year and 30 year fuels.) The particular method of fuel management to be considered in this chapter is the establishment of fuel breaks.

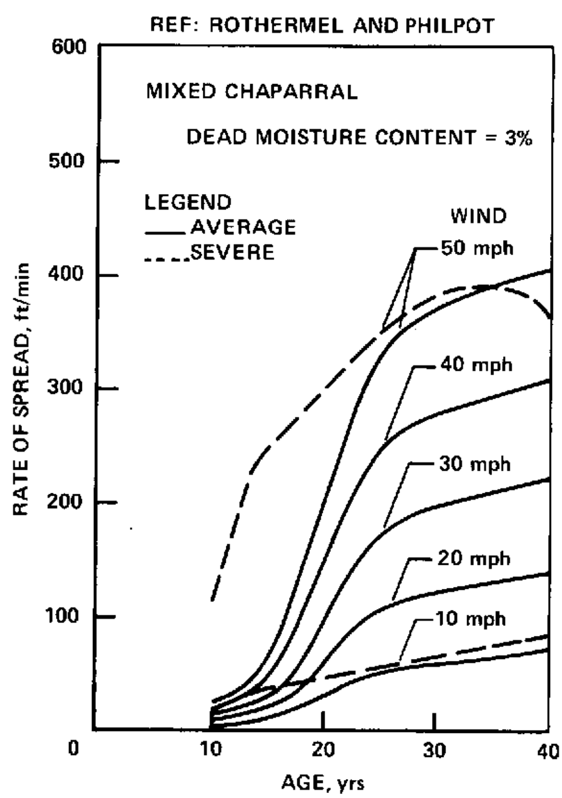

Figure 4-1 Spread Rate vs Fuel Age

*This chapter was prepared by J. Zarling and W. Feldt.

A fuel break is defined as a wide strip or block of land on which the native vegetation has been partially or totally modified so that fires burning into the fuel break can be more readily suppressed and extinguished. The fuel type established on the fuel break is usually more susceptible to fire control. In addition, fuel breaks are located to strategically divide large expanses of brush or timber into smaller areas to aid the firefighter in the suppression activity. (It should be emphasized that an unattended fuel break will not by itself stop a fire.)

Probably the first fuel break established in California was the "Ponderosa Way" constructed along the entire central west slope of the Sierra-Nevada in the early 1930's. The purpose of this fuel break was to separate the brush fields of the foothill region from the valuable timber found at higher elevations.

Since that time both the U.S. Forest Service and the California Division of Forestry have built fuel breaks throughout the state. It is estimated (Green, 1973), that 1,850 miles of maintained fuel breaks exist in California today.

The fuel-break model developed for the wildland management people to analyze the cost-benefit of fuel-break construction is shown in Fig. 4.2. The inputs to the model are: the output of the fire-spread model (Chapter XI); location, topography, and fuel type for the area in which the fuel break is to be established; and the fuel-break width.

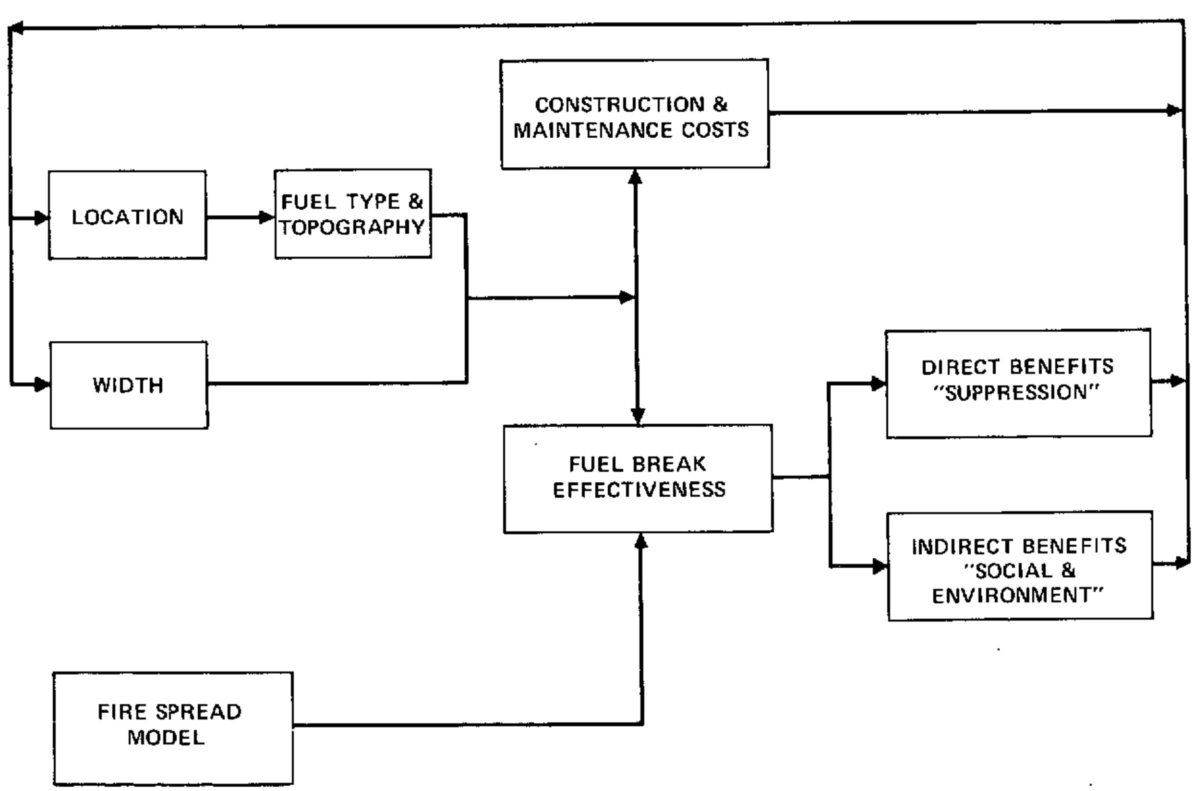

Figure 4-2 Fuel-Break Model

The two central blocks shown in the fuel-break model, construction and maintenance cost, and fuel-break effectiveness, are the main subject of this chapter. Costs of fuel-break construction and maintenance based on the 1971 dollar have been tabulated for two fuel types. Fuel-break effectiveness in terms of the probability of suppression at a fuel break is presented as a function of fire, weather, and fuel conditions for a given fuel-break width.

Finally, the last two blocks, direct and indirect benefits, will be discussed in other sections of this report. It should be mentioned that the measurement of the direct benefits "suppression dollars saved" is fairly easy, whereas the measurement of the indirect benefits "social-ecological dollars saved" is difficult and subjective estimates must be made.

Both the U.S.F.S. and the C.D.F. have had an ongoing Fuel Break Project since 1957 with the assignment of developing, testing, and evaluating new methods for breaking up or otherwise modifying expanses of brush or other wildland fuel to facilitate fire control. The most comprehensive report discussing fuel breaks is an unpublished manuscript by Green (1973), Developing Fuel Breaks for Wildland Fire Control in California. For those interested in a very detailed discussion of all aspects of fuel breaks this text is highly recommended.

B. Fuel-Break Construction and Maintenance Costs

There are a number of stages in the establishment of a fuel-break system through which fire control planners must pass. The first stage is a planning step in which data such as topography, fuel type, effectiveness, construction costs, direct and indirect benefits must be inputted to the fuel-break model to determine the location, width, and intensities of the fuel-break system.

The second stage in the process is the actual construction in which the existing brush and/or tree cover is partially removed. (In many areas, properly designed and constructed fuel breaks should have some of the brush and/or trees remaining at a density so as to not only limit fire spread but also provide an aesthetically pleasing appearance.) The last step of the construction stage is the establishment of a suitable ground cover. These covers could be annual or perennial grasses, or fire-retardant plants such as creeping sage or salt brush. (Currently, there is considerable research interest in the development of fire-retardant plants.)

Finally, an ongoing maintenance program must be established to prevent a succession of brush and/or tree cover, thereby causing the fuel break to become ineffective.

Detailed rate and cost data of fuel-break construction and maintenance on an acre per hour and dollar per acre basis is given in the Appendix in Tables IV.1-IV.5. The cost data estimates were made using the value of the 1971 dollar. The construction cost data given, for example, in Green (1963) was updated to 1971 using price indexes, construction cost indexes, and wage indexes listed in the Statistical Abstract U.S. Bureau of Census (1972).

The rate and cost data in the tables are provided for both manual and mechanical methods of construction and maintenance. These data are based on fair working conditions and gently sloping terrain where both men and mechanical equipment are most effective.

An example of using Tables IV.1-IV.5 for estimating fuel-break construction costs will be demonstrated below.

Assume six miles of fuel break 800 foot wide is to be constructed along a ridge in medium density brush using a D-7 bulldozer to crush the brush and then burn the crushed vegetation.

(1) Determine from fuel-break width, the number of acres/mile and then calculate the total number of acres to be treated. (95 acres/mile × 6 miles = 570 acres)

(2) Estimate cost of D-7 bulldozer to complete project, Table IV.2. ($7.50/acre × 570 acres = $3,250)

(3) Estimate cost of burning crushed brush, Table IV.4. (570 acres × $4.80/acre = $5,730)

(4) Estimate cost of spraying brush crowns with hand sprayers, Table IV.3. ($36.85/acre × 570 acres = $21,000)

(5) Estimate cost of aerial sowing of grass on fuel break, Table IV.5. (2 days--$0.50/acre × 570 acres = $285) (Helicopter Ferry = $180) (Labor and Supervision $35/day × 2 days = $70)

(6) Estimate cost of pre-attack planning, Table IV.1. ($1.15/acre × 570 acres = $655)

(7) Total project cost $31,200 or $55/acre.

The California Division of Forestry has been constructing a shaded fuel break from Bear Valley to Harmony Ridge along Highway 20 (this portion of Highway 20 has been designated a scenic highway). Work began on this fuel break in 1964 using wards of the Washington Ridge Youth Conservation Camp. The estimated rates and costs per acre are:

			$/Acre
Hand Crew	100 man-day/acre	$3.47/man day	$346.50
Transportation	160 miles/acre	.30/mile	48.00
Chipper	.7 hr/acre	3.00/hr	2.10
Chain Saw	7 hr/acre	.75/hr	5.25
		TOTAL	$401.85/acre

The cost of this shaded fuel break at $401.85/acre compares with other C.D.F. construction costs of $140.00/acre in woodland brush areas and $270.00/acre in heavy mixed brush areas (Weaver, 1973), using wards for labor within the Nevada-Yuba Ranger District.

C. Fuel-Break Effectiveness

Very little quantitative data exists on the effectiveness of fuel breaks in stopping a wildfire. Agreement does seem to exist that given a certain minimum width (~400 feet), fire crosses the break (assuming it has been burned out) by spotting. Attempts to arrive at probabilities of containment of a fire at a break have been based on intelligent guesswork and subsequent confirmation with decision gaming by boards of fire experts.

It has been commonly reported that during periods of high winds, such as the Santa Ana conditions in California, spotting of the fire front can occur up to several miles in advance of the head of the fire. In situations such as these, the existence of a fuel break several hundred feet wide probably will not be effective in controlling the head of a fire. However, properly located fuel breaks can aid during periods of high winds in containing the flanks of the fire and also provide access to the fire and zones of safety for men and equipment.

There are reported in the literature (Jay, 1967) numerous instances where under less severe conditions fuel breaks have been effective aids in stopping the head of a fire. For example, on a very high fire danger day in 1962, an upslope crowning fire which built up too fast for initial attack was stopped at the Paper Cabin Ridge Fuel Break on the Duckwall test unit of the Stanislaus National Forest.

Experts seem to agree that fuel-break effectiveness is a complex function of its location and width along with the fire-spread parameters (weather, topography, fuel type and condition). However, no functional relationships for effectiveness have been based on either theoretical or empirical grounds that takes into account all of these factors. Most concern has centered on obtaining empirical probabilities under severe, or Santa Ana, conditions which limit the parameters to fuel-break location, width, and wind direction. For such conditions, the wind is assumed to be "strong" (30 mph) but allowance is made for its direction to vary; fuels are assumed dry and highly combustible.

A graph indicating the probability of containment versus fuel-break width is shown in Fig. 4.3. Two sets of curves are drawn, one for a strong cross-wind and one for a strong side-wind. This data is currently used by USFS Region 5 in a computer-based fire simulation to construct a benefit/cost ratio for proposed fuel modification programs (Carter, 1973).

Within sets, each curve denotes a different ridge condition. It is assumed that the fuel break is located on the ridge top (except, of course, in the case of flat terrain). Generally, the sharper the ridge and the smaller the wind velocity, the higher is the probability of containment.

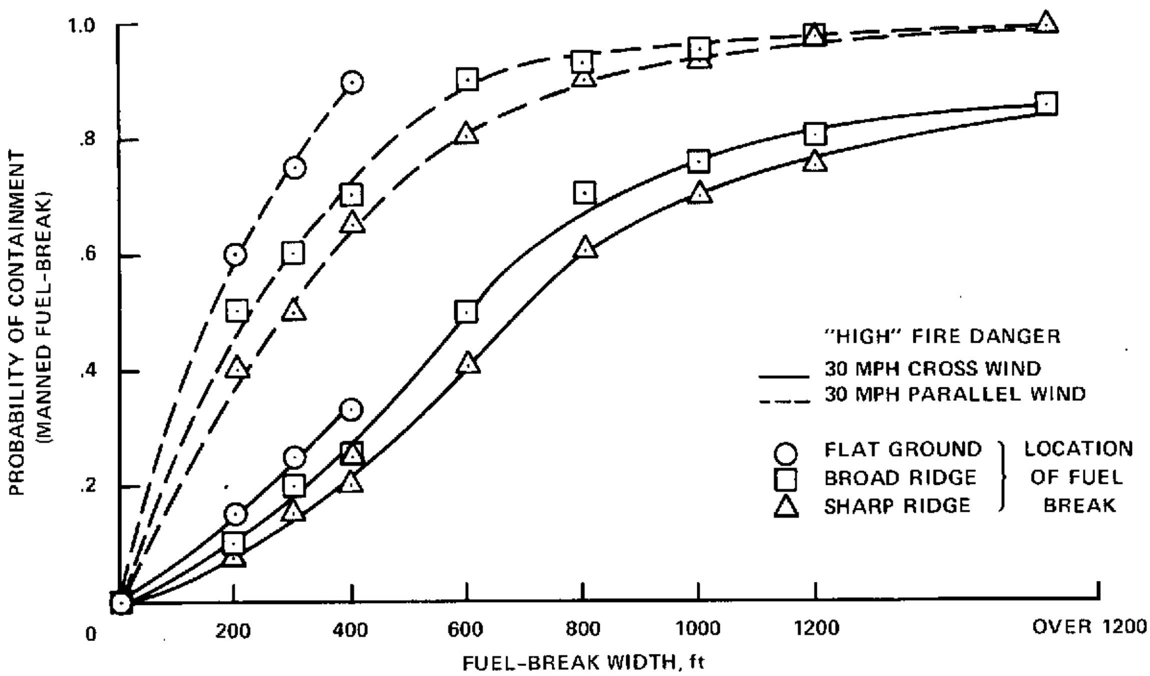

Figure 4-3 Probability of Fire Stop at Fuel Break   Chapparal Fuels

It is important to note that the fuel break must be manned to recommended levels in order to burn it out and provide for direct suppression of spotting.

A somewhat different approach is taken by Davis (1965), in a gaming study carried out for the western foothills of the Sierra-Nevada range. Davis considers a more complete model in which fire-spread and transportation difficulties are included.* The results show (Figs. 4.4 and 4.5) that a broader fire front has less chance of containment with a given suppression level. The probabilities are difficult to compare to the USFS Region 5 probabilities because of the differences in assumptions, but presumably Davis shows less probability of containment at each fuel-break width because of the multiplicative effects of the probability of manning the break effectively.

A study very similar in methodology to Davis' was that conducted by Murphy (1965) on the Duckwall Unit of the Stanislaus National Forest. The probability of containment on a manned fuel break was determined for three burn indices for two different fuel types (timber and brush). His results showed the highest probabilities of successful suppression of all the studies.

---

*His methods are more rigorous and area specific, being valid only for the western foothills of the central Sierra-Nevada. He assumes two different suppression levels and two fire front widths. The gaming was performed with 10 experts in 32 situations (some repeated as controls) to determine the mean probability of suppression and standard deviations about that mean.

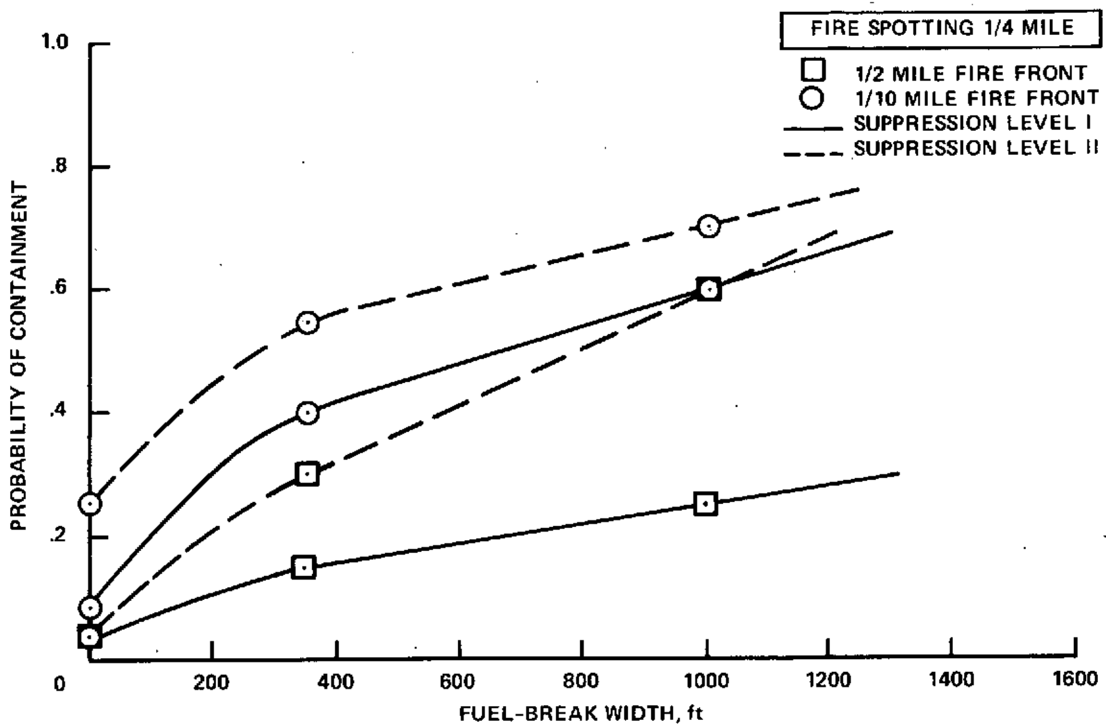

Figure 4-4 Probability of Fire Stop at Fuel Break, Quarter-Mile Fire Spotting
(Western Foothill Region of Sierra Nevada. Davis, 1964)

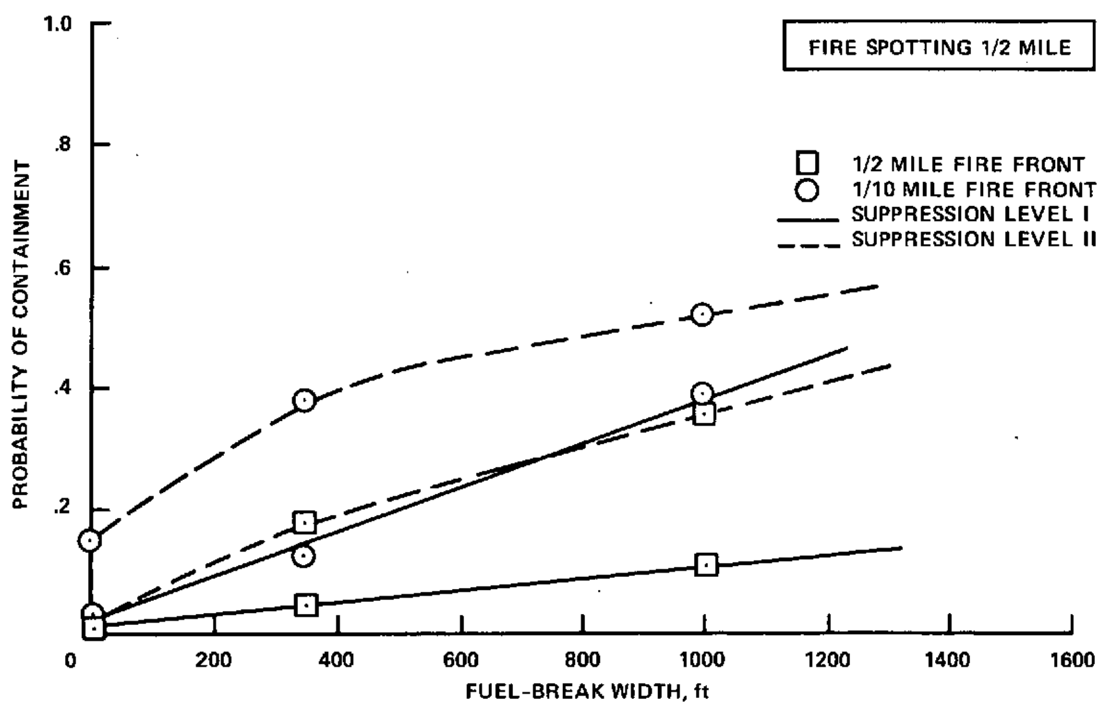

Figure 4-5 Probability of Fire Stop at Fuel Break, Half-Mile Fire Spotting
(Western Foothill Region of Sierra Nevada. Davis, 1964)

D. Expansion and Maintenance of a Fuel-Break System

Of the total existing 1,850 miles of maintained fuel breaks within the State of California, about 1,350 miles are maintained by the California Division of Forestry. More than 60 percent of these fuel breaks are less than 300 feet in width (see Fig. 4.6). Yet, upon studying the effectiveness of fuel breaks in containing a fire (Fig. 4.3), the data shows that fuel breaks become most effective in the 700 to 900 foot width range.

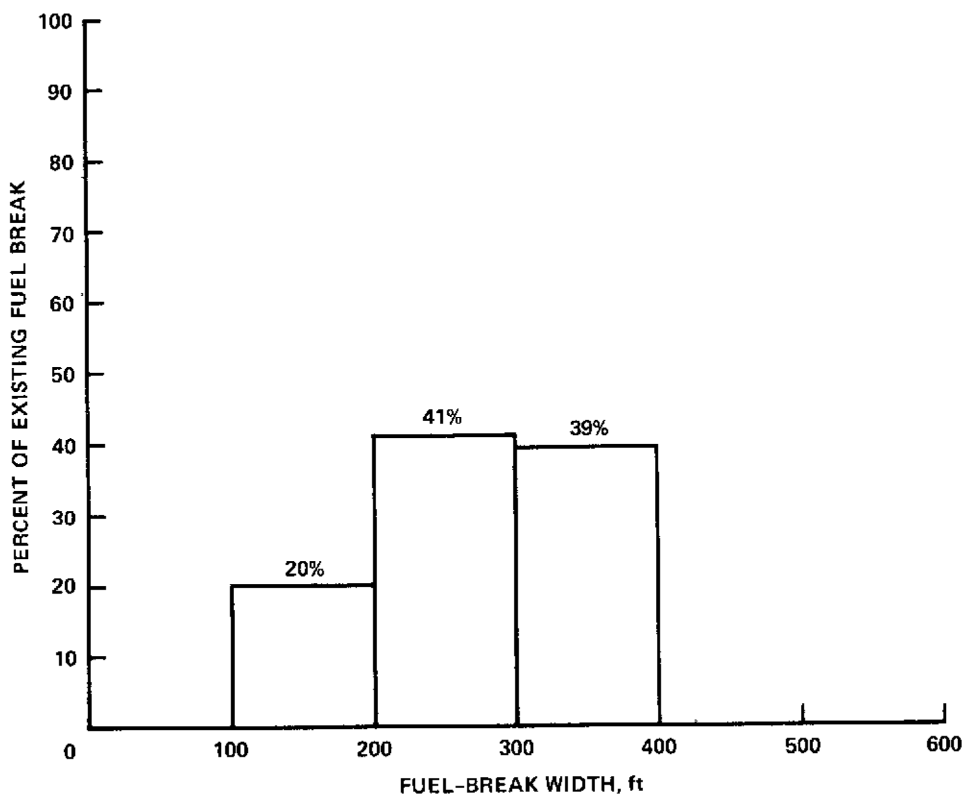

Figure 4-6 Distribution of Fuel Breaks by Width, California Division of Forestry, 1970

An approximate economic model based on values protected* can be constructed as

$$C_{\omega} = P_{\omega} \cdot V$$

*This simple analysis neglects the effects of savings in suppression costs due to fuel-break effectiveness.

where C_ω is a measure of the fuel break effectiveness in protecting values, P_ω is the probability of containment on a manned fuel break, V is the value of the resources protected, and ω is the subscript indicating the fuel break width. Then for two fuel break widths the following relationship can be written since the value V of a protected area is constant.

$$\frac{C_{\omega_1}}{C_{\omega_2}} = \frac{P_{\omega_1}}{P_{\omega_2}}$$

Using the above relationship in the example of a 300 foot versus 900 foot wide fuel break located on a broad ridge normal to the spread direction of a fire, Fig. 4.3 ($P_{300} = .18$, $P_{900} = .72$) yields

$$\frac{C_{300}}{C_{900}} = \frac{.18}{.72} = \frac{1}{4}$$

or

$$C_{900} = 4C_{300}$$

The above result indicates that if the cost of constructing a 900 foot wide fuel break is <u>less than 4 times</u> the cost of constructing a 300 foot wide fuel break a gain will be made in benefits. Similarly, there should be a net savings effected by widening existing fuel breaks. Harrison et al (1973) have also shown greater benefits through the construction of an expanded fuel-break system.

It is also estimated, Green (1973), that there exists approximately 900 miles of unmaintained fuel breaks within the state. For both cases, maintained and unmaintained fuel breaks, the fire protection agencies should re-examine the existing fuel-break systems on a cost-benefit analysis in terms of expanded widths.

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Appendix IV

COSTS OF FUEL-BREAK CONSTRUCTION AND MAINTENANCE

Table IV.1

ESTIMATED 1971 COSTS OF FUEL-BREAK ESTABLISHMENT IN MIXED CONIFERS (GREEN, 1971)

Job and/or Task	Direct Cost $/Acre
Preattack planning	1.15
Marking trees, etc.	3.25
Tractor clearing of brush, bunching of slash and debris	45.00
Supervision of tractor clearing	1.25
Hand thinning small conifers	65.00
Prunning leaved trees, shrubs	35.00
Hand cutting of brush	70.00
Hand piling of slash	26.00
Chipping 10 tons/acre	85.00
Swamper burning	45.00
Burning piled or windrowed brush or slash	14.00
Mopup and patrol	1.00
Contract snag felling per snag	1.50
Snag felling per snag by F.S. crew	2.50
Safety meetings	
Drill seeding including seed	15.00
Hand broad cast seeding, including seed	14.00
Helicopter seeding, including seed	7.00
Helicopter spraying, including herbicides	15.00
Tractor boom spraying, including herbicides	15.00
Hand spray of scattered plants	14.00
Tree planting	49.00
Handwork for erosion control	10.00
Prescribed burning for fuel-break maintenance	5.00

Table IV.2

ESTIMATED 1971 COSTS OF CLEARING BRUSH FROM SOUTHERN CALIFORNIA FUEL-BREAK SITES

Job and equipment	Light brush, 15 tons/A		Medium brush, 15-30 tons/A				Heavy brush, 30 tons/A			
	Chamise, sage chaparral		Chamise chaparral		Mixed chaparral		Mixed chaparral		Woodland chaparral	
Mechanical clear and pile (1):	A/hr	$/A	A/hr	$/A	A/hr	$/A	A/hr	$/A	A/hr	$/A
D-8, 12-ft blade	1.0	25.60	1.0	25.60	0.8	33.00	0.6	43.00	0.4	64.00
D-7, 12-ft blade	1.0	22.75	1.0	22.75	0.8	28.00	0.5	45.00	0.3	68.00
D-6, 8-ft blade	0.7	27.00	0.7	27.00	0.5	37.00	0.3	61.00	---	---
D-4, 6-ft blade	0.5	28.40	0.5	28.40	0.3	47.00	---	---	---	---
Mechanically crush brush (1):										
D-7, 12-ft blade	3.0	7.50	3.0	7.50	2.5	9.10	2.0	11.40	---	---
D-6, 8-ft blade	2.0	9.20	2.0	9.20	1.5	11.10	---	---	---	---
D-4, 6-ft blade	1.5	9.50	1.5	9.50	1.0	14.20	---	---	---	---
D-6, 10-ft roller	2.5	7.40	2.5	7.40	---	---	---	---	---	---
D-4, 10-ft roller	2.0	7.10	2.0	7.10	---	---	---	---	---	---
D-8, heavy 10-ft disk	2.4	10.65	2.4	10.65	2.0	12.80	---	---	---	---
D-7, heavy 10-ft disk	2.1	10.80	2.1	10.80	1.5	15.00	---	---	---	---
D-7, Anchor Chain	4.0	5.70	3.0	7.60	---	---	---	---	---	---
D-8, Fleco brush rake	---	---	2.0	17.00	---	---	1.0	34.00	---	---
Eimco 105, Ferris Brush-grubber	---	---	---	---	---	---	0.4	44.00	---	---
Mechanically clear and pile Regrowth (1):										
D-7, 12-ft blade	---	---	1.2	18.95	---	---	---	---	---	---
D-4, 6-ft blade	---	---	0.6	23.65	---	---	---	---	---	---
Mechanically crush regrowth (1):										
D-7, 12-ft blade	---	---	3.0	8.50	---	---	---	---	---	---
D-4, 6-ft blade	---	---	1.5	9.45	---	---	---	---	---	---
D-7, 10-ft disk	---	---	2.5	9.10	---	---	---	---	---	---

Table IV.2

CONTINUED

Job and equipment	Light brush, 15 tons/A		Medium brush, 15-30 tons/A				Heavy brush, 30 tons/A			
	Chamise, sage chaparral		Chamise chaparral		Mixed chaparral		Mixed chaparral		Woodland chaparral	
Mechanically mulch:	A/hr	$/A	A/hr	$/A	A/hr	$/A	A/hr	$/A	A/hr	$/A
Bromford brush cutter (2)	---	---	---	---	0.3	84.00	---	---	---	---
Roanoke Robot brush cutter (3)	---	34.00	0.7	68.00	---	---	0.5	82.00	---	---
Tree Eater (4)	---	---	---	---	0.5	40.00	---	---	---	---
Hand clear brush (1):	Man-days/A	$/A	Man-days/A	$/A	Man-days/A	$/A	Man-days/A	$/A	Man-days/A	$/A
Cutting, piling, and burning mature brush	15	375	25	625	45	1,125	65	1,625	75	1,875
Cutting, piling, and burning 2 to 5 year old regrowth	10	250	15	375	25	625	35	875	35	875
Cutting unburned stems after fire	---	---	---	---	---	---	15	375	---	---
Grubbing, piling, and burning mature brush	20	500	35	875	65	1,625	110	2,750	120	3,000
Regrubbing, piling and burning	5	125	10	250	25	625	40	1,000	50	1,250

(1) Green (1963)
(2) U.S.D.A. (1968)
(3) Sherman (1972)
(4) U.S.D.A. (1970)

Table IV.3

ESTIMATED 1971 COSTS OF AERIAL, MECHANICAL, AND HAND SPRAYING OF HERBICIDES (GREEN, 1963)

Job and Equipment	Chamise - Sage & Chamise		Mixed and Woodland	
	A/hr	$/A	A/hr	$/A
Aerial Spraying				
Chemicals				
2,4-D		6.00		3.00
2,4,5-T		---		5.60
Helicopter (3 hr/day)	100	1.80	100	1.80
Helicopter Ferry	180/job		180/job	
Labor and Transportation (2 men)	50/day (5 hrs)		50/day (5 hrs)	
Mechanical Spraying				
Chemicals				
2,4-D		4.00		2.00
2,4,5-T		---		3.70
D-7, 300 gal. cap., 25 ft-Boom	5	4.55	5	4.55
TD-340, 170 gal. cap., 24 ft-Boom	3	3.60	3	3.60
Labor and Transportation (2 men)	80/day (8 hrs)		80/day (8 hrs)	

	Average Distance between Plants							
	12 ft		8 ft		6 ft		4 ft	
Hand Spraying	A/day	$/A	A/day	$/A	A/day	$/A	A/day	$/A
Two men w/power sprayer	4	7.50	2	15.00	1	30.00	1/2	60.00
Service man for each spray man	4	7.50	2	15.00	1	30.00	1/2	60.00
Chemicals		1.45		2.85		5.20		11.40
Transportation and supervision		2.00		4.00		8.00		16.00

Table IV.4

ESTIMATED 1971 COSTS OF FUEL-BREAK MAINTENANCE
BY PRESCRIBED BURNING (SCHIMKE, 1970)

1 Torchman, 8 hours	$0.65
2 Linemen, 8 hours	1.30
1 Supervisor and Torchman, 8 hours	0.95
1 Tank Truck Operator, 8 hours	0.65
1 Transportation, Pumper and Pickup	0.25
1 Class III Pumper, 6 hours at $11.50	0.30
1 D-4 size Bulldozer, 2 hours	0.70
Total Cost Per Acre	$4.80

Table IV.5

ESTIMATED 1971 COSTS OF GRASS SEEDING ON FUEL BREAKS (GREEN, 1963)

Job and Equipment	Seedbed Conditions			
	After Fire		Cleared	
Drill Sowing:	A/hr	$/A	A/hr	$/A
D-6, 10-ft drill	2	9.25	3.6	5.20
D-4, 10-ft drill	1.8	7.90	3.3	4.20
TD-340, 10-ft drill	---	---	2.8	
Equipment Transport:				
D-4		1.50		1.50
D-2 or TD-340		0.25		0.25
Rangeland drill		0.85		0.85
Mileage		0.85		0.80
Labor		5.90		1.60
Supervision		0.45		0.45
Drill Maintenance		0.70		0.35
Perennial Grass Seed		5.00		5.00
Aerial Sowing:				
Helicopter	370	0.50	370	0.50
Helicopter Ferry		180/job		180/job
Labor & Supervision		35/day		35/day
Transportation				

Chapter V

FUEL MANAGEMENT: PRESCRIBED BURNING AND LET-BURN POLICIES

Chapter V

FUEL MANAGEMENT: PRESCRIBED BURNING AND LET-BURN POLICIES*

A. Introduction

It is well known that approximately 3% to 5% of the wildland fires cause 95% of the damage and loss of life. Despite increases in efficiency of fire suppression forces, these large conflagrations continue to occur. Generally, there is little that can be done to stop the advance of a large fire. A weather change, most often a reduction of wind, must occur before containment is possible. This has led many investigators in forest fire research to conclude that an extensive fuel management program is the only alternative to large scale wildland fires. By periodically removing or substantially reducing the volume of the heavy fuels, when a fire start occurs, the fire will not burn with an intensity that is either difficult to control or that will result in large scale damage.

The previous chapter described one method of fuel management, the construction of fuel breaks; this chapter considers another method, prescribed burning. This is, in fact, a burn that is carried out intentionally using a "prescription" which includes the fuel type, fuel loading, conditions under which the burn can be carried out (discussed more fully in a later section), area to be burned, and safety precautions to be taken to insure that the burn will be controlled.

Although prescribed burning has long been recognized as a method by which fuel loading can be reduced (Campbell, 1972; Wilson, 1971), as well as being effective for other purposes, such as range improvement (Blanford, 1962), and fuel-break construction (Schimke, 1970), there has been widespread reluctance on the part of both the United States Forest Service and the California Division of Forestry to initiate an extensive prescribed burn policy. There are several reasons for this, some of which are the following:

(1) There is a general fear and distrust of fire which is based on experience with wildfire, particularly large fires. The feeling that all fires are bad has undoubtedly developed, at least in part, by the "Smokey the Bear" policy which has been in effect for a number of years.

(2) There is a general lack of knowledge of what prescribed burns can do, and how, when, and where they should be used.

(3) There is a fear of adverse secondary effects such as soil damage and air pollution.

*This chapter was prepared by R. Sennett.

(4) There is a widespread fear of a prescribed burn escaping.

Since there are a number of ecological considerations connected with burning, these will be discussed in the next section.

B. Ecological Considerations

It is well known that a number of tree species are fire dependent: fire is a necessary part of their reproductive cycle. The most notable of these is the Sequoia, the seeds of which must germinate in mineral soil. Without fire to eliminate the litter and duff on the forest floor, propagation is virtually nonexistent. The policy of complete fire suppression in the Sequoia forests has created considerable concern among many foresters (Kilgore, 1972). Only recently have let-burn and prescribed-burn policies been initiated in some sequoia forests by the U.S. Forest Service (Kilgore, 1970).

Ponderosa Pine is also aided by fire. As pointed out by Biswell (1956, 1959, 1972), fire reduces heavy needle mats, windfalls and snags, and aids in recycling nitrogen and other nutrients tied up in the litter. In fact, pot tests on lettuce gave five times the yield when grown in soil that was recently burned over versus unburned. Precipitation easily reaches the soil and encourages the growth of grasses and nitrogen-fixing leguminous plants. Although brush habitat for rodents and ground story birds is reduced, browse is increased and shade-tolerant trees and shrubs are kept out of the understory, a very important factor in reducing crowning when fire occurs. Thus, the structure of the forest becomes one of open and park-like stands.

It has been estimated (Green) that there are, in California, between seven to eight million acres of chamise chaparral, which is also fire dependent. Montgomery (1972) relates the following sequence of events that occurs after a chaparral fire.

(a) New sprouts from the remaining crown appear, often within a few days after the fire.

(b) Annual and perennial wildflowers and grasses germinate from seeds dormant for many years.

(c) Seedlings of many short-lived shrubs appear. These eventually die out as a return to chaparral occurs.

(d) The ash fertilizes the soil and destroys phytotoxins which accumulate in soil and inhibit growth.

(e) Generally, within two to three years the new cover stabilizes slopes, and as a result water runoff and soil erosion return to prefire levels. The longer the time between burns, the longer the time of recovery.

Other consequences of fire include the effects of smoke on fungi. It has been shown (Biswell, 1972) that brown-spot disease in longleaf pine is inhibited by smoke, and spores of western gall rust fungus failed to germinate after exposure to as little as five seconds of wood smoke.

A number of effects of fire or fire suppression are indirect. It is speculated (Oberle, 1969) that the near extinction of the California Condor is related to complete fire suppression. The condor requires relatively long runways for take-offs, and clearings on ridgetops for feeding. With the prevention of fires, there has been regrowth in these clearings, thus limiting the condors niche in the wildands.

One of the reasons for the lack of a general prescribed burning policy was stated previously as the fear of possible soil damage. If the depth of the original mantle on the mineral soil is very heavy and dry enough to burn, the effects of fire can be destructive (e.g., extensive erosion). However, this condition generally occurs only under a complete fire suppression policy. With proper fuel management, the damages from direct heating effects may be considerably lessened (Davis, 1959).

Other questionable effects are due to the smoke generated by fires. Results from studies dealing with the air pollution potential from burning have indicated (Murphy, 1972) that emissions are quickly diluted and are not harmful in the concentrations measured. For example, carbon dioxide concentrations measured 60 feet from the edge of the fire were 1000 parts per million, and decreased to 500 ppm at 150 feet. Industrial health standards allow an 8 hour exposure time to concentrations of 8000 ppm. Carbon monoxide was measured at 40 ppm at 60 feet from the edge. Industrial standards allow levels of 100 ppm over an 8 hour exposure.

Also, most hydrocarbons measured from forest burning are chemically saturated and therefore do not contribute to the formation of photochemical smog. The quantity of these hydrocarbons is approximately 12 pounds per ton of material burned compared to 130 pounds per ton of gasoline.

The effects of smoke shading of fruit crops can be minimized or eliminated by burning at the correct time of year.*

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*More difficult to evaluate are the total direct costs of visible smoke to area residents. The question here can be best stated in the following form: What compensation would area residents require in order to voluntarily endure the smoke from prescribed burns? An estimate of this compensation would reflect not only real opportunity costs (arising for example from smoke interference with transportation) but also the psychic costs of smoke to individuals. This is, of course, a difficult question to answer with precision; some approximate answers, however, would be desirable before regular prescribed burning is instituted on a regular basis in areas with significant population.
An interesting related question is how the costs of smoke from prescribed burning differ from the expected costs of smoke from wild fire without a prescribed burn policy. If it can be demonstrated to residants that the former is less than the latter, it would clearly make prescribed burning a more attractive alternative.

In general, it appears that the net ecological effects of limited fire are weighted on the positive side. Of course, due to the fuel buildup under an almost complete suppression policy, fires of the type that have naturally occurred for eons are not possible unless the fuel loadings are modified before burning. This is discussed in a following section.

C. Selection and Preparation of Areas

The selection of the areas to be burned is extremely critical, as is the initial preparation of the area. Since there is always a certain degree of uncertainty and risk associated with the use of fire, it should not be used in areas of high structure density. Other methods of fuel removal such as bulldozer or hand clearing will have to be used in this situation.

One group of data which is desperately needed in order to initiate a complete fuel management program for California is a set of maps showing:

(1) Fuel Types by Area

(2) Fuel Loading by Area

(3) Fuel Types and Loadings by Population Density

This would enable a priority system to be set up as a function of fuel type, loading, proximity of structures, and method of fuel reduction, including both prescribed burning and let-burn policies.

The principal factors involved in the preparation for burning an area include:

(1) the combustible fuel types and loadings

(2) topography of the burn area

(3) weather conditions

(4) firebreaks and barriers

(5) preparation of fuels

(6) ignition techniques to be used

The fuel types are important for several reasons. There are wide variations in fire resistance of trees. For example, Davis (1959) lists the relative resistance to fire kill as follows:

Redwood - Extreme Resistance

Western Larch - Extreme

Ponderosa Pine - High

Douglas Fir - High

White Fir	- Medium
White Pine	- Medium
Lodgepole Pine	- Medium
Western Red Cedar	- Low
Western Hemlock	- Low
Engelmann Spruce	- Low
Sitka Spruce	- Low
Alpine Fir	- Very Low

The bark thickness appears to be the most important factor in fire resistance.

Thus, the selection of areas to be burned in heavily forested land must take into account the vulnerability of trees that are to remain in the area, as well as those to be removed.

Flammability varies with fuel type also. This is due not only to moisture content of the fuel but also the ratio of live to dead material and the size distribution of fuel within a given species (surface to volume ratio). Chamise chaparral has been studied (Countryman, 1970), in order to determine its physical characteristics as a wildland fuel. The type of fuel also determines to a large extent the fuel loading, and the value of the burn index for recommended prescribed burning.

The topography of the burn site will contribute to the spread of the fire and determine the method of firing the area.

Weather conditions are extremely important during a prescribed burn. Investigators (Green, 1970), have recommended ranges on certain conditions within which prescribed burns may be accomplished. These limits are listed below:

	Maximum	Minimum
Air Temperature (°F)	84	40
Fuel Stick Moisture (%)	15	5
Relative Humidity (%)	58	28
Surface Wind Speed (mph)	10	0
Fine Fuel Moisture	10	6
Intensity Index	54	32
Spread Index	16	4
BURNING INDEX		
(timber)	6	2
(brush)	6	2
(grass)	14	3
IGNITION INDEX	52	5

The last five parameters are from the Fire-Danger Rating System.

Artificial firebreaks as well as natural barriers such as ridges, swamps, cover types of low flammability, and roads must enter into planning a burn. Generally irregular boundaries should be avoided if at all possible, and the burn limited to about 200-400 acres, which is approximately the area that can be safely burned in one day in most California fuel types.

Fuel preparation has received considerable attention (Green, 1970). When preparation does take place, generally one or more of the following steps are taken before the prescribed burn:

(1) piling coarse material by hand

(2) crushing with bulldozer

(3) pruning of dead or low limbs and piling

(4) chemical desiccation

In timber areas, pruning and piling heavy logs helps reduce the intensity of the understory burn. That is, the heavy material is burned in piles in relatively open areas. Using this type of preparation, a prescribed burn in ponderosa pine (Biswell, 1967) resulted in a 51% fuel reduction.

Crushing with a bulldozer blade appears to give excellent results in chaparral areas (Blanford, 1962), although steep terrain presents limitations for this technique. Generally, the brush is crushed in fall and winter so that by spring it has dried out and can be fired at lower temperatures and higher humidities. In one case (Murphy, 1967), unburned chamise that was 25 years old and had 95% crown closure was burned in spring after fall crushing. The fuel loading at that time was measured to be 10 to 20 tons/acre, and nearly 100% fuel reduction was attained.

Application of herbicides by helicopter has been investigated experimentally (Green, 1970). The resulting desiccation is virtually complete in about a year. Costs of this technique are generally higher than other methods of preparation.

D. Execution of Burn

There are three ignition techniques used most frequently for prescribed burning; center firing, strip firing, and edge firing (Davis, 1959). Center firing results in a very intense fire and its primary use is in clearing timberland. Edge firing is used principally for small areas (1-2 acres) between fuel breaks, either natural or man made, or in areas with low fuel loading. Strip firing is generally used in areas where slopes exceed 20% and appears to be the most useful technique for brush areas. Depending on weather and fuel conditions, it is possible to burn either up or down a slope. It has been suggested that by burning strips of brush in an area, it is possible to leave cover for wildlife, maintain appearance, and create little watershed damage. Different strips would be burned each year, the previous burns serving as fuel breaks. A complete cycle in chaparral would take 8-10 years (Biswell, 1967).

E. Cost of Prescribed Burning

The direct costs of prescribed burning are heavily dependent on the amount and type of preparation required, as well as the size of the burn and local terrain. (Sampson and Burcham, 1954) used 1947-1948 data to determine that rancher costs for prescribed burns varied from approximately \$3.65/acre for a 40 acre burn to 60¢/acre when the acreage burned reached 440. This was contrasted to estimated suppression costs of \$5.50/ acre and 80¢/acre, respectively. The costs increased for areas greater than 440 acres. Green (1970) estimated that present burning costs would be \$4-\$5/acre allowing for a 3% annual cost increase. 1962 estimates (Blanford, 1962) for bulldozer crushing and burning chamise were \$10.53/ acre.

When herbicides are applied by helicopter for purposes of desiccation, costs increase due to the costs of herbicides (\$3.50-\$9.00/acre) and application costs (\$5.00/acre). Green (1970) recommends using a 1967 cost of \$13.50/acre for preparation and burning costs in chaparral on rough terrain for areas of 40-100 acres.

In areas which have had fuel management programs operating for a number of years, costs often show a dramatic decrease. For example, the Bureau of Indian Affairs has prescribed burned 300,000 acres of ponderosa pine in north central Arizona for a cost of 10¢-20¢/acre (Biswell, 1972). This low cost is due in part to the uniformity of the forests. In addition, the ridges and slopes in the burn areas make ignition and control easy.

Indirect costs of burning are much more difficult to estimate. These costs include planning, environmental impact studies, risk of escape, smoke and air pollution, erosion, and esthetics. Of course, many of these costs would be present with other methods of fuel management. It has been suggested (Green, unpub.) that if the costs of these factors was added to the direct costs of burning, other methods of fuel management such as bulldozing brush, harrowing light to medium chaparral, or hand cutting heavy chaparral could be competitive in cost to burning. This would certainly be true in areas of high structure density.

F. Recommendations

(1) Mapping of fuel types and fuel loadings by area and population density must be accomplished throughout California in more detail than presently available through the use of U.S. Coast and Geodetic Survey maps. This information would allow decisions to be made with respect to all types of fuel management techniques.

(2) Instruction in prescribed burning techniques should be initiated by both the United States Forest Service and the California Division of Forestry for their personnel. Experienced people from all sources, including commercial timber organizations and universities, should be used as instructional staff for these programs.

(3) Consideration should be given to the expansion of let-burn areas.

(4) An educational campaign, the purpose of which would be to instruct the public with respect to the necessity for a statewide fuel management program including prescribed burns, should be initiated. The "all fires are bad" attitudes must be altered.

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Chapter VI

PREVENTION THROUGH EDUCATION

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Chapter VI

PREVENTION THROUGH EDUCATION*

A. Causes of Man-Made Wild Fires

For convenience, we classify the causes of man-made fires into four major categories:

(1) Equipment uses: including fires caused by autos, trucks, and tractors, logging, construction, and farm equipment. Railroad and power line fires are not normally included here.

(2) Carelessness: including fires caused by campers, smokers, and debris burners. Children-caused fires are not included here.

(3) Incendiarism: or intentionally set fires.

(4) Miscellaneous: which includes all man-made fires not included in the first three.

If we look at fire-cause statistics over the last ten years (Tables VI.1 to VI.3 in Appendix VI.A and Figs. 6.1 and 6.2), we see that on most of the land protected by CDF, a roughly equal number of fires are due to equipment and incendiary causes, but that 1-1/2 to twice as many fires are due to carelessness. On the other hand, damage due to these three causes is very much alike, though there are wide variations from year to year. What is more important is that the damage due to equipment and incendiary fires has gone up over the years while that due to carelessness shows no clearly perceptible trend upward or downward.** The USFS data are not as definitive, though they too show clearly an increase in the number of incendiary fires over the years while equipment caused fires may actually have decreased somewhat.

Fires caused by children have become increasingly numerous lately.† Until recently, the statistical reports did not separately list children as a cause; therefore, our tables do not reflect this increase.

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*This chapter was prepared by E. Chilton.

**"An analysis of these (major) fires (in CDF District V), over 300 acres in size, showed the major causes were equipment use (28%) and incendiarism (26%)," Bernardi (1973). "Children-caused fires, incendiarism, and machine use fires are responsible for almost 60% (21, 19 and 17% responsible) or more of the wildland fires," Moran (1972).

†"In 1954 children accounted for 10.5% of the 1955 man-caused fires (in CDF controlled land)... In 1970 children were responsible for 23.5% of the 4,955 man-caused fires," Folkman (1966). In 1972, children-caused fires burned 19,231 acres in the National Forests of California, nearly 50% of all acreage burned.

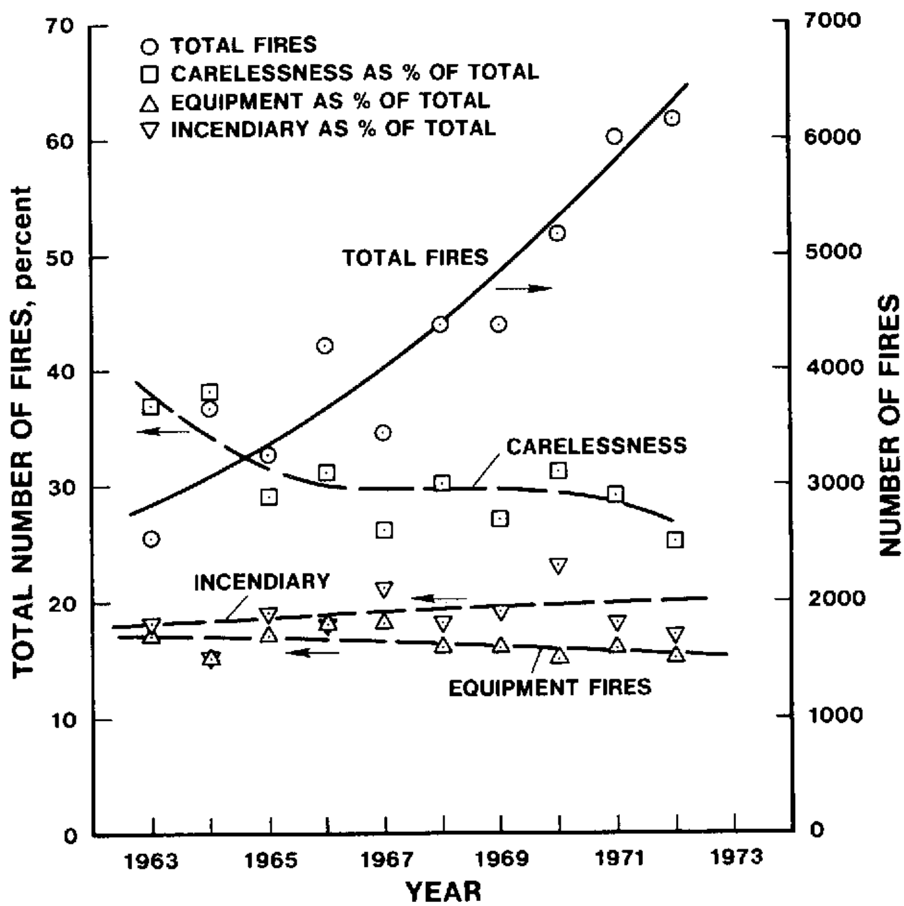

Figure 6-1 Fire-Cause Statistics, CDF Zones I and II

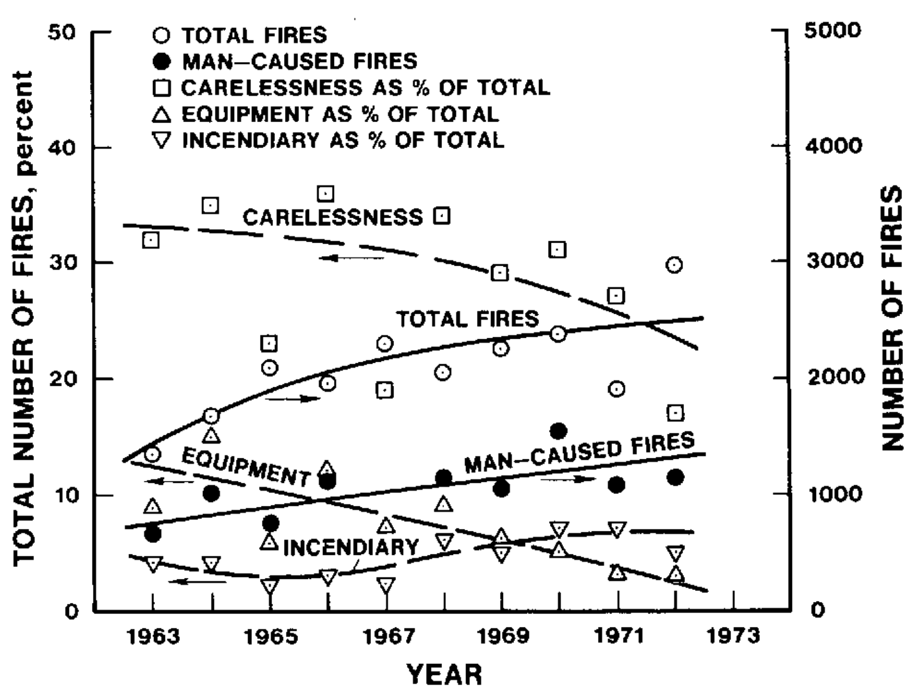

Figure 6-2 Fire-Cause Statistics, USFS Region V

Since many of our projections and conclusions will be based on these statistical data, it is necessary to ask how reliable they are. This question is considered in Appendix VI.B, where the conclusion is reached that the data is sufficiently reliable to predict trends and to use as a basis for policy in fire prevention.

To develop sensible prevention strategies, we need to look at a more detailed breakdown of the causes:

(1) Equipment-Use Fires: A recent survey by G. Bernardi (1973) indicates that "more than 2/3 of equipment-use fires...were caused by road transport vehicles as opposed to farm or construction equipment, power tools, or stationary engines...automobiles and trucks were the major causes." To be more specific, Bernardi claims that "40-50% of all major equipment fires were caused by...automobiles and trucks...Just under 1/3 were caused by harvesters." Although this study was confined to major fires in CDF District V, we believe that its numbers are generally applicable in other CDF districts, though perhaps less so in the National Forests.

The direct causes that are most often cited are glowing particles flying out of the exhaust system, the hot exhaust system itself when it gets in contact with dry vegetation, and friction, the last more often a problem with cables in logging operations.

(2) Carelessness: Campers and Smokers have, for years, been the target of Smokey-the-Bear advertising. As pointed out above, carelessness fires have not grown appreciably in number despite the large population increase and the increasing popularity of outdoor recreation, possibly because of the effectiveness of Smokey. A Canadian observer has stated: "Woods travellers and other outdoor recreationists are not increasing in relative importance as causes of fire... After a certain level of woods travel is reached, the number of fires caused by people travelling in the woods appears not to be related to the number of travellers." (Telfer, 1969).

Although there seems to be a slight increase in the number of fires due to debris burning, the total damage caused by them in California is small and has not increased over the years.

(3) Incendiarism: The reasons why a person would purposely set fire to the woods are many and varied. Davis (1959) prepared the list shown in Table VI.4 in Appendix VI.A. As the Oregon State Forestry Department wrote in 1973: "Incendiary fires...are generally set during the worst burning conditions.

Incendiarism for malicious reasons appears to be replacing burning for pasture or hunting improvement as the most frequent motive in recent years." As to the importance of the pyromaniac or firebug, opinions differ. The Oregon State Forestry Department, just quoted, lists 16 pyromaniac fires out of a total of 44 incendiary fires, i.e., more than 35%. On the other hand, a Canadian survey by Doyle (1951) states that "The main single reason for setting incendiary fires is to obtain work. Fires set for spite against neighbors are twice as important as those set for the purpose of forcing the opening of land for settlement or to obtain cutting rights. Fires set 'for the love of it'--that is, by firebugs, rank lowest on the incendiary list." Although one may question the applicability to today's California of a report that old and distant, personal interviews of the writer with CDF and USFS rangers seem to confirm the comparative rarity of the adult firebug in some parts of California today.

(4) Miscellaneous: Closely related to incendiary fires are fires set by children. Fire appears to have a great fascination for young children, particularly boys. Most children will learn from the frightening experience of having caused an uncontrolled fire and not repeat it, though the lesson may be costly. But some, for reasons to be discussed later, will set fires again and again.

Railroad and power line fires are caused by specific technical problems. They start, of course, on or near their respective rights-of-way. We are told that close cooperation between the railroads and power companies on the one hand, and CDF and USFS on the other has made appreciable reductions in the fires from these causes. The CDF State Forester's Report for 1971 states: "'The Railroad Right-of-Way Hazard Reduction Guide' was completed and distributed to the field and railroads in October 1971."

B. People Who Cause Wild Fires

It is already fairly obvious from the foregoing that, contrary to public belief, most wild fires are not started by campers and hikers or other infrequent visitors to the wildlands. In fact, "the principal threat today...seems to come from persons who spend much time in the forests. They are likely to be ignorant of fire prevention practices, are irresponsible, become careless, have grudges towards their employers or Forest Service personnel, or are required by employers to operate unsafe machinery or vehicles." (Christiansen and Folkman, 1971). "...nearly 80% of fires whose cause is known are started by local residents." (Chandler, 1960). This is true also in Canada where "on the average, local citizens cause more fires than visitors or tourists

(84% vs 16%)" (Doyle, 1951). In other words, the majority of fire starters come from rural areas or small towns in or near the forest land.

As to the types of people, Folkman (1965) says that the "high risk people tended to be young (under 25), unmarried, and with...limited... schooling for their age...If not in school, they tended to have low-paying part time jobs." It should be kept in mind that this described not just incendiarists but also people who start fires by carelessness and those who operate mechanical equipment.

Let us also look at children who start fires. "12% of the children responsible (were) less than 5 years old. Nearly 75% were 10 years old or younger." (Folkman, 1972). The same author, in an earlier publication (1966) states that "most of the offenders are males (92%)". "This sex bias gives some credance to the psychoanalytical linkage of fire fascination to psychosexual development. It is also quite clear that fire, like sex play, is an object of the most general prohibition for children" (Folkman, 1972). "The data...suggest that fire education is likely to be more successful when it removes some of the taboos which intensity its fascination" (Siegelman and Folkman, 1971).

This comment leads us directly to methods for prevention. But, before we consider these, a few remarks should be made about the child recidivist, who sets fires repeatedly. Siegelman and Folkman (1971) find that "recidivists (boys who have set 3 to 5 fires) do seem to fit roughly in one or the other (of two) categories...The first type is given to impulsive acting out...The second type...is...overly active and (has) difficulty in relationships with other children. The primary symptom, however, appears to be anxiety rather than obvious anger...For the former (fire setting) may be a means of revenge, a way to gain attention... For the latter it may be primarily a cry for help...Many of the children... showed the symptoms of an organic disturbance (or) minimal brain dysfunction syndrome...Having set one fire, a child coming from a disturbed family situation, who is having difficulty in school, and shows some of the psychological or medical problems noted, is a high risk candidate for recidivism."

C. Education Effectiveness

The fire causes listed above might be described as accidental, careless, or intentional. Many writers, however, have said that in fact there are no accidents; that, with sufficient care, all accidents could be prevented. If this is so, and if, for the moment, we leave out the intentional fires, the problem may be viewed as one of teaching people to be careful at all times when they are in or near a forest. There are two basic social approaches to this task: education and law enforcement.

The philosophy of the educational approach is to make every man and woman realize the value of the forest to him or her, understand the danger and cost of wildfires, and learn how to properly handle potential fire sources. If this is done--so the theory holds--people will be motivated to protect their forests.

A study in Butte County, California attempted to evaluate the effect of a combined inspection and education effort on the attitudes and fire knowledge of a large sample population. The results of this test were discouraging. "...the before and after surveys reveal very little influence of the program on either knowledge or attitude... The experiment demonstrated that it is difficult to produce large-scale, rapid changes in autonomous individuals. Results were most apparent...with children" (Folkman, 1973). Inspection and personal contact can be effective in obtaining compliance with fire regulations and thereby can reduce fire hazards noticeably (see Chapter III). However, the attitudes of adults are not readily affected.

Several attempts have been made to use media--newspapers, radio, and television--to educate the public. Again, the consensus of opinion by researchers is that the effectiveness of media in changing behavior is questionable and person-to-person communication, especially through groups, appears more successful (Bernardi, 1970). Such person-to-person or group activities are difficult to arrange, particularly with the type of people who are the worst fire risks. They do not tend to be easily identifiable in groups, and they tend to be suspicious of anyone but their peers, particularly any authority figure, such as a ranger. An attempt at group influence by peers is now being made by CDF who have established a "speaker's bureau wherein college students are trained to give fire prevention and conservation talks to service clubs, high schools, parent-teacher associations, etc." (CDF State Forester's Report, 1971). It is too early to evaluate the effectiveness of this approach.

The education of children is one of the few bright spots in fire prevention by education. Gladen and Carkin (1970) have found that "learning behavior can be directed toward rather specific outcomes with well-planned and supported instructional materials in conservation and forest fire prevention education." Since the statistical evidence shows that the predominance of juvenile fires are started by very young children, it is vital to start this education early. "The experiment seems to have its greatest impact in the kindergarten and first grade, with good, but less dramatic, results in the second and third grades" (Ibid).

Folkman and Taylor (1972) report on one such program tried at the Riverside County, California, Headstart Project. "The Headstart fire prevention materials were developed (1) to satisfy normal curiosity about fire; (2) to improve understanding of the cause-and-effect relationships between the child's action and the production of fire, and his actions and the resulting harmful effects to himself, to other people, and to his environment; and (3) to develop or reinforce positive attitudes toward fire-safe behavior." The researchers found that "to achieve the goals of satisfying curiosity and changing attitudes, active learning through experience is undoubtedly necessary." However, "the problem of how to expose children to fire safety has not been satisfactorily solved...Most teachers would prefer to leave this responsibility to the parents." (Ibid). The situation is reminiscent of sex education in the schools, though the societal taboos are probably not as strong.

Although education appears to be effective in educating young children--and, to a degree, even adults--to prevent careless fires, it will do little for the intentional fire setter, the incendiarist. Those who favor law enforcement techniques do so in part because they believe that these techniques will be effective against both the incendiarist and the careless fire setter.

It is obvious that neither education nor law enforcement will have much effect on juvenile incendiarists, that is, that group of children who set fires repeatedly. We have previously referred to the study by Siegelman and Folkman (1971) who tell us that there are clear and observable distinctions between the child who starts one fire and learns not to do so again, and the child who sets fires repeatedly, and that these distinctions are deeply rooted in anxieties closely connected with the child's home life and/or minor organic or brain dysfunctions. The only help that is likely to be effective for these children is psychological counseling which can attack the root causes of their problem.

At present there is no way to force a child into psychological counseling or psychiatric help unless he is a ward of the court. In some cases, advice to his parents may be sufficient; in others, some financial assistance from federal, state, or local agencies may be enough to help the child into a happier life, and protect the country from a series of dangerous fires.

D. Cost-Benefit Example

To estimate the cost of a people management program is difficult enough. To estimate its benefits a priori is almost hopeless. The best we can do here is to make order-of-magnitude estimates and to suggest that these attempts be augmented by more complete statistical data and by pilot experiments to prove or disprove the results. To obtain some estimate of the approximate magnitude of costs and benefits, let us look at the fire education of young children. We shall assume that the kindergarten and first grade program will cost about $1 per pupil.* There are approximately 400,000 pupils in each of the lowest grades in the California schools, making the annual cost of the program about $400,000.

During 1972 CDF reported 847 children-caused fires (ten year estimates are not available) with a total damage of $168,000; USFS reported children-caused fires with damages of $1,848,500, a total cost to the tax-payer of about $2 million. Consequently, if in 1972 the educational program had prevented more than 20% of all children-caused fires, it would have been cost-effective. The 20% minimum-success figure is probably not an unreasonable one.

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*In fact, at present, program material is made available by CDF to all California schools at cost ($6.30). Since that's all that is needed except source duplication costs and the teacher's time, and since the package can be used repeatedly, the actual cost per pupil is even less than $1. Our estimate includes costs for material to permit students actual experience with fire. This is not now a part of the CDF package.

C-2

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Appendix VI.A

FIRE-CAUSE STATISTICS

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Table VI.1

NUMBER OF FIRES AND DAMAGE CAUSED, CDF ZONES I AND II

Data from: "Fire Statistics for (year) Activities - CDF 1963-1969 and "(year) Wildfire Activity Statistics - CDF 1970-1972.

Number of Fires							Percent of Total				
Year	Equip- ment	Careless- ness*	Incen- diary	All Man Caused†	Ltn.	Total	Equip- ment	Careless- ness*	Incen- diary	All Man Caused†	Ltn.
1963	437	952	459	2,372	173	2,545	17	37	18	93	7
1964	547	1,390	549	3,464	201	3,665	15	38	15	95	5
1965	568	955	627	2,925	331	3,256	17	29	19	90	10
1966	768	1,317	750	3,981	222	4,203	18	31	18	95	5
1967	611	899	713	3,196	273	3,469	18	26	21	92	8
1968	708	1,313	788	3,973	414	4,387	16	30	18	91	9
1969	721	1,175	850	3,801	596	4,397	16	27	19	86	14
1970	798	1,588	1,171	4,955	215	5,170	15	31	23	96	4
1971	989	1,742	1,057	5,853	148	6,001	16	29	18	98	2
1972	938	1,558	1,050	5,697	470	6 167	15	25	17	92	8
						Average	16.3	30.3	18.6	92.8	7.2

*For Breakdown, see Table VI.2.

†Includes 'Miscellaneous' fires in 1963-1970; 'Miscellaneous,' 'Railroad,' 'Elect. Power,' and 'Play with Fire' in 1971 and 1972.

Table VI.1

CONTINUED

Data from: "Fire Statistics for (year) Activities - CDF 1963-1969 and "(year) Wildfire Activity Statistics - CDF 1970-1972.

Damage $ (Thousands)							Percent of Total				
Year	Equipment	Carelessness*	Incendiary	All Man Caused†	Ltn.	Total	Equipment	Carelessness*	Incendiary	All Man Caused†	Ltn.
1963	110	237	70	561	10	571	19	42	12	98	2
1964	141	3,960	1,421	6,434	19	6,453	2	61	22	~100	~0
1965	1,548	376	154	5,179	4	5,183	30	7	3	~100	~0
1966	180	187	742	1,409	14	1,423	13	13	52	99	1
1967	174	242	40	3,818	9	3,827	5	6	1	100	~0
1968	1,329	318	243	2,507	30	2,537	52	13	10	99	1
1969	246	268	205	1,511	43	1,554	16	17	13	97	3
1970	469	297	3,183	21,025	7	21,032	2	1	15	~100	~0
1971	1,532	389	573	5,420	16	5,436	28	7	11	~100	~0
1972	1,725	785	1,069	6,660	37	6,697	26	12	16	99	1
						Average	19.3	17.9	15.5	99.2	0.8

*For Breakdown, see Table VI.2.

†Includes 'Miscellaneous' fires in 1963-1970; 'Miscellaneous,' 'Railroad,' 'Elect. Power,' and 'Play with Fire' in 1971 and 1972.

Table VI.2

BREAKDOWN OF 'CARELESS' FIRE CAUSES, CDF ZONES I AND II

(Data from same sources as Table VI.1)

Number of Fires					Percent of Total		
Year	Camper	Smoker	Debris Burning	Total Fires	Camper	Smoker	Debris Burning
1963	36	637	279	2,545	1	25	11
1964	97	854	439	3,665	3	23	12
1965	83	559	313	3,256	3	17	9
1966	94	787	436	4,203	2	19	10
1967	69	459	371	3,469	2	13	11
1968	122	740	451	4,387	3	17	10
1969	135	696	344	4,397	3	16	8
1970	231	955	402	5,170	4	18	8
1971	254	862	626	6,001	4	14	10
1972	238	772	548	6,167	4	13	9
					Ave. 2.5	17.5	9.8
Damage $ (Thousands)					Percent of Total		
1963	6	189	42	571	1	33	7
1964	10	3,737	213	6,453	~0	58	3
1965	1	131	244	5,183	~0	3	5
1966	2	123	62	1,423	~0	9	4
1967	0	165	77	3,827	~0	4	2
1968	11	224	83	2,537	~0	9	3
1969	12	213	43	1,554	1	14	3
1970	60	69	168	21,032	~0	~0	1
1971	125	202	62	5,436	2	4	1
1972	33	390	362	6,697	~0	6	5
					Ave. 0.4	14.0	3.4

Table VI.3

NUMBER OF FIRES AND DAMAGE CAUSED, USFS REGION 5

Data from: "Annual Fire Report for the National Forest - USFS 1963-1968 and "National Forest Fire Report USFS 1969-1971.

Number of Fires							Percent of Total				
Year	Equipment	Carelessness*	Incendiary	All Man Caused†	Ltn.	Total	Equipment	Carelessness*	Incendiary	All Man Caused†	Ltn.
1963	127	431	48	683	660	1,343	9	32	4	51	49
1964	256	588	63	1,007	656	1,663	15	35	4	61	39
1965	127	481	50	742	1,340	2,082	6	23	2	36	64
1966	236	706	62	1,115	823	1,938	12	36	3	58	42
1967	155	426	45	696	1,597	2,293	7	19	2	30	70
1968	176	683	113	1,113	919	2,032	9	34	6	55	45
1969	144	648	120	1,040	1,210	2,250	6	29	5	46	54
1970	120	732	174	1,530	856	1,899	3	27	7	57	43
1971	55	519	138	1,090	809	1,899	3	27	7	57	43
1972	76	519	151	1,117	1,859	2,976	3	17	5	37	63
						Average	7.5	28.3	4.5	49.5	50.3

*Includes 'Smoker,' 'Recreation,' 'Forest Utilization,' and 'Land Occupancy' 1963-1969.
Includes 'Smoker,' 'Camper,' 'Debris Burning' 1970-1971.

† Includes 'Miscellaneous' 1963-1969; 'Miscellaneous,' 'Railroads,' and 'Children' 1970-1971.

Table VI.3

CONTINUED

Data from: "Annual Fire Report for the National Forest - USFS 1963-1968 and "National Firest Fire Report USFS 1969-1971.

	Acres Burned**						Percent of Total				
Year	Equip-ment	Careless-ness*	Incen-diary	All Man Caused†	Ltn.	Total	Equip-ment	Careless-ness*	Incen-diary	All Man Caused†	Ltn.
1963	3,467	2,841	263	7,137	2,060	9,197	38	31	3	78	22
1964	1,152	96,237	7,445	105,489	490	105,979	1	91	7	~100	~0
1965	1,487	5,792	1,401	8,695	583	9,278	16	62	15	94	6
1966	102,555	29,593	14,106	150,908	11,094	162,002	63	18	9	93	7
1967	6,214	11,011	640	18,270	1,133	19,403	32	57	3	94	6
1968	45,662	31,550	4,423	89,255	370	89,625	51	35	5	~100	~0
1969	7,143	8,566	1,022	16,811	2,834	19,645	36	44	5	86	14
1970	7,506	85,189	4,396	266,041	616	266,657	3	32	2	~100	~0
1971	889	5,017	19,973	32,601	580	33,181	3	15	60	98	2
1972	149	6,846	4,933	35,432	4,167	39,599	0	17	12	89	11
						Average	[24.3	40.2	12.1]	93.2	6.8

*Includes 'Smoker,' 'Recreation,' 'Forest Utilization,' and 'Land Occupancy' 1963-1969. Includes 'Smoker,' 'Camper,' 'Debris Burning' 1970-1971.

† Includes 'Miscellaneous' 1963-1969; 'Miscellaneous,' 'Railroads,' and 'Children' 1970-1971.

**Acres Burned is used because the breakdown on damages in dollars was not available.

Table VI.4

CLASSIFICATION OF INCENDIARY FIRES

1. Fires set for direct personal economic gain to:

    Burn property of others to protect owned property

    Improve grazing, control of stock, or hunting

    Facilitate logging or naval stores operations

    Clear for collecting fish bait, firewood, or other materials

    Receive pay--hired to burn

2. Fires set for indirect economic gain to:

    Make landowner come to terms on use of land

    Obtain employment

    Kill timber to make its sale necessary

    Control pests and diseases, ticks, chiggers, snakes, etc.

    Force sale of property at reduced price

3. Fires set to attain a goal or personal satisfaction:

    Spite against large ownership

    Personal grudges and neighborhood quarrels

    To make public forest employees work or to cause their removal

    Because they feel the woods need burning (habit)

    Obeying an impulse, malicious mischief, drunk and disorderly conduct

4. Fires set to conceal a crime:

    Whiskey-still camouflage and decoy smokes

    To destroy evidence of timber or cattle theft, illegal hunting, or other trespass

    To delay pursuit or obliterate trail

5. Fires set by mentally afflicted and immature:

    Pyromaniacs--the true "firebug"

    Incompetent persons

    Children

Appendix VI.B

THE VALIDITY OF FIRE-CAUSE STATISTICS

Fire cause statistics are compiled from fire reports which must be filed after each fire by the ranger in CDF and USFS districts. The paper work is not cherished by outdoorsmen. Also, on small, readily extinguished fires (fires that burn less than 300 acres and consume no valuable structures)--and this makes up more than 98% of all fires in California--no extensive effort can be made to search the cause. It must either be fairly obvious, or it must be arrived at by elimination of unlikely causes. Folkman, in a study of fire prevention in Butte County, California, suggests that a known cause was determined in less than 1/3 of the forest fire reports in the Butte County ranger unit prior to the arrival of trained fire prevention officers in 1967.

In order to prevent rangers from using the "easy way out," fires may not be classified as of unknown source, and the range is required to find the most likely cause if the true cause is not clearly evident. As a consequence, many fires are classified as smoker fires. Chandler (1960) claims that "the accuracy of the smoker category, and, possibly, of the incendiary class, is markedly below that of any other cause. The conclusion here is that most guesses are called smoker fires." Nevertheless, Chandler estimates that fire-cause estimates are all more than 80% accurate, except smoker, which are better than 60% reliable. He concludes that the statistics "are sufficiently accurate to be used as a basis for planning."

Since we are concerned more with trends than exact values, and since trends are less likely to be influenced critically by the errors and prejudices mentioned, we believe that we can draw fairly reliable conclusions from them.

Chapter VII

LAND MANAGEMENT: INTERMINGLED OWNERSHIP

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LAND MANAGEMENT: INTERMINGLED OWNERSHIP*

A. Introduction

"Today, the Nation as a whole is beginning to experience the pressures once felt only in its major population centers. In all parts of the country, conflicting demands over limited land resources are placing severe strains upon economic, social, and political institutions and processes and upon the natural environment--farmers groups oppose real estate developers; environmentalists fight the electric power industry; homeowners struggle with conservationists; shoreline and water recreation are pitted against oil companies; cities oppose the states; and suburbs oppose the cities." (Land Use Policy, 1973).

As a consequence of these conflicting demands upon limited land resources, unusual requirements are being placed upon management. Some new management techniques must be found if these requirements are to be met; obstacles to sound management practices must be removed. It is well recognized that "the natural processes of physical and biological systems that comprise the land do not necessarily accommodate themselves to the artificial boundaries and restrictions that law and political economy impose upon them. The stress of human demands upon the land tends to displace natural processes thoughout its ecosystems and to impair the capacity of the natural environment for self renewal." (Caldwell, 1970).

An even less acceptable lack of accommodation and a particularly tiresome aggravation for wildland forest management is found in the strong mixture of public and private ownership of the lands situated <u>within</u> the external boundaries of the national forests. This anomalous ownership pattern not uncommonly reflects itself in a checkerboard effect on an ownership map of national forest lands. Thus, side-by-side there are tracts of land in which the traditional bundle of private property rights inhere, on the one hand, and other tracts in which the public interest is paramount through the ownership of the land by the federal government, on the other.

There is, then, a built-in conflict between private and public ownership of lands within the boundaries of national forest lands which surfaces most observably in connection with forest management practices (Clawson and Held, 1957). Generally, the privately owned lands are not subject to the same degree of control and regulation as federally owned lands with respect to a rational cost-effective policy of forest land management. And with respect to wildland forest fire prevention and control activities as a part of forest management, specifically, the degree of difference in control and regulation between privately owned and publicly held lands becomes even more pronounced. This pronounced

*This chapter was prepared by H. Young.

difference is present in both prevention and suppression activities. The difference becomes even more acute, and sometimes critical, in times and areas of high fire danger.

Due to the rights which traditionally inhere in privately owned property in this country and the inclusion of privately owned tracts within national forest boundaries, a uniformly applied plan of forestry management is precluded within the forests. In addition, there is an inequitable distribution of the costs and benefits of forest management expenditures, including those for wildland fire prevention and control actions, which favors the privately owned land in a variety of ways, resulting in higher benefits and less costs proportionately for the owners of private lands than for the public generally.

B. History of Development of Intermingled Ownership

Prior to 1891 when the forests were thought to be "inexhaustible," the basic policy was the encouragement of unrestrained exploitation by private owners. That era saw large transfers of forest lands from public to private ownership. Timber cutting was done with little thought of the future (Dana, 1956). Not infrequently such cutting was followed by fire.

Then in 1891 a rider to an act revising the general land laws authorized the President to set aside forest reserves. Another rider to the Sundry Civil Appropriations Act of June 4, 1897, provided for the administration of the reserves, and among other things instructed the Secretary of the Interior to protect the reserves from fire and depredations and authorized him to make rules for the use and occupancy of the forest reserves. In 1905 jurisdiction over the reserves was transferred to the Secretary of Agriculture. The name of the reserve was changed to national forests in 1907.

By an act of the Congress passed in 1907, the President was denied authority to create national forests from the public domain by procloma-tion in any of the Far Western states except Montana, Utah, and Nevada. However, national forests may be created by purchase under the provisions of the Weeks Act of 1911 as well as the Clarke-McNary Act of 1924 and by exchange with the states or private owners under the terms of the General Exchange Act of 1922.

For a country whose policy up to that time had been to transfer the public lands into private ownership as rapidly as possible, the reversal of that well-established policy in the early 1890's amounted to a remarkable change in attitude and was a turning point in public land policy (Dana and Krueger, 1958). Two acts in 1890 were passed that withdrew some 2 million acres of public land in the Yosemite Valley and in what is now Sequoia National Park. Then the Forest Reservation Act was passed in 1891. But the haste with which the forest reserves were established and the inclusion within them of many improvements, as well as vast areas that seemed to have little relevance to forest management, disturbed many westerners. This perturbation turned to outright alarm when they realized that a large proportion of the natural resources of the West was no longer open to homesteading, lumbering, or grazing without permission of the United States Forest Service.

The hasty establishment of the forest reserves and their quick conversion into national forests followed a long period of equally fast disposal. During this disposal period, private individuals, companies, and the several states each selected choice land from the public domain. This provides an understandable explanation for the present-day erratic pattern of ownership within many national forest boundaries with some tracts being privately owned, some owned by states, and others owned by the federal government. In mountain areas it was not uncommon for the valley bottoms to pass into private ownership with the steeper hillsides remaining in federal ownership. Lumbermen often bought only the finest and most accessible stands of timber. Some bought only occasional tracts in order to provide an appearance of legality while logging the federal lands in trespass. In some situations, large solid blocks passed into private ownership. Thus, the extent of privately owned lands within any given national forest today depends largely upon the date at which the federal unit was first established in relation to the history and economic development of the area, and, of course, upon the policy utilized in drawing the boundary of the forest (Clawson and Held, 1957).

Also, while national forests can legally be created only for protection of the watershed and production of timber, they can be used for other purposes not inconsistent with these primary objectives. Grazing, recreation, and mining are some of the important economic uses to which the forest reserves have been put. They have become multiple-use reservations (Loesch, 1971), with strong, but not exclusive emphasis on the utilization of forest resources for the support of economic activities. However, it has been noted that "forest administrators increasingly recognize that multiple-use decisions must weigh the value of trees as trees and the value of the wilderness in watershed protection and water production, as habitat for wildlife, as a source of recreation, inspiration, and scientific research, and as a vanishing species of earth forms." (Frome, 1971). Likewise, it is increasingly clear that the noncommodity benefits of the forest are assuming a much greater place in the public mind than ever before. The priorities have rather sharply shifted, and the pristine forest areas, without roads, now compete with logging, grazing, mining, resort building, and other commercially oriented activities (Clawson, Held, and Stoddard, 1960). Coordination of these diverse and often conflicting uses, with due regard given to the biological, physical, economic, social and esthetic considerations, creates a most difficult problem in the rational administration of the national forests (Davis, 1966). And "management must decide between the competing demands on the forests," (Reich, 1962).

C. Administrative and Economic Problems of Intermingled Ownership

Serious problems involving fire, disease, and insect hazards often require consistently applied efforts if the danger or hazard is to be controlled effectively. Erosion control on land of one ownership may be difficult or impossible without similar control on land of another ownership. Yet forest management is limited to seeking cooperative efforts with private landowners without the possibility of mandatory action among the divided owners. (However, although the federal government can not deny the private owner the right to use his land as he sees fit, it may prevent his injuring the federal land in the process of utilizing private land.)

In order to administer the federal land effectively, the administrator must know where the boundaries of the private land are in relation to the federal lands. This is necessary to prevent the users of federal land from trespassing on private lands and vice versa. In view of the unreliable nature of many land surveys, particularly in mountainous regions, this becomes a very tiresome and unsatisfactory task. The federal government cannot deny the private owner access to his land, although it does prescribe reasonable conditions for passage over federal lands.

Right of passage over federal land as an access way to private land often entails a seldom recognized but important economic advantage. Ownership of intermingled timber lands and investment in a road system for their common timber harvesting may be very advantageous to a lumberman bidding for timber rights on the adjacent federal land. Due to the practicalities of the situation, there are times when an owner of mixed land enjoys nearly all of the benefits of owning the adjoining federal lands without the customary accompanying costs and responsibilities (Clawson and Held, 1957).

> "Cases of market-failure seem especially common in the natural resources area. Forest fire and disease control by one forest owner affects other owners; well drilling practices can affect the production of large numbers of firms; operations of upstream dams affect downstream dams; many other examples will come immediately to mind. The intersecting question is why market-failure seems more prevalent here than in manufacturing.
>
> The explanation is that in the industrial sector, markets and firms tend to adjust in size in order to internalize spill-overs. The organizational structure changes to give managers control over interrelated decisions. In the natural resources area, property rights problems and the magnitude of the investment that would be required to internalize spill-overs hamper this remedy. Consequently, externalities are more visible in the natural resources area," (Hall, 1967).

D. Recommendation for Realignment of National Forest Boundaries

In 1940, the Assistant Chief of the Forest Service reported that there were 52 million acres of private and state owned land within all the national forests throughout the United States, of which 36.1 million acres should be administered by the federal government if the best and most economical administration were to be accomplished (Gates, 1968). At that time, nonfederally owned lands in the national forests amounted to one out of every five acres. California's national forests had the same ratio (Dane and Krueger, 1958).

By 1972 there were 187.1 million acres of federally owned land within the boundaries of all of the national forests and 38.3 million acres of nonfederally owned lands (U.S.D.A., 1972). That is, more than one acre in six of the total ownership within the external boundaries of national forests was in state or private ownership. This same ratio again holds true in California, where 20 million acres of federally owned land are within external boundaries of national forests, and 4 million acres of nonfederally owned lands complicate management and fire control (U.S.D.A. 1972).

Thus, almost 17% (or one acre out of each six) of the lands within the NFS boundaries, both nationally and within California, are lands owned by other than the federal government; i.e., in private, state, county, and municipal ownership. Among the 22 NFS units wholly or partially within California, the ratio of federally/nonfederally owned lands ranges from 60/40 in Tahoe National Forest and 62/38 in Shasta National Forest to 100/0 in Calaveras Bigtree National Forest (USDA, 1972). It would, however, be misleading to consider this mixed or intermingled ownership only in terms of the area occupied by each type of ownership. As was mentioned earlier, not uncommonly the most productive, valuable, and strategically situated lands passed into private ownership very early in the disposal era (Clawson and Held, 1957).

With the recent advent of environmental concern as a national policy and with the increasing emphasis placed upon preserving and conserving natural resources for their esthetic values, wildland forest fire control offers a new focus for considering eliminating or alleviating forest management administrative problems aggravated by mixed ownership of the lands within national forest boundaries.

Two concise examples will illustrate, for the purposes of this preliminary report, ways in which elimination of mixed ownership would materially aid fire control. First, pre-ignition efforts would be improved by the application of uniform policies of limiting or denying entry to national forest lands during periods of high fire danger without respect to ownership of individual tracts within the boundaries. Also, uniform conditions could be applied to limiting the type of activity by requiring safety measures without regard to private or publicly owned lands. Secondly, in fire suppression efforts the strong predeliction evidenced by firefighters to save private structures, sometimes at the expense of acres of adjacent public forest lands, could be ameliorated.

Realignment of external national forest boundaries should not result in a loss of the total amount of federally owned land. It has been observed that such a result would amount to an abuse of discretion (McFarland, 1970). The public Land Law Review Commission also reflects that sentiment. Significantly, however, the Commission's 35th recommendation provided that "public land agencies should be authorized to exchange, acquire and dispose of forest lands when necessary to improve ownership patterns and to ease administrative problems." (Public Land Law Review Commission, 1970; and Hagenstein, 1972).

Basically, three options are available for consolidating federal ownership through national forest boundary realignment. First, exchanges of privately owned lands within the national forest boundaries for lands presently in the public domain outside forest boundaries would appear to have promise. The necessary legislation is on the books. Exchanges could be accomplished on the basis of appraised values arrived at by competent land appraisers. The exchange option would entail the least amount of dollar financing, and would be the most cost-effective method for eliminating intermingled ownership.

A purchase option could be resorted to after the present market value of the privately owned land were determined by the Forest Service by way of estimation for the purpose of assessing the cost effectiveness of purchase, as well as comparing the exchange option with the purchase option.

A third option could be a hybrid of exchange and purchase in order to achieve the effectiveness of flexibility in solving difficult land acquisition problems.

A substantial amount of preliminary data will have to be compiled in order to determine the gross value of private lands within national forest boundaries. The Chief of the Forest Service reported in a private communication in July 1973 that information concerning such value was not available in his Washington Office (U.S.D.A., private communication: McGuire to Sen. Henry Bellman). The letter also stated, "as far as we know there has never been a definitive study to determine these values," and suggested that representative figures might be obtainable from County Assessors (Ibid.).

Of course, land valuations are highly localized by their nature. The suggestion of going at least to the level of County Assessor is a sound one. Several of the states are now having, or have recently had, statewide appraisals prepared in connection with a more realistic and updated advalorem tax base. The task is a large one, but it can be done. The necessity for going to local sources for values is revealed dramatically in the range found in cumulative net purchases to June 30, 1971, under the Weeks Act of March 1, 1911, of 149,088 acres within national forest boundaries in California. The average price per acre ranges from a low of $3.62 for 101,891 acres in the Tahoe National Forest to a high of $621.52 for 323 acres in the Mendocino National Forest, with an overall average of $13.89 per acre for all of the 149,088 acres (Annual Report, National Forest Reservation Commission, 1972).

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Chapter VIII

FIRE-DANGER RATING SYSTEM

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Chapter VIII

FIRE-DANGER RATING SYSTEM*

A. Need for a Rating System

Many areas of prevention as well as suppression have a need for an index that is related to actual fire danger. The prevention people, employing prescribed burning and other operations requiring burning, need to know when it is safe to burn, and the suppression forces need to know the extent of fire danger when deploying their equipment on a fire call. The index that gives an indication of fire danger is provided by a fire-danger rating system.

B. Basic Elements of a Fire-Danger Rating System

The basic variables necessary for any fire-danger rating have been studied and are well known. These variables are: fuel type and loading, fuel moisture content, weather components, an ignition element (source of fire start), and terrain. All but the terrain are time dependent elements. The most active is the weather, followed by the fuel moisture content, and both of these elements may change on a daily, if not hourly, basis. The fuel type and loading change over a much longer period. In California, the ignition component is mostly man caused, is quite seasonal in nature, and directly related to human activity and weather in a given area.

The major factor in the preignition stage is the dead fuel moisture content. The minimum value supporting ignition depends on the fuel type, but a typical value would be about 6% (lbs water × 100/lbs dry fuel) or less. On the other extreme, a dead fuel moisture content in excess of approximately 30% is considered no risk for possible ignition. The problem arises in how to obtain a value for this dead fuel moisture content as it is a function of the size and type of fuel and the weather conditions, primarily relative humidity and temperature. The standard method used today for obtaining the fuel moisture is to base it on the measured weather conditions and other input data. These readings are usually done manually once a day. Although the dead fuel moisture is related to the weather conditions, there is a timelag involved in the fuel moisture response to a change in the weather conditions. For fine fuels this response can be very fast, say an hour or less, but for heavier fuels the timelag can be days (i.e., a six inch log has a timelag of approximately 1000 hours). Timelag is defined as the time required for a fuel to lose 63.3% of its equilibrium moisture. This relationship between the weather conditions and the fuel moisture timelag, coupled with the fact that actual measurements are usually taken only once a day, results in a mechanism being established for determining a value for the fuel moisture

*This chapter was prepared by R. Romig.

content that best represents the total fuel load in a given situation. The derivation of the mechanism used in the 1972 National Fire-Danger Rating System, 1972 NFDRS (Deeming et al, 1972), is given in several papers (Fosberg, 1971a; Fosberg, 1971b; Fosberg, 1972).

C. The 1972 National Fire-Danger Rating System

1. Philosophy and General Description of the System

The question now arises as to how to combine the various elements of fire danger together to give an indication of the threat of fire. The state of California has adopted the 1972 NFDRS, and partial implementation has been carried out throughout the state. The basic philosophy of the NFDRS is: (1) the system should consider the initial stages of a normal fire that is spreading without spotting or crowning through fuels which are continuous with the ground; (2) the system should provide a measure of effort that is required to contain the fire due to the fire itself. This effort was assumed to be solely related to the length of the flames at the head of the fire. Factors not considered were accessibility, soil conditions, suppression forces, and equipment, etc.; (3) the system should be structured such that it gives the highest possible danger rating at the measurement area. Thus, all extrapolations of fire danger to other areas will be in the downward direction; (4) the system should provide ratings which would be physically interpretable in terms of fire occurrence and behavior; and (5) ratings should be relative and not absolute, and they should be linearly related to the activity being evaluated. The 1972 NFDRS is structured as shown in Fig. 8.1. The system determines three fire-danger indexes: (1) Occurrence Index (OI)--a number related to the potential fire incidence within a rating area; (2) Burning Index (BI)--a number related to the potential amount of effort needed to contain a fire in a particular fuel type within a rating area; and (3) Fire Load Index (FLI)--a number related to the total amount of effort required to contain all probable fires occurring within a rating area during a specified period. These indexes are scaled from 0 to 100 and are obtained from the risk factor and three basic fire behavior components: (1) ignition component (IC), (2) spread component (SC), and (3) energy release component (ERC). The risk factor and the three fire behavior components are also scaled from 0 to 100.

The field data inputs to the system are related to station identification, variables measured directly, and variables obtained by subjective estimates. These variables are shown in Table 8.1.

A major improvement of the 1972 NFDRS over previous systems is that it has an analytical (as opposed to empirical) base for most of the elements. The present system was also designed to give maximum flexibility for future changes. At present, eighteen states have adopted this system, and this number is expected to double within two years. Approximately fifteen years ago, there were eleven different systems used throughout the United States and Canada (Davis, 1959).

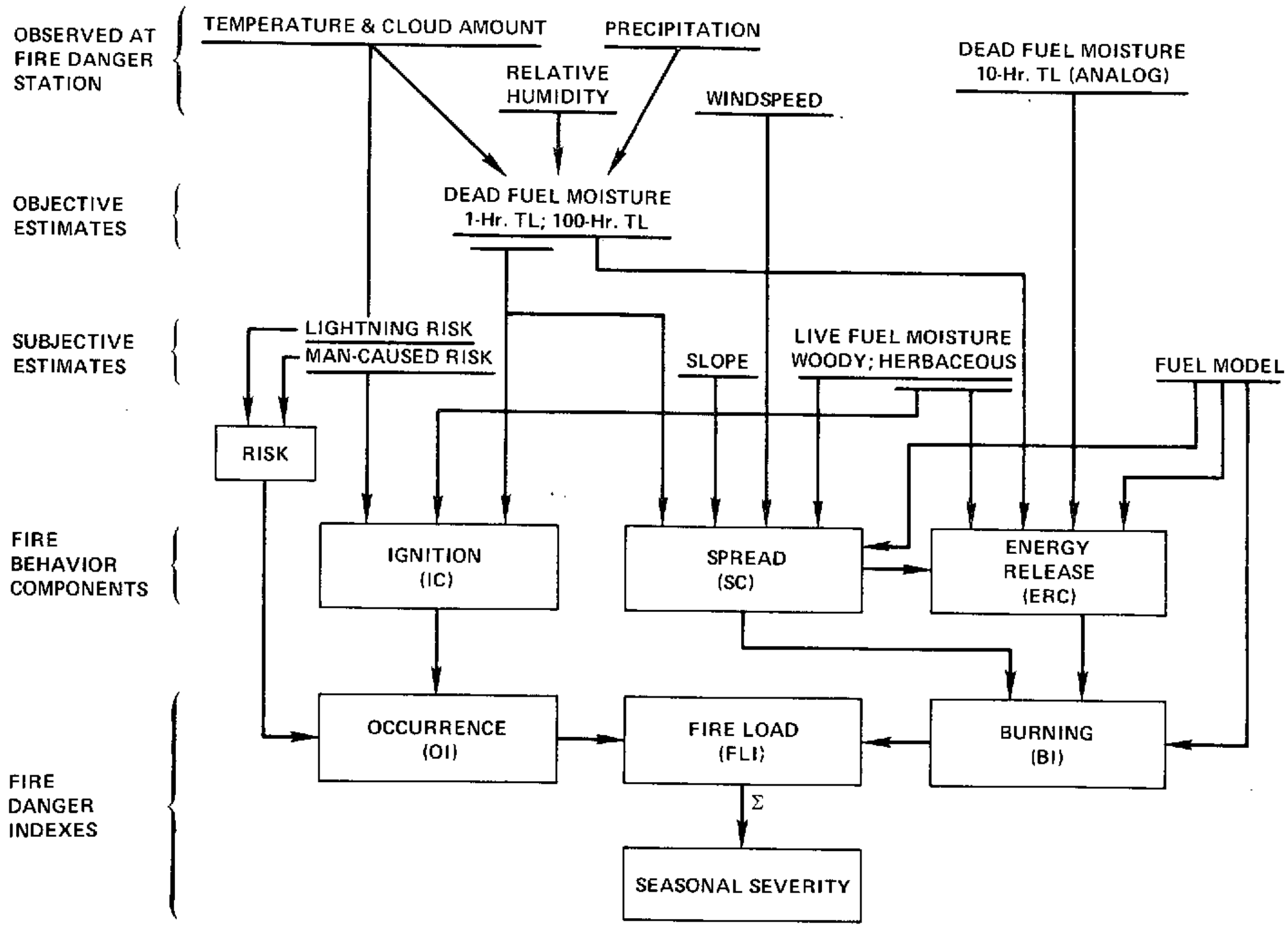

Figure 8-1 Structure of the National Fire-Danger Rating System

Table 8-1 Input Data for NFDRS

STATION IDENTIFICATION:
1. STATION NUMBER
2. STATION ELEVATION
3. DATE

MEASURED DIRECTLY:
4. WET AND DRY BULB TEMPERATURES
5. WIND SPEED
6. WIND DIRECTION
7. PRECIPITATION KIND
8. PRECIPITATION AMOUNT
9. 24-HOUR MAXIMUM AND MINIMUM TEMPERATURES
10. 10-HOUR TIME LAG FUEL MOISTURE (½-INCH FUEL MOISTURE STICKS)
11. 24-HOUR MAXIMUM AND MINIMUM RELATIVE HUMIDITIES

SUBJECTIVE ESTIMATES:
12. FUEL MODEL
13. STATE OF THE WEATHER
14. SLOPE CLASS
15. HERBACEOUS VEGETATION CONDITIONS
16. WOODY VEGETATION (FUEL MODELS B AND F ONLY)
17. RISK, LIGHTNING AND MAN CAUSED
18. PRECIPITATION DURATION
19. PRECIPITATION BEGINNING AND ENDING TIMES
20. LIGHTNING ACTIVITY LEVEL

2. Rate-of-Spread Model

One advance of the 1972 NFDRS was the development of an analytical model to calculate the rate of spread of a fire. This rate-of-spread model (Rothermel, 1972) is based solely on the fuel properties and loading for a given wind and slope. Rothermel's equation is:

$$\text{Rate of spread, } R = \frac{I_R \xi (1 + \phi_w + \phi_s)}{\rho_b \epsilon Q_{ig}}$$

where

I_R = reaction intensity, Btu/ft^2-min

ξ = propagation flux ratio, dimensionless

ϕ_w = wind factor, dimensionless

ϕ_s = slope factor, dimensionless

ρ_b = bulk density of fuel, lbs/ft^3

ϵ = effective heating number, dimensionless

Q_{ig} = heat of preignition, Btu/lb

These terms are computed on the basis of a number of environmental input variables and a set of rather complex equations. This set of equations constitutes the mathematical model. The basic fuel and environmental input variables for the model are summarized in Table 8.2.

Table 8-2 Inputs to Fire-Spread Terms

INPUT VARIABLES	TERMS IN THE SPREAD EQUATION						
	I_R	ξ	Φ_w	Φ_s	ρ_b	ϵ	Q_{ig}
LOADING	X	X	X	X	X		
HEAT CONTENT	X						
FUEL DENSITY	X	X	X	X			
SURFACE TO VOLUME RATIO	X	X	X			X	
DEPTH OF FUEL	X	X	X	X	X		
FUEL MOISTURE CONTENT	X						X
TOTAL SALT CONTENT	X						
SILICA-FREE SALT CONTENT	X						
WIND VELOCITY			X				
SLOPE ANGLE				X			
EXTINCTION MOISTURE CONTENT	X						

It should be noted that the interrelationship between some of the basic variables and components of the model is not fully understood. For example, the wind and slope factors were studied independently of each other. This analysis may prove to be one of the weaknesses of the model. Also, the moisture of extinction may be related to the fuel type and loading. A detailed sensitivity analysis should be done on all input parameters. This will indicate where more or better data are needed.

A good description of a test of Rothermel's equation to the burning of slash fuels has been given (Brown, 1972). Brown's paper gives field data on twenty-six test fires that were conducted in plots eight feet by thirty feet. In most cases, Rothermel's equation gave a higher value for the rate of spread than that observed in the field. The average overprediction was approximately 100%. Possible reasons for this overprediction are given in the paper.

Rothermel's model was discussed in some detail because it is used to determine the burn index and two of the three fire behavior components: the spread component and the energy release component. This can be seen in Fig. 8.1 where the spread component is connected to the energy release and burning boxes.

3. Fuel Models

To apply the spread model, as well as other components of the NFDRS to the fire situation, a series of fuel models had to be developed such that the system could indeed be used throughout the nation. The fuel types within a model were divided into five classes, three dead and two living. The dead fuels were classified according to their timelag, TL, and the three subdivisions are 1-, 10-, and 100-hour TL as shown in Table 8.3. Studies have shown that dead fuels with timelags greater than

Table 8.3

RELATIONSHIP BETWEEN TIMELAG CLASS AND FUEL SIZE

	Timelag Class		
	1-Hour	10-Hour	100-Hour
Timelag class interval	0-2 hours	2-20 hours	20-200 hours
Approximate equivalent fuel dimensions:			
Roundwood	Less than 1/4-inch	1/4 - 1 inch	1+ - 3 inches
Litter and/ or duff	Surface layer only	Surface - 3/4-inch	1/4+ - 4 inches

200 hours need not be considered in fire danger. Living fuels were classified according to whether they are herbaceous or woody. The 1972 NFDRS describes nine fuel models; each represents a broad grouping of fuel types with common characteristics. In very basic terms the fuel models are described as follows:

Fuel Model	Brief Description
A	fine fuel--primarily grass
B	California chaparral
C	grass, brush, and trees
D	southern rough
E	open canopy hardwood
F	high ratio living to dead
G	heavy fuels
H	compact litter layers
I	slash

The basic loading parameters for these nine fuel models, as related to the timelags, the surface-to-volume ratio σ of the 1-hr TL class, and the maximum values for the three behavior components and the burn index are given in Table 8.4. Additional input parameters used and assumed constant for all fuel types are: fuel particle density of 32 lbs/ft^3; heat content of 8000 Btu/lb; total mineral content of 5%; silica-free mineral content of 2%; and extinction moisture content of 25%. The loading parameters for the various fuel models are combined on a weighted average, and Rothermel shows the details of this in his paper.

Table 8-4 Selected Values for 1972 NFDRS Fuel Models

FUEL MODEL	FUEL DESCRIPTORS						MAXIMUM FIRE DANGER VALUES			
	LOADINGS (TONS/ACRE)				σ 1-HR (1/ft)	BED DEPTH (ft)	SC	ERC	IC	BI
	1-HR	10-HR	100-HR	LIVE						
A	1.25	0	0	0	3000	0.75	100	19	100	12
B	5.0	4.0	2.0	2.0	2000	6.0	87	100	100	100
C	1.5	1.0	0	0	2700	1.0	74	34	100	41
D	1.5	2.5	2.0	0	1750	2.5	33	31	100	51
E	1.5	1.0	0	0	2500	0.3	17	36	100	22
F	1.0	0.5	0	2.0	1500	2.0	14	11	100	8
G	3.0	2.0	5.0	0	1500	1.25	13	85	100	58
H	1.0	1.0	1.0	0	2000	0.4	8	34	100	27
I	4.0	5.0	10.0	0	1500	3.5	28	96	100	90

4. <u>Fire Behavior Components and Fire-Danger Indexes</u>

As stated previously, all components and indexes of the 1972 NFDRS are scaled from 0 to 100. The maximum value of 100 for the SC, ERI, and BI calculations is based on assumed conditions of a fire spreading on level ground in a 32 mph wind with a fine fuel moisture content of 1%. These values are obviously subjective in nature and were not intended to represent the maximum possible conditions of a real fire. It should be remembered that the 1972 NFDRS is based on a normal fire and was not intended for use under extreme conditions. The above conditions give a maximum rate of spread R of 692 ft/min (fuel model A), a maximum reaction intensity I_R of 11,921 Btu/ft^2-min (fuel model B), and a maximum flame length L' of 163.5 ft (fuel model B). Thus the following equations were established:

$$\text{Spread component, } SC = R/6.92,$$

Energy release component, ERC $= I_R/119.21$,

Burn index, BI $= L'/1.635 = (0.45(I_R R\tau)^{0.46})/1.635$

which give scaled values from 0 to 100. The terms appearing in the expression for the burn index, BI, are obtained from Rothermel's model and are applied to an equation for the flame length given by Byram (Davis, 1959).

The ignition component, IC, does not have a strong analytical base as exhibited by the other two components (SC and ERC). The IC value is a function of the temperature and fine fuel moisture content of the fuel and the probability of ignition. All fuel models have a maximum value of 100 for the IC as shown in Table 8.4.

The occurrence index, OI, and the fire load index, FLI, are given by the following equations:

$$OI = \frac{(IC)(MCR + LR)}{100}$$

$$FLI = \frac{(OI)(BI)}{100}$$

The man caused risk, MCR, and the lightning risk, LR, terms in the OI are based on historical fire statistics in the various fire cause categories and the present day activity level in those categories. Both of these risk terms are subjective in nature and thus represent an area that must be used with extreme caution.

Actual calculations for all the fire behavior components and the fire-danger indexes are done through the use of tables rather than the equations just cited. These tables and detailed instructions in their use are given in the paper describing the 1972 NFDRS and the reference has previously been given. Programmed instructions for the NFDRS are also available (USDA, Forest Service, 1972). It is expected in the near future that computer terminals will be available throughout the fire control districts and all calculations will be done by a computer.

5. Future Modifications in the 1972 NFDRS

There are several modifications to the system that are now being studied and initial estimates are that they will be implemented around 1975-1976. These areas of investigation are:

(1) The fire load index, FLI, will be modified such that its value will be equal to or greater than the burn index. Under the present system, if the burn index is at its maximum value, the FLI can be near zero with a low OI, and this concept is being changed.

(2) Additional fuel models will be added as they are identified. It is predicted that ultimately there may be as many as thirty fuel models as opposed to the nine presently in use.

(3) The determination of the man-caused risk may be revised.*

(4) The numerical values for various parameters in the spread model may be changed as additional data is obtained. This is especially true for the moisture of extinction as previously stated.

(5) A technique may be developed whereby the spread model can be applied to discontinuous fuel loading. This may also necessitate the development of a transient rate-of-spread model.

6. Use of the 1972 NFDRS

The NFDRS is used daily to determine the present fire danger and to predict fire danger based on the most recent weather forecasts. Fire control officers use the various components or indexes of the NFDRS in planning their initial dispatch forces on a fire call. It should be remembered that the NFDRS was intended to be just one of a number of inputs to be used by fire management. The NFDRS system does not consider the suppression forces available, the conditions of the soil, accessibility, location of property, and other factors that must be considered by fire management. It cannot be over emphasized that any fire control officer must have a thorough understanding of the philosophy, structure, and limitations in the NFDRS in order to effectively integrate it into the other factors that must be considered during the fire season.

D. Use of the 1972 NFDRS in California

1. Fire-Danger Areas

California has approximately 350 fire weather stations covering approximately 95,000 square miles under fire control management. This gives an average of about 275 square miles for each weather station. In practice the state is divided into fire climate areas and the weather stations are distributed in these fire climate areas according to fire danger. With areas this size it should be evident that moderate temperature, wind, and relative humidity gradients will exist throughout a given fire danger area as identified by a weather station. Several fire weather meteorologists in the State of California have indicated that, in some districts, less than 30% of the weather stations are at a proper location; the reason for this will be explained later.

*See also Chapter X for recommendations of changes in the definition of risk.

2. Components and Indexes Used in California

At present, very few, if any, fire districts in California use all indexes identified in the 1972 NFDRS. This is partially due to the fact that the system is new. Two separate factors are used in the state. The Forest Service uses the burn index, BI, and the California Division of Forestry uses the ignition component, IC, in their fire management decisions. Both units employ various initial suppression forces depending on the value of their respective component and index taken from the 1972 NFDRS.

3. Typical Dispatch Plans and Input Sensitivity

Each district within the state has its own dispatching plan as it is a function of variables not included in the NFDRS, such as accessibility and potential damage. One difficulty in this concept is the weight placed on the numerical value for a given index. This point can be illustrated by looking at Table 8.5 which gives the dispatch class for the various values of the burn index and the ignition component as used by the Forest Service and the California Division of Forestry respectively.

Table 8.5

DISPATCH CLASS VS BURN INDEX AND IGNITION COMPONENT FOR SEVERAL FUEL MODELS

Dispatch Class	BI - Range of Values					IC - Range of Values
	Fuel Model					All Fuel Models
	A	B	C	D	G	
I	0-3	0-30	0-8	0-14	0-16	0-19
II	4-8	31-37	9-14	15-19	17-25	20-64
III	9+	38+	15+	20+	26+	65+
Maximum BI or IC	12	100	41	51	58	100

The values given in Table 8.5 represent a typical district and do not apply statewide. The higher the dispatch class, the larger the initial dispatch forces that are sent on a fire call. It can be seen from Table 8.5 that the minimum difference in numerical values of the burn index between a Class I and a Class III dispatch varies from six to ten, depending on the fuel model selected. With this apparent small difference in going from a minimum dispatch to a maximum dispatch the question of the sensitivity of the value of the burn index to its input parameters must be investigated. To see the effect of moderate changes in the input variables to the calculated outputs of the NFDRS, consider the cases identified by Table 8.6.

Table 8-6 Examples of Weather and Slope Inputs to the NFDRS

WEATHER AND FUEL CONDITIONS	CASE I	CASE II	CASE III	CASE IV
TEMPERATURE, °F	88	88	88	82
RELATIVE HUMIDITY, %	25	25	25	35
WIND, mph	15	15	0	12
SLOPE, %	40+	0	40+	40+
WEATHER	SUNNY	SUNNY	SUNNY	CLOUDY
PREVIOUS RAIN	NONE	NONE	NONE	NONE
HERBACEOUS VEGETATION CONDITION	0	0	0	0
WOODY VEGETATION CONDITIONS	7	7	7	7

In this table, Cases II and III differ from Case I only in the slope set equal to zero in Case II and the wind set equal to zero in Case III. Case IV differs from Case I in that the temperature and wind are reduced, the relative humidity is increased, and a cloudy day is assumed. In addition to the above condition, the following assumptions are made in order to calculate the output values:

$$\text{10-hr TL FM} = \text{FFM} + 3$$

$$\text{100-hr TL FM} = \text{FFM} + 9$$

where TL FM is the timelag fuel moisture and FFM is the fine fuel moisture content. The above equations were used for this example only. In a real calculation the proper values are obtained through the appropriate tables. Cases I, II, and III correspond to a fine fuel moisture content of 4% and Case IV has a calculated value of 7%. With the input data from Table 8.6 and the assumptions given above, the spread component, ignition component, and the burn index were calculated for the fuel models identified in Table 8.5, and the results are shown in Table 8.7.

Examination of Table 8.7 shows the following trends: (1) the ignition component is not a function of the wind or the slope. It is basically a function of the fine fuel moisture content as previously stated; (2) due to its effect on increasing the fine fuel moisture content, an increase in the relative humidity from 25% to 35% greatly reduces the ignition component, IC; and (3) a 15 mph wind has a much greater effect on the

Table 8-7 Selected NFDRS Outputs under Conditions of Table 8-6

FUEL MODEL	CALCULATED COMPONENT	CASE I	CASE II	CASE III	CASE IV
A	SPREAD COMPONENT (SC)	32	25	5	15
	BURNING INDEX (BI)	6	5	3	3
	IGNITION COMPONENT (IC)	70	70	70	38
B	SPREAD COMPONENT (SC)	23	19	4	12
	BURNING INDEX (BI)	44	40	21	27
	IGNITION COMPONENT (IC)	70	70	70	38
C	SPREAD COMPONENT (SC)	20	16	4	10
	BURNING INDEX (BI)	19	17	10	12
	IGNITION COMPONENT (IC)	70	70	70	38

calculated values than a 40% slope. These trends can be combined to conclude that the most important preignition variable is the fine fuel moisture content, and after a fire has started the wind is the main factor. Looking at the values of the burn index given in Table 8.7, it can be seen that the difference between Case I and Case III varies from three to twenty-three and from Case I to Case IV varies from three to seventeen depending on the fuel model selected. These differences are approximately the same as those between the maximum and minimum dispatch values shown in Table 8.5. Comparing the numerical values directly shows these differences represent at least one change in dispatch class, and in several cases a change from one extreme to the other.

A similar analysis can be made on the ignition component. From Table 8.3 and Table 8.7 it can be seen that Cases I, II, and III have a Class III dispatch while Case IV has a Class II dispatch. The ignition component is independent of the fuel model and is primarily a function of the fine fuel moisture content, FFM, and the temperature. As a rough approximation, for a FFM of less than 8% the following equation can be used for all fuel models:

$$IC = 110 - (10)(\%FFM) .$$

The above equation can be used for any temperature greater than 70°F. It is thus evident that the ignition component is very sensitive to the fine fuel moisture content when the fire danger is high. The relative humidity has the greatest effect of any variable on the fine fuel moisture content. Thus, small changes in the relative humidity can have a tremendous effect on the ignition component as shown by the figures from Tables 8.6 and 8.7.

From the above calculations and discussion it should be evident that when the fire danger is high the fire behavior components and fire-danger indexes are very sensitive to the input values. Thus the location of the data stations as well as the time the data are taken has a direct, if not critical, influence on the calculated fire behavior components and the fire-danger indexes. Thus, dispatch decisions based on a small change in a calculated value should be made with extreme caution.

4. Input Data Measurements

Up to this point nothing has been said regarding data measurement. At present, nearly all data are taken manually in the field. The U.S. Weather Bureau has standards for fire weather stations and instruments. Temperatures are usually measured in an enclosed shelter located forty-eight inches off the ground. The rain gauge is located three feet above the ground. The wind velocity is obtained from an anemometer located twenty feet above open, level ground. Values that may be measured directly or obtained by objective estimates are maximum and minimum relative humidities and the 10-hr timelag fuel moisture. Subjective estimates are made on the remaining input data required. The capital cost of one of these manually operated weather stations is approximately three hundred and fifty dollars. Because of their requirement for manual operation, many of the stations are poorly located with regard to reporting useful fire-weather data. Thus, the stations are typically located near lookouts, ranger stations, etc. where men are normally located.

An alternative to these manual stations would be an automatic remote station requiring very little maintenance. NASA at Ames Research Center in California presently has a prototype remote station operating near Sunol, California. NASA receives the data via satellite several times a day. This unit gives excellent agreement with data obtained manually at a station in the immediate vicinity of the remote station. An improved model has been proposed with an estimated cost of $3,500,000 for each unit. This improved model will contain radiation measuring sensors, and this may make it attractive to air polution studies and a joint ownership of the unit would reduce the costs to each party involved. In the near future the cost of remote units will certainly be reduced, and they will undoubtedly be employed on a limited if not statewide scale.

E. Recommendations

Based on the study of the 1972 NFDRS used in California the following recommendations are made.

(1) The state should have a single agency for collecting and analyzing all fire data. This agency would in turn report their data to the fire control divisions in the state such as the California Division of Forestry and the U.S. Forest Service. Of importance here is uniform handling of all statistics and studying fires versus some fire index so the reliability of the index can be confirmed.

(2) More actual and accurate fire data must be taken. This should include both weather and rate of spread. This data will be of value to the suppression forces rather than directly used in a fire-danger system.

(3) In high fire-danger areas it would be desirable to have weather history regarding wind speed and direction available. Of importance here would be the time of day major changes take place. Very little of this data is presently available. Wind plays a major factor in both fire-danger ratings and containment of an actual fire.

(4) All wildland fire control divisions in the State should adopt the same fire-rating indexes and the same dispatch nomenclature as soon as possible.

(5) The sensitivity of the 1972 NFDRS to its various inputs should be fully understood by fire management.

(6) The consequences of poor location of weather stations should be understood by fire management.

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Chapter IX

AN ANALYSIS OF THE PREVENTION EFFECTIVENESS OF PENALTIES AND ENFORCEMENT

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A. Introduction

In this chapter we turn to a large class of questions surrounding man-caused wildfires. In particular, we will be concerned with analyzing several types of ignition-related decisions and assessing the sensitivity of these decisions to changes in various economic and legal incentives. The analysis itself is an application of the theory of choice, a set of general principles for analyzing decisions taken by an individual under whatever constraints may be operative.

In the analysis which follows we will examine two classes of time-allocation decisions: the incendiarist's decision as to how much time to spend planning and executing ignitions, and the decision of any other wildland user as to how much care to exercise with ignition sources (the time allocated for precautionary activity). In each case, the time spent by the individual in the respective activities turns out to be a function of the probability of apprehension if a fire is started, the individual's wealth level and his "tastes and preferences," and the severity of the penalty if apprehended. The fact that penalties may be zero for some "accidental" ignitions is irrelevant as far as our analysis is concerned, since we are interested ultimately in whether assessment of penalties would alter the number of "accidental" (negligent?) ignitions.

Before proceeding, a few words about the role of "tastes and preferences" in the analysis are in order. By definition, psychological factors, including those we have loosely termed "tastes and preferences," are attributes which are unique to the individual and determined by some as yet inexplicable combination of environment and heredity. An economic analysis of individual decision-making takes these psychological attributes of individuals as given and hence investigates decisions taken when "tastes and preferences" are datum. Since the analysis is individual specific, the extent to which any consequences may be generalized, depends largely upon the generality of the assumptions made about the individual. These assumptions fall into two categories: Assumptions about psychological characteristics of individuals (e.g., the individual enjoys planning and executing ignitions), and secondly, assumptions about how individuals choose among competing risky alternatives open to them (how the uncertain consequences of actions are evaluated in the process of reaching a decision). We will assume that individuals choose among risky alternatives in accordance with the axioms of the expected utility theorem of J. von Neumann and O. Morgenstern.**

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*This chapter was prepared by J. Heineke.

**The classical reference to the expected utility theorem is Theory of Games and Economic Behavior (von Neumann and Morgenstern, 1947). Updated versions can be found throughout the literature of "decision making under uncertainty."

In somewhat more detail, the expected utility theorem states under fairly general conditions that the decision maker will choose among risky alternatives as if he were maximizing the expected utility associated with uncertain alternatives. This is not the place to list the axioms upon which this important theorem rests. Suffice it to say that the use of expected utility in decision analysis began with David Bernoulli, the eighteenth century mathematician, was placed on a solid logical foundation by von Neumann and Morgenstern, and is now widely used in operations research, economics, and decision analysis as a framework for analyzing choices with stochastic consequences.

In the first section of the paper, the basic model is presented which, with appropriate interpretation, suffices as an analytical structure for both the incendiarist's decision problem and the decision problem confronting nonincendiarists. In the next sections, the analysis is focused on incendiary ignitions for the case where punishment is by fines only. The sensitivity of incendiary activity to several policy changes is investigated. In a following section, prison sentences are added to fines as a possible punishment for incendiarism and the effects of the same policy changes are explored. Finally, the time allocation decision to activities designed to prevent ignitions (precautionary activities) is briefly examined.

B. The Model

For analytical purposes, it is convenient to classify wildland users as being either incendiarists or nonincendiarists, since incendiarists have distinctly different motives for entering wild areas than any other group of wildland users. Following this classification, ignitions are categorized as either incendiary or nonincendiary (due to negligence, carelessness, accident, etc.) in origin. Both incendiary and nonincendiary ignitions are viewed as the outcome of a time-allocation decision with uncertain consequences. More precisely, the incendiarist is viewed as making a decision as to how much time to spend planning and executing ignitions, while any other wildland user (hiker, camper, logger, etc.) is viewed as making a decision as to how much care to exercise with ignition sources and hence how much time to allocate to (fire) precautionary activity. The outcome of the time-allocation decision is uncertain since once a fire is started the individual may be apprehended and subjected to a fine, a prison term, or both.

The central concept in our analysis of the time allocation to incendiary activity (model 1) or precautionary activity (model 2) is the individual's utility function. This function contains all information pertaining to the individual's evaluation of the various "states of the world," and as such, provides a ranking of "states of the world" in terms of relative worth as perceived by the individual. We denote the utility function as $U(W,L)$, where W represents the individual's wealth and L his time allocation to incendiary activity (model 1) or precautionary activity (model 2). The function $U(W,L)$ yields the decision maker's evaluation of his well-being over all wealth levels and time allocations.

Generally, one would expect $U_W > 0$* since people usually prefer more wealth to less wealth. For the case of the first model $U_L > 0$ since the planning and starting of fires is a desirable activity in the eyes of an incendiarist. (Starting fires is "enjoyable.") In model 2, the function U_L will be everywhere negative since the more time one spends on activities designed to prevent ignitions, the less time one has for whatever the primary purpose of the wildland visit might be (lumbering, recreation, etc.).** One additional point: Suppose W^* and W' are two different wealth levels and $W^* > W'$. Then, for any values of L, we know that U_W is larger when evaluated at W^* than at W', but how much larger (how much better off the individual is) depends upon the individual in question.

The following definitions will be used:

$D(L) \equiv$ the damage caused by a fire. In model 1, damage is a function of the amount of time the incendiarist spends planning and executing ignitions. It seems reasonable to assume that the more time spent the higher will be the damages. That is, $D'(L) > 0$. Obviously, $D(0) \equiv 0$. In model 2, it seems quite natural to assume that the more time one spends taking precautions against fire starts, the lower will be losses. That is, in model 2 $D'(L) < 0$.

$p \equiv$ the individual's estimate of the probability he will be apprehended if he starts a fire (either intentionally or through carelessness, accident or neglicence).†

$W^o \equiv$ the individual's "initial" wealth.

$F \equiv$ the fine as a proportion of fire damages, $0 \leq F \leq 1$.

$W \equiv W^o - FD(L)$, the individual's wealth if apprehended.

According to the expected utility theorem, the time allocation decision will be made by the individual as if it were the solution to

*Differentiation is indicated by a subscripted letter and, when no ambiguity exists, by a prime.

**For a general analysis of the allocation of time under uncertainty, see (Block and Heineke, 1972, 1973).

†The line between negligent and accidental ignitions is hazy at best. In this paper, the position is taken that there would be no careless or accidental ignitions if sufficient time were spent preventing them. It then follows that all nonincendiary fires are attributable to negligence, since they could have been prevented.

$$(1) \qquad \max_{L} \left\{(1 - p)\ U(W^o,L) + pU(W^o - FD(L),L)\right\}$$

subject to the condition that $W,L \geq 0$. The necessary condition for a relative maxima in L is

$$(2) \qquad H_L = (1 - p)\ U_L^1 + p\left[U_W^2(-FD') + U_L^2\right] \leq 0\ ,$$

where $H \equiv (1-p)U(W^o,L) + pU(W^o - FD(L),L)$, $U^1 \equiv U(W^o,L)$ and $U^2 \equiv U(W^o - FD(L),L)$. Since the qualitative properties of the model depend upon the interpretation given the functions U_L and $D(L)$, at this point the analysis is divided into two parts, the time allocation to incendiary activity and the time allocation to precautionary activity.

C. The Time Allocation to Incendiary Activity (Model 1)

In this model, L is the time spent planning and starting fires and, as indicated previously, $U_L > 0$. Inequality (2) indicates that there are two fundamentally different methods of combating incendiarism. Since by inequality (2) it is clearly possible to eliminate incendiarism if "tastes" can be changed sufficiently, the first approach would rely on theraputic or educational programs aimed at "taking the fun out of fire." Whether in practice such a "Skinnerian" approach is feasible is quite another matter.

The second approach to combating incendiarism is economic in method. Intuition leads one to suspect that increasing p or F or both should result in decreases in incendiarism. The reasoning is simple: Increases in either of these policy variables has the effect of increasing the expected costs of starting fires and hence will tend to deter incendiarism. Unfortunately, such reasoning is not valid in general as examination of inequality (2) indicates. Since F and p enter both U_W^2 and U_L^2 it will not be possible to determine the response of L without further analysis. In any event, it will generally not be desirable to adopt policies which completely deter incendiarism (if such policies exist). Of course, the reason for this is that investigating the origins of fires, apprehending those who start them, and then convicting them in a court of law is a resource consuming process. It will be desirable to plow resources into these activities only as long as increases in expenditure yield even greater decreases in losses. Typically, the optimal policy will be to tolerate some incendiarism and, in this case, the marginal response of L to policy changes is of interest. To explore this question in more depth, we consider the responsiveness of L to changes in wealth, the severity of punishment, and the level of enforcement.

D. Incendiary Activity and Wealth

The first question to be examined is the response of incendiary activity to changes in the level of wealth, W^o. This may be accomplished by differentiating (2) with respect to W^o, keeping in mind that the solution to (2), say L^*, is a function of p, F, and W^o.* In this case

$$(3) \qquad \partial L^*/\partial W^o = \left[pFD'U^2_{WW} - (1-p)\,U^1_{LW} - pU^2_{LW}\right]/H_{LL} .$$

Although the denominator of (3), H_{LL}, must be negative for an interior relative maxima and p, F, and D' are each positive, signing (3) will require, at a minimum, some assumption about the signs of U^2_{WW} and EU_{LW}.

The function U_{LW} measures the sensitivity of U_L to changes in wealth, where U_L represents the "enjoyment" the incendiarist derives from planning and executing ignitions (at the margin). The question to be answered at this point is what effect small changes in wealth have on the marginal psychic rewards to incendiarism? It would seem to be acceptable as a first approximation to assume that these psychic rewards are invariant in wealth. The sign of $\partial L^*/\partial W^o$ will then be determined by U_{WW}, the individual's behavior toward risk. Since both risk neutrality and risk preference seem to be at odds with most observed behavior, analysts usually infer from the available evidence that individuals tend to be risk averse, an assumption we shall accept.** In this case

$$(3') \qquad \partial L^*/\partial W^o > 0 .$$

For those individuals who "enjoy" starting fires, incendiarism is a normal activity. This conclusion obviously assumes that "tastes" do not change with wealth. For example, if increased wealth were automatically accompanied by an "emotional maturity" that made incendiarism repugnant, then inequality (3') would not hold. But, since there is little evidence that wealth induces such character transformations, we may conclude that as long as incendiary activity is punishable only by fine, transfer payments of any kind will exacerbate the wildfire problem. As is implicit in the last statement, punishment which includes prison sentences <u>may</u> alter this conclusion, a point returned to below.

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*This procedure requires that inequality (2) hold as an equation and that the Jacobian associated with equation (2) be nonzero at L^*. These conditions are assumed to hold for the remainder of the paper.

**The reader unfamiliar with the concept of behavior to risk may consult the brief introduction to this subject in the Appendix.
Note that risk aversion in wealth, $U_{WW} < 0$, in no way prevents the incendiarist from being a risk taker in L, $U_{LL} > 0$. For a discussion of behavior toward risk in arguments of U other than wealth, see (Block and Lind, 1972).
The two assumptions $U_{LW} = 0$ and $U_{WW} < 0$, will be maintained throughout.

E. Incendiary Activity and Fines

In this section the response of incendiary activity to changes in the severity of the punishment is considered. At this point, the "severity of punishment" is given by the magnitude of the fine. The response of the incendiarist's time allocation to changes in the magnitude of the fine is given by

$$(4) \qquad \partial L^*/\partial F = \left(pD'U_W^2\right)/H_{LL} + Dp\left(U_{LW}^2 - FD'U_{WW}^2\right)/H_{LL} \ .$$

Under the assumptions adopted, both terms in this sum are negative and

$$(4') \qquad \partial L^*/\partial F < 0 \ .$$

Increasing the severity of monetary punishments has a deterrent effect on incendiary activity.

It should be kept in mind that this result does not imply that it will be possible to reduce incendiarism to zero or to any other arbitrary level by increasing the fine sufficiently. The reason for this lies in the limit on the magnitude of fines which is imposed by the nonnegativity constraint on wealth. Clearly, it may not be possible to increase F sufficiently to reduce L^* to some desired level and still have $W \geq 0$. In other words, the effectiveness of fines is limited by "ability to pay." Even if W^o is interpreted as the discounted life-time earnings of the individual, the same problem may appear. Of course, the "more fun" it is to start fires (the larger is EU_L), the more difficult it will be to deter such activity via fines or any other means.

In summary, the effectiveness of fines in combating intentional ignitions is limited by the "ability to pay" on the part of incendiarists. If perceived benefits are high, it may not be possible to raise monetary costs enough to reduce incendiary fires to the desired level. This seems to be especially true for those individuals with little wealth to lose. Of course, "costs" can be increased through a combined program of fines and incarceration. (In less humane times, "costs" were increased much more directly; for example, burglary was often punished by amputation of an offending hand.)

F. Incendiary Activity and Enforcement

We next investigate the response of incendiary activity to changes in the level of enforcement. The enforcement variable is p, the probability of apprehension once a fire is started and, like F, is a policy variable in the model. Differentiation of equation (2) yields

$$(5) \qquad \partial L^*/\partial p = \left(U_L^1 - U_L^2 + FD'U_W^2\right)/H_{LL} \ .$$

It can be shown that

$$(5') \qquad \partial L^*/\partial p < 0 \ ,$$

independent of any assumption about the individual's preferences other than behavior in accordance with the axioms of the expected utility theorem.* In particular, no assumption about U_{LW} is needed, nor is any needed about the individual's behavior toward risk.

There is one crucial assumption behind both this result and the "fine result." In each case it is implicitly assumed that policy changes are perceived by the potential incendiarist. If p and F are changed unbeknownst to potential offenders, there will be no decrease in ignitions. In other words, the model does not explain the relationship between the individual's perception of, say, the probability of apprehension and the actual value of this parameter. It is the individual's perception of consequences and the associated subjective probabilities, and not the actual consequences and the actual probabilities, that are important. Now, there are many cases where it is reasonable to assume that individual assessments of the likelihood of various consequences will bear a close relationship to the actual relative frequency, but it is clear that effective communication of changed policies is a necessary condition for inducing changes in behavior.

G. Enforcement Versus Fines: The Relative Effectiveness

It has been shown that increases in either the probability of apprehension or the severity of the fine will have a deterrent effect on incendiary activity. The obvious extension of the analysis is to ask, "which is most effective?" That is, would a one-percent increase in p or a one-percent increase in FD (by increasing F) have a greater impact in reducing incendiarism?

To anser this question, consider a simultaneous change in p and FD which leaves the expected punishment unchanged, i.e., $d(pFD) = 0$. Increasing p and decreasing F so that the expected punishment is unchanged is a formal method of determining which of the two policy variables has the larger deterrent capability. The requirement on the expected fine is then

$$d(pFD) = 0 = pdFD + FdpD$$

*To see this, note that for internal solutions, the first order conditions may be written as $U_L' = p[U_L^1 - U_L^2 + FD'U_W^2]$. Since $U_L^1 > 0$, the right-hand side of this expression is positive. But the right-hand side is the numerator of (5) and hence $\partial L^*/\partial p < 0$.

so that

$$(dF/dp) = -(F/p)$$

is the condition that insures that expected punishment is unchanged when p and F are both varied. Calculation of $\partial L^*/\partial p$ when this condition holds, yields:

$$\left.\frac{\partial L^*}{\partial p}\right|_{d(pFD)=0} = \frac{\partial L^*}{\partial p} - \frac{\partial L^*}{\partial F}\left(\frac{F}{p}\right) . \tag{6}$$

The terms $\partial L^*/\partial F$ and $\partial L^*/\partial p$ were derived and signed above in equations (4) and (5). Since each is negative, $\partial L^*/\partial p$ and $-\partial L^*/\partial F(F/p)$ are of opposite sign. If the sign of equation (6) is determinable, then one of these two opposing effects dominate--which one depends upon the sign.

Using equations (4) and (5), equation (6) may be rewritten as

$$\left.\frac{\partial L^*}{\partial p}\right|_{d(pFD)=0} = \left[U_L^1 - U_L^2 + DF\left(FD'U_{WW}^2 - U_{LW}^2\right)\right]\Big/H_{LL} \tag{6'}$$

and hence

$$\left.\frac{\partial L^*}{\partial p}\right|_{d(pFD)=0} > 0 . \tag{6''}$$

Percentage increases in the probability of apprehension will deter incendiarism less than will equal percentage increases in fines.* This important result holds for risk averse individuals for which $U_{LW} \geq 0$ and in penalty systems which are based on fines only.

The results shown as inequalities (3'), (4'), (5'), and (6") rest upon several assumptions about individual preferences and underscore an important, although somewhat pedantic point: Policy recommendations in general, and policy recommendations designed to deter incendiarism in particular, rest upon assumptions about the preferences of individuals. For example, in a penalty system based on fines only, a sufficient condition for the recommendation that the probability of apprehension be increased as a means of deterring incendiarists, is merely that individuals act in accordance to the axioms of the expected utility theorem. No other preference information is necessary. On the other hand, deducing

*That is, the second term in equation (6) dominates the first.

the deterrent capabilities of fines requires additional preference restrictions. For example, for risk averse individuals, unambiguous deterrence via fines requires $U_{LW} \geq 0$.

H. Prison Sentences and Fines as Punishment

We have seen that the wealth of an individual imposes limits upon the monetary penalty which can be assessed. This is an exceedingly important point in the design of a system of penalties. Should penalties be fines or prison sentences? This question is briefly explored in this section as an extension of the previous model. It is assumed that both fines and prison sentences are possible penalties if an incendiarist is apprehended.

The individual's utility function is $U(W,L,S)$ where S represents the time length of a prison sentence. Obviously, $U_S < 0$. The expected utility associated with L "hours" on incendiary activity is

$$(1 - p)\ U(W^o,L,0) + pU(W^o - FD(L),L,S)\ . \tag{7}$$

The individual will choose the amount of time to spend at incendiary activity as if he were maximizing (7). The level of incendiary activity is then given by solving

$$(1 - p)\ U_L^1 + p\left[U_W^2(-FD') + U_L^2 + U_S^2 f'\right] \leq 0 \tag{8}$$

for L, where sentence length is assumed to be a positive function of L, i.e., $S = f(L)$ and $f'(L) > 0$. As before, superscripts on functions indicate the point where the function has been evaluated.

Calling the solution to (8) L^o, the three "policy derivatives" from above are now repeated in this more general context:*

$$\partial L^o/\partial W^o = \left[pFD'U_{WW}^2 - pf'U_{SW}^2 - E(U_{LW})\right]/H_{LL} \tag{9}$$

$$\partial L^o/\partial F = \left[pD'U_W^2\right]/H_{LL} + Dp\left[U_{LW}^2 + f'U_{SW}^2 - FD'U_{WW}^2\right]/H_{LL} \tag{10}$$

$$\partial L^o/\partial p = \left[U_L^1 - U_L^2 + FD'U_W^2 - f'U_S^2\right]/H_{LL} \tag{11}$$

*Only "internal" solutions to (8) are considered in what follows.

The only unsigned term in these expressions is U_{SW} for which there would seem to be an obvious choice, viz. $U_{SW} < 0$--increasing the length of a prison sentence "hurts" more the wealthier one is. Or, equivalently, increases in sentence length become more disagreeable the more that is given up.

Inspection of equations (9) and (10) reveals that the effects on incendiary activity of changes in wealth levels and the effects of changes in the amount of the fine are inherently ambiguous when penalties are a mixture of fines and prison sentences. In a penalty system based upon fines only, increased wealth and increased fines have incentive and disincentive effects, respectively, on incendiary activity. But if the penalty system is a mixture of fines and sentences, the effects of the same wealth and fine changes are qualitatively ambiguous. Of course, increases in, say, fines may deter incendiary activity but at this level of generality it is impossible to say for sure.

Although $\partial L^o/\partial W^o$ is qualitatively ambiguous, equation (9) does reveal one interesting conclusion that can be drawn about policies directed toward changing wealth levels: If incendiarism is punishable only by prison sentences $(F \equiv 0)$, then

$$(12) \qquad \partial L^o/\partial W^o < 0 \ .$$

Increases in affluence will deter incendiary activity. Wealth increases have incentive effects in a fine-only penalty structure and disincentive effects in a sentence-only penalty structure. This result not only explains the ambiguity of the mixed fine-sentence penalty structure, but also has interesting policy implications.

The only remaining policy variable in the model is the enforcement variable p. It was shown above that increases in the probability of apprehension had deterrent effects on incendiary activity if punishment was by fine. This result required no preference information other than behavior in accordance with the expected utility theorem. According to equation (11), the same conclusion may be drawn about increases in the probability of apprehension in a mixed fines-sentences penalty structure. That is,

$$(13) \qquad \partial L^o/\partial p < 0 \ .^*$$

This remarkable result requires only that incendiarists be expected utility maximizers. So, whether penalties are fines or a mix of fines and prison terms, increases in the probability of apprehension will unambiguously deter incendiarism.

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*The proof of this statement is identical to that presented for inequality (5').

I. The Allocation of Time to Precautionary Activity (Model 2)

In this final section, we examine the factors which influence the individual wildland user's decision as to how much care to exercise with ignition sources (the time allocation to precautionary activity). This is a particularly simple task since each of the above equations remains valid after some reinterpretation. First, the variable L is now interpreted to be the amount of time allocated to precautionary activity; the function $D(L)$ then expresses the damages as a function of precautionary activity. Obviously, $D'(L) < 0$. Finally, U_L is now everywhere negative since the more time one spends on activities especially designed to prevent ignitions, the less time is left for logging, recreation, or whatever might be the primary purpose of one's presence in the wildland area. As was indicated previously, it does not seem to be productive to differentiate between "accidental" fires and fires due to "negligence." This is due to the fact that virtually all ignitions could be eliminated if enough time were spent "being careful" (at precautionary activity). In this sense, all nonincendiary, man-caused fires are due to negligence. Finally, it is assumed that nonincendiary ignitions are civil offenses and, hence, punishable only by fines.

With these changes, equation (2) above determines the amount of time allocated to precautionary activity, say, L'. The response of L' to changes in wealth levels, fines, the probability of apprehension, and fine compensated changes in the probability of apprehension is given in equations (3), (4), (5), and (6') above, respectively. Keeping in mind the qualitative changes in the several functions which were discussed in the previous paragraph, these policy derivatives become

$$(3'') \qquad \partial L'/\partial W^{o} < 0$$

$$(4'') \qquad \partial L'/\partial F > 0$$

$$(5'') \qquad \partial L'/\partial p > 0$$

$$(6''') \qquad \partial L'/\partial p \Big|_{d(pFD)=0} < 0$$

Each response is consistent with what one's intuition would advise. Increases in wealth levels will in general cause less time to be devoted to precautionary activity, everything else being the same. Increasing the severity of fines will cause wildland users to be more careful. Again, for this incentive effect to be realized, the structure of fines for wildfire starts must be communicated (i.e., the "F" in inequality (4") is the individual's perception of the fine, not the actual fine).

Inequality (5") indicates that increases in the probability of being apprehended if one is responsible for an ignition, will increase the time one spends trying to prevent ignitions.* So, both increases in enforcement and increases in the severity of punishment provide unambiguous inducements to wildland users to be more "fire careful," while increases in wealth have the opposite effect. Finally, since $D' < 0$ for precautionary activity, inequality (6''') reinforces the previous result concerning the relative effectiveness of fines and enforcement in deterring incendiarism. Once again, fines are seen to be relatively more effective in reducing wildfire ignitions.

J. Summary and Conclusions

In this study, wildfire ignitions were classified as either incendiary or nonincendiary in origin. And even though the motivation of incendiarists and nonincendiarists are vastly dissimilar, we have found that policy prescriptions imploring increased enforcement as a means of deterring both types of man-caused wildfires are on firm theoretical ground. In each case, increases in apprehension probabilities unambiguously induce the desired changes in behavior. Even more surprising was the fact that this result was invariant to the type of penalty and required no assumption about preferences other than expected utility maximization on the part of the individual in question.

The policy effectiveness of fines was also investigated. For the class of risk-averse wildland users (incendiarists and nonincendiarists) the assumption $U_{LW} = 0$ was shown to be sufficient to establish the deterrent capabilities of fines, as long as fines were the only form of penalty. In addition, this same assumption was seen to imply the superiority of fines relative to enforcement in deterring all types of wildfire ignitions. Finally, we found that if penalties were fines, then incendiarism is a normal activity and precautionary activity is inferior. Only when incendiarists are punished exclusively with prison terms does incendiarism become an inferior activity.

*Again, a sufficient condition for this result is merely that the individual be an expected utility maximizer.

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Appendix IX

BEHAVIOR TOWARD RISK

A decision maker's behavior in the face of risk is usually described in terms of the wealth argument of his utility function. If, when confronted with a choice between an uncertain prospect with expected returns W^o and a certain prospect with returns W^o, the decision maker prefers the certain prospect, he is said to be risk averse. In other words, risk-averse decision makers require a more than fair bet before surrendering a certain return and prefer a certain return of less than W^o to a gamble with expected return W^o.

There are obviously two other general categories of behavior toward risk, risk neutrality, and risk preference. A risk-neutral decision maker is indifferent between the above uncertain prospect and a certain prospect of W^o, while individuals with a preference for risk prefer the uncertain prospect to its expected value as a certainty. Both risk neutrality and preference seem to be at odds with most observed behavior. The existence of vast insurance markets and the fact that individuals typically diversify their asset holdings, accepting less than maximum expected returns, are clear testimonials to risk aversion. The only example of risk preference commonly cited is the existence of gambling. But even in this case, it is likely that most serious gamblers feel they have a "system" which insures them a more than fair gamble. If so, gambling is also consistent with risk aversion. In any event most analysts infer from the available evidence that individuals tend to be risk averse, an assumption we shall accept. In terms of the utility function, risk aversion means that possible gains are held to be worth less than an equiprobable loss, i.e., U_W is falling in wealth $(U_{WW} < 0)$.

Chapter X

A MODEL OF IGNITIONS AND DAMAGES, WITH APPLICATIONS TO ACTIVITY REGULATION

LIST OF FIGURES

Chapter X

A MODEL OF IGNITIONS AND DAMAGES, WITH APPLICATIONS TO ACTIVITY REGULATION*

A. Introduction

This chapter is concerned with the subject of fire control through ignition prevention. A model of man-caused ignition generation will be developed which, together with a model for fire damages and for decision costs, can be used to determine prevention decisions that minimize the expected value of cost-plus-loss. The model can conceptually treat any prevention decisions; it will, however, be applied in detail to entry and activity regulation. The model can also treat decisions other than ignition prevention, such as fuel modification, fire-break construction, and structure protection measures, permitting an optimization to be ultimately performed over a full range of fire control decisions; some of these decisions are treated in Chapter XI.

The main purposes of this chapter are two-fold: First, to provide a definitional and conceptual framework for putting prevention management on a badly-needed firm logical foundation; it is hoped that it will in this sense contribute to the beginning of systematic and rigorous prevention planning.** Second, a number of specific results are obtained for the particular prevention technique of activity regulation; optimal decision rules are found and some of their properties and policy implications explored.

The fullest use of the ignition model would lead to the determination of the optimum set of ignition prevention decisions under uncertainty. Measurement as well as control decisions would be considered. Although such comprehensiveness is beyond the scope of this study, it is hoped that this work may be a beginning in this direction.

One specific use of the ignition model, more restricted than the above, also deserves mention here, although it, too, will not be developed in detail. Often it is of interest to determine the effectiveness of various prevention programs such as education, enforcement, inspection, and roadside or campground fuel modification; it is also of frequent interest to determine if ignitions from various sources are more or less frequently occuring than in the past, due to effects other than conscious fire-management decisions (the two problems are clearly of the

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*This chapter was prepared by J. Heineke and S. Weissenberger.

**Presently, such management is largely characterized by intuitive judgments and ad-hoc decisions. For example, in (USFS, 1972b) the simple and unlaborated advice is given that "if the probability of man-caused fires is high, some additional resources of the unit probably should be diverted to patrol and prevention work." It is the purpose of this study to add detail, clarity, and rigor to such prescriptions.

same sort). Using the ignition model to be presented shortly, standard statistical techniques can be used in conjunction with fire occurrence data to tell fire control managers whether or not the evidence supports a conclusion of a significant increase or decrease in the frequency of fire starts.

The following is a brief outline of the chapter, with a summary of the main results. It may serve either as a substitute for a reading of the remainder or as a guide through the analytical detail of the main development, depending on the reader's interests.

In Section B, a mathematical model of ignition generation is developed. The probability of k ignitions being caused by a particular activity in a given time period T is expressed as a function of a number of variables, including activity type i, the number of users x_i engaged in the activity, the time period T, the ignition index ("ignition component") I, and a parameter λ_i, the mean number of ignitions per user-day by activity and ignition index, which may be estimated from fire data. This probability is found to be given by the Poisson distribution

$$(5) \quad P_i(k;x_i,I) = e^{-\lambda_i T}(\lambda_i T)^k/(k)! , \qquad k = 0,1,2, \ldots$$

where

$$(7) \qquad \lambda_i = \lambda_i(x_i,I) .$$

The mean number of ignitions in any period T is given by $\lambda_i T$. Properties of (5) and (7) and associated basic assumptions are discussed in detail in Section B. A simple case arises when λ_i depends on x_i linearly,

$$\lambda_i = \lambda_{io}(I)\ x_i .$$

Then λ_i may be determined from the ignition history for the i^{th} activity simply through the calculation of the quantities $\lambda_{io}(I)$,

$$(13) \qquad \lambda_{io} = N_i(I)/X_i(I) ,$$

where $N_i(I)$ is the total number of ignitions due to the i^{th} activity for ignition index I in some time period and X_i is the total number of user-days in the i^{th} activity, for ignition index I in the same period.

The probability distribution of damages per fire is introduced in Section C. It is shown there that if the probability of fire occurrence is given by (5) and if the distribution of damages does not depend on the number of fires occurring in any given time period, then the expected damage $E(S)$ due to fire over a period T for all n activities is given by

$$(21) \qquad E(S) = T \sum_{i=1}^{n} \lambda_i E(d_i)$$

where $E(d_i)$ is the expected total cost-plus-loss ("damages") due to a fire ignited by the i^{th} activity. Thus the expected total damage is equal to the sum of the expected damages from each activity, which are in turn simply equal to the product of the expected number of ignitions and the expected fire damage per ignition in the particular activity. It is important to note that the expected damages $E(d_i)$ will be functions of the burning index as well as various fuel modification and suppression parameters, although the latter two effects are not exploited in this chapter.

In Section D, the expected loss expression (21) is used as the basis for a detailed investigation of optimal activity regulation. Decision rules are derived under a variety of conditions to minimize total expected cost-plus-loss. Under certain plausible assumptions, the optimal decisions turn out to be the following: satisfy <u>all</u> of the demand or satisfy <u>none</u> of the demand, for each of the activities, on the basis of the sign of a function ψ_i which is the difference between the total costs of complete activity prohibition and the total costs of complete activity allowance.

The decision rules take on a particularly simple form if costs, expected damages, and the expected number of fires are linear functions of user-days, burning index, and ignition index. Then, a quantity, the "risk," r_i, may be defined as

$$(34) \qquad r_i \equiv \mu_{io}\alpha_i / c_{io}$$

where

$\alpha_i \equiv$ mean number of fires per user-day per ignition index in activity i

$\mu_{io} \equiv$ mean \$ cost-plus-loss per fire per unit burn index in activity i

$c_{io} \equiv$ \$ cost of prohibiting activity i per user day (administrative + opportunity costs)

A "Fire Load Index" F_i may then be defined as

$$F_i \equiv r_i IB \tag{35}$$

where I is the ignition index and B is the burning index, a form which is structurally analogous to that proposed in the Fire-Danger Rating System (USFS, 1972a), the differences being that "risk" takes into account expected damages and costs, and the fact that the new index F_i is defined for each ignition generating activity.

In terms of the new index F_i, decisions are: allow all of activity i if $F_i < 1$ or allow none of activity i if $F_i > 1$. F_i has a meaningful interpretation as

$$F_i = \frac{\text{expected \$ cost + loss per user day from admission to activity } i}{\text{\$ cost per user day from exclusion from activity } i}$$

If policies dictate that all activities be either prohibited or permitted together, then a similar all-or-nothing decision should be made for all activities on the basis of a single Risk value r,

$$r \equiv \sum_{i=1}^{n} \mu_{io}\alpha_i \Big/ \sum_{i=1}^{n} c_{io} \,, \tag{41}$$

and a single Fire Load Index F,

$$F \equiv rIB \,. \tag{42}$$

In Section F, the effect of a budgetary constraint on the fire protection agency is considered. Modifications of the entry and use decisions are determined for this case.

In Section G, the sensitivity of costs to measurement errors is considered. With respect to the quantity F_i, it is shown that under high fire-danger conditions, relatively inaccurate measurements may be tolerated without cost.

Finally, in Section H, the problem of calculating wildland values is considered, both for the purpose of estimating fire losses and for estimating the opportunity costs of various activities. Since the existence of a market makes evaluation straightforward, this section concentrates on those uses of wildlands for which there are not active markets. An evaluation procedure is outlined for these cases, and some of the relevant literature is listed.

One last remark is appropriate regarding the sphere of application of the results of this chapter. The primary prevention technique described here is activity regulation and hence direct application of these results are limited to the Forest Service. It should be noted, however, that this work may be extended to include decisions on the timing and intensity of other prevention activities, including those engaged in by the Division of Forestry such as roadside fuel modification, incendiary surveillance, and various inspection programs.

B. Ignition Model

The block diagram of Fig. 10.1 describes the process of fire control, specifically with regard to ignition prevention decisions. Decisions, shown circled, fall into two important classes:

(1) "Control" decisions

(a) activity control decisions, involving the determination of the number of users x_i allowed to engage in activity i, $i = 1,2,\ldots,n$, denoted collectively by the vector $\underline{x}$.* A user may be an individual, an organization, or simply an identifiable activity unit. One user may be engaged in more than one activity. Examples of x_i are the number of campers, off-the-road vehicles, debris burners, children, incendiarists, and loggers (by type of logging activity).

(b) other prevention decisions, including determination of the type of education and fuel modification to be undertaken and the allocation to each. Also includes the type and severity of penalty for incendiary and negligent fire starts and the allocation to go into enforcement. These prevention decisions are devoted collectively with the vector $\underline{q}$.

(2) Measurement decisions, involving determination of the optimal allocation to activities designed to reduce measurement uncertainty. These decisions specify the degree of uncertainty to be permitted regarding:

(a) the "true" state of nature represented here by a generalized fire danger rating, FDR, which in general has multiple components. The measured fire danger rating $\widetilde{FDR}$, is a random variable and will in general differ from the true value. The resulting error will have an associated cost and hence some benefit will be associated with error reduction.

*Vectors are denoted by an underbar.

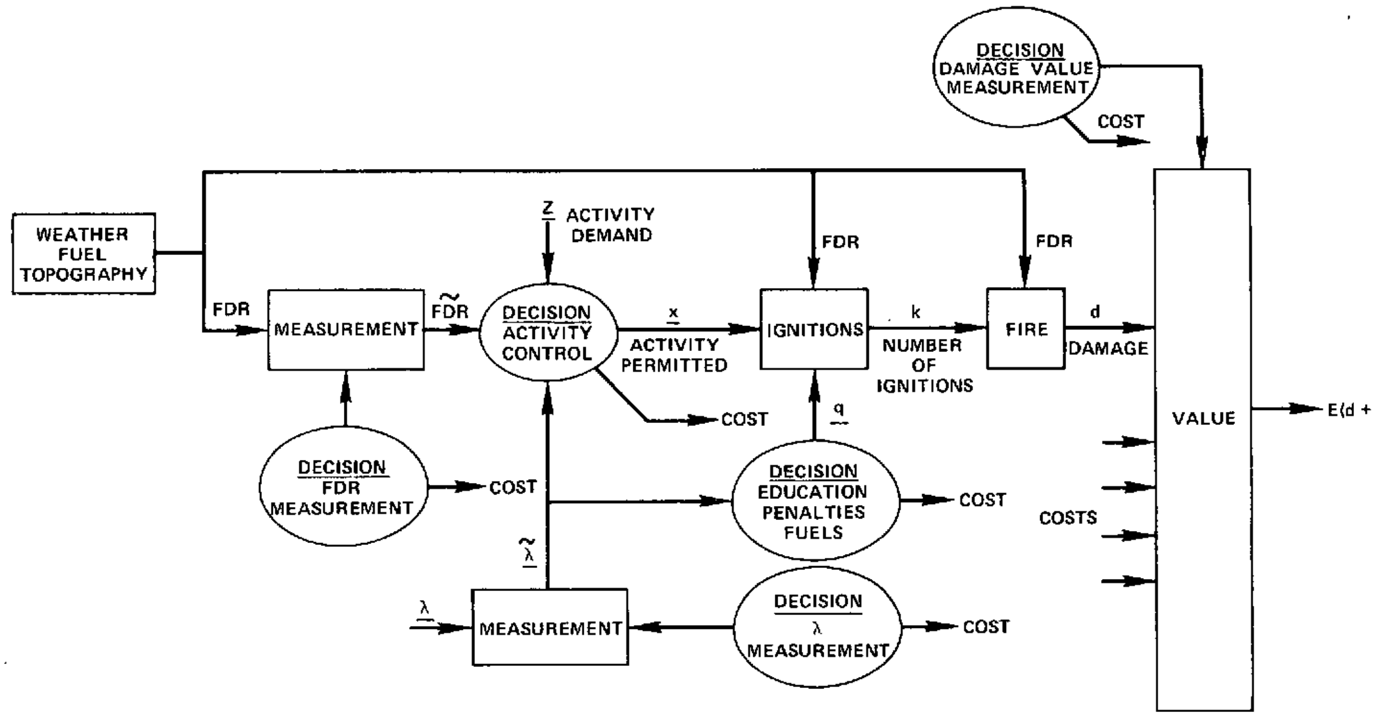

Figure 10-1 Block Diagram of the Ignition-Prevention Process

(b) the mean number of ignitions by activity $\underline{\lambda}$. Again, costs will be associated with variance in the measured value of $\underline{\lambda}$, $\tilde{\underline{\lambda}}$.

(c) the value of damages and costs.

The ultimate criterion of system performance is assumed to be the expected value of total fire control cost plus fire loss (in dollars) and decisions will be taken so as to minimize this quantity. It should be noted, however, that the physical quantities expected fire damage and the number of fires may be in themselves useful measures of system effectiveness: Certain inefficient decisions may be discarded on this physical basis alone without assigning prices to physical damages.

The ignition model is described schematically in Fig. 10.2. Its output, the probability of k ignitions in activity i, is conditional on the length of the time period T (in days) (time periods of length T in the summer will normally be associated with higher ignition probabilities than periods of the same length in the winter); the number of users by activity $\underline{x}$;* the prevention state $\underline{q}$; the ignition index I;

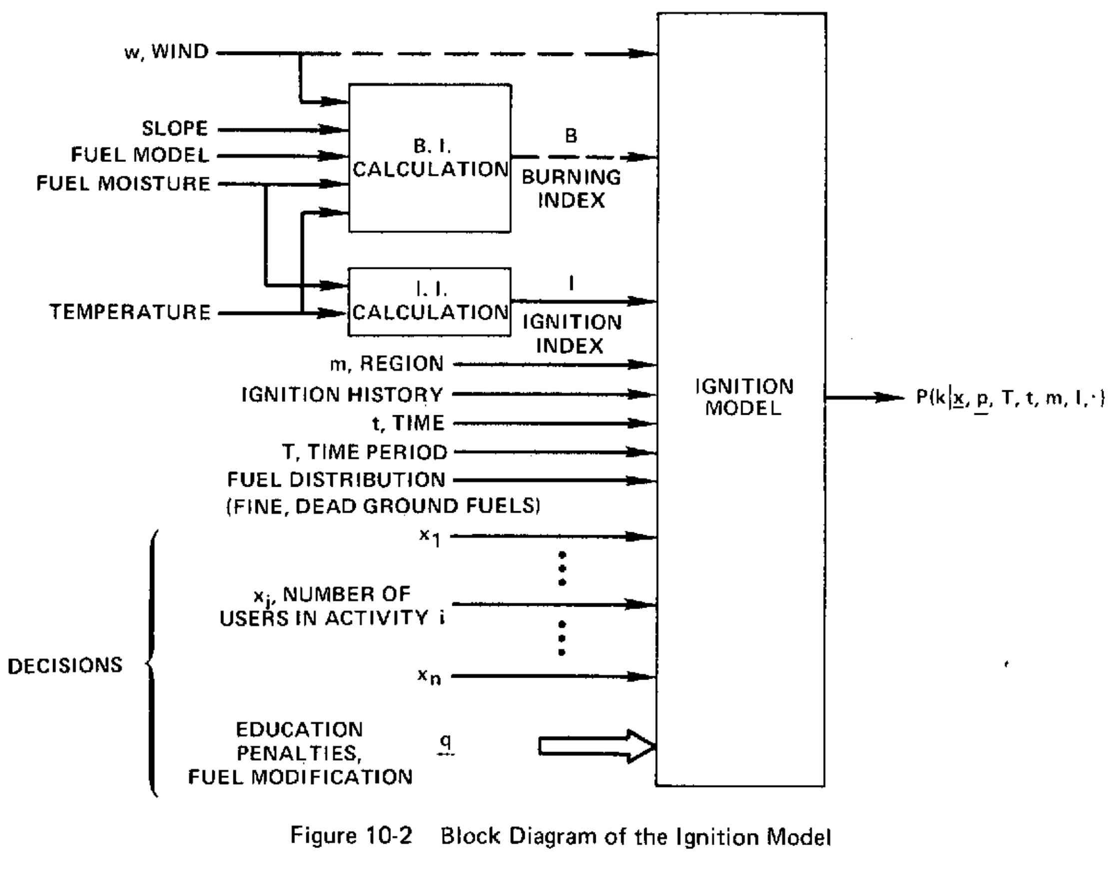

Figure 10-2 Block Diagram of the Ignition Model

*The variables x_i will be considered to be continuous in the subsequent analysis.

the specific area m (included in m is the distribution of fine, dead ground fuels in the area and the ignition history of the area); and finally, ignition probabilities may depend upon the burning index B and the wind W.* All indices and states of nature are initially assumed to be known. (See Chapter VIII for the U.S. Forest Service definition of the indices I and B. Note that our terminology "ignition index" for I is at variance with the USFS "ignition component.")

Each user in each activity is a potential source of ignitions through the production of fire brands. The occurrence of an actual ignition depends on the type of user, the area, the point in time, the prevention state, and the ignitability of fuels, the latter of which is described by the ignition index. We assume that the j^{th} user in the i^{th} activity generates ignitions according to the Poisson probability law

$$(1) \quad P(k_{ij};I,m,\cdot) = e^{-\lambda_{ij}T}(\lambda_{ij}T)^{k_{ij}}/(k_{ij}!) , \qquad k_{ij} = 0,1,2, \ldots \quad **$$

where $P(k_{ij};I,m,\cdot)$ is the probability of k ignitions by the j^{th} individual in activity i and λ_{ij} is the mean number of ignitions per day for the j^{th} individual in the i^{th} activity.†

It is important to emphasize the naturalness of assuming that k_{ij} is Poisson distributed. To this point, recall that two major axioms must be fulfilled if (1) is to accurately represent the number of ignitions by the j^{th} user in activity i: First, the number of ignitions in any two nonoverlapping intervals must be independent. Given the particular user and the ignitability of fuels, there wolld seem to be little reason to suspect that the number of ignitions in one period in any way influences the number in another period.‡ The second axiom requires

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*B and W are shown as dashed lines in Fig. 10.2 because they are considered to be of minor influence on most ignition sources. Wind will affect the spread of fire brands and hence may be significant only for certain kinds of activities such as debris burning (Ryan, 1971). Although the burning index does not describe ignitability, it is probably highly correlated with the generation of incendiary ignitions (Ryan, 1971). (Since incendiarists have the explicit objective of starting fires of significant size, they tend to take burning conditions into account in making ignitions.) Also note that W and B will effect contagion ignitions which are not considered explicitly as ignitions _per se_, but are implicit in the model of damages below.

**The notation $(\cdot)$ is used to indicate conditional variables which are not given explicit citation, e.g., in (1) k_{ij} is conditional not only on I and m but also on $\underline{q}$, T, etc.

†We assume (1) is stationary over the period T, i.e., $\lambda_{ij}(t';\cdot) = \lambda_{ij}(t'';\cdot)$ for all $t', t'' \in T$.

‡A possible exception is incendiary activity by pyromaniacs.

that the probability of one ignition in a time interval Δt be proportional to Δt if Δt is sufficiently small, and that the probability of more than one ignition in this period be approximately zero. For the case at hand, this requirement is readily satisfied.

We now assume that the ignition production of any one individual is statistically independent of that of other individuals, but possibly dependent on the total number x_i of individuals in the area, i.e.,

$$(2) \qquad \lambda_{ij} = \lambda_{ij}(x_i, I, m, \cdot)$$

with

$$(3) \qquad P(k_{ij} | k_{rs}) = P(k_{ij}) \;, \qquad \begin{aligned} i,\ r &= 1,2,\ \ldots,\ n \\ j &= 1,2,\ \ldots,\ x_i \\ s &= 1,2,\ \ldots,\ x_r \end{aligned}$$

where k_{rs} is the number of ignitions produced by the s^{th} individual in activity r. The significance of equations (2) and (3) is that the expected number of ignitions produced by individual users may depend on the number of users, but that ignition events are statistically independent from one user to another across all activities: There is no direct causal connection between an ignition event of one wildland user and an ignition event of any other user.* For instance, people may become more careful with fire as more people use a given area, from the restraining effect of the surveillance of others; or firebrands may be extinguished with greater frequency when there is a higher density of use.**

For a collection of x_i individuals, the total number of ignitions in activity i, k_i, is the sum of the x_i independent random variables k_{ij}, the number of ignitions produced by each individual:

$$(4) \qquad k_i = \sum_{j=1}^{x_i} k_{ij} \;.$$

The probability distribution for the sum of independent random variables is the convolution of the individual probability distributions.† Since

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*Again, a possible exception might be that past ignition events actually trigger ignition generation by pyromaniacs.

**A more general specification of this relationship is obtained by writing (2) as $\lambda_{ij} = \lambda_{ij}(\underline{x}, I, m, \cdot)$: Mean ignitions in activity i by individual j depend upon the number of users in all activities.

†See (Feller, 1966), pp. 248-278.

individual ignitions are Poisson distributed, the distribution of the sum of the k_{ij} takes on the particularly simple form,*

$$(5) \quad P(k_i;x_i,I,m,\cdot) = e^{-\lambda_i T}(\lambda_i T)^{k_i}/(k_i!) \ , \qquad k_i = 0,1,2, \ldots$$

where

$$(6) \qquad \lambda_i = \sum_{j=1}^{x_i} \lambda_{ij}(x_i,I,m,\cdot)$$

$$(7) \qquad \equiv \lambda_i(x_i,I,m,\cdot)$$

is the mean number of ignitions per day for activity i as a function of the number of users of activity i, the ignition index, etc. Note that $\lambda_i(0,I,m,\cdot) \equiv 0$. The function λ_i may be estimated from the ignition history by regression analysis.

On <u>a priori</u> grounds, we make the following assumptions about the function λ_i:

$$(8) \qquad \partial\lambda_i/\partial x_i > 0$$

$$(9) \qquad \partial^2\lambda_i/\partial x_i^2 \leq 0$$

$$(10) \qquad \lambda_i(x_i,0,m,\cdot) = 0 \quad \text{and} \quad \partial\lambda_i/\partial I > 0$$

These assumptions are all obvious ones except perhaps for inequality (9), for which there is some evidence.** The following special cases are of interest:

$$(11) \qquad \partial^2\lambda_i/\partial x_i^2 = 0 \ ,$$

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*See (Feller, 1966), p. 252.

**(Telfer, 1969) as well as various fire prevention experts tend to support this view.

in which case

$$\lambda_i(x_i, I, m, \cdot) = \lambda_{io}(I, m, \cdot)x_i \quad \text{where} \quad \partial\lambda_{io}(I, m, \cdot)/\partial x_i = 0 \ ;$$

and also the case in which

$$\lambda_i(x_i, I, m, \cdot) = \alpha_i(m, \cdot)Ix_i \quad \text{where} \quad \partial\alpha_i/\partial I = \partial\alpha_i/\partial x_i = 0 \ , \tag{12}$$

and hence

$$\partial^2\lambda_i/\partial I^2 = 0 \quad \text{and} \quad \partial^2\lambda_i/\partial x_i^2 = 0 \ .$$

The determination of $\lambda_i(x_i, I, m, \cdot)$ for these cases is particularly simple. The function $\lambda_{io}(I, m, \cdot)$ may be calculated from the ignition history of an area simply as

$$\lambda_{io}(I, m, \cdot) = N_i(I)/X_i(I) \tag{13}$$

where $N_i(I)$ is the total number of ignitions due to the i^{th} activity for ignition index I and X_i is the total number of user-days in the i^{th} activity, for ignition index I. Both numbers are calculated for area m, a particular time period, given management policies, and any other parameters that actively affect λ_i. This procedure will generate a value of λ_i for each value of I. The collection of these values is an estimate of the function $\lambda_{io}(I, m, \cdot)$.

Finally, it is important to reemphasize two of the assumptions which underpin the ignition model:

(a) The probability distribution of the number of ignitions produced by one user in one activity in time period T is independent of the number of ignitions produced by any other user in that or any other activity in the same time period.

(b) The probability distribution of the number of ignitions in any time period T, is independent of the number observed in the preceding period.

The former assumption rules out phenomena such as pyromaniacal activity triggered by other fires, as well as intensification of an individual's precautionary activity resulting from the observation of fires (the one effect is in a sense the converse of the other; both represent modification of ignition generating behavior as a function of observed fires). The latter assumption rules out significant effects of fire history on ignitability, e.g., the time period T in the model cannot be so long that past ignition events begin to affect future ignition events through changes in the ignitability of fuels.

C. Fire Damage Model

In this section, a model of fire damages is derived from our basic model of individual ignition generations. To begin, we define the random variable d_{iv} as the loss associated with the v^{th} ignition in activity i. If there happen to be k_i ignitions in the period, the losses will be denoted $d_{i1}, d_{i2}, \ldots, d_{ik_i}$ and

$$(14) \qquad S_{ik_i} \equiv \sum_{v=1}^{k_i} d_{iv}$$

is the conditional random variable total losses in activity i given k_i ignitions. Deletion of the subscript k_i on S_{ik_i}, will be used to represent the total losses in activity i from a random number of ignitions. (That is, the variable S_i is not conditioned on the number of ignitions.) Finally, we define

$$(15) \qquad S \equiv \sum_{i=1}^{n} S_i$$

as the total fire losses across all n activities. We first derive the probability distribution of S_i, $f_i(S_i)$, using the fact that the number of ignitions in activity i, $i = 1,2,\ldots,n$, is governed by the probability law given by equation (5), and then use (15) to obtain needed information about the density of S, $f(S)$.

In general, the distribution of loss from the v^{th} ignition in activity i is conditioned both by decisions which have been made prior to the period and by the "state of nature." In particular, we would expect losses to depend primarily upon fuel modification decisions $\underline{q}$, the burn index B, and the resources which have been allocated to fire suppression in the area in question $\underline{R}$. Symbolically, we denote this dependence as $\ell_{iv}(d_{iv};\underline{q},\underline{B},\underline{R},\cdot)$, where ℓ_{iv} is the probability density of d_{iv}. In the analysis that follows it is important that this density be independent of time, i.e., stationary over the period T. In this period, the major influence of time will be changes in "burnability" which are induced by weather changes. Since these influences on ℓ_{iv}

are "picked up" by the burn index, stationarity over T seems to be an acceptable assumption.

If we call $h_i(S_i|k_i)$ the conditional density of total loss in activity i given that there are k_i ignitions, then the density of total losses in activity i is

$$(16) \qquad f_i(S_i) = \sum_{k_i=0}^{\infty} \left[e^{-\lambda_i T} (\lambda_i T)^{k_i} / (k_i!) \right] h_i(S_i|k_i) .$$

This density is the product of the probability k_i ignitions will occur with the density function of total losses given k_i ignitions, summed over all k_i ignitions. The function $h_i(S_i|k_i)$ is readily deducible from the distributions of individual ignition losses $\ell_{iv}(d_{iv};\underline{q},\underline{B},\underline{R},\cdot)$. In particular, $h_i(S_i|k_i)$ is the k_i fold convolution of ℓ_{iv} with itself.*

Since the objective of wildland management decision making has been taken to be minimization of expected cost-plus-loss, we are especially interested in the mean of the distribution given in (16). Notice that $E(S_i)$ is a function not only of the "state of nature" as given by I, B, the distribution of fuels, etc., but also of the values of the decision variables $x_i, \underline{q}$, and $\underline{R}$. Since expected cost-plus-loss depends explicitly on these decision variables in the model we have formulated, it should be possible to derive their optimal values for various "states of nature."

The mean loss in activity i is by definition

$$(17) \quad E(S_i) = \sum_{k_i=0}^{\infty} \left[e^{-\lambda_i T} (\lambda_i T)^{k_i} / (k_i!) \right] \int_o^{\infty} S_i h_i(S_i|k_i)\, dS_i \ , \qquad i = 1,2, \ldots, n$$

where

$$(18) \qquad \int_o^{\infty} S_i h_i(S_i|k_i)\, dS_i \equiv E(S_i|k_i) = \sum_{v=1}^{k_i} E(d_{iv}) .$$

Mean losses in activity i are then

*See (Feller, 1966) or (Cramer, 1955).

$$(19) \qquad E(S) = \sum_{k_i=0}^{\infty} \sum_{v=1}^{k_i} \left[e^{-\lambda_i T} (\lambda_i T)^{k_i} / (k_i!) \right] E(d_{iv}) \;,$$

$$i = 1, 2, \ldots n$$

and from (15) the expected total loss over all n activities is given by

$$(20) \qquad E(S) = \sum_{i=1}^{n} \sum_{k_i=0}^{\infty} \sum_{v=1}^{k_i} E(d_{iv})\, e^{-\lambda_i T} (\lambda_i T)^{k_i} / (k_i!) \;.$$

Since the objective of wildland management was assumed to be minimization of the expected total cost-plus-loss, expression (20) is the fundamental quantity in the derivation of decision rules that satisfy this objective. Although (20) presents no difficulties from the point of view of analytic tractability, the implied optimal decision rules are extremely unwieldly and suffer somewhat from lack of straightforward interpretation. This situation can be greatly improved by assuming that the variables d_{iv}, $v = 1, 2, \ldots, k_i$ are identically distributed. That is, in a given area and in a given activity losses from individual ignitions obey the same probability law. This would seem to be a reasonable assumption and allows equation (20) to be expressed as

$$(21) \qquad E(S) = T \sum_{i=1}^{n} \lambda_i E(d_i)$$

where $E(k_i) = \lambda_i T$ and $E(d_{i1}) = E(d_{i2}) = \ldots = E(d_{iv}) \equiv E(d_i)$.* In words, the total expected loss over the period of length T is the expected number of ignitions in activity i, times the expected loss per ignition in activity i, summed over all activities. This surprisingly

*As long as areas are relatively homogeneous, this assumption will hold. But, if T were chosen long enough so that areas could become heterogeneous with respect to, say, fuels, then the assumption of identically distributed losses will not be valid. For example, over long periods of time, the incidence of fires in an area will create dramatic differences in the distribution of fuels and hence will imply different loss densities within an area. The way out of this problem is to choose T short enough to eliminate these effects. Of course, in principle, if an area becomes heterogeneous, one need only break it up into homogeneous sub areas. See (Harrison, 1973) for a model which yields essentially the same result as reported in equation (21).

simple result depends upon no assumption about the distribution of losses from a single ignition $\ell_{iv}(d_{iv};\underline{q},\underline{B},\underline{R},\cdot)$, and is most attractive from a decision analytic point of view. As we have noted, the Poisson parameter associated with activity i is a function of a number of decisions including entry control, education, penalty, and fuel modification decisions and the "state of nature." Likewise, $E(d_{iv})$ depends upon suppression activity, fuel modification decisions, and the "burn index." The simple functional form of expected losses given in (21) makes the decision optimization problem especially easy to solve.

Recall that fire losses depend upon the state of prevention activities, the burn index, the level of suppression, etc., in which case expected total losses, equation (21), for the period T are

$$(22) \qquad E(S) = T \sum_{i=1}^{n} \mu_i(\underline{q},\underline{B},\underline{R},\cdot)\ \lambda_i(x_i,I,m,\cdot)$$

where

$$(23) \qquad \mu_i(\underline{q},B,\underline{R},\cdot) \equiv E(d_i;\underline{q},B,\underline{R},\cdot)\ .$$

Equation (22) is the basis for the optimization of prevention decisions. In what follows, we will concentrate on those prevention decisions which affect x_i.

D. Regulating Entry into and Use of a Wildland Area

Denote the number of people excluded from activity i by y_i. Then the cost $c(\underline{y})$ of excluding y_i people in activity i, $i = 1,2,\ldots,n$ is given by

$$(24) \quad c(\underline{y}) = \sum_{i=1}^{n} a_i(y_i,T,\cdot) + \sum_{i=1}^{n} b_i(y_i,T,\cdot) \equiv \sum_{i=1}^{n} c_i(y_i,T,\cdot)$$

where $a_i(y_i,T,\cdot)$ is the opportunity cost of excluding y_i people in period T from the i^{th} activity* and $b_i(y_i,T,\cdot)$ is the administrative cost of the same exclusion. We now make several plausible assumptions

*The opportunity cost of excluding the j^{th} individual from activity i is defined as the amount individual j would pay to be able to use the wild area in question for activity i.

regarding the forms of these cost functions: that marginal opportunity costs are constant in the number of users and that marginal administrative costs are nonincreasing in the number of users. That is

$$(25) \qquad a_i(y_i,T,\cdot) = a_i(T,\cdot)y_i \quad \text{where} \quad \partial^2 a_i/\partial y_i^2 = 0 \ , \quad i = 1,2, \ldots, n$$

and

$$(26) \qquad \partial^2 b_i/\partial y_i^2 \leq 0 \ , \qquad i = 1,2, \ldots, n \ .$$

Note that (25) and (26) imply that

$$(27) \qquad \partial^2 c/\partial y^2 \leq 0 \ , \qquad i = 1,2, \ldots, n \ .$$

The total expected cost-plus-loss entailed in a decision to permit activity by x_i people is then given by

$$(28) \qquad \phi(\underline{x}) \equiv \sum_{i=1}^{n} \phi_i(x_i) \equiv E(c + S)$$

$$\equiv \sum_{i=1}^{n} \left[c_i(z_i - x_i,T,\cdot) + T\mu_i(\underline{q},B,\underline{R},\cdot)\lambda_i(x_i,I,m,\cdot)\right]$$

where z_i is the demand for the i^{th} activity and $y_i \equiv z_i - x_i$. The problem is then to

$$(29) \qquad \underset{\underline{x}}{\text{minimize}} \ \phi(\underline{x})$$

subject to the constraints

$$0 \leq \underline{x} \leq \underline{z} \ .$$

The special structure of $\phi(\underline{x})$ considerably simplifies the solution of (29). In particular, from equations (9) and (27),

$$(30) \qquad \partial^2 \emptyset / \partial \underline{x}^2 \leq 0$$

and $\emptyset(\underline{x})$ is convex in $\underline{x}$.* Consequently, there are no local interior solutions to (29).** Using x_i^o to represent the optimal admission decision in activity i, we have

$$(31) \qquad x_i^o = \begin{cases} 0 & \text{if} \quad \psi_i < 0 \\ z_i & \text{if} \quad \psi_i > 0 \end{cases}$$

where $\psi_i \equiv [\emptyset_i(0) - \emptyset_i(z_i)]$.

The decision rule given as equation (31) is illustrated schematically in Fig. 10.3. Note that the rule is always of an all or nothing sort: either everyone is permitted entry to activity i or no one is and that the decision criterion is based simply on the difference between the cost of total exclusion and total admission. These simple results depend crucially on the convexity properties of the functions c_i and λ_i. If these properties are not satisfied, then the appropriate decision rule may be one that requires that $0 < x_i^o < z_i$ and only partial satisfaction of demand occurs.

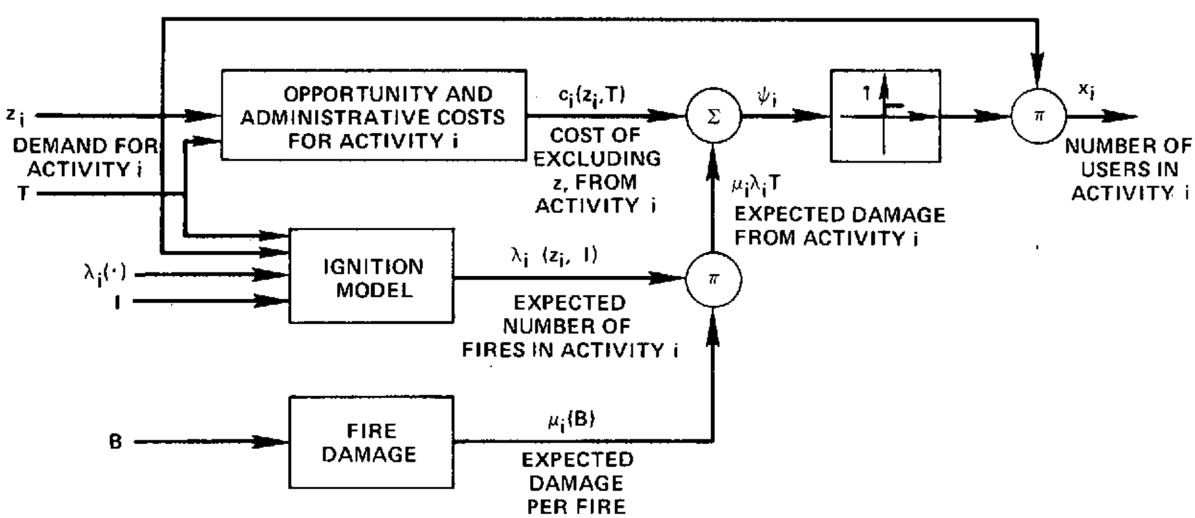

Figure 10-3 Activity-Decision Block Diagram

*It is assumed that $\emptyset(\underline{x}) \in C^2$.

**This statement is not precisely correct. If $\emptyset'(\underline{x}) = 0$ for all $\underline{x}$, every value of $\underline{x}$ minimizes $\emptyset$. This case is of little interest and will be ignored henceforth.

An examination of the decision rule (31) also reveals the following interesting features:

(i) For sufficiently small I, demand is satisfied for the i^{th} activity, independent of the magnitude of other parameters.* This result follows from the fact that $\lambda_i(z_i, 0, \cdot) = 0$.

(ii) The converse (that no activity be permitted for sufficiently large I) is not necessarily true. There may be conditions under which demand should be satisfied for <u>all</u> parameter values. Specifically, this is true if

$$\phi_i(0) > \phi_i(z_i)$$

for all $\underline{q}$, B, $\underline{R}$, $\cdot$, etc. That is, the expected damage due to full activity never exceeds the costs of complete exclusion.

A special, but practically important, case of the decision rule given in (31) occurs when cost functions have the following properties:

$$\partial c_i/\partial y_i = c_{io}T \quad \text{and} \quad \partial c_i/\partial T = c_{io}y_i \ ,$$

where

$$\partial c_{io}/\partial y_i = \partial c_{io}/\partial T = 0 \ ;$$

and

$$\partial \lambda_i/\partial x_i = \lambda_{io} \quad \text{where} \quad \partial \lambda_{io}/\partial x_i = 0 \ .$$

Marginal costs with respect to the number of individuals excluded and the length of the decision period are constant and losses per unit time are linear in the number of users. The decision rule (31) then becomes

$$(32) \qquad x_i^o = \begin{cases} 0 & \text{if} \quad c_{io} < \mu_i(\underline{q}, B, \underline{R}, \cdot)\ \lambda_{io}(I, m, \cdot) \\ z_i & \text{if} \quad c_{io} > \mu_i(\underline{q}, B, \underline{R}, \cdot)\ \lambda_{io}(I, m, \cdot) \end{cases}$$

*This result also holds for sufficiently small B, independent of all other parameters if $\mu_i(\underline{q}, 0, \underline{R}, \cdot) = 0$.

Note that the rule given as equation (32) does not require knowledge of the demand for any activity and is time invariant. It is illustrated in Fig. 10.4 for the case where $\lambda_{io}(I,m,\cdot) = \alpha_i(m,\cdot)I$ and $\mu_i(\underline{q},B,\underline{R},\cdot) \equiv \mu_{io}(\underline{q},\underline{R},\cdot)B$. In this case the decision rule is

$$(33) \qquad x_i^o = \begin{cases} 0 & \text{if} \quad I > (c_{io}/\mu_{io}\alpha_i)\ B^{-1} \\ z_i & \text{if} \quad I < (c_{io}/\mu_{io}\alpha_i)\ B^{-1} \end{cases}$$

This formulation is particularly easy to use in practice in that once c_{io}, μ_{io}, and λ_{io} have been estimated, one needs only the value of the ignition and burn indices to reach a decision. Note that in this and in previous cases both B and I must be considered in making activity regulation decisions. Current practice appears to base such decisions on the value of the burning index B alone, which is reasonable to the extent that B and I are closely correlated. However, to the degree that they differ (due for example to wind, topography, or heavy fuel effects), errors will be introduced into decisions.

The decision rule (33) may be reformulated in a useful and interesting fashion. To this end, define the "risk" in activity i, r_i, as

$$(34) \qquad r_i \equiv \mu_{io}\alpha_i/c_{io} \ ,$$

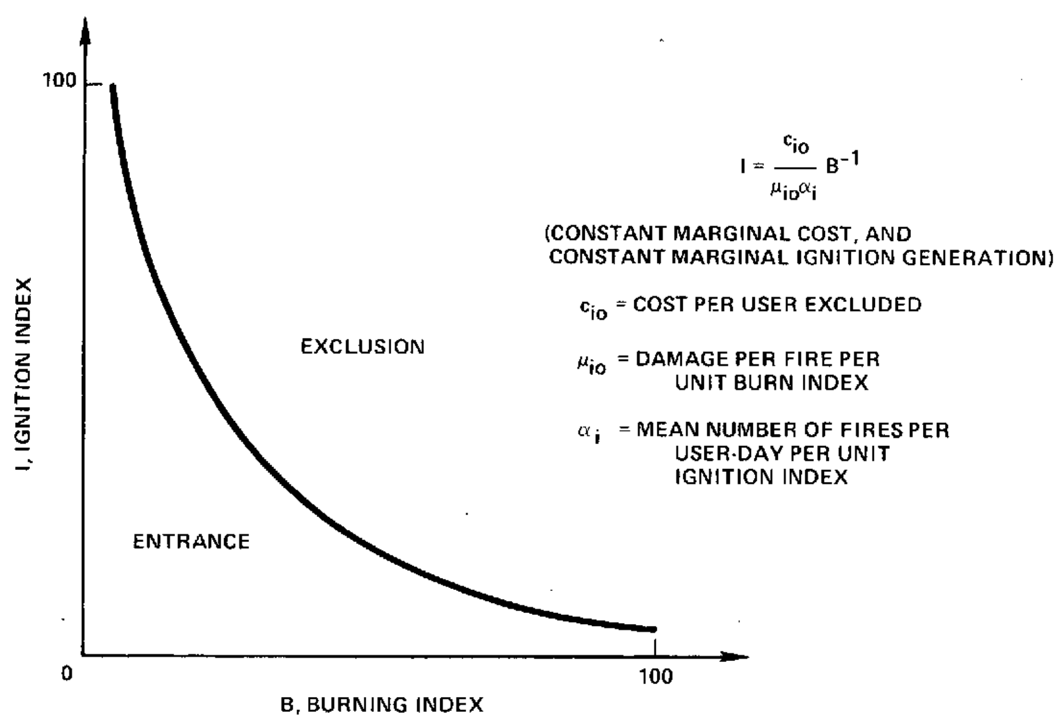

Figure 10-4 Decision Rule for the ith Activity

and the "Fire Load Index" as

$$F_i \equiv r_i IB \ . \tag{35}$$

The index F_i has precisely the same form as that recommended in the U.S. Forest Service Fire-Danger Rating (FDR) System (USFS, 1972a); however, here "risk" has been given a new definition by including the effects of costs and damages. These new definitions of risk and the Fire Load Index also differ from the existing ones of the FDR by being computed for each of the various activities.*

In terms of the new index F_i, equation (35), the decision rule (33) has the simple form

$$x_i^o = \begin{cases} 0 & \text{if} \quad F_i > 1 \\ z_i & \text{if} \quad F_i < 1 \end{cases} \tag{36}$$

The Fire Load Index F_i is dimensionless and is merely the cost-benefit ratio

$$F_i = \frac{\text{expected \$ cost + loss per day from admission to activity } i}{\text{\$ cost per user day from exclusion from activity } i}$$

Obviously, if $F_i > 1$, entry for purposes of using activity i should be prohibited and $F_i < 1$ implies all interested parties should be allowed to use the area for activity i. Note that the index F_i has precise significance only for activity regulation. For other fire prevention decisions, e.g., various types of fuel modification, a procedure identical to that we have followed will yield an index appropriate to the decision in question.

It should be emphasized that use of the Fire Load Index F_i in place of the more general test given by equation (31), is justified only to the extent that the following approximations are valid:

(i) The mean number of fires per user-day per unit ignition index in activity i is constant in x_i and I. ($\partial\lambda_i/\partial x$ = constant; $\partial\lambda_i/\partial I$ = constant)

(ii) The mean \$ cost-plus-loss per fire per unit burning index in activity i is constant in B. ($\partial\mu_i/\partial B$ = constant)

*The term $r_i I$ is analogous to the "Occurrence Index" of the FDR.

(iii) The cost of prohibiting activity i per user day (administrative plus opportunity costs) is constant in x_i. ($\partial c_i / \partial x_i$ = constant)

E. Entry and Use Control under Homogeneity Constraint

Next, we consider a modification of the decision problem to account for a policy which prohibits the exclusion of specific users. For example, it is a USFS policy that all users be treated "the same" in the sense that,

> "Closures and restrictions ... should be applied equally to all forest users, and not to any one category of visitors, such as hunter, hiker, fisherman, or logger." (USFS, 1972b)

This policy can be interpreted as implying the following constraints on decisions:

$$(37) \qquad x_i = \beta z_i \quad \text{iff} \quad x_j = \beta z_j \,, \qquad 0 \leq \beta \leq 1 \,, \quad i,j = 1,2, \ldots, n \,^{*}$$

If condition (37) is added as a constraint on the decision problem posed in (29), the optimal decision rule is

$$(38) \qquad x_i^o = \begin{cases} 0 \,, & i = 1,2, \ldots, n \,, \quad \text{if} \quad \sum_{i=1}^{n} \left[\emptyset_i(0) - \emptyset_i(z_i) \right] < 0 \\ z_i \,, & i = 1,2, \ldots, n \,, \quad \text{if} \quad \sum_{i=1}^{n} \left[\emptyset_i(0) - \emptyset_i(z_i) \right] > 0^{**} \end{cases}$$

The increased cost of the decision given by (38) over the basic optimal decision rule (31) is readily found to be

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*More generally, these constraints might apply only to a subset of the n activities.

**This result follows from setting $\underline{x} = \beta \underline{z}$ and minimizing $\emptyset(\beta)$ subject to the constraint $0 \leq \beta \leq 1$.

$$(39) \quad \Delta\varnothing = \Delta E(c + S) = \min \left\{ \sum_{i=1}^{n} c_i(z_i,T), \quad T \sum_{i=1}^{n} \mu_i(\underline{q},B,\underline{R},\cdot)\ \lambda_i(z_i,I,m,\cdot) \right\}$$

$$- \sum_{i=1}^{n} \min \left\{ c_i(z_i,T),\ T\mu_i(\underline{q},B,\underline{R},\cdot)\ \lambda_i(z_i,I,m,\cdot) \right\}$$

The cost of the policy given by (37) will be positive unless decisions under rules (31) and (38) happen to agree, i.e., unless the basic decision rule (31) says either <u>prohibit all</u> n activities or <u>permit all</u> n activities (the latter event will occur for sufficiently low fire danger, although the former will not necessarily occur for sufficiently high fire danger--cf. page 171). Since the additional cost may be significantly large, such policies should be carefully examined.

For the case where expected cost and loss may be collapsed into the index F_i [see (36)] decision rule (38) may be written as

$$(40) \quad x_i^o = \begin{cases} 0 & \text{if} \quad I > \left[\sum_{i=1}^{n} c_{io} / \sum_{i=1}^{n} \mu_{io}\alpha_i \right] B^{-1} \\ z_i & \text{if} \quad I < \left[\sum_{i=1}^{n} c_{io} / \sum_{i=1}^{n} \mu_{io}\alpha_i \right] B^{-1} \end{cases}$$

This decision rule suggests the following definitions: Let "overall risk," r, be defined as

$$(41) \qquad r \equiv \sum_{i=1}^{n} \mu_{io}\alpha_i \Big/ \sum_{i=1}^{n} c_{io} \ ^*$$

and the "overall" Fire Load Index, F, as

---

* Note that in general $r \neq \sum_{i=1}^{n} r_i$.

$$(42) \qquad F \equiv rIB \,.$$

Then, the decision rule (40) becomes

$$(43) \qquad x_i^o = \begin{cases} 0 & \text{if} \quad F > 1, \quad i = 1,2, \ldots, n \,, \\ z_i & \text{if} \quad F < 1, \quad i = 1,2, \ldots, n \,, \end{cases}$$

F. <u>Entry and Use Control under Budgetary Constraint</u>

Let us consider now the more realistic situation where the fire protection agency operates under budgetary constraints. We consider for simplicity the linear case whose unconstrained solution is given by (36). Let the total maximum administrative budget available for activity regulation during a time period T be given by bT, where b is a positive constant. Then the basic cost minimization problem (29) is modified simply by the addition of one more constraint on the activity vector $\underline{x}$; this constraint can be written as the inequality

$$(44) \qquad \underline{b}_o'\underline{x} - d_o \geq 0 \,,$$

where $\underline{b}_o \equiv [b_{o1}, b_{o2}, \ldots, b_{on}]$ is a vector of (constant) administrative costs of activity exclusion per user-day, and $d_o \equiv \underline{b}_o'\underline{z} - b$ is the difference per day between the administrative costs of total exclusion and the total available budget. Clearly, if $d_o \leq 0$, the available administrative resource is sufficient to exclude <u>all</u> users in <u>all</u> activities, and the previous unconstrained solution (36) remains valid. Assume then that $d_o > 0$.

We can rewrite the basic cost minimization problem (29) as

$$(45) \qquad \begin{cases} \underset{\underline{x}}{\text{minimize}} \quad \emptyset(\underline{x}) \\ \text{subject to the constraints} \quad \underline{z} \geq \underline{x} \geq 0 \\ \qquad\qquad\qquad\qquad \text{and} \quad \underline{b}_o'\underline{x} - \underline{d}_o \geq 0 \end{cases}$$

To simplify the statement of the solution of (45), let us also rewrite the (linear) cost function $\emptyset$ as

$$\emptyset(\underline{x}) = T\underline{c}_o'z + T\underline{g}'\underline{x}$$

where $\underline{g}' \equiv [c_{1o}(F_1 - 1), c_{2o}(F_2 - 1), \ldots, c_{no}(F_n - 1)]$ is a vector of total net cost per user-day in each activity.

This problem is a standard linear programming problem, but of such simple structure that the following elementary algorithm readily produces its solution:

(1) Take $\underline{x} = \underline{z}$, which always satisfies the constraints.

(2) Label activities so that $g_i \geq g_{i+1}$ for all i. Let $F_i \geq 1$ and, consequently, $g_i \geq 0$ for $i = 1,2,\ldots, k \leq n$; let $F_i < 1$ for $i > k$. Then, keep $x_i = z_i$ for $k < i \leq n$, and subsequently, consider only $i = 1,2,\ldots,k$. Starting with x_1,

(3) decrease x_i until either

(4) $x_i = 0$, in which case repeat step (3) for x_{i+1}, until $i+1 = k$, or

(5) $\underline{b}_o'\underline{x} - d_o = 0$, in which case the process is terminated.

In general, if the process terminates in step (5) with the budget equality satisfied, there will be some activity ℓ, $1 \leq \ell \leq k$, for which demand will be partially satisfied, i.e., with $0 < x_\ell < z_\ell$. There will thus be at most one activity with $0 < x_\ell < z_\ell$; in all other activities either $x_i = 0$ or $x_i = z_i$, that is, all other users are either totally excluded or permitted full use. In the situation where the optimal decision requires use of the entire budget, it is of interest to determine the sensitivity of net costs to increases in the budget allotment, i.e., to determine the shadow price of the budget resource. (The shadow price is the value of an extra unit of resource, the dollar amount by which total cost will be decreased through the expenditure of an additional dollar of budget. In the situation where the optimal solution does not require the whole budget, clearly the shadow price of the budget will be zero.) Consider the case of partial regulation where the optimal decision requires $0 < x_\ell < z_\ell$ for some $1 \leq \ell \leq k < n$. Then, a simple calculation shows that the shadow price of $\overline{b}$, $\overline{\partial}\emptyset^*/\partial b$, is given by

(46) $$\partial\emptyset^*/\partial b = -c_{\ell o}(F_\ell - 1)/b_\ell$$

where $\emptyset^*$ is the optimal cost.

G. Error Sensitivity

It is of considerable interest to determine the effects of various uncertainties and measurement errors on the optimal decision rules which were derived above. In this section we assess the effect of errors in measuring the Fire Load Index, F_i.* To this end, let $\tilde{F}_i$ be the measured value of F_i. The measurement error ΔF_i is then given by

$$\Delta F_i \equiv \tilde{F}_i - F_i \ . \tag{47}$$

Examination of the optimal decision rule (36) shows that a decision error will be made whenever

$$\tilde{F}_i \begin{cases} > 1 & \text{and} \quad F_i < 1 \\ < 1 & \text{and} \quad F_i > 1 \end{cases} \tag{48}$$

A simple calculation further shows that the error cost $\Delta\phi_i$ (the cost associated with an erroneous decision) is given by

$$\Delta\phi_i = c_{io} z_i T |1 - F_i| \ . \tag{49}$$

The error costs (49) occur only for values of $\tilde{F}_i$ and F_i which satisfy (48). To interpret these results, suppose that measurement errors are bounded by ϵ_i, i.e.,

$$|\Delta F_i| \leq \epsilon_i \ .$$

Then, from (48) and (49) we have that

$$\max \Delta\phi_i = \begin{cases} c_{io} z_i T \epsilon_i & \text{for} \quad |1 - F_i| \leq \epsilon_i \\ 0 & \text{for} \quad |1 - F_i| > \epsilon_i \end{cases}$$

where $\max \Delta\phi_i$ is the maximum cost associated with a measurement error in F_i and therefore

$$\Delta\phi_i \leq \max \Delta\phi_i \ .$$

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*Recall that "costs and losses" may be collapsed into F_i when marginal costs with respect to the number of individuals excluded and the length of the decision period are constant and losses per unit time are linear in the number of users.

Hence, the optimal decision rule (36) has two desirable properties with respect to measurement errors in F_i: (1) Maximum error costs may be made arbitrarily small by making measurements sufficiently accurate; and (2) error costs are zero for sufficiently large F_i. Thus, relatively inaccurate measurements may give satisfactory results for the conditions of most interest (high fire danger).

H. Calculation of Wildland Values

In previous sections we used the variable S to denote the stochastic quantity "total loss." We saw that if the objective of wildland management decisions was to minimize expected cost-plus-loss, then for a large class of decisions, all that need be known about the density of losses $f(S)$ was its mean. This result greatly simplifies the estimation task which is a necessary precursor to any operational set of decision rules. But, even so, difficult problems remain.

By equation (21) mean losses may be obtained by adding up mean losses by activity, where the expected loss in an activity is the product of the mean number of ignitions and the mean loss per ignition in that activity. Estimating the mean number of ignitions by activity should present few difficulties. Unfortunately, the same statement cannot be made about estimation of the expected loss per ignition. The problem, of course, stems from the fact that calculation of expected losses requires assigning values to the wildlands in question. In this section we address several of the difficulties which must be overcome.

Precisely the same problem arises in calculating the opportunity costs of activities in the wildlands. The optimal decision rules derived in Section D require a knowledge of these costs [a_i in equation (24)]. The problem is to assign values to the wildland in its various uses.

Before proceeding, note that the difficulty of value assignment varies directly with the number of uses to which the land is, or could be, put and the "more removed" is the value of a particular activity from a market valuation. For example, if a wildland area is suited almost exclusively to logging, then it will be relatively easy to assign a value to the area. There is only one use, and in that use there is an active market which would allow an immediate value calculation once an estimate is made of the number of board feet of timber in the area.*

*An analogous situation holds in "wildland" areas which are primarily residential. Once again, the market provides a ready measure of the value of the area. Although market values are readily available for such wildland uses, there is a category of cases for which these market values will not accurately reflect the value to society of the area. This occurs when loss of an area to fire has "spillover effects" on the surrounding area. Watershed damage, winter mudslides, reservoir siltation, etc., which may follow a fire are examples. In these cases, the value to society of the area will be larger than the market value. For purposes of wildland management decisions an estimate of these "spillover costs" must be added to market values to obtain the value to society of preventing a fire in the area.

If the area could be used either for lumber sales or recreation, the problem is not so simple. Here there are two competing and largely inconsistent uses with no readily available market valuation in the latter use. In what follows, we will be primarily concerned with value determination for wildland uses like those recreational activities which are not market priced. We shall also briefly treat the "multiple use" problem once valuation has been discussed.

To begin, let's consider an often-heard argument against trying to place specific monetary values on the aesthetic and recreational benefits derived from wildland use. The argument is essentially that the valuation process is inapplicable to subjective, intangible experiences. It is asked how one can put a value on the unique and highly personal experience of viewing Yosemite Valley or the Big Trees for the first time. Proponents of this position emphasize the uniqueness of such experiences, their emotional content, and their intensely personal character and conclude that valuation is impossible by definition of the "commodity." Unfortunately, arguments of this nature have in the past often relegated wildland valuation to a special case not amenable to the valuation process. But most, if not all, commodities have some degree of aesthetic value associated with their use or consumption. Consumption of a steak at an exclusive or not so exclusive restaurant involves want satisfaction in addition to that provided by the steak itself. Purchase of a suit likewise involves a great degree of aesthetics, yet the economic value is subject to determination. An evening at the symphony is an experience or commodity whose appeal is almost entirely aesthetic, yet its economic value is capable of being analyzed by virtue of the admission price. Clearly, the argument that aesthetic experiences cannot be valued is fallacious. No meaningful distinction can be made between the aesthetic qualities associated with symphonies and those related to, say, outdoor recreation.

But one distinction can be made, a distinction related to market pricing, which dramatizes the basic problem of valuing the recreational and aesthetic benefits derived from the wildlands. In our example, the symphony was market priced. Given this value indicator, estimates of consumer valuation of the symphony are feasible. Given the appropriate valuing mechanism, estimates of the value of wildland recreation are equally feasible. Unfortunately, most public recreation is not market priced and thus estimates of comparable value are difficult. But it is the lack of market pricing and not the associated "intangibles" which complicates the valuation process.

It is possible to admit that the value of these resources is capable of being monetized, but that they shouldn't be. Those who take this position claim that wildland management decisions should be based on grounds other than monetary values. They argue for example that outdoor recreation is a healthful activity or a socially necessary one and deny that monetary values should be the chief criterion. Indeed, they would support certain areas for certain types of recreation, <u>regardless</u> of monetary values (Clawson, 1959). This position is virtually indefensible as it stands. The basic problem is the immense number of activities which, according to proponents, enjoy precisely the same status--they are "absolutely necessary" (i.e., costs are irrelevant in decisions concerning these activities). Unfortunately, a basic fact of life is that resources are finite, and indeed very finite. From this, it follows that society benefits most when these limited resources are allocated over activities in such a manner that net social benefits are maximized. But if this is the case, decisions regarding all activities and all projects must be taken such that any single decision is taken only if it adds more to net benefits than any other decision. If not, valuable (finite) resources are being used in a less than efficient manner. Of course, in practice, the task of calculating costs and benefits may be formidable, but this in no way affects the veracity of the principle. Since what is "absolutely necessary" to one group is nonsense to another group, no set of decisions should be above this basic principle. If a project or an activity cannot be justified on the basis of its net benefits, there would seem to be no meaningful alternative way of justifying it.

Let's return once again to the problem of imputing monetary values to nonmarket valued commodities. In general, the value or benefit, in an economic sense, which is derived from a given use of resources is simply the value it has for the consumer and is measured by his willingness to pay for it. Actual payment may or may not be made, depending on whether or not an organized market exists. The relationship between willingness to pay and specified volumes of an activity is termed a demand function. That is, a demand function portrays the quantities buyers (users) would be willing to take at various prices. The problem in the case of valuing the aesthetic and recreational benefits of wildlands stems from the fact that markets do not exist which yield observations on prices and volumes from which demand schedules can be estimated. And since total demand for a given wildland use is an expression of willingness of potential users to pay, it follows that the area under the demand schedule represents the value of the wildland area in the given use. Hence valuation of aesthetic and recreational benefits will require estimation of a demand function for these commodities, an estimation problem constrained by the lack of market transactions.

It appears that the most useful approach is one based upon travel and related cost considerations used as a proxy for market transactions. In other words, "willingness to pay" (which is represented by prices in organized markets) is estimated using cost data as an indirect means of determining the appropriate prices. Since examples of this procedure are plentiful in the literature, it will not be pursued here.*

In summary, the major difficulty in valuing the aesthetic and recreational benefits associated with wildland areas lies in the lack of an organized market which would yield prices and volumes upon which value computations could be made. The fact that benefits are subjective,

*The following is a very incomplete listing of the literature concerned with this problem (many of the references contain bibliographies): (Knetsch, 1963), (Clawson, 1959), (Trice, 1958), (Davis, 1963), (Boyet, 1966), (Cicchetti, 1969), (Davis, 1966), (Milstein, 1966), (Eckstein, 1958), (USFS, 1972c).

unique, intangible, or whatever, is irrelevant and poses no problems for the valuation process. The concept that individual expenditures incurred in the consumption process reflect the value of an experience to the consumer provides a useful and widely used approach to establishing the value of a commodity that lacks conventional market pricing. When expenditures are properly delineated, statements of value can be generated which are essentially equivalent to those normally developed for market priced commodities.

With an extensive literature concerned solely with valuation of non-marketed commodities and numerous applications which lend considerable credability to several approaches, it is difficult to understand why those responsible for wildland management have not in the past made more effort toward estimating these values. From our limited survey of USFS and CDF literature, internal or internally subsidized attempts to arrive at recreational values are, with a few recent exceptions, hopelessly inadequate. This inadequacy stems not from the lack of an established methodology for attacking the problem, but rather from the fact that personnel with the technical qualifications have seldom if ever been used. This state of affairs may well derive from the questionable manner in which funds are allocated to suppression activity with the consequent under-funding of other areas, and the suspicion (perhaps subconscious) that if values were calculated, they would indicate over-funding in fire suppression and perhaps other areas.*

I. Summary and Conclusions

In this paper we have examined the logical framework of a class of decisions confronting fire protection agencies using expected cost plus fire loss as the measure of system performance. More specifically, we analyzed fire prevention decisions under the "cost-plus-loss" criterion. The decision problem was formulated for an arbitrary prevention activity and then solved for a particular activity, controlling entry into and use of a wild area. Optimal decision rules were presented under a number of different assumptions about system parameters and several types of institutionally imposed constraints. Since system parameters are a function not only of the number of users by activity but also of the level of all other prevention activities, the same basic procedure we have used will generate optimal decision rules for any other prevention activity.

It should be emphasized that the optimal prevention decision rules presented here are solutions to a suboptimization within the overall fire-control decision problem and hence no inferences are possible from our

*(Trice, 1958), p. 198, claims that the Forest Service has refused to place dollar values on the recreational use of the forests under its jurisdiction primarily because it does not have to "resort to dollar comparisons to justify its program." Hopefully, things will change in the future. (There is some basis for this hope in terms of recent preliminary work in the Forest Service. See, e.g. (USFS, 1972c).)

analysis concerning the redistribution of wildfire management resources between fire suppression activity and fire prevention activity. Almost certainly optimal wildfire management will involve a mixture of fire suppression and fire prevention activities, with the specific mixture depending upon a number of local characteristics of the area protected. Determination of the activity mix and its dependence upon these characteristics is considerably beyond the scope of the present study. Quite obviously, the central concept in such a determination is the shadow price of resources in fire suppression activities vis à vis their shadow price in fire prevention activities.

Use of the ideas presented here as a basis for making entry and use decisions, of course, awaits verification of the model. And as is often the case, the major problem encountered in any attempt to test (and, for that matter, use) a model lies in the quality and quantity of available data. In particular, data is needed by area on the number of users by activity, the number of ignitions, and the ignition index for given areas and given time intervals. This information would allow estimation of the functions λ_i via regression analysis. In addition, data on fire losses (by area) as a function of the level of prevention and suppression activities and the burn index would be sufficient for estimation of the functions μ_i. Finally, information is needed on the cost of administering an entry and use control program (for estimating the functions b_i) and on the opportunity costs of excluding people from wild areas (for estimation of the functions a_i). There would seem to be no inherent difficulty in collecting data on these variables with the possible exception of the fire damage and "opportunity cost" categories.*

The basic problem in estimating the opportunity cost of exclusion or the value of an area burned is essentially the same: Public wildland use (by activity) is for the most part not market priced and hence observations on prices and volumes needed to estimate the relevant functions (demand functions) do not exist.** In these cases, as described in Section H, proxy variables for market transactions are used as an indirect means of determining the appropriate values.

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*Indeed, data is available on many of the variables mentioned. As always, improvements could be made in collection procedures.

**An exception is logging activity where timber is sold to private loggers. To the extent sales are at market prices, observations on market prices and volumes are available and valuation is straightforward.

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Chapter XI

A SIMULATION MODEL OF SUPPRESSION, WITH APPLICATIONS TO PRESUPPRESSION DECISIONS

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Chapter XI

A SIMULATION MODEL OF SUPPRESSION, WITH APPLICATIONS TO PRESUPPRESSION DECISIONS*

A. Introduction

This chapter presents a simulation model of the wildfire suppression process. The model is described in detail and tentatively verified to show reasonable agreement with fire statistics in California. The results of one particular simulation are presented in detail to show behavior under conditions of variable wind and topography.

The model is used in the analysis of several presuppression decisions. In one, uniformly distributed fuel breaks of different widths and separation distances are evaluated. In another application, errors in initially dispatched suppression capability are considered. Changes in area burned are determined for two cases where the fire-danger level of dispatch differs from the true fire-danger level. Finally, area-wide fuel modification is examined by considering the effect of fuel age on the area burned.

The nature of the wildland fire control problem depends directly on the climate, topography, structural and nonstructural values, and fuel type(s) of the area being considered. In our simulation of the fire spread and suppression effort for the purposes of assessing various prefire prevention strategies, it is normally assumed that the area being modeled has representative, constant, homogeneous values of the wind, slope, fuel, fuel moisture content, and nonstructural values; structures and the fire-break system will be treated in a discrete fashion.

It is well known that as a result of different climatic conditions and fuel types, Southern California and Northern California have rather different wildland fire control problems. To account for these differences, the simulation is conducted for two areas, one typical of Southern California and the other typical of Northern California. The Southern California area, referred to here as Itlpainia Canyon, has chaparral, brush-like fuels with high structure and watershed values and minimum recreation and timber values. The Northern California area, referred to as Treedom, has coniferous-forest-type fuels, minimum structure values and high timber, watershed and recreation values. The details of the description of these two areas is given in Appendix XI.

It is important to recognize here that the assumptions of constant, homogeneous wind, fuel, fuel moisture content, slope, and nonstructural values are only for the purposes of ease of comparison of the effect of various prefire prevention decisions. The fire simulation and suppression model developed herein is fully capable of application to situations

*This chapter was prepared by M. Jischke and J. Shamblin.

where these quantities are varying with time and/or position. To illustrate this capability, there is included the results of a simulation of a fire in which the temporal and/or spatial variations of wind, slope, fuel, and fuel moisture content have been taken into account.

The simulations were all performed by hand, using a combination of graphical constructions, hand calculations, and table look-ups. It should be emphasized, however, that the model algorithms are eminently suitable for implementation by digital computer; only limitations on time available for programming prohibited our doing so here.

It should also be noted that the model should be useful in certain applications not considered here. Among these are training of fire control personnel, and use for predictive purposes on the fire site.

B. Suppression and Fire-Behavior Simulation Model

Consider the area to be simulated as shown in Fig. 11.1a. The location of the fire suppression resources and structures is shown as well as a representative fuel-break system. This fuel-break system is characterized by the location of the fuel breaks and the probability of fire containment. To assess the effect of fuel breaks in a typical area, consider a uniformly distributed system of fuel breaks characterized by the length ℓ_{fb} and a probability of containment. Such a uniformly distributed system is sketched in Fig. 11.1b. Generally, the simulated area is assumed to have a constant mean slope S and a specified fuel bed and fuel moisture content. The fuel for the Treedom simulation is taken to be timber litter and understory while that for Itlpainia Canyon is chamise. The specific fuel-bed parameters are listed in Appendix XI. The wind is normally assumed to have an average speed and direction which is uniform over the area of interest; also, the wind speed and direction are assumed constant at given values during the "daytime" (10:00 a.m. to 6:00 p.m.) with different constant values during the "nighttime" (6:00 p.m. to 10:00 a.m.). It is important to recognize that these assumed constant wind speeds are averages and will be less than the maximum wind speeds often

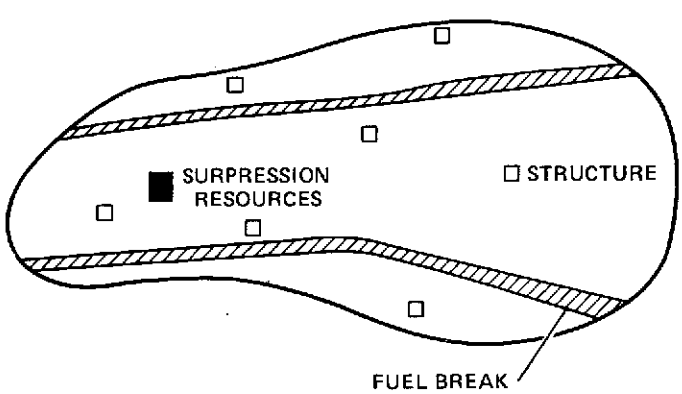

Figure 11-1a Simulated Fire Area

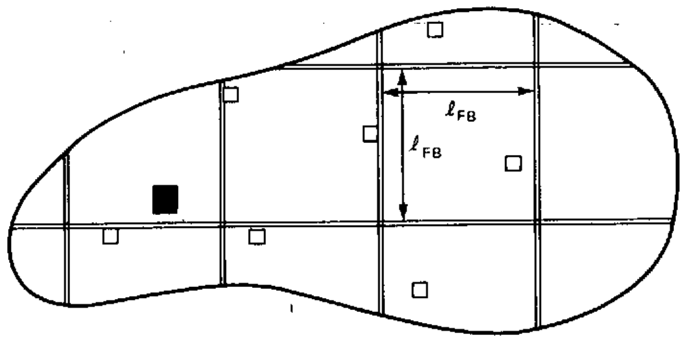

Figure 11-1b Uniform Fuel-Break Distribution

quoted in fire reports. While the fire simulation can include time-varying wind conditions, the assumption of constant wind speed and direction in order to evaluate the effectiveness of various prevention strategies makes hand calculations substantially easier. For purposes of illustration, however, we shall later discuss a simulation in which time-varying wind conditions are considered. Histograms of the average daytime midflame height wind speed occurrence for three different ranges of fire danger have been estimated. The three ranges of fire danger, each assumed to occur one-third of the time, correspond to the green (low) orange (medium) and red (high) fire danger ranges of the California Division of Forestry. These histograms are shown in Figs. 11.2 through 11.4.

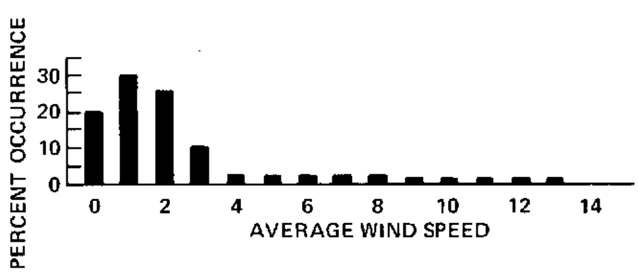

Figure 11-2 Wind-Speed Histogram Green Day

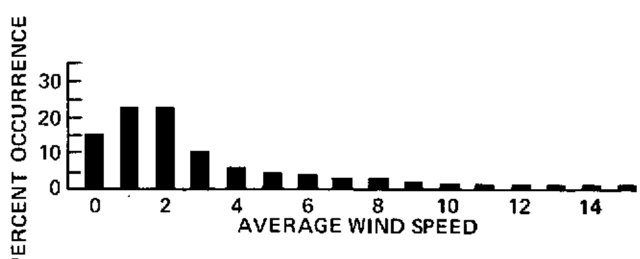

Figure 11-3 Wind-Speed Histogram Orange Day

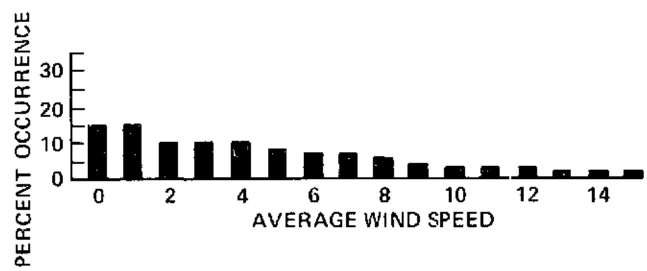

Figure 11-4 Wind-Speed Histogram Red Day

The wind histograms have been adjusted so as to yield a distribution of fire sizes which is comparable to that observed. The night wind speeds are obtained from the daytime wind speed by a multiplicative factor C_n, a histogram of which is shown in Fig. 11.5. This distribution for C_n reflects the fact that the night winds are usually lower than those in the day. The winds are assumed to occur along a single direction. Other directional distributions could be used without difficulty including those which vary with time.

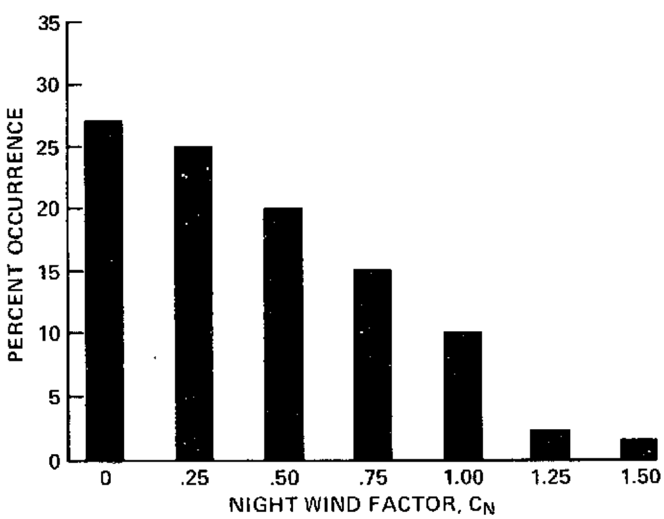

Figure 11-5 Night Wind-Factor Histogram

With the wind, slope, and fuel bed specified, the simulation of the fire spread is conducted in the following fashion. The Rothermal rate-of-spread equations (Rothermal, 1972) are used to compute the rate of spread r_o without wind or slope, the wind factor ϕ_w, and the slope factor ϕ_s. All points along the active perimeter of a fire are advanced in a time step Δt by a vector displacement. This displacement is the sum of three vectors: a no-wind, no-slope vector of length $\dot{r}_o\Delta t$ normal to the perimeter, a wind-induced vector of length $\dot{r}_o\phi_w\Delta t$ parallel to the wind direction, and a slope-induced vector of length $\dot{r}_o\phi_s\Delta t$

parallel to the direction of maximum slope. This is illustrated in Fig. 11.6 for point P on the active perimeter of a fire.

Noting that the wind and slope are assumed to remain constant during day or night in the simulation, we can add the wind and slope vector contributions to obtain a constant wind-slope vector of length $\dot{r}_0 K \Delta t$ in the resultant wind-slope direction. K is the vector sum of the wind and slope factors and is referred to as the wind-slope factor. If a point on the active perimeter advances to a position inside the burned area (e.g., point Q in Fig. 11.6), we interpret this to mean that the point in question cannot spread into unburned fuel and thus remains fixed. This method of vectorially adding the wind and slope contributions to the no-wind, no-slope result is new. It agrees with the Rothermel model in the one-dimensional case where the normal to the perimeter, the wind direction, and the slope direction all agree. Further, for the case of zero wind and zero slope, a circular fire remains circular. Finally, for cases in which variable topography is to be simulated, the present method of advancing the fire perimeter distinguishes between upslope and downslope spreading. The advancement of the complete perimeter for one time step is illustrated in Fig. 11.7.

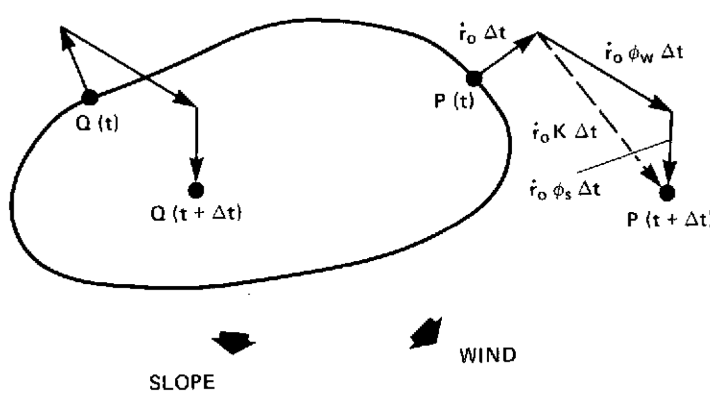

Figure 11-6 Advance of Points on the Fire Perimeter

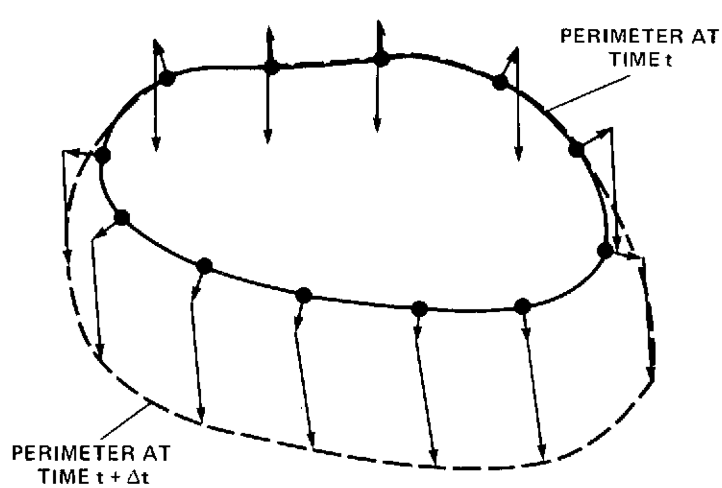

Figure 11-7 Fire-Perimeter Advance

Fire suppression capability is measured in terms of the number of feet of fire-line that can be laid per unit of time under nominal no-wind, no-slope conditions. This capability differs for different types of suppression devices and may also depend on the fuel type. We have considered five types of suppression--twenty-man hand crews, fire truck with crew, bulldozers, helicopters, and air tankers--and have developed data for three fuel categories--"light brush and grass," "medium brush," and "heavy brush and slash." "Light brush and grass" includes grass, scattered sage, mature timber, bear clover, light to medium chamise, and woodland with little chopping. "Medium brush" includes open manzanita, medium reproduction timber, brush mixtures with sage, mixed Douglas fir, and heavy pure manzanita, chamise and buck brush. The third category of "heavy brush and slash" includes oak, heavy mixed brush, second growth with medium poles, and slash in cut-overs.

Hand-crew capability was determined from the Fireline Notebook (USDA-1) in the following way. The number of manhours needed to construct one hundred chains of fireline in one hour was determined for each fuel type. To this is added the number of manhours required to hold this 100 chains of line. Dividing the one hundred chains of line by the total number of manhours gives the number of chains per man hour which can be constructed, corrected for holding requirements. These values are then averaged for each category of fuel types. The numerical results are listed below in Table 11.1. A fire truck with crew is

Table 11.1

HAND CREW LINE-LAYING CAPABILITY

Fuel Category	Feet Line/Hour	Line Width (Feet)
Light brush and grass	188	2.5
Medium brush	48	4.0
Heavy brush and slash	13	5.1

assumed to be as effective as one twenty-man hand crew. Bulldozers efficiencies are taken from the Fireline Notebook for single pass construction of fireline for a D-4 bulldozer as a function of percent slope and fuel category. The results are given below in Fig. 11.8.

Aircraft line-laying capability is determined assuming two gallons of retardant are required to create one effective foot of fire line under nominal conditions. The number of feet of line laid by an airtanker in a single drop then equals $0.5\ \eta G$, where G is the aircraft capacity in gallons and η is the wind efficiency factor (itself a function of wind speed, drop height, and aircraft capacity). The wind efficiency factor, estimated from data obtained by Honeywell, Inc. (USDA-2) is shown in Fig. 11.9 as a function of wind speed for aircraft in the one thousand gallon capacity class dropping from one hundred feet altitude.

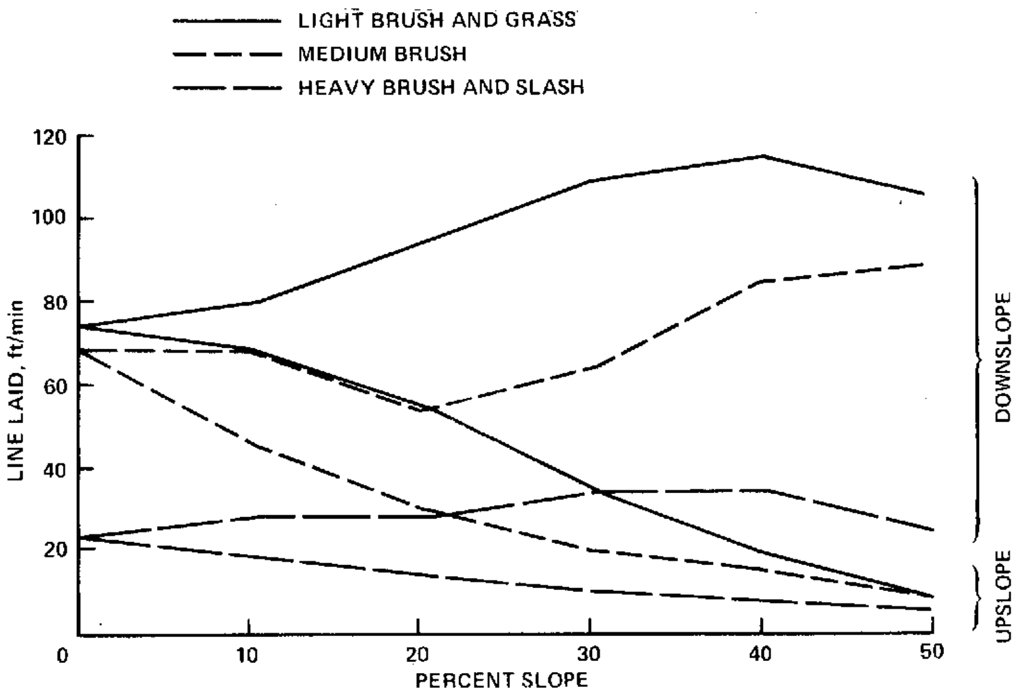

Figure 11-8 Rate of Single-Pass Fireline Construction for D-4 Bulldozer

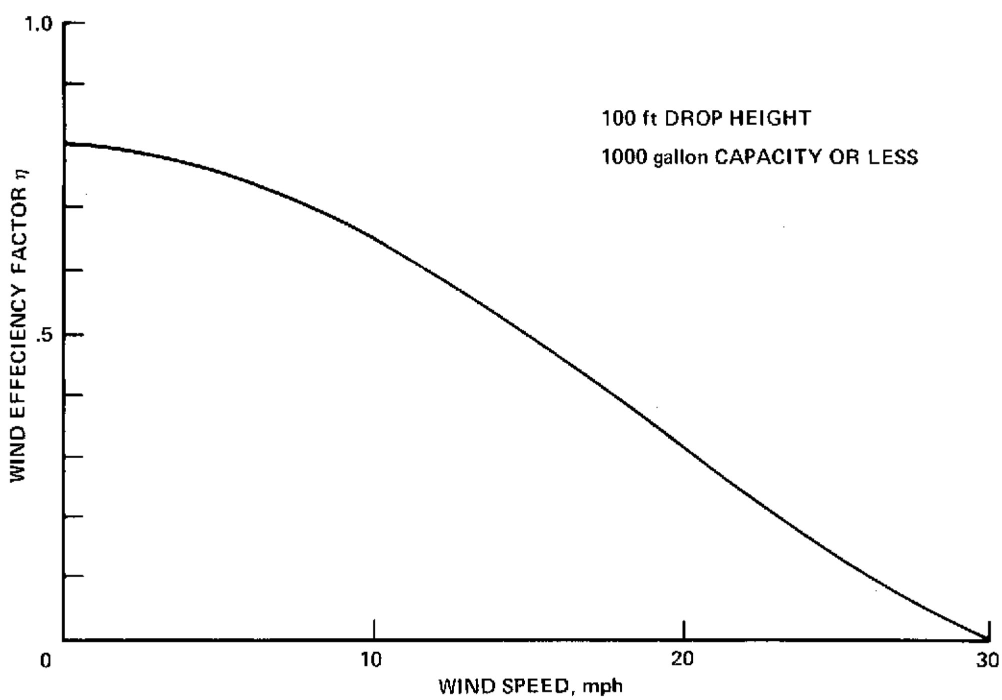

Figure 11-9 Wind Efficiency Factor

The number of feet of line laid per hour is then given by the number of feet of line laid per drop times the number of drops per hour. The number of drops per hour is given by $(t_{TA} + 2D/V)^{-1}$ where t_{TA} is the turnaround time for the airtanker at its base (taken to be twelve minutes), D is the distance of the tanker base from the fire, and V is here the aircraft cruise speed (taken to be 150 miles per hour). Thus, N aircraft can lay

$$\frac{N\eta G}{2(1/5 + D/75)(60)}$$

feet of fire line per minute. Helicopter line-laying capacity is obtained assuming two gallons retardant are required to create one effective foot of fireline. Helicopters are assumed to make five drops per hour with one hundred gallons per drop (typical of a Bell Jet Ranger) giving 250 feet of line per hour per helicopter. All aerial vehicles are assumed to fly only from 7:00 a.m. to 7:00 p.m. and are not used at night.

The initial dispatch of suppression resources was modeled after the C.D.F. automatic initial dispatch. Data from three different areas of California (Humboldt County, Riverside, and Truckee) indicate the following initial dispatch levels to be typical:

Green Day (Low Fire-Danger Rating)

- 2 Engines
- 1 Helicopter

Orange Day (Medium Fire-Danger Rating)

- 4 Engines
- 1 Bulldozer
- 1 Air Recon
- 2 Air Tankers
- 1 Hand Crew

Red Day (High Fire-Danger Rating)

- 6 Engines
- 1 Bulldozer
- 1 Air Recon
- 2 Air Tankers
- 1 Helicopter
- 2 Hand Crews

Using these results and assuming 20% slopes, we can compute the line laying capability L initially dispatched on green, orange, or red days for the three categories of fuel types. For green days we have:

Table 11.2

GREEN-DAY INITIAL DISPATCH

Fuel Category	$\dot{L}$ (Feet/Hour)
Light Brush and Grass	7,800
Medium Brush	3,000
Heavy Brush and Slash	1,000

Because of the use of aircraft, the initial dispatch for orange and red days depends upon the wind speed and the distance D from the air tanker base to the fire. Figures 11.10, 11.11, and 11.12 show lines of constant initial dispatch capability $\dot{L}$ for various wind speeds and distances D, assuming air tanker capacity of 600 gallons. Also, for initial dispatch only, we assume that air tankers require five minutes to get off the ground. Figures 11.10, 11.11, and 11.12 hold for the "light brush and grass," "medium brush," and "heavy brush and slash" category of fuels. Given an ignition at a particular location and a particular time of day, with known wind, fuel, and slope conditions, the simulation takes the initial dispatch level of suppression and assumes it arrives at the fire at a time t_A after the ignition. This time t_A is composed of a detection time (assumed to be eight minutes), a dispatching time (assumed to be two minutes), and a transit time given by the distance of the fire from the suppression forces divided by an average speed of transit (assumed to be 25

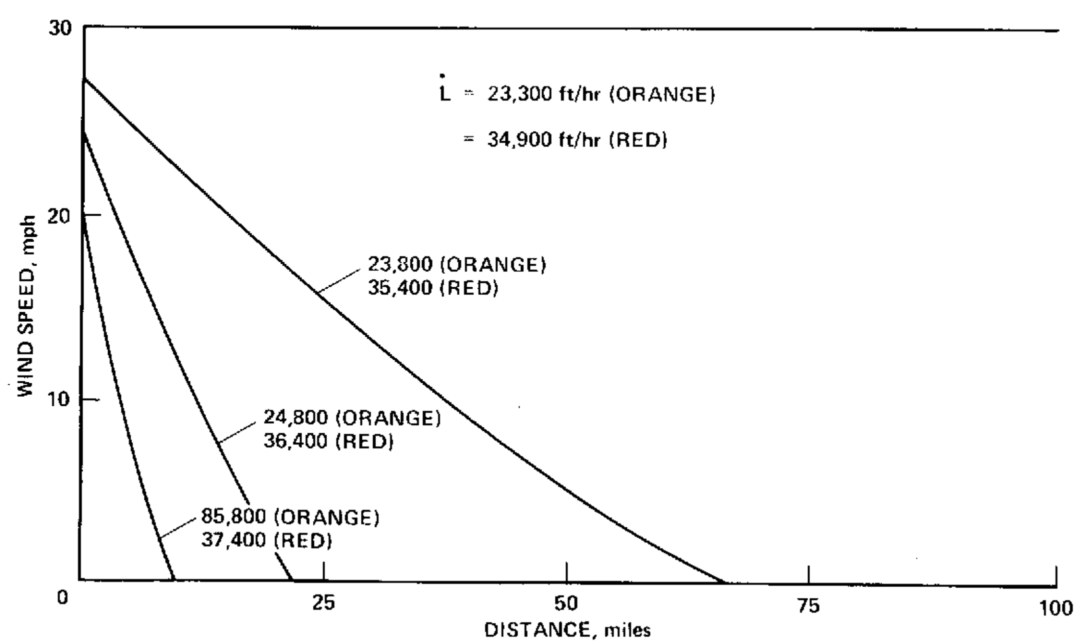

Figure 11-10 Initial Dispatch for Orange and Red Days. Light Brush and Grass.

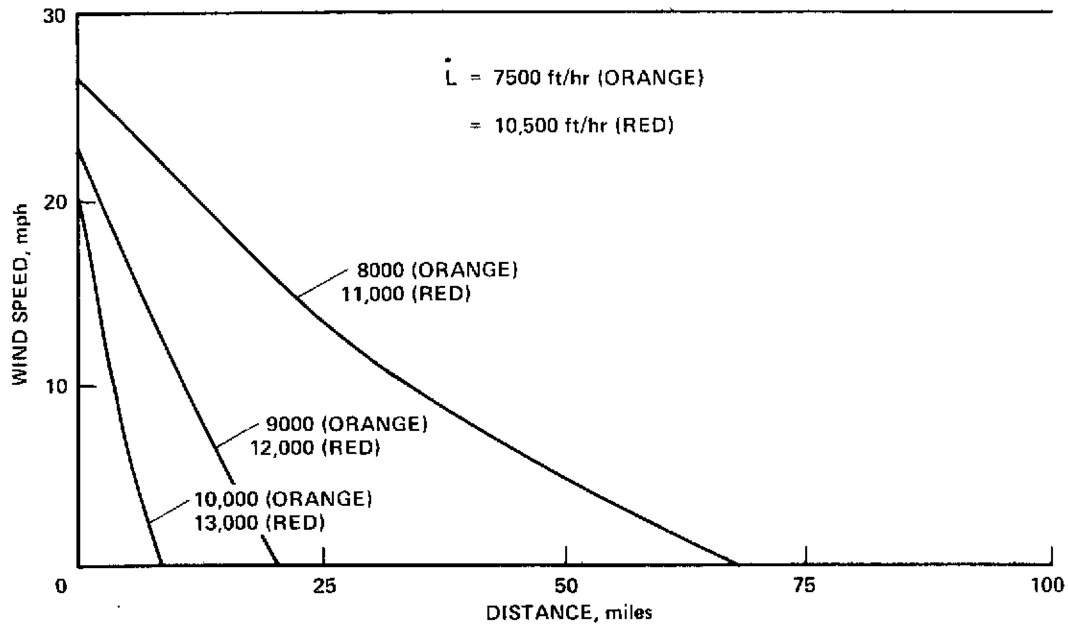

Figure 11-11 Initial Dispatch for Orange and Red Days. Medium Brush.

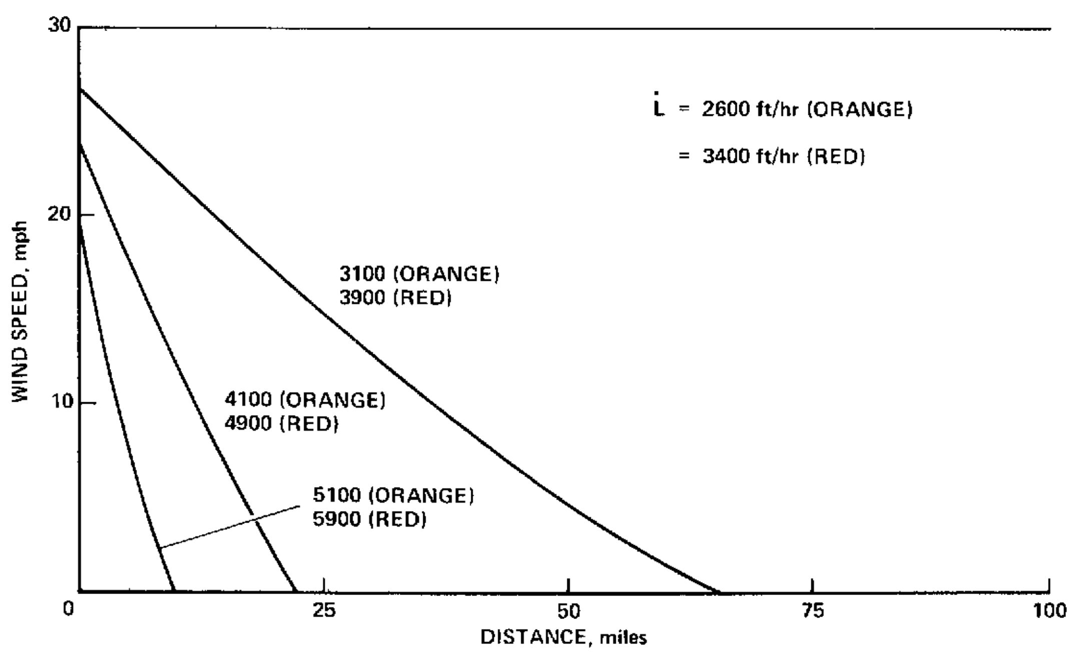

Figure 11-12 Initial Dispatch for Orange and Red Days. Heavy Brush and Slash.

miles per hour). Figure 11.13 is a nomograph on which the transit time can be obtained from the x and y coordinates of the fire location. The area being simulated is of rectangular shape and 20,000 acres in extent with side lengths in the ratio of two to one.

The time of day of the ignition is determined from the distribution given in Fig. 11.14. This distribution emphasizes the afternoon hours. Over 50% of the fires occur between 12:00 noon and 6:00 p.m.

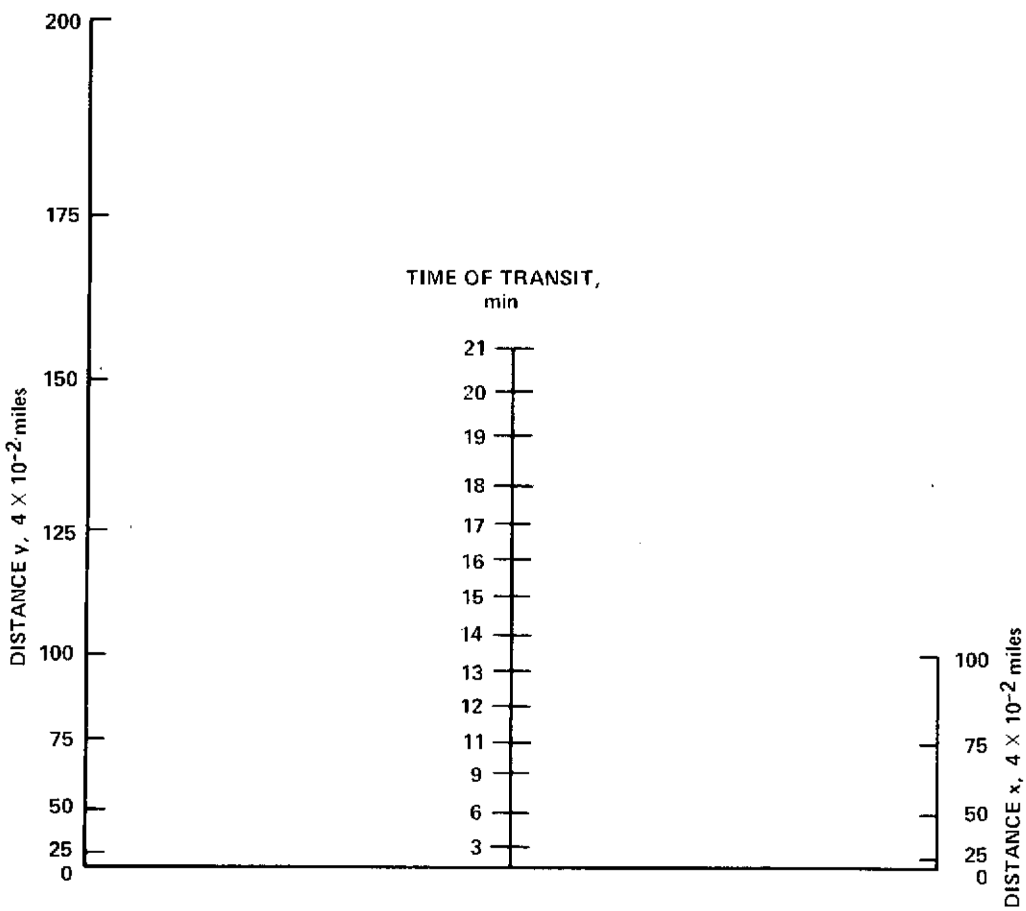

Figure 11-13 Transit-Time Nomograph

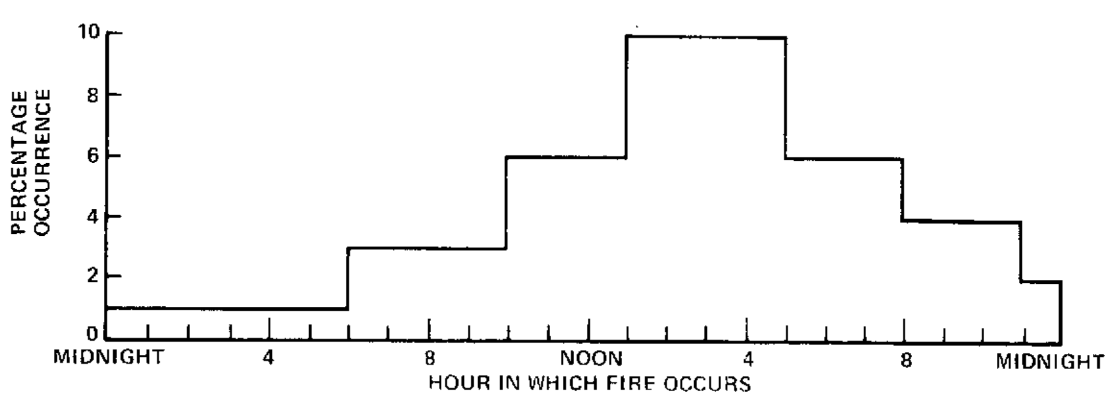

Figure 11-14 Distribution of Ignition Times Throughout Day

3

At the time of arrival of the suppression forces t_A, the fire area is $A(t_A)$ and the rate of change of the fire perimeter is $\dot{P}(t_A)$. The suppression strategy employed at this point in the simulation is of the indirect type. This indirect suppression strategy uses a flanking tactic and fights the fire by construction of fire lines around the fire in an effort to separate the fire and the fuel. The fire is said to be contained when it is completely surrounded by effective fireline and/or fuel breaks. The fire line construction begins at an anchor point and is assumed to proceed symmetrically around the fire with Length $\dot{L}t$ of fire line being constructed in time t. For our simulation, the anchor point is taken to be the point on the active perimeter with the slowest rate of spread, as illustrated in Fig. 11.15.

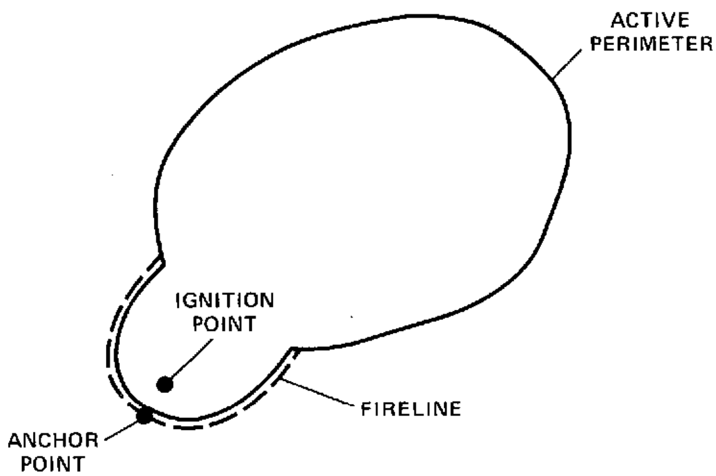

Figure 11-15 Indirect Suppression Tactic

Fireline is assumed to be constructed so as to be completely effective. This implies that as the wind and slope increase, the required fireline width must increase and hence the length of line which can be laid per unit time decreases commensurately. We have empirically estimated the factor by which $\dot{L}$ must be decreased for wind and slope. The result is shown in Fig. 11.16. Further, for winds in excess of 30 miles per hour, we assume that only flanking line can be constructed. That is, safety precautions prohibit building fireline on the front of the fire.

The probability of fire containment by fuel breaks is taken to be a function of the wind, slope, fuel-break width and the angle θ between the fuel break and resultant wind-slope direction. Data from the U.S. Forest Service (Carter, 1973) has been used to develop the following formula for the probability of containment p as a function of wind speed V and fuel-break width W (see Chapter IV).

$$p = \left(\frac{V}{30}\right)^2 p_{V=30}\ (W,\theta)$$

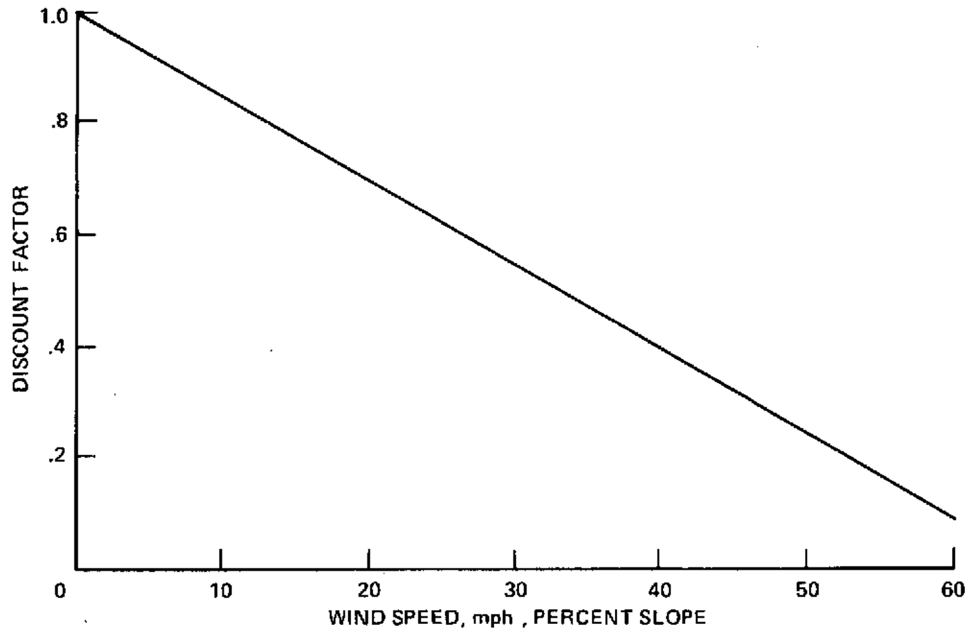

Figure 11-16 Wind and Slope Discount Factor

The probability of containment for 30 mile-per-hour winds (measured at 20 feet above the ground) is given in Fig. 11.17 for medium brush type fuels for fuel breaks parallel to ($\theta = 0°$) and normal to ($\theta = 90°$) the resultant windslope direction. For angles between 0° and 90°, a linear interpolation is used.

Reinforcement of the initially dispatched suppression force is determined in this simulation by the 10:00 a.m. rule which can be stated in the following form: reinforcements are requested so that the fire will be controlled by 10:00 a.m. of the following day. Of course, the reinforcements requested cannot exceed some maximum rate of arrival and

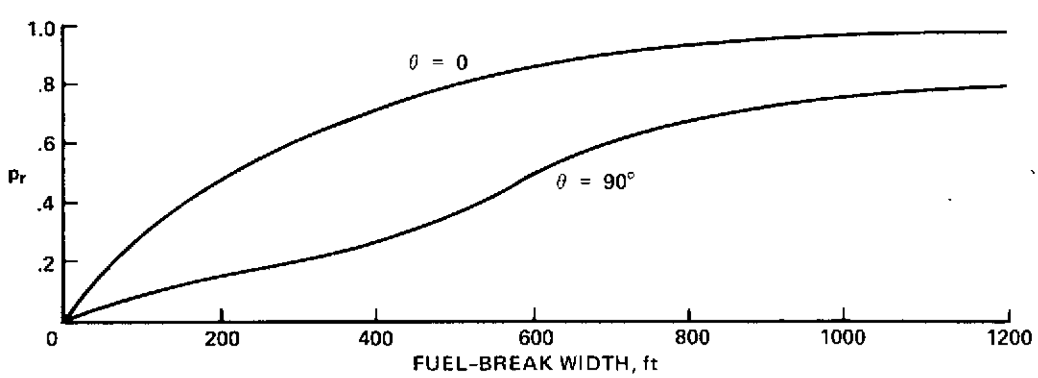

Figure 11-17 Probability of Containment for Various Fuel-Break Widths. 30 MPH winds. Medium Brush.

some maximum total level as dictated by suppression resource availability and location. A conservative estimate of the line-laying capability needed to satisfy the 10:00 a.m. rule is

$$\dot{L}_{needed} \cong 4\dot{r}_o(3 + K)$$

This result neglects the changing of the winds at night and assumes that reinforcements arrive at a constant average rate.

The maximum reinforcements available have been estimated as corresponding to 150 twenty-man hand crews (each working one 12 hour shift per day), 90 D-4 size bulldozers, 150 fire trucks (with crews), 15 air tankers (600 gallon capacity), and 12 helicopters. The hand crew and truck reinforcements have been discounted by a factor of two (in comparison with initially dispatched forces) for fatigue resulting from 12 hour shifts and the bulldozers have been discounted by a factor of 2 to account for the wider fireline needed in medium and heavy brush fuels. The maximum increase in line laying capability per day is then determined by assuming that the maximum capability can be assembled in four days. Further, assuming Treedom has fuels corresponding to the heavy brush and slash category with 20% slopes and Itlpainia Canyon has medium brush fuels with 55% slopes, the maximum increase per day in line laying capability (in feet per hour) as a function of wind speed is given below in Table 11.3. Given the need for reinforcements exceeding the maximum available, the maximum is then ordered. One-fourth of the reinforcements are assumed to be air support which arrives three hours after ordering, the remaining three-fourths arriving in two equal increments, six and twelve hours after being ordered.

Table 11.3

MAXIMUM REINFORCEMENTS PER DAY (FT/HR)

Wind (mph)	L (Treedom)	L (Itlpainia Canyon)
0	46,600	23,300
10	39,000	19,800
20	32,000	16,300
30	25,600	12,800
40	18,600	9,300
50	11,600	5,800
60	4,600	2,300

The simulation of the spread and suppression of a fire thus involves the following steps in the order given:

1. Determine the type of day--green, orange, or red.

2. Choose a random number* and from Table 11.4 determine the time of day.

3. Choose two random numbers and after doubling the first, determine the point of ignition within the simulated area and the transit time from the location of the suppression resources to the point of ignition using the nomograph given in Fig. 11.13.

4. Add the detection (8 minutes) and the dispatch (2 minutes) times to the transit time to obtain the time of arrival t_A.

5. Choose two random numbers and determine the wind direction and speed from Tables 11.5 and 11.6. If the time of day corresponds to night time (6:00 p.m. to 10:00 a.m.), choose another random number and determine the night wind factor C_n from Table 11.7.

6. Determine the average slope and its direction.

7. Determine the no-wind, no-slope rate of spread $\dot{r}_o$ and slope factor ϕ_s from Table 11.8. Determine the wind factor ϕ_w from Table 11.9.

8. From the wind and slope directions and factors, determine the wind-slope factor K and the resultant wind-slope direction.

9. Determine the initially dispatched line laying capability $\dot{L}$ from Table 11.2 and Figs. 11.10, 11.11, and 11.12.

10. Determine if reinforcements are needed by evaluating $\dot{L}_{needed}$ and comparing with initial dispatch. Using

$$\dot{L}_{needed} \cong 4\dot{r}_o(3 + K)$$

determine if

$$\dot{L}_{needed} < \dot{L}_{initial}$$

If it is true, then order reinforcements up to the maximums given in Table 11.3 and determine the time of arrival. If the needed reinforcements exceed the maximums available, order the

*All random numbers are assumed to be in the range from zero to ninety-nine.

maximum and submit another order at 10:00 a.m. the following morning if necessary.

11. If no reinforcements are needed, and the topography, weather, and fuels remain constant, use the following empirically established expressions for the suppression time and area burned by the fire, A_{burn}, in acres,

$$t_s = \frac{t_A \dot{r}_o (3 + 2K)}{\dot{L} - 2\dot{r}_o (2 + K)}$$

$$A_{burn} = \frac{\dot{r}_o^2 (2t_A + t_s)(t_s + t_A)(1 + K)}{(209)^2}$$

Here $\dot{r}_o$ is in feet per minute and time is measured in minutes. Go to step 20. If reinforcements were needed, continue.

12. Determine the time increment for perimeter advancement Δt so as to give a fire perimeter advance of the order of 0.1 to 0.25 miles. An estimate of Δt follows as

$$\Delta t = \frac{0.2 \text{ miles}}{\dot{r}_o (1 + K)}$$

with $\dot{r}_o$ in miles per minute.

13. Advance the fire perimeter as illustrated in Fig. 11.7.

14. Determine if a fuel break is intercepted. If so, choose a random number and, given the fuel-break width, wind speed and wind direction, determine if the fire is contained from Fig. 11.17.

15. Lay fireline of length $\dot{L}\Delta t$ symmetrically about the fire perimeter starting from the anchor point as illustrated in Fig. 11.15.

16. Determine if the fire is contained. If so, go to step 20. If not, continue.

17. Have the reinforcements arrived? If so, add the reinforcements to the current $\dot{L}$ and continue.

18. Will the weather, fuel, or slope conditions change in the next time interval? If so, repeat steps 6, 7, and 8 and continue.

19. Return to step 13.

20. Determine the area burned.

Table 11.4

TIME OF DAY

Time	Random Number	Time	Random Number	Time	Random Number
Midnight	0	8:00	12-14	4:00	66-71
1:00	1	9:00	15-17	5:00	72-77
2:00	2	10:00	18-23	6:00	78-83
3:00	3	11:00	24-29	7:00	84-87
4:00	4	Noon	30-35	8:00	88-92
5:00	5	1:00	36-45	9:00	93-96
6:00	6-8	2:00	46-55	10:00	97-98
7:00	9-11	3:00	56-65	11:00	99

Table 11.5

WIND DIRECTION

Direction	Random Numbers
0°	0-24
30°	25-49
60°	50-74
90°	75-99

Table 11.6

MIDFLAME WIND SPEED

Speed (mph)	Random Number	Speed (mph)	Random Number
Green Day			
0	0-19	7	91-92
1	20-49	8	93-94
2	50-74	9	95
3	75-84	10	96
4	85-86	11	97
5	87-88	12	98
6	89-90	15	99
Orange Day			
0	0-14	8	89-91
1	15-37	9	92-93
2	38-60	10	94
3	61-70	11	95
4	71-76	12	96
5	77-81	13	97
6	82-85	14	98
7	86-88	15	99
Red Day			
0	0-14	8	82-87
1	15-29	9	88-90
2	30-39	10	91-92
3	40-49	11	93-94
4	50-59	12	95-96
5	60-67	13	97
6	68-74	14	98
7	75-81	15	99

Table 11.7

NIGHT WIND FACTOR

Factor	Random Number
0.00	0-26
0.25	27-51
0.50	52-71
0.75	72-86
1.00	87-96
1.25	97-98
1.50	99

Table 11.8

NO-WIND, NO-SLOPE RATE OF SPREAD (FT/MIN), SLOPE FACTOR (1)

Type of Day	$\dot{r}_o$ (Treedom)	$\dot{r}_o$ (Itlpainia Canyon)
Green	0.50	1.19
Orange	0.73	1.65
Red	1.20	2.13
Slope Factor	0.71	8.88

Table 11.9

WIND FACTOR

Midflame Wind Speed (mph)	ϕ_w (Treedom)	ϕ_w (Itlpainia Canyon)
0	0.00	0.00
2	2.63	4.60
4	7.09	12.90
6	12.66	23.60
8	19.11	36.22
10	26.30	50.49
12	34.14	66.24
14	42.56	83.34
16	51.52	101.67
18	60.98	121.16
20	70.90	141.74

The fire-spread and suppression model just described was verified in the following manner. Twenty fires each were simulated for green, orange, and red fire-danger rating days. Assuming the green, orange, and red days occur with equal frequency, the percentage occurrence of fires by fire size obtained from the model for chamise type fuels was compared with results reported for the federal forests of California (Roberson, 1972). This comparison is shown in Fig. 11.18.

The comparison shows the distributions to be qualitatively the same and in acceptable quantitative agreement. In addition, many of the intermediate results of the simulation, not shown here, agree with rules of thumb that have been established over the years by field experience. For example, our results show that the wind speed is the most critical factor in determining fire size. Also, the fuel-break calculations show that a four-hundred foot fuel break cannot contain fires with wind speeds in excess of about thirty-six miles per hour. In fact, the results indicate that most large fires are contained only when there is a change in the weather conditions--specifically, in the wind speed. Very large fires occur in the simulation only when high daytime winds do not subside at night. The agreement of these and other results of the simulation with the accounts given by experienced fire fighters adds to confidence in the essential correctness of the model. Refinements in many of the numerical values used in the simulation--line laying capabilities and rate of spread calculations, for example--

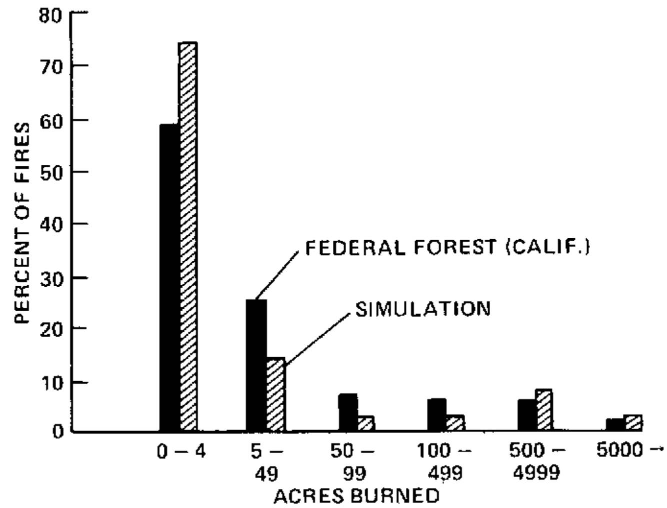

Figure 11-18 Comparison of Fire Sizes

are possible and would be useful. Nonetheless, it is left that the structure of the fire-spread and suppression model is correct and will permit the evaluation of the effect of different prevention decisions on the wildland fire control problem.

C. An Illustrative Simulation

To illustrate a simulation involving both time- and space-varying conditions, consider the canyon-like area shown in Fig. 11.19; lines

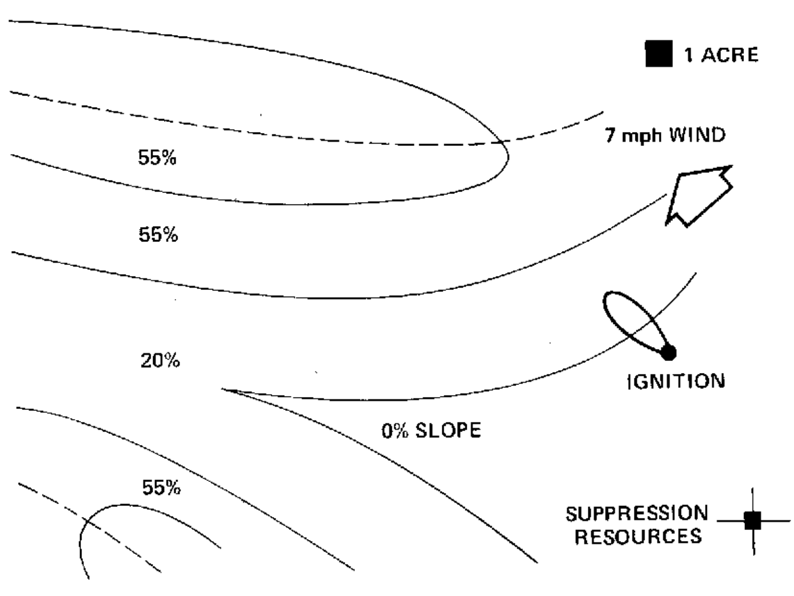

Figure 11-19 Fire Perimeter at Twelve Minutes

of constant height are shown along with numbers indicating the slope in different regions of the simulated area. The fuel is fifteen-year-old chamise as given in Appendix XI. Furthermore, it is assumed to be a red (high fire-danger rating) day. Choosing the random number 49 from the tables, we find from Table 11.4 that the fire begins at 2:00 p.m. Choosing the two random numbers 59 and 30 and then doubling the first, Fig. 11.13 gives the time of transit as 12 minutes, which, when added to dispatch (2) and detection (8) times, gives a time elapsed at the arrival of the suppression forces of 22 minutes. Choosing the two random numbers 85 and 77, we have from Tables 11.5 and 11.6 that the wind direction is initially 90° from the topographic contour* with a midflame height speed of 7 miles per hour. These conditions are assumed to hold for the first twelve minutes. The slope at the point of ignition is 0% and thus the slope factor is zero. From Tables 11.8 and 11.9, the no-wind, no-slope rate of spread is 2.13 feet/minute, and the wind factor is 29.9. The fire perimeter at the end of twelve minutes is shown in Fig. 11.19. Since no suppression forces have arrived in the first twelve minutes and there are no fuel breaks, we now skip the remaining steps in the simulation and advance the fire again. Choosing the random numbers 44 and 81, the wind direction is 0° and the wind speed is 7 miles per hour. The slope at the fire perimeter is either 0% or 20% with slope factors 0 and 3.2, respectively. The no-wind, no-slope rate of spread is, from Table 11.8, 2.13 feet per minute and from Table 11.9 the wind factor is 29.9. Assuming these conditions hold for the next ten minutes, the fire perimeter after twenty-two minutes is obtained as shown in Fig. 11.20.

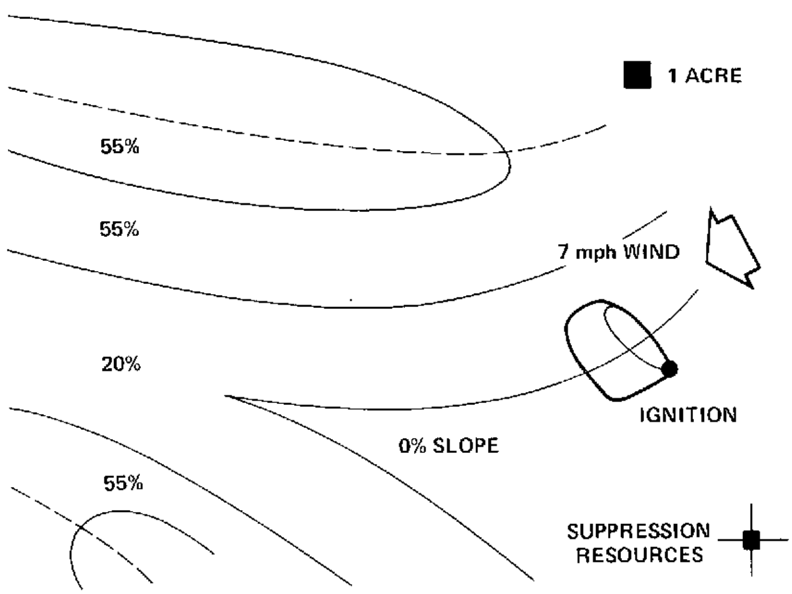

Figure 11-20 Fire Perimeter at Twenty-Two Minutes

*The reference wind direction at any point is taken to be parallel to constant height contours.

Again, no suppression forces have been at work in this time period; thus the fire can be spread once again. Choosing the random numbers 78 and 62 the wind direction is 0° and the wind speed is 5 miles per hour. The slope factors do not change and the wind factor is 18.3. Assuming these conditions hold for the next ten minutes, the fire perimeter after thirty-two minutes is obtained as shown below in Fig. 11.21.

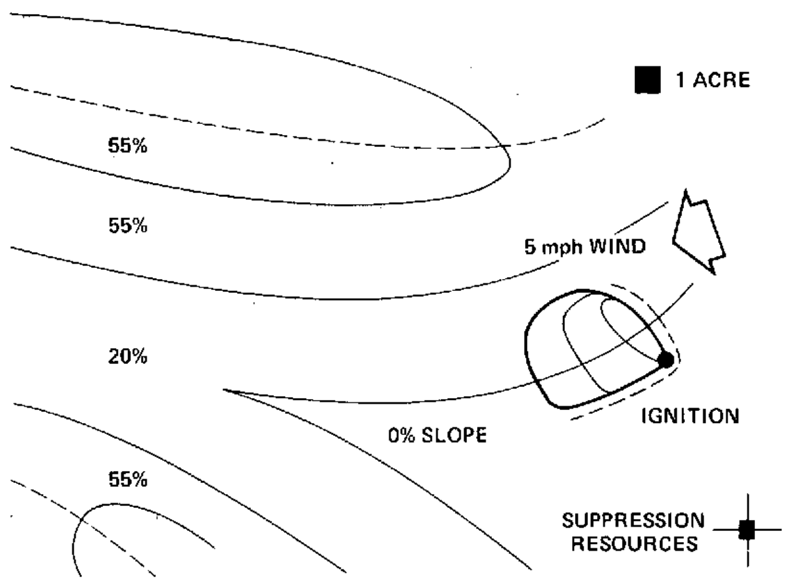

Figure 11-21 Fire Perimeter at Thirty-Two Minutes

As this is a red day, the initially dispatched suppression capability is 175 feet per minute from Fig. 11.11. Thus, in the ten minute period after the suppression forces arrive, they lay 1750 feet of fireline which is indicated in Fig. 11.22 by a dashed line. This fireline is laid symmetrically about the anchor point at the point of ignition. Estimating the needed suppression capability to extinguish the fire by 10:00 a.m. shows that the initial dispatch forces should be sufficient and no reinforcements are needed. Choosing the random numbers 87 and 95, Tables 11.5 and 11.6 give the wind direction as 90° and the wind speed as 12 miles per hour. The associated wind factor is 66.2 from Table 11.9 while the slope factor in the 55% slope region becomes 8.9 from Table 11.8. Using these conditions for the next ten minutes, the result given in Fig. 11.22 is obtained. Continuing this process, we obtain the complete fire simulation as shown in Fig. 11.23. Table 11.10 gives the wind speeds and directions for every ten minutes of the simulation. The fire was controlled after 102 minutes with 147 acres burned.

This suppression and fire-spread simulation is sufficiently simple that it could be used as part of the planning activity for campaign fires. Indeed, in the process of running the simulation, several shortcuts have been developed which sufficiently simplify hand calculations

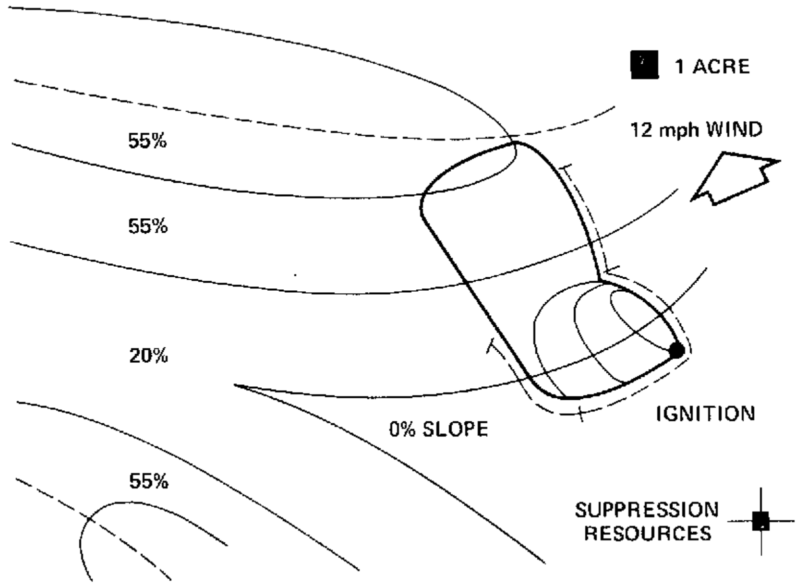

Figure 11-22 Fire Perimeter at Forty-Two Minutes

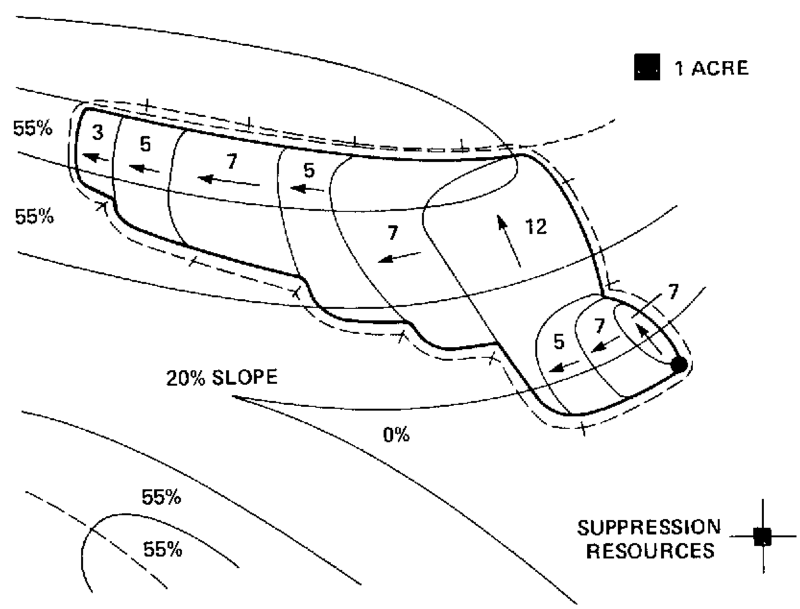

Figure 11-23 Simulated Fire History

Table 11.10

WIND SPEED AND DIRECTION

Time Since Ignition (minutes)	Wind Speed (mph)	Wind Direction
12	7	90°
22	7	0°
32	5	0°
42	12	90°
52	7	0°
62	5	0°
72	7	0°
82	5	0°
92	3	0°
102	Fire	Contained

so that they may be made under actual fire conditions. In addition to providing the Fire Boss with more accurate predictions of fire behavior, such on-the-scene simulations could also provide an invaluable data base for use in further improvements of the simulation model itself.

D. Fuel Breaks

The effect of fuel breaks on fire damage has been assessed for the Itlpainia area. Uniformly distributed fuel breaks were assumed, as indicated in Fig. 11.1b. Two fuel-break widths W (400 feet and 1000 feet) and two fuel-break separation distances ℓ_{FB} (20,000 feet and 40,000 feet) have been considered, implying four possible fuel break systems. The same sixty fires which were described earlier as part of the verification (without fuel breaks and fuel modification) were again simulated with the four different fuel-break systems. Expected values of acres burned have been obtained and compared with the acres burned without fuel breaks. The results are shown in Fig. 11.24 where the expected number of acres burned (as a percentage of those burned in the simulation without fuel breaks) is given as a function of fuel-break width. Numerical results are given in Table 11.11.

The most striking contrast is obtained by comparing the 400-feet fuel breaks having a 20,000 feet separation distance (referred to here as Case A) and the 1000-feet wide fuel breaks having a 40,000 feet separation distance (referred to here as Case B). In Case A there is a 15% reduction in area burned while Case B has an 81% reduction. To develop this comparison further, note that for a sufficiently large area,

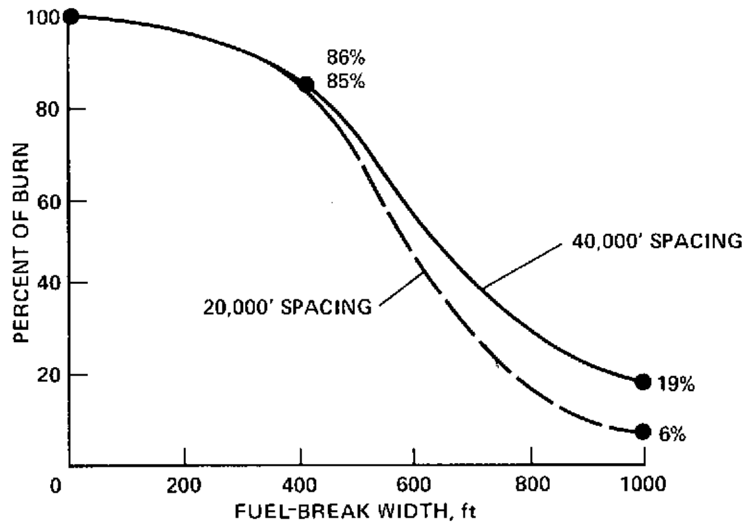

Figure 11-24 Effect of Fuel-Break Width and Spacing on Area Burned

Table 11.11

EFFECT OF FUEL BREAKS ON AREA BURNED
(Percentage of Area Burned without Fuel Breaks)

Separation ℓ_{FB} \ Width W	400 ft	1000 ft
20,000 ft	85%	6%
40,000 ft	86%	19%

the total length of fuel breaks with 20,000 feet separation distance is twice the total length of the fuel breaks with 40,000 feet separation distance. Thus, the area which must be cleared to construct the Case A fuel break system is eighty percent of that which must be cleared to construct the Case B fuel break system. Thus, assuming the cost of clearing to be proportional to the area cleared and the damage to be proportional to the acres burned, we see that the Case B (wide) fuel-break system is roughly five times as effective as the Case A (narrow) fuel-break system (for approximately the same cost per acre of construction and neglecting the savings in suppression costs).

The dramatic effect of an increase in fuel-break width on area burned has been reported by others (Harrison, 1973), and may be explained as follows: Fuel breaks affect the area burned by reducing the size of the larger fires. The larger fires are the only ones that are significantly affected because the spacing between fuel breaks, which is a measure of the fire length scale beyond which the fuel break is effective, is of the order of several miles. Also, the larger fires only occur when the fire danger is high--typically when there are high winds. Thus, those large fires, which are affected by fuel breaks, are contained only by rather wide fuel breaks, and consequently increasing the fuel-break width can have a striking effect on the acreage burned.

An elementary calculation shows that if the fire is assumed to spread one-dimensionally with a constant width, then the expected area burned with at most N fuel breaks being encountered (as a percentage of the area burned without fuel breaks) is approximately

$$\frac{E(A)}{A_{\text{no fuel breaks}}} \cong \frac{1}{N}\,\frac{1-p}{p}$$

assuming a large number of fuel breaks are potentially intercepted. Using this result to compare Case A and Case B, we obtain

$$\frac{E\,(A \mid \text{Case A})}{E\,(A \mid \text{Case B})} \cong \frac{9}{2}$$

($N_A = 2N_B$, $p_A = 0.25$, $p_B = 0.75$) which agrees remarkably well with the number obtained from the simulation, 4.47. The implication of the result is clear: increasing the effectiveness of fuel breaks while decreasing their number so as to keep the area cleared constant can be advantageous. It is clear, however, that one cannot continually decrease the number of fuel breaks and commensurately increase their effectiveness without bound. Thus, there appears to be an optimum combination of fuel-break width and separation distance which depends upon the distribution of fire sizes.

E. Effects of Dispatching Uncertainties

The California Division of Forestry today uses an automatic initial dispatching system. The suppression force level initially dispatched to a fire depends on the measured fire danger. Different suppression capabilities are dispatched depending on whether the measured fire danger falls into a low (green), medium (orange), or high (red) range.

It is well known, and was also observed in this simulation, that for a given actual fire danger (as contrasted with a measured fire danger), the final fire size depends critically upon the suppression force level initially dispatched. Below a critical level, a fire can easily get away. Beyond another critical level of dispatch, diminishing returns become evident as further increases in dispatched suppression capability yield a negligible decrease in fire damage. Given the higher costs of increased suppression capability, there is clearly an optimum level of initial dispatch in which cost-plus-loss per fire is minimized. Dispatching this optimum level requires a certain accuracy in the measurement of the actual fire danger. On the basis of arguments such as these, advanced data gathering systems have been proposed (see Volume II of this report) in order to obtain more accurate measurements of fire danger. In this way uncertainties in the initially dispatched suppression levels (using, say, the current three-level dispatch system) would be reduced, leading to reductions in fire damage. Alternatively, with more accurate data, the initially dispatched suppression level could be made to vary continuously in contrast to the present three-level system.

An analysis was made to determine the desirability of more accurate measurements by determining the sensitivity of the fire damage to errors in the initially dispatched suppression force. Specifically, it compared the relative change in area burned when the medium (orange) level of suppression capability is initially dispatched on high fire-danger (red) days (corresponding to a twenty-nine percent decrease in the initial dispatch) and when the high (red) level of suppression capability is initially dispatched on medium fire-danger (orange) days (corresponding to a forty percent increase in the initial dispatch). These represent extreme cases of uncertainty in the measured fire danger. Each case used twenty fires, the conditions of which were the same as in the twenty red- or orange-day fires simulated as part of the verification. The results are given below in Table 11.12.

Table 11.12

EFFECT OF DISPATCHING ERRORS ON AREA BURNED

Dispatch	Area Burned
Orange Dispatch, Red Days	19% increase
Red Dispatch, Orange Days	40% decrease

In both cases, the change in the area burned is due primarily to changes in the area burned by a few large fires. For example, in the second case in which a red level dispatch is sent on orange level days, over 99% of the obtained 40% decrease is due to the change in the area burned by one fire which occurred under unusually bad conditions. The implication of these (preliminary) results is fairly clear: Uncertainties in the initially dispatched levels are most important during conditions of high actual fire danger. Errors in the initial dispatch due to errors in the measured fire danger can, for large fires, lead to changes in the area burned of the order of twenty to forty percent.

These results, along with experience obtained in conducting the simulation, suggest a dispatching procedure could be developed which would be optimal in the sense that the optimum initially-dispatched suppression capability gives a minimum expected cost-plus-loss for the fire. To see this, recall that the suppression time t_s and the area burned A_b (in square feet) are given by

$$t_s = t_A \frac{(3 + 2K)}{\frac{\dot{L}}{\dot{r}_o} - 2(2 + K)}$$

$$A_b = \frac{(\dot{r}_o t_A)^2}{(209)^2}\left(2 + \frac{3 + 2K}{\frac{\dot{L}}{\dot{r}_o} - 2(2 + K)}\right)\left(1 + \frac{3 + 2K}{\frac{\dot{L}}{\dot{r}_o} - 2(2 + K)}\right)(K + 1)$$

For a given state of nature in which the weather, fuel, and topography are fixed, the no-wind, no-slope rate of spread $\dot{r}_o$ and the wind-slope factor K are determined. Also, for a given fire location, the time of arrival of the suppression forces t_A is fixed. The area burned then depends upon the initially-dispatched suppression capability $\dot{L}$ (assuming sufficient forces are always sent so that reinforcements are never needed). Assuming that the fire damage is proportional to the area burned and that the cost of suppression is proportional to the suppression capability $\dot{L}$ and the total time that the suppression forces are employed, the total cost-plus-loss due to a fire is given by

$$C + L = C_1 A_b + C_2 \dot{L}(t_s + t_A + t_T)$$

Here C_1 is the loss per square foot due to fire damage (C_1 could include mop-up costs which should be proportional to area burned), and C_2 is the suppression cost per unit time per unit of suppression capability. Also, t_T is the transit time required for the suppression forces to return to their original location. For simplicity, we assume t_T is equal to t_A, the arrival time. Substituting for A_b and t_s in terms of $\dot{L}$, K, $\dot{r}_o$, and t_A we obtain an expression for the total cost-plus-loss. Assuming K, $\dot{r}_o$, and t_A are held constant, the initially-dispatched suppression capability $\dot{L}^*$ which gives the minimum cost-plus-loss can be computed by calculus in the form

$$\dot{L}^* = 2(2 + K) + F\left(C_1 \frac{\dot{r}_o t_A}{C_2}, K\right)$$

where F is a complicated function of the two variables indicated. The significance of this solution is that the optimum initially-dispatched suppression force depends explicity on K, the wind-slope factor, and the combined variable $C_1 \dot{r}_o t_A / C_2$. The latter variable is independent of the wind and could, in principle, be measured daily or even weekly with little error. The wind-slope factor K, however, varies considerably throughout the day and, if such an optimum dispatching strategy is to be employed, must be determined at the time of ignition. Also, since K increases as a power of the wind speed, there is a special need for accuracy at higher wind speeds.

This analysis thus suggests strongly that once continuous or near-continuous monitoring of the wind speed and direction is achieved, an optimum dispatching strategy of the sort described here would become possible, and the cost-plus-loss due to a given set of ignitions would be minimized.

F. Area-Wide Fuel Modification

A given wildland area, if unburned and left unattended, will experience an increase in the fuel load each year. In areas where wildland fires are a problem, this increasing fuel load is eventually reduced by means of an unplanned fire. The risk associated with unplanned fires is due, in large part, to the lack of fire controllability by suppression forces once the rate of fire spread exceeds some critical value. Valuable structures, watershed, recreation facilities, etc., are jeopardized when the rate of fire spread exceeds the maximum rate which can be controlled by the existing suppression forces. Increasing suppression capability simply increases this critical fire spread rate. At some point, the total area burned may, in fact, increase with further increases in suppression capability since although fewer fires get away, those which do escape become spectacularly large.

Proponents of area-wide fuel modification such as prescribed burning (see Chapter V) argue that the high risk associated with large wildland fires can be substantially reduced and perhaps even eliminated by using area-wide fuel modification. In this way the average (and maximum) fuel age is reduced, implying in turn a reduction in the fire-spread rate so that the rate of spread rarely (ideally never) exceeds the critical value.

To examine area-wide fuel modification, the sixty fires used in the original verification tests (where the fuel age was assumed to be fifteen years) were again simulated, changing only the fuel age. The area burned was determined for five and ten year-old fuel (as a fraction of the value for fifteen year old fuel). The results are shown in Table 11.13. These results show the spectacular effect of fuel age on the area burned.

Table 11.13

EFFECT OF FUEL AGE ON AREA BURNED

Fuel Age (years)	Area Burned
15	100%
10	10%
5	.1%

To determine the cost-effectiveness of area-wide fuel modification, assume the costs to be those of suppression and fuel modification. The suppression cost is assumed, for simplicity, to be proportional to the area burned A_b while fuel modification costs are proportional to the area treated A. The losses due to fire damage are taken to be proportional to the area burned. Thus the total cost-plus-loss is given by

$$C + L = C_s A_b + C_{FM} A + C_L A_b$$

where C_s is the suppression cost per unit area burned, C_{FM} is the fuel modification cost per unit area treated, and C_L is the loss per unit area burned. Comparing the cost-plus-loss with and without fuel modification, the cost-benefit ratio η is

$$\eta = \frac{(C + L) \text{ with modification}}{(C + L) \text{ without modification}} = \frac{A_b'}{A_b} + \frac{A}{A_b} \frac{C_{FM}}{C_s + C_L}$$

where A_b' is the area of modified fuel burned. The simulation results suggest that the ratio A_b'/A_b is generally small. Hence, the cost-effectiveness of fuel-modification depends critically on the ratio of area burned A_b to area treated A and the costs of suppression, fuel modification, and damage.

It is interesting to note that ranchers who prescribe burn to improve the quality of grazing land can be considered to have justified such area-wide fuel modification, not because of reduced fire damage, but because of the low net cost of the modification per unit area C_{FM} resulting from not having to buy additional feed for their cattle. Indeed, one suspects C_{FM} to be negative under such circumstances. One can also begin to understand the use of prescribed burning in sequoia groves as being cost-effective because of the very high value attached to preserving these trees (high C_L).

These results can be used to estimate the cost-effectiveness of prescribed burning. For example, assume the cost of prescribed burning to be five dollars per acre and the cost of suppression to be fifty dollars per acre. Further, assume the fuel modification will have a ten year cycle and that without fuel modification, one percent of the protected area would burn each year (a generous estimate). Taking A_b'/A_b to be 0.1 as determined from the simulation, the cost-benefit ratio of prescribed burning is

$$\eta = 0.1 + \frac{1}{1 + 0.02\, C_L}$$

Thus, prescribed burning is cost-effective if the fire damage per acre exceeds about six dollars. This minimum value of fire damage per acre increases by a factor of ten if the cost of fuel modification doubles or if the area which burns without fuel modification is taken to be one-half of one-percent. Even higher fire damage rates are needed to justify area-wide fuel modification if other more expensive methods of modification are used. For example, clearing with bulldozers or by hand can cost hundreds of dollars per acre.

Area-wide fuel modification can be made substantially more attractive, however, by considering it as a technique for constructing very wide fuel breaks. Consider modifying, say, only ten percent of a given area by means of prescribed burning. Referring to the cost-benefit ratio equation, it appears that A_b'/A_b will increase slightly (perhaps to as much as twenty percent). The second term in the expression for η, however, will decrease by a factor of ten, thus suggesting a very cost-effective prevention technique.

Appendix XI

SIMULATION INPUT DATA

1. Input Data for Itylpainia Canyon

	Days Since May 1	Dead Fuel Moisture
Green	60	0.15
Orange	90	0.06
Red	120	0.03

Slope = 55%

Severe Dead

Severe Load

Age (5, 10, 15 years)

Data processed by Computer Program FIREMOD, version for chamise model, spread rate according to R.C. Rothermel's Model INT-115, written at the Northern Forest Fire Laboratory by Bill Gastineau, 1971 and revised by Dan Ballas in 1973.

2. Input Data for Treedom

	Fuel Moisture			
	Dead			Living
	Fine	Medium	Large	
Green	0.15	0.18	0.24	1.5
Orange	0.10	0.13	0.19	1.0
Red	0.04	0.07	0.13	0.60

	Dead (1)	Dead (2)	Dead (3)	Living
Heat Content Btu/lb	8,000	8,000	8,000	8,000
Particle Density lb/ft^3	32	32	32	32
Total Mineral Content lb/lb	0.0555	0.0555	0.0555	0.0555
Effective Mineral Content lb/lb	0.01	0.01	0.01	0.01
Surface Area/Volume 1/ft	2,000	109	30	1,500
Oven-Dry Loading lb/ft^2	0.138	0.092	0.23	0.092
Moisture of Extension lb/lb	0.3	0.3	0.3	0.3

Fuel Depth = 1 ft

Slope = 20%

Computer Program FIREMOD, determines rate of spread by R. C. Rothermel's model INT-115. This program was written and developed at the Northern Forest Fire Laboratory by Bill Gastineau in 1971 and revised by Dan Ballas in 1973.

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