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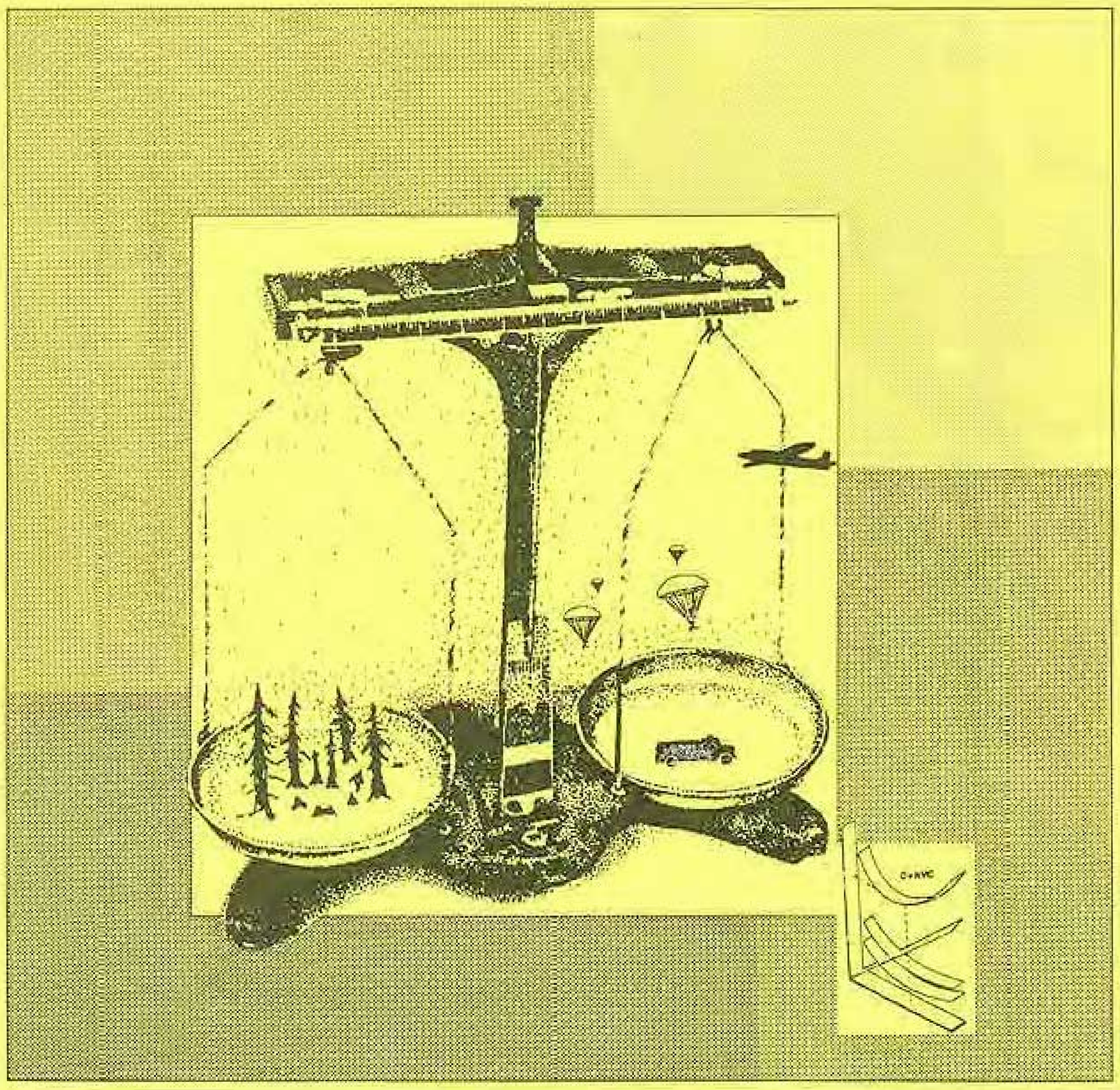
Economic Efficiency and Risk Character of Fire Management Programs, Northern Rocky Mountains

Thomas J. Mills **Frederick W. Bratten**



The Authors:

at the time of the study reported here were assigned to the Station's Fire Management Planning and Economics Research Unit, headquartered at the Forest Fire Laboratory, Riverside, Calif. **THOMAS J. MILLS**, who headed the Unit, is now Director of Resources Program and Assessment, Forest Service, U.S. Department of Agriculture, Washington, D.C. **FREDERICK W. BRATTEN**, formerly an operations research analyst with the Unit, is now retired.

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IN BRIEF . . .

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Because of the fire system's highly stochastic and complex nature, there is relatively little information on the economic efficiency of alternative fire management programs and even less on the tradeoffs between efficiency and risk. Three hypotheses about fire system performance were formulated to guide analysis into these dimensions:

- Economic efficiency is related to both the dollar amount of the fire management budget and the mix or emphasis of the fire management inputs purchased with the budget.
- Risk in the fire management system, where risk is measured by the probability distribution about the expected value economic efficiency, decreases with increasing fire management funding levels.
- The most efficient funding level for a risk-averse fire program manager is higher than for a risk-neutral manager.

These hypotheses were tested on selected public lands in the northern Rocky Mountains using the Fire Economics Evaluation System (FEES), a simulation model designed to evaluate alternative fire management programs for long-term planning and policy analysis purposes across broad regional areas.

Results from this study show that efficiency is strongly affected by the fire management program level, but the impact of the fire management mix or emphasis on efficiency is relatively minor. The most economically efficient initial attack program level is the lowest of those tested, 75 percent below the base level funding for the study period. When only hazard-reduction benefits are credited to fuel treatments, the zero program level is the most economically efficient.

The level of risk embodied in any fire management program option does decrease with increasing program levels, but the decrease in risk is relatively minor. Whether there is justification for a higher program level for the risk-averse than for the risk-neutral decisionmaker is a function of how the tradeoff between expected value efficiency and risk is displayed.

The sensitivity of these findings to changes in three major model inputs—fire prevention effectiveness, large-fire suppression effectiveness, and resource management objectives—were all tested. The general nature of the study conclusions were not affected by realistic fluctuations in these three inputs. Experience with the model showed that modeling of fire behavior and initial attack effectiveness both deserve further research because of their potential to influence model results.

INTRODUCTION

Economic efficiency and risk have long been considered during the selection of fire management programs and the design of fire management policies. The risk consideration was largely subjective, however, and efficiency has only recently been calculated for selected portions of the fire management program. The highly stochastic behavior of the fire system and the high degree of interaction among its components make it difficult to model analytically. Without fairly advanced quantitative models, estimating the risk and efficiency consequences of fire management alternatives was impossible.

The number of acres burned has been the traditional indicator of fire system performance, and variability of acres burned has been the traditional risk indicator (Gorte and Gorte 1979). The number of acres burned integrates many of the physical, vegetative, and fire management effectiveness dimensions of the fire system into a single measure of performance, and number of acres burned may be a proxy for some impacts that cannot be valued in dollars. The acres that burn are themselves highly variable, however, as are the fires that burn them.

Economic efficiency, both its expected value and the probability distribution about that expected value, is a more complete integrator of fire management system behavior than is number of acres burned. Once the suppression cost and resource net value change of the number of acres burned are estimated, the resulting measurement of economic efficiency—ironically—is neither as sensitive to fire management program levels nor as variable from year to year as is number of acres burned. Efficiency and risk measurements are excellent integrators of the diverse interactions within a complex system, but they have been modeled with only marginal success in the past. For these reasons, rather than because of a belief that efficiency considerations should outweigh the effects of fire that cannot be quantified in dollar units, this study focuses on economic efficiency and risk.

To better understand the behavior of the fire management system, we formulated and tested three hypotheses about the economic efficiency and risk character of different fire management program funding levels and program emphases. An additional outcome of the hypotheses tests is identification of the most economically efficient fire management program from among a large number of program options tested in the study area.

The hypotheses were tested through the evaluation of fire management program options on public lands in the Northern Rocky Mountains and Northern Intermountain Fire Climate Zone (Schroeder and others 1964). The Climate Zone, bounded by the Cascade Mountains to the west, the Continental Divide on the east, the Canadian border to the north, and the Idaho-Nevada border to the south, is an area of similar synoptic weather during periods of critical fire weather. The hypotheses were tested with the Fire Economics Evaluation System (FEES) (Mills and Bratten 1982). FEES's design as a long-term planning tool makes it particularly useful for testing the efficiency and risk hypotheses across a broad range of fire management program options.

This paper reports tests of three hypotheses about fire performance to analyze economic efficiency and risk performance of alternative fire management programs by using FEES. The hypotheses were these: (1) economic efficiency is related to dollar amount of fire management budget and the mix of fire management inputs purchased; (2) risk decreases with increasing fire management funding levels; and (3) the most efficient funding level for a risk-averse fire program manager is higher than for a risk-neutral manager. The economic efficiency and risk characteristics of several alternative fire management programs were estimated to test these hypotheses.

ECONOMIC EFFICIENCY

Economic efficiency was first proposed as a criterion for the selection among alternative Forest Service fire management programs during the early years of forest management in the United States (Flint 1924, 1928; Sparhawk 1925). The efficiency criterion, articulated as the "least-cost-plus-loss," was seen as an integrative tool that reduced the physical, biological, and financial complexity of the fire system to a manageable indicator of program performance for decisionmakers. Although an excellent integrative concept, economic efficiency of the fire management program was, at that time, largely unsupported by the analytical tools required to render it into an operational policy (Pyne 1982).

Partially as a result of that inability to make the economic efficiency criterion operational, the economic efficiency criterion on Forest Service lands was rejected in 1934 in favor of a strong suppression-oriented fire management policy. The highly operational "10 a.m. policy" issued at that time (U.S. Dep. Agric., Forest Serv. 1977a) stated that fire control actions should be taken to suppress wildfires during the first burning period, or should that fail, control the fire by 10 a.m. of the next burning period. The 10 a.m. policy demonstrated an overwhelming concern for potential resource "damages" and suppression costs, and implied a great deal of faith in the ability of the fire management organization to suppress wildfires. The 10 a.m. policy also reflected a concern with the risk character of the fire system, although that risk concern was not well articulated at the time. While only a partial indicator of overall performance, the

10 a.m. policy had an elegant simplicity against which individual fire managers could be held accountable.

The suppression-oriented policy, especially when coupled with the "10-acre" fire control planning objective that was added in 1972 (U.S. Dep. Agric., Forest Serv. 1972), contributed to greatly increased costs for presuppression (prevention, detection, initial attack, and fuel-treatment activities) and suppression. Concern that the increases in presuppression costs exceeded suppression cost savings and increasing recognition of fire's beneficial effects to some resources led to a reexamination of the economic efficiency criterion for fire management programs (U.S. Dep. Agric., Forest Serv. 1977b). This reexamination, coupled with a study of the appropriate role for fire management within integrated land and resource management, led to the incorporation of an economic efficiency component in the Forest Service's revised fire management policy of 1978 (U.S. Dep. Agric., Forest Serv. 1981).

The revision of the Forest Service's fire policy coincided with advancements in the conceptual definition of the economic efficiency criterion (for example, Gorte and Gorte 1979, Simard 1976). In recognition of the beneficial effects of fire, for example, the least-cost-plus-loss formulation was changed to the minimization of the fire program costs plus the fire-induced net change in the present net value of resource outputs (C+NVC). The components of the C+NVC curve include the presuppression cost, suppression cost, detrimental net value changes, and beneficial net value changes. A hypothetical set of curves are shown in *figure 1*.

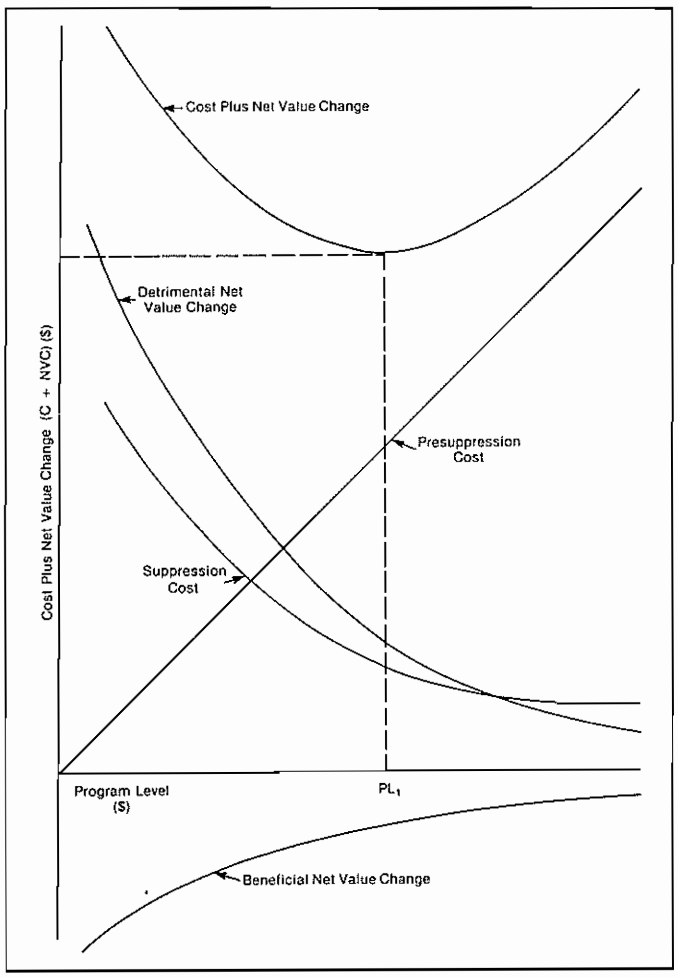

Figure 1—Illustrative components of the C+NVC function.

The C+NVC criterion is a "second-best" criterion used in situations where it is not possible to estimate the cost and resource output consequences in the absence of management. The net value change measures the change in the present net worth of resource outputs with and without the fire, not with and without the fire management program. With state-of-the-art fire behavior and fire suppression models, it is not possible to estimate how large fires would become in the absence of fire management. As a result, C+NVC identifies the most economically efficient program from among those programs tested, but does not show whether any of the programs tested are more efficient than no program at all.

The relationship between the minimization of C+NVC and the maximization of present net value (PNV) was also developed. The incremental PNV between two fire program options equals their C+NVC differences (Mills 1979). Knowing this, it is possible to derive the allocation of constrained fire management budgets among competing management areas that minimizes the foregone PNV. The C+NVC concept has also been applied to forest pest management program evaluations (Herrick 1981).

The conceptual advances in C+NVC were still ahead of the capability to analytically characterize the many interrelated components of the fire management system, however. As a result of this lagging analytical capability, the efficiency criterion was little more operational in 1978 than in 1934. The lack of that capability was apparent in the inability to provide the U.S. Senate (1978) with estimates of the efficiency consequences of reductions in the Forest Service's fire management appropriations for Fiscal Year 1979. A poorly articulated concern for the risk dimension of the fire system contributed to the ambiguity of fire program funding decisions in 1978, just as it had when alternative fire management policies were debated in the 1930's. In a review of the development of operation research procedures for forest fire management, Martell (1982) outlined a similar history of advances that were not transformed into operational tests.

In the absence of effective simulation models, studies of fire management program efficiency based solely on historical data were completed (Fedkiw 1965, Winkworth and others 1981, Oregon State Dept. of Forestry 1972). In those studies, fire years were separated into groups of fire severity according to number of acres burned or average burning index. While there is a strong appeal in the empirical underpinnings of those studies, they have two serious shortcomings. First, there are too many uncontrolled variables in the highly stochastic fire system to award all of the difference in outcome between years to differences in the fire management program. The number and location of ignitions with respect to fuel model and access, weather conditions at the time of ignition, and the management objective and resource values in the burned area are only a few of the additional factors that can materially affect the efficiency conclusions. Second, a historical analysis is restricted to an evaluation of the fire management funding levels and program compositions that existed in the past. There is little basis for extrapolating beyond those constraints.

The analytical capability to estimate economic efficiency across a broad range of fire management program options was later improved substantially through the development of simulation models (U.S. Dep. Agric., Forest Serv. 1982), and several case studies of the economic efficiency of various portions of the fire management program were completed (Bellinger and others 1983, Schweitzer and others 1982, U.S. Dep. Agric., Forest Serv. 1980). Although those simulation studies were major accomplishments in the continuing evolution of attempts to analyze fire program efficiency, more complete analytical models were required to study more fully the economic efficiency and, particularly, the risk dimension of the fire management system.

HYPOTHESES AND MODEL DESIGN

After reviewing previous studies of the fire management system, we formulated several hypotheses about its economic efficiency and risk character. These hypotheses were expansions of the hypotheses considered when the FEES model was designed (Mills and Bratten 1982).

First, we hypothesized that the economic efficiency of the fire management program is a function of the fire management mix or program emphasis, as well as the dollar program level. For example, one program mix may be heavily oriented toward initial attack on wildfires by ground forces while another mix may emphasize fuel treatment or the use of air forces, such as smokejumpers, for initial attack. Each fire management program mix embodies a particular set of production relationships that should encounter diminishing returns, just like any production function. Since there is no reason to expect the various production functions to behave identically, the most efficient fire management mix will likely change with the dollar program level.

This hypothesis implies that a family of C+NVC curves, rather than a single C+NVC curve (*fig. 1*), exists for any one fire management area. The hypothetical curves in *figure 2* illustrate a situation where the most efficient program mix varies with the program level. The most efficient C+NVC envelope is defined by the dashed line at the minimum frontier of the C+NVC set, similar to the way a long-run cost function for a firm is defined by the loci of short-run cost functions.

Families of C+NVC curves may vary in the relative importance of program level and program mix for fire program efficiency (*fig. 3*). Both the program level and the mix may significantly influence efficiency (*fig. 2, 3a*), program level alone may be important (*fig. 3b*), program mix alone may be important (*fig. 3c*), or neither program level or program mix may materially affect the economic efficiency of the fire management program (*fig. 3d*). Characteristics of the fire program area, such as fire occurrence and resource values, probably affect the combined influence of program level and program mix on the C+NVC curve shapes. There is too little information, at this time, to hypothesize where those relationships might occur.

Second, we hypothesized that risk decreases with increasing fire management program levels. We measured risk by the width of the probability distribution about the expected value of C+NVC. A larger percentage of the potentially large fires is likely to be suppressed at a small size with high levels of presuppression funding than would be possible with a lower presuppression program level, thus narrowing the distribution about the expected value. This hypothesis is displayed by the 90th percentile probability envelope about the expected value of C+NVC curve in *figure 4*.

We further hypothesized that infrequent, but severe, events in the fire system impact the distributional characteristics of the C+NVC. The expected value C+NVC is hypothesized to lie much closer to the value of the more severe outcome than to the less severe outcome. The analytical character of this potential "tail-heavy" nature has not been studied fully but is at the heart of the subjective debate about risk in the fire management system.

The amount of risk may also be a function of the characteristics of the fire program area and the fire management mix. Wider swings in the frequency of fire and the fire weather severity, for example, would probably lead to correspondingly wider probability distributions about the expected value C+NVC. Similarly, a presuppression program devoted largely to fuel-treatment activities may have a different risk character than one devoted largely to initial attack. Again, however, there is too little information to develop hypotheses for these relationships.

Third, we hypothesized that the character of the C+NVC distribution would lead the risk-averse decisionmaker to select a higher fire management program level than a risk-neutral decisionmaker. Specifically, the program level at which C+NVC is minimized varies with the percentile of the C+NVC probability distribution. The minimum C+NVC is hypothesized to occur at higher program levels for high percentile C+NVC, i.e., more severe fire seasons, than for the expected value C+NVC. This hypothesis is reflected in *figure 4* where the C+NVC minimum on the top side of the probability envelope occurs at a higher program level than the minimum of the expected value C+NVC curve.

The nature of these three hypotheses had important implications for the design of the FEES model, especially in combination with two important characteristics of the fire management system itself: (1) the interrelatedness of its components, and (2) its stochastic nature. The fire management system's interrelatedness leads to interactions among the major system components that cannot be ignored in any study of fire system behavior. Similarly, the high variation in several key facets of the fire system must be addressed in some explicit manner. Economic efficiency and risk are excellent parameters through which to reflect the integration of these diverse and highly variable fire system components.

The fire system is a highly interrelated set of diverse facets that are predominately physical (fire behavior), biological (fire effects), economic (resource values and cost of management actions), statistical (fire occurrence and weather frequencies), organizational (initial attack and fuel-treatment activities), or

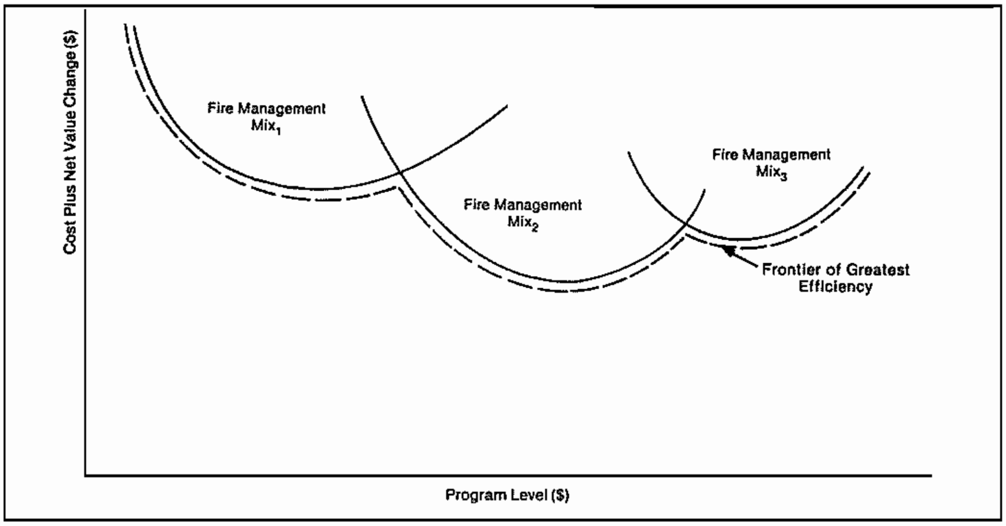

Figure 2—Hypothetical family of C+NVC curves for different fire management mixes illustrating that input mix, as well as funding, affect efficiency.

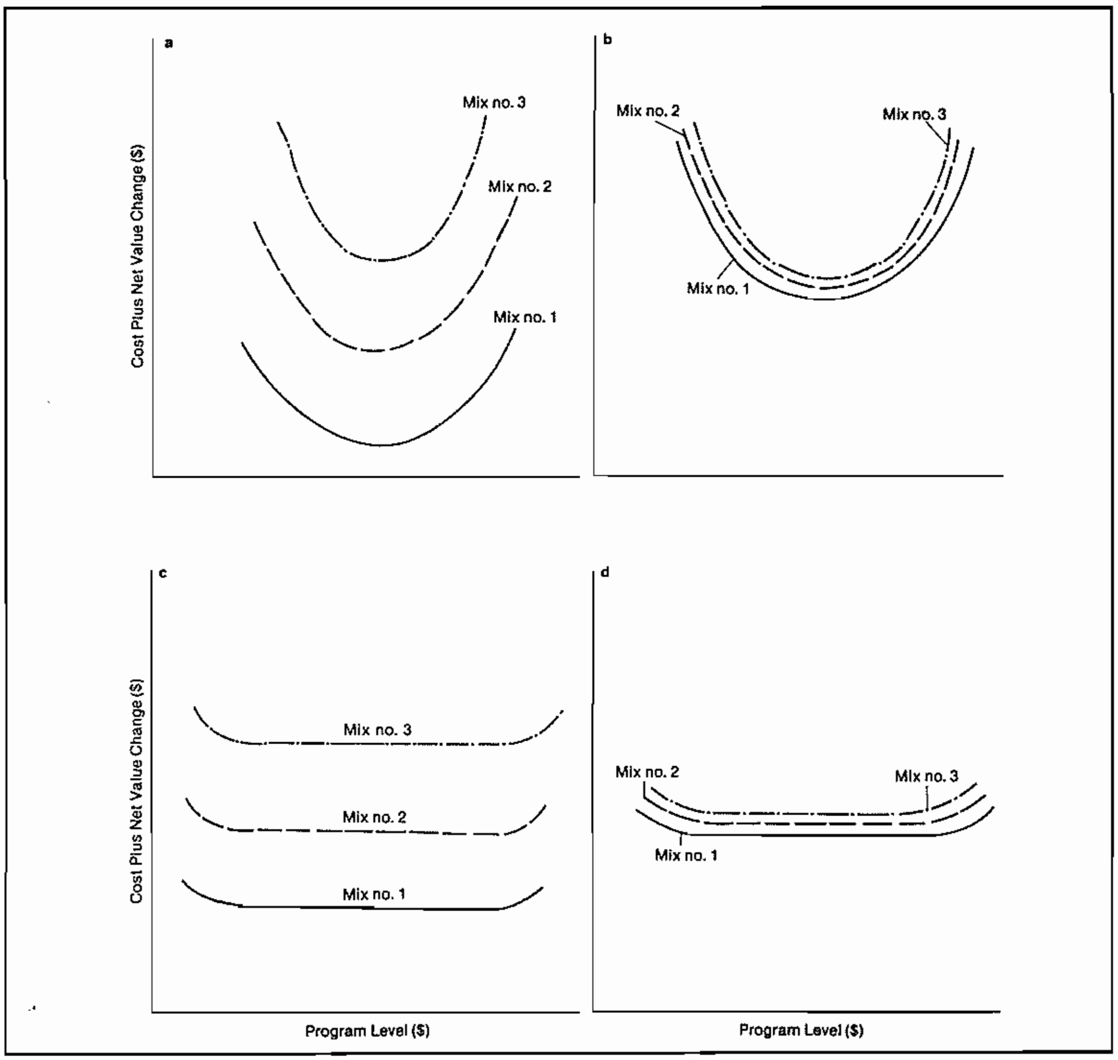

Figure 3—Alternative families of C+NVC curves for different fire management mixes with varying impact of input mix and funding level on efficiency.

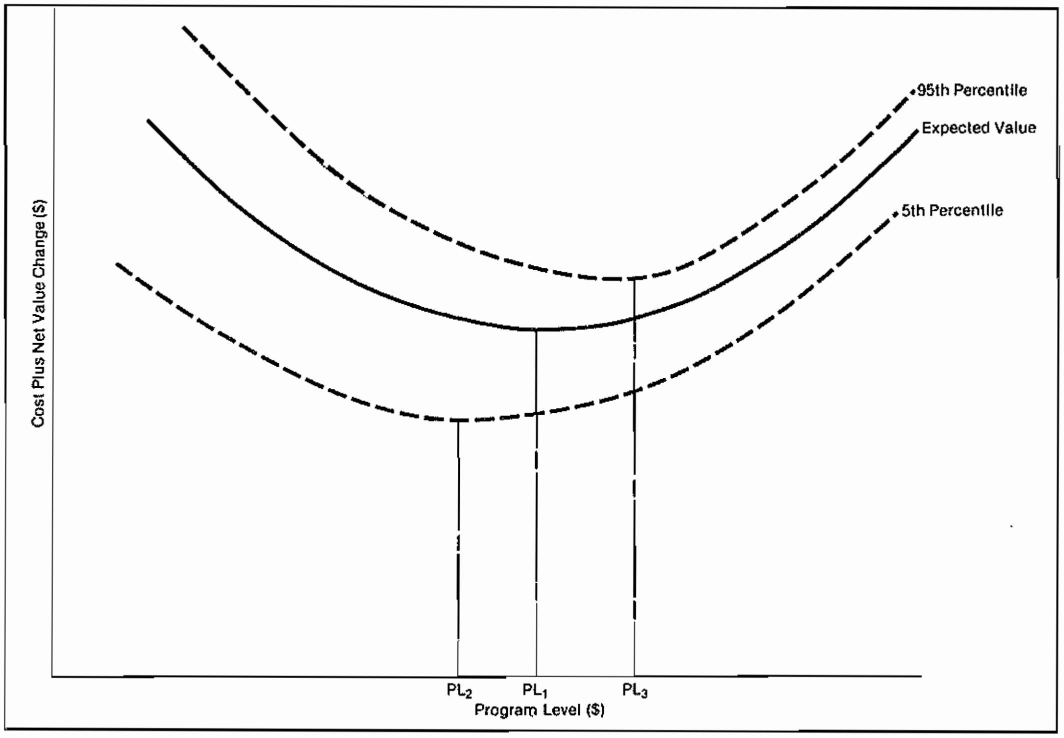

Figure 4—Hypothetical probability envelope about the expected value C+NVC curve.

managerial (fire suppression constraints and resource output objectives) in nature. Fire management program components are highly interactive. Efficiency of one component is in part a function of the magnitude and configuration of the other components. Efficiency of the initial attack program component, for example, is a function of the effectiveness of the prevention program component in reducing fire ignitions or of the fuel-treatment program in affecting the behavior of the fires that do start.

This interrelatedness means that the model used to test our hypotheses must contain modules for all major fire system components. FEES, therefore, has interrelated modules for fire behavior, fire detection, fuel-treatment effectiveness, initial attack effectiveness, large fire suppression effectiveness, suppression costs, fire effects, fire occurrence frequencies, and resource values (*fig. 5*). The effectiveness of alternative initial attack and fuel treatment program options can be simulated directly. While the effectiveness of fire prevention and large fire suppression options cannot be simulated directly because of the general lack of quantified production functions for these activities, the consequences of hypothetical changes in their effectiveness can be.

The fire system is also highly stochastic. There is substantial year-to-year variability in weather, fire occurrences, and the vegetation and terrain of fire locations. The mean annual acres burned in the Climate Zone (1970-1981), for example, is 46,360 acres. The standard deviation of acres burned is 34,171 acres. FEES was designed as a probabilistic model to incorporate the major stochastic dimensions and trace them to a probability distribution about C+NVC (*fig. 6*).

Many of the probability aspects of the fire system are "tail-heavy," i.e., infrequent events have such large impacts that they materially affect even the expected value. For example, less than 1 percent of all fires in the Climate Zone (1970-1981) are over 100 acres, yet 95 percent of all acres burned are in fires over 100 acres. These infrequent larger fires contribute almost all of the net value change in resource outputs and the majority of the suppression costs.

This tail-heavy nature was addressed within FEES in two ways. First, important tail-heavy distributions, such as the probability of large fire size classes, were fit with Weibull distributions to smooth the sparse empirical data. Second, the fire management program areas and fire locations were defined in situation-specific, rather than site-specific, terms. Fire data from all areas having similar terrain and vegetation characteristics were pooled to increase the fire occurrence sample size. Without this data pooling, the fire occurrence data would have been far too sparse to stratify by the terrain and vegetation parameters that affect fire behavior and fire effects. This situation-specific approach is also consistent with a hypothesis that classes of similar areas exhibit similar economic efficiency and risk characteristics.

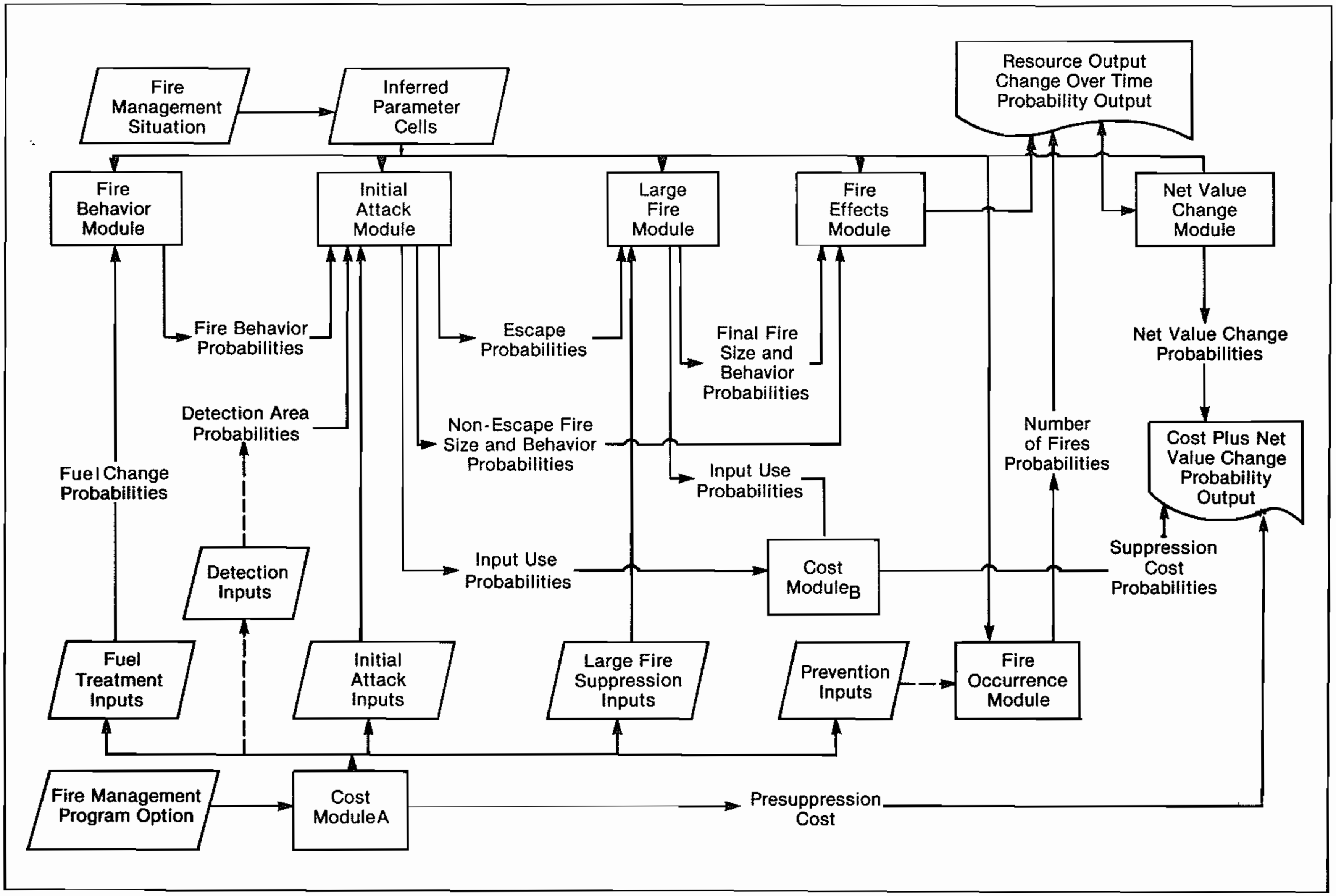

Figure 5—Fire Economics Evaluation System (FEES) flowchart shows the interrelated modules for all major fire system components. (The cost of presuppression inputs is estimated in Cost Module A, and the cost of suppression actions is estimated in Cost Module B.)

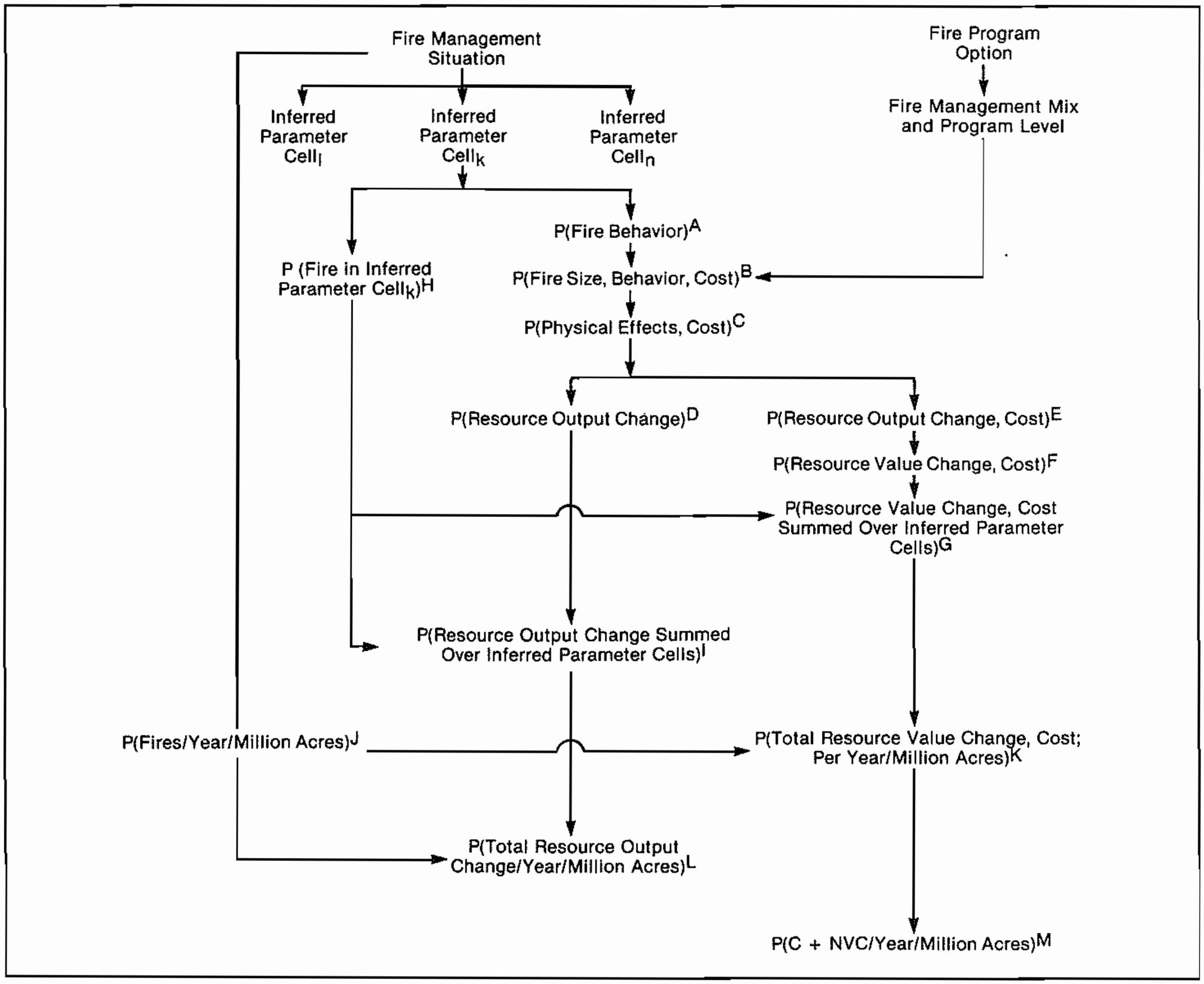

Figure 6—Sequence of probibility distribution combinations and calculations within FEES. Superior capital letters indicate the mathematical sequence of the probability computations.

FIRE MANAGEMENT OPTIONS TESTED

The economic efficiency and risk hypotheses were tested for several different fire management program options applied to several fire management areas or situations in the Northern Rocky Mountains and Northern Intermountain Fire Climate Zone. That Climate Zone was selected for study because it has a broad mixture of vegetative types and a correspondingly wide array of resource outputs. Its mountainous terrain creates access problems that translate into variable initial attack arrival times. It has a fire history that is generally moderate, but occasionally severe. Twenty percent of the fires and 18 percent of the acres burned on all National Forests throughout the nation from 1970 to 1981 occurred in National Forests within the Climate Zone.

Fire Management Situations

The situation-specific "types of areas" or fire management situations (FMS) to which the fire management programs were applied are described by four parameters: Fire Climate Zone (Schroeder and others 1964), vegetative composition (percentages of the area in various existing vegetative cover types [Peterson 1984b]), topographic composition (percentage of the area in slopes over 40 percent), and resource management emphasis among the various categories of resources. The resource management objectives used in this study are consistent with management practices in the Forest Service's Northern Region. The impact of applying private management objectives instead of Forest Service management objectives is displayed in a sensitivity analysis.

Using this classification, three FMS's were selected for study:

- Douglas fir, gentle topography, multiple use/intense timber objective (FMS 1)
- Fir-spruce, steep topography, multiple use/recreation and wildlife objective (FMS 2)
- Ponderosa pine, gentle topography, multiple use/range and recreation objective (FMS 3).

The fire characteristics of the three FMS's are quite different. The ponderosa pine FMS occurs on the relatively dry sites. It has the highest mean historical fire occurrence level of three FMS's from 1970 to 1981—81 fires per million acres per year, and the highest mean historical acres burned—700 acres per million acres per year.

The fir-spruce FMS occurs on higher-elevation, moister, cooler sites. Its mean historical fire occurrence level is the lowest of the three—51 fires per million acres per year, as is its mean historical number of acres burned—412 acres per million acres per year.

The Douglas-fir FMS generally lies between the other two FMS's in elevation, moisture, and fire system activity. Its mean historical fire occurrence level is 53 fires per million acres per year that burn 642 acres per million acres per year. Illustrative model inputs to the Douglas-fir situation (FMS 1) are described throughout the paper for continuity, and simulation results from the Douglas-fir FMS are described first.

Forest Service Ranger Districts in the Climate Zone that were representative of these FMS's were identified through a survey of timber inventory and land management planning data. Individual Fire Reports (Form 5100-29) were then separated into FMS data pools for the calculation of fire occurrence frequencies. From this survey, 9.5 percent of the National Forest area in the Climate Zone is in the Douglas-fir FMS, 6.7 percent in the fir-spruce situation, and 6.5 percent in the ponderosa pine situation. Therefore, approximately one fourth of the National Forest acreage within the Climate Zone is characterized by the three FMS's we studied.

Each FMS is divided into situation-specific "types of fire locations," termed here "inferred parameter cells" (IPC's). Parameters that differentiate IPC's are related to differential fire behavior, fuel-treatment and suppression effectiveness, fire effects, and resource values. The IPC parameters (with number of classes in parentheses) include slope (3), elevation (2), aspect (2), time-of-day (2), time-of-year (2), cover type (13), cover type age class (4), and ignition cause (2). Through a combination of these IPC parameter classes, the FMS's were identified by a set of 3,264 IPC's. The amount of heterogeneity permitted by this IPC structure is needed to adequately reflect the behavior of the varied and interrelated FMS system components.

IPC's are the basic computational building blocks in FEES. FMS's are differentiated within FEES only by the relative fire frequencies among the various IPC's and the frequencies among the large fire size classes. For example, 23 percent of the fires in the Douglas-fir FMS are in the Douglas-fir cover type IPC's, while only 10 percent of the fires in the ponderosa pine FMS are in the Douglas-fir cover type IPC's. FMS's are not defined by the relative acreage among the IPC's. The number of fires, rather than acres, drives the behavior of the fire system.

IPC's are reoriented and consolidated within various modules of FEES to improve computational efficiency. The fire behavior computations, for example, use stylized fuel models rather than cover type to describe the types of fire locations for fire behavior calculations. These reoriented IPC sets within individual modules are termed "input variable combinations."

Fire Management Program Options

FEES was designed to evaluate directly the effectiveness of alternative initial attack and fuel-treatment programs. The initial attack program accounted for 64 percent of the Forest Service's $104 million (1978 dollars) annual fire management program appropriations in Fiscal Year 1983. Fuel-treatment activities accounted for an additional 14 percent. Because of the hypothesized interaction among fire program activities, the program options tested were defined by a combination of initial attack and fuel-treatment activities.

The prevention and detection program activities, which together accounted for 21 percent of the Forest Service appropriations, were assumed constant at their historical levels of funding. Prevention activities are reflected in FEES by historical distributions for fire occurrence levels and detection activities by fire size at time of detection. The large-fire suppression component of the fire management program was similarly assumed to have its historical level of effectiveness, but simulated suppression costs vary in FEES with the suppression cost of initial attack and with the percentage of fires that escape initial attack to become "large fires." The Forest Service suppression expenditures ranged from $19 to $69 million dollars (1978 dollars) nationwide for the period 1978 to 1983, and averaged $38 million.

Initial attack program options were described by one of five program levels (ranging from $100,000 to $800,000) and one of three fire management mixes (Gonzalez-Caban and others 1986). The initial attack program levels were defined with respect to the Forest Service initial attack funding in the Climate Zone in 1979—approximately $400,000 (1978 dollars) per million acres protected. The program levels tested were these:

Initial attack program level	Approximate dollar amount *(1978 dollars/ million acres protected)*
Base minus 75 percent	$100,000
Base minus 50 percent	200,000
Base	400,000
Base plus 50 percent	600,000
Base plus 100 percent	800,000

The actual dollar levels of the fire management input lists deviated slightly from these target amounts because of the lumpiness of initial attack input costs. The economic cost of a small fire engine and its assigned crew for a season, for example, is $31,000. The actual dollar levels tested are recorded in the output tables in the results section of this paper.

The three fire management mixes were similarly defined with respect to the historical or base program composition in the Climate Zone. One mix was the same as the historical program composition, one was more heavily oriented toward ground forces, and the other emphasized air forces. The relative composition of the three emphases among handcrew (Category I, Category II, and project crews), engine (engines and bulldozers), and air inputs (helitack, smokejumper, and air tanker) were:

Fire management mix	Handcrews	Engines	Air inputs
	——(Percentage of dollars)——		
Historical emphasis	27	29	44
Ground emphasis	27	65	8
Air emphasis	19	6	75

The fire management inputs were further defined by whether they were pooled or not, i.e., whether their use and cost were shared with other FMS's or financed entirely by the one FMS studied. If an input was pooled, the FMS studied financed only a percentage of the pool's cost. The FMS received access to all of the inputs in the pool for initial attack, but the initial attack arrival times were increased as the share of the pool financed by the FMS decreased. The pooling or sharing was generally restricted to Category I and II handcrews and to air inputs (helitack, smokejumpers, and air tankers). This method of adjusting the costs and arrival times for pooled inputs overcomes the problem of restricting the number of initial attack inputs at some higher organizational level, e.g., a Region, and holding them fixed when evaluating program options at the lower organizational level, e.g., a National Forest.

These initial attack program levels in dollars and fire management mixes were translated into lists of fire management inputs available for dispatch on initial attack. This transformation was based on the per-hour cost in dollars of each input, as estimated by Gonzalez-Caban and others (1984), and the length of time the input was available within the year. A sample fire management input list is shown in *table 1*.

The fire program costs used here are long-run economic costs, rather than short-run budgetary costs. The per-unit costs treat program management overhead and facility charges as variable in the long run. For example, the program management and general support services are included in an hourly cost estimate for each fire management input. When the dollar level of the fire management program is changed, the program management and facilities are assumed to change proportionally with the direct firefighting forces. Overhead and facility components are variable in the long run, even if they are not variable in the short run.

One consequence of the long-run nature of the costs used here is that the actual number of firefighting forces available for dispatch changes less with changes in the dollar program level than would be the case if short-run cost estimates were used.

Table 1—*Fire management input list for base-level funding and historical program emphasis, per million acres protected*

Fire management input	Personnel[1]	Number of units	Cost	Pool share[2]
	(People/ unit)		*(1978 dollars)*	
Category I crew	20	1	32,544	0.20
Category II crew	20	3	38,490	.66
Project crew	2	17	36,720	1.00
Helitack (5 teams and helicopter)	10	1	93,240	.70
Smokejumpers (4 teams and aircraft)	8	2	66,816	.40
Engine—small	2	3	49,680	1.00
Engine—medium	3	2	48,960	1.00
Bulldozer—medium	2	1	15,480	.50
Air tanker—medium	—	3	14,489	.18
Total	154	33	396,419	

[1]Number of fire-line-building personnel per input unit.

[2]Proportion of a shared pool of that particular input type financed by the fire management situation.

Program management and facilities costs are fixed in the short run, so the entire change in dollar program would be allocated to the more easily varied firefighting inputs if short-run costs were used.

The fuel-treatment program options were similarly described by program levels and fuel-treatment mixes or emphases (Salazar 1983b, 1984). The fuel treatments were applied to slash fuels to maximize reduction of fire hazards. Other benefits provided by fuel treatments, such as site preparation or browse production, are not reflected in FEES.

The fuel-treatment program levels, also set with respect to the historical or base-level funding of approximately $126,000 per million acres protected on National Forests in the Climate Zone, and the acres treated per million acres in the Douglas-fir FMS were:

Fuel treatment program level	Approximate dollar amount *(Dollars per million acres protected)*	Acres treated *(Acres per million acres protected)*
Base minus 100 percent	$0	0
Base minus 50 percent	63,000	327
Base	126,000	609
Base plus 50 percent	189,000	884
Base plus 100 percent	252,000	1,128

If left untreated, slash fuels will deteriorate naturally. Treatment simply speeds removal of the hazard. If acres of slash fuel were available for treatment but funds were insufficient to treat them, the untreated fuels were assumed to deteriorate naturally according to the rates developed by Salazar and Bevins (1984).

The fuel-treatment mixes were described by the percentage of the program level spent on prescribed burning, bulldozer piling, and hand-piling methods of fuel treatment. Just as with the initial attack program mixes, one of the fuel-treatment mixes corresponded to the historical mix of these treatment methods, which emphasized bulldozer piling. A second emphasis included a relatively high component of prescribed burning. The third fuel-treatment mix contained more of an equal balance between bulldozer piling and prescribed burning than did the other two mixes, and the other two were varied from that historical base. The percentages of acres treated by the three treatment methods at the base program level in the Douglas-fir FMS were these:

Fuel-treatment mix	Treatment method: Prescribed burning	Bulldozer piling	Hand piling
	(Percentage of dollars)		
Historical emphasis	27	73	6
Burning emphasis	66	27	7
Equal balance	34	51	15

These program levels and fuel-treatment mixes were translated into acres of slash fuel treated for each FMS using long-run fuel-treatment cost estimates (Gonzalez-Caban and McKetta 1986). Treatments were assigned to vegetative cover types consistent with the existing priority on National Forests in the Climate Zone and to treatment sizes typical in Montana on State and Forest Service lands.

For brevity, all the initial attack and fuel-treatment program options listed in the above tabulations are hereafter identified by letter for the program mix and by number for the program level:

Program emphasis	Program funding level
IA—Initial attack	
H—Historical	1—Base minus 75 pct
G—Ground	2—Base minus 50 pct
A—Air	3—Base
	4—Base plus 50 pct
	5—Base plus 100 pct
FT—Fuel treatment	
H—Historical	1—Base minus 100 pct
B—Burning	2—Base minus 50 pct
E—Equal balance	3—Base
	4—Base plus 50 pct
	5—Base plus 100 pct

For example, the historical mix and base-level funding for each of the two components are labeled IA(H,3),FT(H,3). The option with initial attack ground mix funded at the base minus 50 percent and the burning fuel treatment mix funded at the base plus 100 percent is labeled IA(G,2),FT(B,5).

MODEL STRUCTURE

The probabilistic simulation within FEES processes one IPC at a time through the several modules (*fig. 5*). The output of each module becomes the input for the next. FEES was constructed in a modular fashion so that existing modules could be replaced or modified without disrupting the entire model structure. Since the most highly stochastic components of the fire management system are reflected as probability distributions, most of the modules are probabilistic in design. After a brief overview of the module linkages within FEES, each module is described in more detail. The mathematical sequence of probability computations, in order of the superscript letters, is shown in *figure 6*.

After the fuel-treatment program is reflected through adjustments of the IPC composition of the FMS, fire behavior probabilities are calculated for each IPC within the fire behavior module from the weather distribution, terrain, and fuel character of the IPC. The fire behavior distribution, along with a probability distribution for fire sizes at the time of detection from the fire detection module, is input into the initial attack module. Along with initial attack arrival time distributions and fireline production rates, the fire behavior probability input is used to calculate the probabilities of fire size and of the firefighting input use through the initial attack phase. For those fires that are simulated to escape initial attack, the final fire size and large fire suppression cost are then calculated in the large fire suppression module. The probability distribution of total suppression costs is calculated within the cost module from the probabilities of firefighting input usage simulated in the initial attack module and the probability distribution of total suppression costs for escaped fires.

The probability distribution of final fire sizes, along with the vegetative composition of the IPC and resource management emphasis of the FMS, is used in the fire effects module to calculate the probability of changes in the output of natural resources, such as timber and recreation outputs, for the IPC. When similar simulation results are provided for each IPC in the FMS, the individual IPC's are weighted together by their respective fire occurrence frequencies and expanded by the probability distribution for total fire ignitions in the FMS. This expansion by IPC fire occurrence frequencies produces an estimate of the probability distribution of resource output changes for the whole FMS. Similarly, the probability distribution for net change in the present net value (net value change) is calculated in the resource values module for each IPC and expanded to the FMS by the fire occurrence frequency among the IPC. The individual fires are assumed to be independent, and their consequences are assumed to be additive.

The probability distributions for net value changes and suppression costs are combined through a multinomial probability computation, then added to the presuppression program cost to yield the probability distribution of C+NVC. Note that the net value changes and suppression cost distributions are the only sources of variation in the C+NVC distribution. The presuppression cost is a deterministic input into the fire management system.

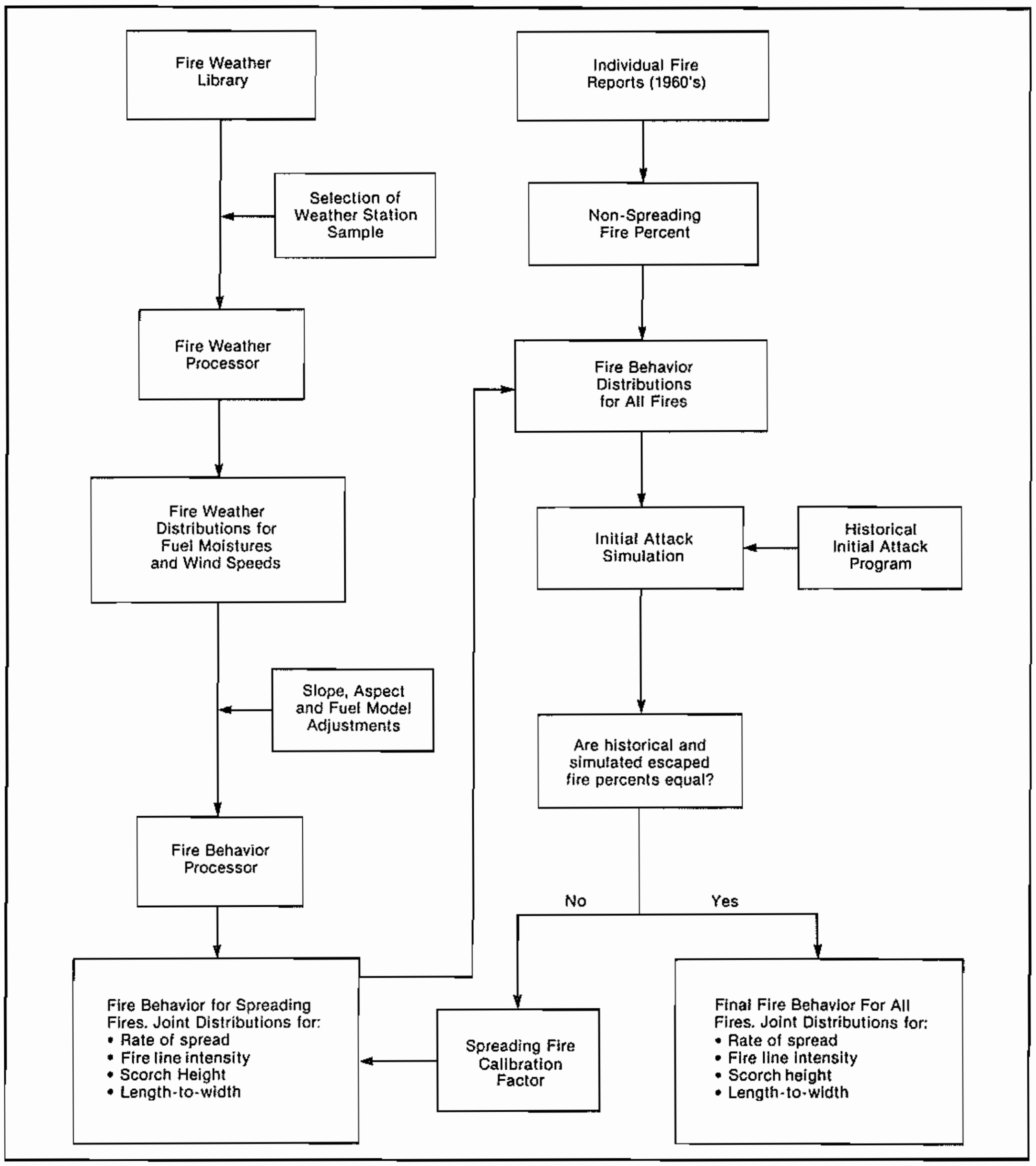

Figure 7—Fire behavior module flowchart.

Fire Behavior Module

A joint probability of forward rate-of-spread, Byram's fireline intensity, fire ellipse length-to-width ratio, and scorch height for each of 1,008 fire behavior input variable combinations was estimated in the fire behavior module (Salazar and Bradshaw 1984). The "input variable combinations" in each module are modifications of the IPC classes that improve computational efficiency for that module. The fire behavior input variable combinations (with number of classes in parentheses) are defined by slope (3), aspect (2), elevation (2), time-of-day (6), time-of-year (2), and fuel model group (7). The six original time-of-day classes used in the fire behavior module were subsequently weighted into two classes using the relative frequency of fires, thus reducing the number of variable combinations considered by the initial attack module to 336. The 13 Northern Forest Fire Laboratory fuel models (Albini 1976) were combined into seven fuel model groups based upon similarity of rate-of-spread distributions in the Climate Zone to reduce the number of input variable combinations in the module.

Two types of fires were recognized in FEES—spreading and nonspreading (*fig. 7*). The fire behavior probability distribution for spreading fires was derived from minor modifications of state-of-the-art fire behavior models. The frequency of nonspreading fires and their final size were derived from the Individual Fire Reports (Form 5100-29) from 1960 to 1969 in the Climate Zone.

The fire behavior simulation for spreading fires started with fire weather input described by a joint probability distribution of fuel moistures, relative humidity, temperature, and windspeed for each fire behavior input variable combination (Salazar and Bradshaw 1986). This joint distribution was derived using software developed by Radloff and others (1982) from a subset of 92 National Fire-Danger Rating System weather stations located in the Climate Zone. The 92-station subset, each with complete data for 10 years or more, was statistically selected using clustering routines to reduce computational costs. Weather data on all days for which records were available were used to construct the weather distribution.

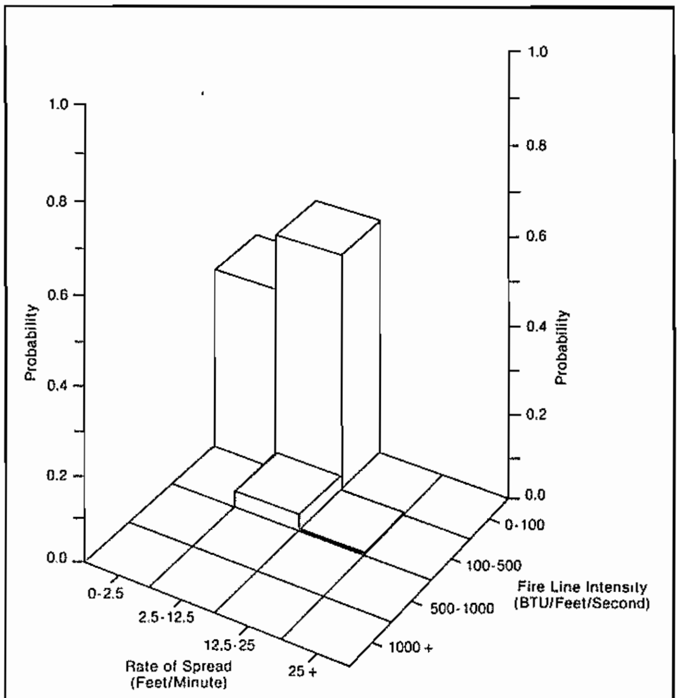

Figure 8—Joint probability of forward rate-of-spread and fireline intensity output from the fire behavior module for one inferred parameter cell (IPC).

The weather station data are generally recorded at the most severe time of day and location—early afternoon on exposed southwest slopes. To avoid bias toward severe fire weather conditions, the fuel-moisture observations were adjusted for slope, aspect, vegetative cover, and time-of-day differences to the time and location characteristics of the fire behavior input variable combinations. Most of these adjustments were made using the factors that are typically applied during real-time fire behavior predictions (Rothermel 1983). Diurnal temperature was adjusted using McCutchan's (1979) relationships. The joint fire behavior probability distributions for the spreading fires were then calculated using a minor adaptation of the fire behavior model developed by Rothermel (1972). Illustrative fire behavior module output for spreading fires in a mixed fuel model composed of 40 percent fuel model 2—open pine with grass understory, and 60 percent fuel model 9—long-needle pines, is shown in *figure 8*.

The "Rothermel" model calculations apply to fires burning in equilibrium through surface fuels. The fire behavior from the Rothermel model greatly overestimates the rate-of-spread and intensity of fires that creep through ground fuels or smolder in snags.

Using a procedure developed by Salazar (1983a) to transform the cover type recorded on the Individual Fire Reports into fire behavior fuel models, rate-of-spread estimates recorded on the Individual Fire Reports from the Forest Service's Northern Region for 1960 to 1969 were tallied. A large percentage of the fires recorded in those reports were essentially nonspreading. For example, 67 percent of the fires in fuel model 2 (open pine with grass understory) had rates-of-spread along the most severe

Table 2—*Percentage of fires with forward rates-of-spread of 0 to 1/2 chain per hour, as reported in the Individual Fire Reports (form 5100-29) from the Forest Service Northern Region (1960 to 1969), by fuel model and ignition cause*

Fuel model	Ignition cause		
	Lightning	Human	Total
	(Percent)		
1	67	43	57
2	80	64	77
5	74	50	67
8	86	76	84
9	74	62	71
10	84	77	83
12	78	53	73

portion of the fire perimeter of zero to one-half chain per hour. The accuracy of the rate-of-spread estimates on the Individual Fire Reports are suspect, but there should be little error in the very low estimates of spread rate. If the rate-of-spread estimates are biased, the bias is probably upward rather than downward.

Nonspreading fires were assigned a spread rate of 0.1 chain per hour, and we assumed that they continued to spread at that rate, even if initial attack was delayed because of reduced fire management program levels. In reality, some nonspreading fires do become spreading fires. Failure to incorporate that rate-of-spread dynamics underestimates true spread rates, but there are no data on which to estimate the probability of a nonspreading fire becoming a spreading fire. Some of this deficiency is removed in the rate-of-spread calibration process described later.

The percentage of fires in the 1960 to 1969 Individual Fire Reports with spread rates of zero to one-half chain per hour were compiled by fuel model and ignition cause (*table* 2). The probability distribution of Rothermel spreading fires was then merged with that of the nonspreading fires to estimate the joint distribution of fire behavior described by probability expression (1):

$$\text{Prob(Fire Behavior)} = P(ROS, INT, LWR, SCH \mid IPC_1, CAUSE) \qquad (1)$$

in which

ROS = class interval number (1-4) for forward rate-of spread.

INT = class interval number (1-4) for fireline intensity.

LWR = class interval number (1-4) for fire length-to-width ratio.

SCH = class interval number (1-4) for tree crown scorch height.

IPC_1 = one of 1,008 fire behavior input variable combinations.

CAUSE = ignition cause class: 1—lightning, 2—human.

The expected values in the class intervals were also calculated for each of the variables.

Ignition cause was included because of the noticeable difference in percentages of nonspreading fires by cause (*table* 2) and because nonspreading fires have different initial attack characteristics. Initial attack arrival times to human-caused fires are faster than to lightning-caused fires because human-caused fires tend to occur where access is better. In spite of shorter arrival times, the human-caused fires in the Douglas-fir FMS (1970-1981) exceeded 100 acres about seven times as frequently (2.27 pct of all human-caused fires) as the lightning-caused fires (0.34 pct of all lightning-caused fires).

Escape percent was then simulated in the initial attack module by ignition cause for the historical fire management mix and program levels for both the initial attack and fuel-treatment programs, IA(H,3),FT(H,3), using the IPC fire occurrence probabilities for the entire Climate Zone. Even with this addition of nonspreading fires to the Rothermel spreading fires in FEES, the simulated percent of fires exceeding 100 acres, termed "escaped" here, was consistently higher than the historical frequency of fires over 100 acres in size.

The FEES fire behavior distributions were therefore calibrated to bring the simulated and historical escape percent into agreement for the Climate Zone. Calibration was accomplished by reducing the expected value rate-of-spread in each rate-of-spread class for spreading fires. The percentage of nonspreading fires by ignition cause was held constant at its historical level. The fire behavior distributions for the two ignition causes were calibrated separately. The fireline intensity and crown scorch height probability distributions for spreading fire were changed correspondingly.

The calibration factor for the behavior of lightning-caused spreading fire was 0.1623, i.e., the expected value rate-of-spread in each class was multiplied by 0.1623. The calibration factor for human-caused fires was 0.3957. Just as with the percentage of nonspreading fires, differences in the calibration factor by cause indicate that the population of spreading, lightning-caused fires appears to have less severe fire behavior than the human-caused fires. These differences show the need to separate fire behavior distributions by cause in fire system models. A second calibration step was added for each FMS during the operation of the initial attack module. That second calibration step is explained below in the initial attack module description. Even with all of its components for adjustments of fire weather and fuel model, the fire behavior prediction model appears to overestimate the rate-of-spread for a large percentage of the ignitions. The addition of nonspreading fires to spreading fires is necessary if the restrictive assumptions behind the fire behavior prediction model for spreading fires are retained. Even with that addition, the fire behavior distributions required calibration.

Fire Detection Module

Within the initial attack module, simulation of the fire spread started at the time of fire detection. Fire behavior was assumed to be in equilibrium at that time. The distribution of fire size at detection was derived from the data taken from the 1960 to 1969 Individual Fire Reports (Salazar and Mills 1984). The fire report data were adjusted for changes in the source of detection between the 1960's and the late 1970's. We then fit the data to a Weibull distribution to smooth the tail at the large-detection size end of the distribution because there were few observations. The probability of fire size at detection was discovered to be joint with the rate-of-spread. Fires that were large at detection were more likely to have higher rates-of-spread. The resulting distribution of fire size at detection was described by probability expression (2):

$$\text{Prob(Detection Size)} = P(SAD \mid ROS, CAUSE) \qquad (2)$$

in which

SAD = class interval number (1-4) for fire size at the time of detection.

ROS = class interval number (1-4) for forward rate-of-spread.

CAUSE = ignition cause class: 1—lightning, 2—human.

Expected values in the fire size class intervals were also calculated.

The distribution of detection size was heavily weighted toward small sizes, just as the fire behavior was heavily weighted toward the lower rates-of-spread. The mean detection size for lightning-caused fires was 0.17 acres and the mean for human-caused fires was 0.38 acres. Less than 3 percent of the lightning-caused fires and less than 7 percent of the human-caused fires were detected at sizes larger than 1 acre. The detection data, just like the percentages of nonspreading fire, support the need to describe lightning fires and human-caused fires separately in fire system models.

Data on detection size from the 1960 to 1969 reports are of questionable quality. Salazar and Mills (1984) analyzed the sensitivity of escaped-fire percentages to shifts in the entire distribution of fire size at time of detection to study the importance of data quality. They found that increases of even 10 times in the mean fire size at detection had almost no impact on the percent of simulated escaped fires. The 1960 to 1969 fire reports are certainly accurate to within that margin of error.

Initial Attack Module

The primary objective of the initial attack module was to estimate the percentage of fires that escape initial attack and become "large" fires. This was accomplished in FEES using a Monte Carlo simulation of initial attack on fires. The small percentage of fires that escape account for the vast majority of the suppression costs and resource effects. Only 0.84 percent of the fires exceeded 100 acres in the Climate Zone (1970-1981), but that small percentage of the fires accounted for 95 percent of the acres burned.

A fire was declared "escaped" in FEES when it exceeded 100 acres. This arbitrary escape threshold was selected because it approximates the size at which the fire behavior assumptions concerning homogeneous fuels and terrain are violated. Limited data on the contiguous acreage of homogeneous cover type and terrain areas (Bevins 1983) suggest that areas homogeneous in fuels and terrain in the northern Rocky Mountains are somewhat smaller than 100 acres. Future initial attack model refinements should examine the escape threshold.

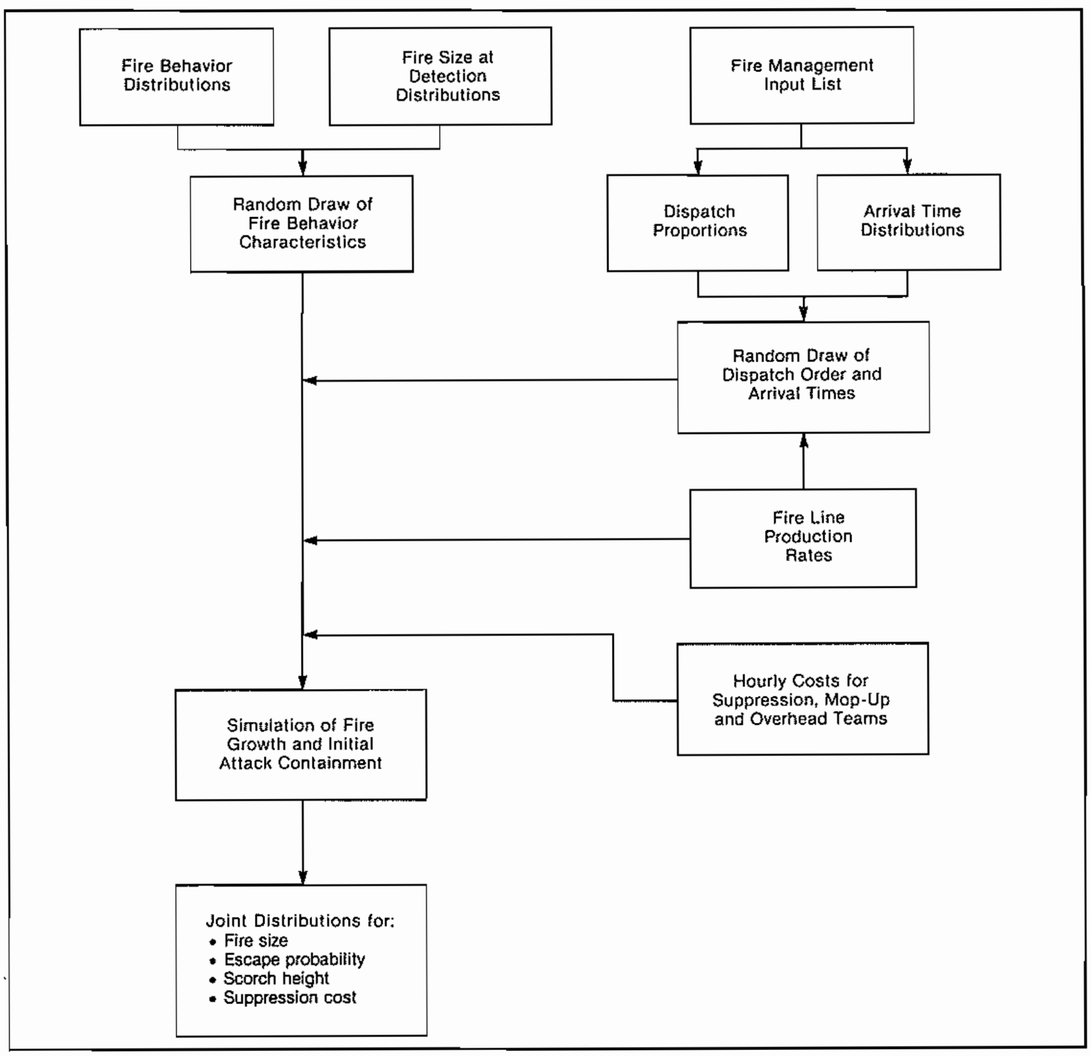

Figure 9—Initial attack module flowchart.

The initial attack module output is an estimate of escape probability and a joint probability distribution of fire size, suppression cost, and scorch height for those fires contained during initial attack (*fig. 9*) (Smith and Shockley 1984). The initial attack simulations were conducted for input variable combinations identified by slope (3 classes), aspect (2 classes), elevation (2 classes), time-of-day (2 classes), time-of-year (2 classes), fuel model group (7 classes), and ignition cause (2 classes). In addition to the use of ignition cause to differentiate fire behavior and fire size at time of detection, ignition cause was used as a proxy for access. Access was reflected through ignition cause in the selection of the initial attack forces that could be dispatched to fires of the two cause classes and initial attack arrival times.

Initial attack simulation is one of the most costly computational steps in the model. To reduce computational costs, initial attack effectiveness was modeled for a sample of 225 of these 672 input variable combinations. The 225-cell subset includes all input variable combinations with 10 or more fires in the Climate Zone from 1970 to 1981. The subsets account for 88 percent of all the fires in the Climate Zone over that period. The Monte Carlo simulation of initial attack was exercised 50 times for those input variable combinations with fewer than 50 historical fires in the Climate Zone for 1970 to 1981. For input variable combinations with more than 50 historical fires, the Monte Carlo simulation was executed as many times as there were historical fires.

All fires are assumed to be independent and occur one at a time, as opposed to being one in a set of multiple fires. The presence of multiple fires raises difficult data and modeling problems, particularly in the dispatching and arrival time simulation. At historical National Forest program levels in the Climate Zone, however, up to six simultaneously burning fires apparently have little impact on initial attack arrival times (Hunter 1981). A future refinement could consider treating multiple fires as a queuing problem as Hochman and others (1982) have.

The core of the Monte Carlo initial attack module is a deterministic simulation of fire containment. The dispatch and arrival of initial attack forces at the fireis simulated along with the elliptical spread of the fire. Fireline construction is simulated to determine if the initial attack line-building forces are capable of containing the fire before it reaches 100 acres. Other than modifications in the dispatching process, this deterministic core is essentially the same fire containment algorithm found in the FOCUS model (Bratten and others 1981).

In this fire containment algorithm, fire spread stops along those portions of the perimeter where a fireline has been constructed. This differs from a simpler and computationally less costly algorithm (U.S. Dep. Agric., Forest Serv. 1982) that simulates the perimeter growth of a free-burning fire separately from the construction of the fireline. In spite of its greater computer cost, we used the more complete algorithm because the two algorithms sometimes lead to substantially different answers. The simpler algorithm consistently estimates final fire sizes that are larger than the more complete algorithm under some circumstances. Where a head attack on the fire is feasible, the difference in estimated fire size is substantial (Mees 1985).

This deterministic fire containment model core of the initial attack module is surrounded by a Monte Carlo exterior. The exterior contains input data described by probability distributions for fire behavior (expression 2), for fire sizes at time of detection (expression 3), for type of initial attack force dispatched, and for initial attack arrival times. Deterministic fireline construction rates were also input into the module.

The probability distributions of initial attack arrival times and type of force dispatched were drawn from the Forest Service Individual Fire Reports in the Climate Zone for 1970 to 1981. The arrival times and dispatch proportions were differentiated by fire management input type, e.g., handcrews versus engines, and ignition cause for both first dispatch to the fires and subsequent dispatches. All fire management inputs purchased with the presuppression budget were available for initial attack dispatch except the Category I handcrews. Those "interregional crews" are typically reserved for large fire suppression.

Derivation of arrival times and dispatch proportions from historical data permits the simulation model to mirror historical performance of the initial attack organization. Historical dispatching procedures may or may not be the most economically efficient. The various input distributions also reflect a major source of variability, the variability of fire locations with respect to the location of the initial attack bases.

Fireline production rates were developed from various sources of data: handcrews and engines from Schmidt and Rinehart (1982); bulldozers from the National Wildfire Coordinating Group (1980); and air tankers from George (1982), Swanson and others (1976), and LaMois (1961). Fireline production rates were varied by fuel model.

As documented by Haven and others (1982) for handcrews, there is a great deal of variability in productivity rates with terrain and fuel conditions. Smith (1984) studied the sensitivity of escaped fire percent to changes in the productivity of the base fire management input list (IA(H,3),FT(H,3)) in four IPC's. Those results indicate that the error in simulated escape percent caused by likely errors in the productivity rate input is within acceptable bounds.

After substantial testing of the initial attack module, a second calibration step apparently was necessary beyond Climate Zone-wide calibration of the rate-of-spread. The first-step calibration of fire behavior in the entire Climate Zone performed fairly well, but simulated escape fire percents were still higher than historical rates. A small error in escape percent leads to major errors in suppression costs and net value changes.

The second calibration was applied directly to the escape percent in each FMS. The simulated escape percent in each FMS was calibrated directly to the historical escape percent with a proportional adjustment factor. Just like the first calibration step, the calibration factor for escape percent was developed for the base fire management program option and held at that level across all other program options tested.

The output from the initial attack module is described by probability expressions (3) and (4):

Prob(I.A. Output)
$= P(SIZE,SCH,COST|IPC_2,CAUSE)$ (3)

Also

$Prob(Escape) = P(IPC_2,CAUSE)$ (4)

in which

SIZE = class interval number (1-3) for final fire size.
SCH = class interval number (1-4) for tree crown scorch height.
COST = class interval number (1-3) for suppression cost.
IPC_2 = one of 672 combinations of values of I.A. input IPC variables.
CAUSE = ignition cause class number: 1—lightning, 2—human.
ESCAPE = fire size greater than 100 acres.

Expected values in the output class intervals for SIZE, SCH, and COST were also calculated, dependent on IPC_2 and CAUSE. *Table 3* shows initial attack module outputs for one input variable combination.

Initial attack simulation results for two input variable combinations show that there is differing sensitivity of the simulated escape percent to changes in the program level (*table 4*). The escape percent was more sensitive to program level in the "short grass" fuel model situation, for example, than in the "closed timber with litter" fuel model. Even in the higher rate-of-spread grass fuel model, however, there are signs of diminishing returns in escaped fire percent with increased fire management program levels.

Large-Fire Suppression Module

The objective of the large (escaped) fire suppression module was to simulate the joint probability of final acres burned, suppression cost, and scorch height of fires that escaped initial attack (Bratten 1984b). The probabilities of final large fire sizes were developed from historical data in the Individual Fire Reports, rather than being derived from an independent evaluation of large fire suppression effectiveness. Implicit in the use of historical data on large fire sizes and suppression costs is that the suppression strategy, and especially the degree of suppression aggressiveness, will be the same in the future as it was on National Forests in the Climate Zone during the sample period (1970-1981). Just as in the use of historical dispatching data in the initial attack module, there is no implied assumption here that the historical large fire suppression strategies are or are not economically efficient.

The large-fire probability expression is:

Prob(Large Fire Results)
$= P(LFSIZE,SCH,LFCOST;CAUSE,FMS)$

Table 3—*Illustrative mean simulation results from the initial attack module for one inferred parameter cell (IPC)*[1]

IPC description:
Fuel model = 2 (40 percent) open pine with grass understory and 9 (60 percent) long needle pines

Slope = 0-39 percent | Elevation = 0-4500 feet
Aspect = north | Time of day = 0500-2000
Ignition cause = lightning | Time of year = July-September

Simulation results:	Final fire size *(acres)*			
	0-9	10-29	30-99	100+
Percent of all fires	98.17	0.41	0.61	0.81
Detection size (acres)	0.07	19.83	.01	4.97
Rate of spread (chains/hour)	0.13	.09	3.81	4.45
Final fire size (acres)	0.17	23.49	75.52	—
		(1978 Dollars/acre)		
Travel cost	821.00	2.00	3.00	—
Suppression cost	96.00	9.00	6.00	—
Overhead cost	0.00	46.00	8.00	—
Mop up	865.00	231.00	209.00	—
Total cost	1782.00	288.00	226.00	—

[1]All simulation results are mean outcomes of all fires in the Monte Carlo simulation for the IPC.

$= P_1(LFSIZE,LFCOST;CAUSE,FMS) \times P_2(SCH;CAUSE,FMS)$ (5)

where

LFSIZE = large fire size class interval number (1-5)

SCH = class interval number (1-4) for tree crown scorch height.

LFCOST = large fire cost class interval number (1-5)

CAUSE = ignition cause class: 1—lightning, 2—human.

FMS = fire management situation being analyzed.

Expected values in the class intervals for LFSIZE, SCH, and LFCOST were calculated also.

The large fire size probability function, P_1 in expression (5), was obtained from historical distributions of fire sizes by cause in the Ranger Districts within the Climate Zone that had the same vegetation and terrain characteristics as the FMS being analyzed. Separate arrays of large fire size probabilities were developed for each of the three FMS's. The large fire suppression cost per acre burned drops substantially as fire size increases (*table 5*).

The scorch height probability function, P_2 in expression (5), was derived from the FEES fire behavior results (expression 2), summed over other variables, and weighted by historic fire occurrences for each cause and IPC_1.

The fire frequency data were fit to a Weibull distribution because of the sparseness of large fires in the historical data. For example, there were only 263 fires over 100 acres in the entire Climate Zone during the sample period of 1970 to 1981, or 0.42 "escaped" fires per million acres protected per year. The advantage of the situation-specific design of FEES is evident here. The number of large fires in any one planning unit within the Climate Zone is far too few to conclude anything about large fire potentials. The data must be pooled across planning units.

The large-fire probabilities in *table 5* dramatize the tail-heavy character of the fire system. Only a very small percentage of all fires escape, and only a small percentage of the escaped fires get large, but that small percentage has a substantial impact on the expected value size of all fires. For example, only 0.84 percent of the fires in the Douglas-fir FMS escaped in the period 1970 to 1981. Of those few that escaped, only 2.5 percent exceeded 10,000 acres. Yet those few fires above 10,000 acres, 0.02 percent of all fires, accounted for 56 percent of all acres burned.

The same historical array of large-fire-size class probabilities was held constant across all of the presuppression program options tested. This assumes independence between the size of the initial attack organization and large fire suppression effectiveness. Independence was assumed for the same reason that alternative large fire suppression program options were not tested in FEES; there is currently no acceptable means of developing programmatic production functions of large-fire suppression effectiveness. While some techniques have been developed to evaluate alternative large fire suppression force levels on individual fires (Seaver and others 1983) and there is some promise that a structured expert opinion gaming process (Joseph and others 1985) might be used to develop production functions for large fire suppression programs (Smith and Harrod 1984), programmatic production functions are not yet available.

The ability to move initial attack forces from their normal base to a large fire lends support to the assumption of independence, however, and mobility of firefighting forces even between States is common once locally available forces are exhausted.

Table 4—*Impact of program level on mean fire size and inferred parameter cells (IPC's)*

IPC description:

	IPC-1	IPC-2
Fuel model	1—Short grass	8—Closed timber litter
Slope	40-79 percent	40-79 percent
Aspect	South	South
Ignition cause	Lightning	Lightning
Elevation	0-4500 feet	0-4500 feet
Time of day	0500-2000	0500-2000
Time of year	July-September	July-September

Simulation results	Initial Attack Program Option[1]				
	Base minus 75 pct	Base minus 50 pct	Base	Base plus 50 pct	Base plus 100 pct
IPC-1					
Mean size of fires					
Under 100 acres (acres)	3.52	3.44	2.69	2.22	2.17
Escaped fires (percent)	7.03	5.47	4.69	4.69	4.69
IPC-2					
Mean size of fires					
Under 100 acres (acres)	0.116	0.124	0.111	0.103	0.103
Escaped fires (percent)	0.0	0.0	0.0	0.0	0.0

[1]All program options in this illustration hold the fuel treatment program at its base level and historical emphasis. All program options for initial attack were at historical emphasis.

This mobility function would be enhanced by an initial attack emphasis heavily oriented toward air inputs. The ability to hire and quickly train fire suppression handcrews, as was done during the exceptional 1985 fire season, is also a means to separate the size of the initial attack program from large-fire suppression capability. In spite of these opportunities, however, the assumption of independence will probably lead to some underestimation of the increase in burned acreage that will result from a reduction in initial attack funding.

Suppression Cost Module

The objective of the suppression cost module was to estimate the cost of both initial attack and large fire suppression actions. These two problems were approached differently.

Initial attack cost was estimated by adding (1) the cost of travel to and from the fire, (2) the cost of building the fireline, (3) the cost of overhead supervision on the fire, and (4) the cost of mopup on the contained fire. The costs of travel and fireline construction were developed from Forest Service fire management costs in the Northern Region (Gonzalez-Caban and others 1984).

The hourly cost of placing individual initial attack types on the firefighting force on the fireline included cost components for wages, training, supplies, equipment, basing facilities, supervision while on the fireline, program management overhead, and general overhead. The wage component included benefits and a hazard pay premium of 25 percent. Regular time and overtime wage rates were weighted together by the relative percentages that the two time classes were used in the Northern Region. Consistent with current Forest Service accounting rules, only the cost increment above what would normally be covered while the initial attack force was not fighting fire is charged to suppression cost.

The cost estimates vary significantly among the different fire management input types and by status of deployment (*table 6*). The large cost increment between the stand-by status and fireline status suggests that the variable cost of using an input, even once the substantial fixed cost is incurred to have the input available for dispatch, is large enough that it probably affects efficient dispatching procedures. Initial attack dispatching in FEES, however, reflected historical dispatching, whether historical dispatching was economically efficient or not.

Travel cost per hour is generally higher than the per-hour cost on the fireline. As increases in the initial attack program lead to a larger percentage of small fires, travel time becomes a larger percentage of the total time the initial attack forces are used. Average suppression cost per acre burned will therefore increase as the initial attack program is increased, reflecting another dimension of diminishing returns.

Mopup cost was estimated using the cost equations developed by Gonzalez-Caban (1983a). Calculated from observations of time spent doing mopup on National Forest fires in the Climate Zone, the mopup cost varied by fuel model and acreage of the fire. The mopup cost per acre burned was often greater than the cost of fireline construction per acre burned (*table 3*). The overhead expansion team cost (Gonzalez-Caban 1983b) was estimated by calculating the cost of personnel needed in typical overhead teams that supervise suppression activities in the Forest Service.

The suppression cost of escaped (large) fires was estimated from a regression equation (Smith and Gonzalez-Caban 1984) developed from records of the number of large fires in the Northern Region and supplemental appropriations for suppression cost in the Northern Region from 1964 to 1974, excluding the 1967 outlier. The large-fire suppression cost regression equation estimates suppression cost as a function of the square root of fire size. The suppression cost per acre was estimated using this regression equation for each large fire size class (*table 5*). The per-acre suppression costs display substantial reductions in suppression cost per acre burned as the size of the fire increases. An alternative engineering cost approach was not used for large fire suppression costs because of the difficulty of collecting data across the substantial variation in suppression force use among large fires.

Table 5—*Conditional probabilities of large fires given an escape, expected value of acres burned per fire, and suppression cost per acre burned (1978 dollars) for the Douglas-fir fire management situation (FMS) and the entire Climate Zone*

Situation	Large fire size classes (*acres*)				
	100-299	300-999	1,000-2,999	3,000-9,999	10,000+
Douglas-fir FMS					
Conditional probability[1]	0.4933	0.2877	0.1265	0.0606	0.0320
Expected acres burned/fire	172	539	1,701	5,297	30,808
Suppression cost/acre	601	269	129	66	25
Climate Zone					
Conditional probability[1]	.4900	.2916	.1286	.0604	.0293
Expected acres burned/fire	173	542	1,700	5,279	30,401
Suppression cost/acre	599	268	129	66	25

[1]The probability of the large fire size class is conditioned on a fire escaping initial attack, i.e., exceeding 100 acres.

The initial attack module output (expression 3) and the large fire module output (expression 5) were combined using escape probability (expression 4) as a weighting factor to give the complete large fire suppression module outputs. The resulting probabilities, conditional on IPC, were multiplied by IPC probabilities to give the joint probability function:

$$\text{Prob(Suppression module results)} = \text{P(SIZE,MORT,COST,IPC;CAUSE)} \quad (6)$$

where

SIZE = class interval number (1-8) for all fire sizes.

MORT= tree mortality class interval (1-3), needed for timber fire effects calculations and used as fire severity indicator for other resource effects. This quantity is calculated using mortality functions (Peterson 1984a)

COST = class interval number (1-8) for all fire sizes.

IPC = index (1-816) for set of values for fire environment variables, including cover type, stand size, slope, aspect, elevation, and time-of-year.

CAUSE = ignition cause class: 1—lightning, 2—human.

Fire Effects and Net Value Change in Resource Outputs

There have been many studies of the direct effects of fire on resources, e.g., the effects of fires on tree mortality. Very few of the fire effects studies, however, extended the estimated direct fire effects into changes in future resource outputs. The output changes over time must be combined with resource values and changes in management costs to translate the physical fire effect into the change in the present net value of the affected resource for the calculation of fire program economic efficiency.

The physical output change and associated net value change were estimated for all the natural resources that could reasonably be assigned dollar values (Althaus and Mills 1982, Mills and Flowers 1985). These included timber, rangeland grazing, water yield, sediment yield, and recreation. The hunting and fishing component of recreation output was measured in recreation visitors per day units, rather than acres of habitat or animal populations.

Resources for which dollar assignments were not possible, such as threatened and endangered species, were not included in our net value change calculations. The loss of structures, such as homes and administrative buildings, was also excluded. From the limited evidence available, there are very infrequent structural losses in the Climate Zone. Existing records on structural losses to wildfire are often incomplete and inconsistent, however, and need to be improved for use in long-term fire management planning evaluations (Frost and Gardner 1982). Structural losses are probably important in other regions.

Similarly, the loss of human life was not included in the net value change computations. There is far too much debate over the appropriate dollar value of a life to incorporate an estimate here. There is, however, a question of whether loss of life is related to the level of initial attack program. Training of individual firefighters may have more effect on the potential loss of life than does the number of initial attack forces available. The per-unit cost of initial attack inputs used in this study includes a component for training. Therefore, funds are provided for the training of each crew, irrespective of how many crews are available with any program level.

Wilson (1977) reported that 145 firefighters died from fire-induced injuries in Forest Service fires between 1926 and 1976, and 77 died in areas protected by other Federal, state, county, and private fire agencies during the same period. These totals translate into fewer than 0.01 lives lost per million acres protected per year in the United States. Most of the wildfire fatalities were firefighters rather than civilians. The common denominators of those fire fatalities were often abnormal localized weather, terrain, and fuel conditions. The outcome might not have been different even if more initial attack forces had

Table 6—*Hourly costs (1978 dollars) for select fire management inputs in the Forest Service's Northern Region by deployment status*

Fire management input	Input composition	Deployment status		
		Standby	Suppression on small fires	Suppression on large fires
		(1978 dollars/hour)		
Category I crew	20 people w/handtools	220	268	328
Category II crew	20 people w/handtools	26	309	364
Project crew	2 people w/handtools and pickup	3	31	36
Helitack team	2 people w/handtools	25	30	39
Smokejumper team	2 people w/handtools	42	48	59
Engine—small	2 people w/handtools and pickup engine	23	29	34
Engine—medium	3 people and 500-gallon engine	34	45	70
Bulldozer—medium	2 people and crawler tractor	43	58	7

been available.

A major conceptual issue in the calculation of the fire-induced net value change is the delineation of the area from which the fire-induced change in output will be measured, the fire site only or the extended management unit within which the fire lies (Althaus and Mills 1982; Brown and Boster 1978; Mactavish 1966; McLean 1970; Mills and Flowers 1985; Van Wagner 1979, 1983). Unlike the fire-site-only computation, the consumption of resource outputs from unburned sites within the management or analysis unit can be substituted for resources that were originally scheduled to be consumed from the burned site. This conceptual question about the fire net value change computation is directly parallel to the allowable cut effect question in the computation of returns to inventory enhancing activities, such as planting (Schweitzer and others 1972, Teeguarden 1973). While the extended-management-unit option places the computation well within the existing operational planning context, it confounds the fire's effect on resource productivity with management and policy constraints that often change in time periods far shorter than the typical timber rotation. Previous studies (e.g., Bell and others 1975, Brown and Boster 1978) have demonstrated that the net value changes resulting from the fire-site-only computation are substantially higher, i.e., the losses are greater, than from the extended-management-unit computation.

We included only the fire site effects on resource outputs, rather than the extended management area effects, because we wanted to measure as closely as possible the effects of the fire program on the interaction between fire severity and site productivity. The only exception was that we included substitution of unburned for burned sites by recreationists to the extent that the data indicated such substitution occurs. Policy constraints that affect the management of individual sites were induced in our net value change computations. Rotation ages and maximum harvest block sizes typical in the Region, for example, were reflected in the net value change computations.

For those readers who are more interested in the operational fire program setting on National Forests, these fire-site-only computations provide a partial opportunity cost estimate of the harvest scheduling constraint. Since the fire-site-only computation produces higher loss estimates, the estimated fire management program efficiency would be lower than that estimated here if the extended-management-unit approach had been used instead.

The physical output and net value changes were calculated for a number of "fire situations" for each resource category. The fire situation parameters were a subset of the IPC parameters, augmented by fire characteristics and the resource management parameter of the FMS. For timber analysis, for example, the fire situation parameters were slope, cover type, age class, productivity class, access, fire size, mortality percent, and resource management emphasis. The number of fire situation parameters varied among the resource categories. Physical output change and net value change were calculated for 12,096 timber, 296 range, 8 water, 54 sediment, and 6 recreation fire situations in the Climate Zone.

Both the physical output change and net value change calculations were deterministic. The possibility of postfire insect infestations or subsequent fires was ignored for simplicity. The estimates for each fire situation were then combined within FEES using the probability of each fire situation occurring within each fire situation.

The net value change estimates were derived through a four-step process for each fire situation. An example for timber is shown in *figure 10*. The steps are:

- Estimate the "without-fire" time stream of per-acre management costs, resource output quantities, and revenues in the individual stand.
- Estimate the direct physical and biological effects of the fire, such as tree mortality in the timber calculation, and the

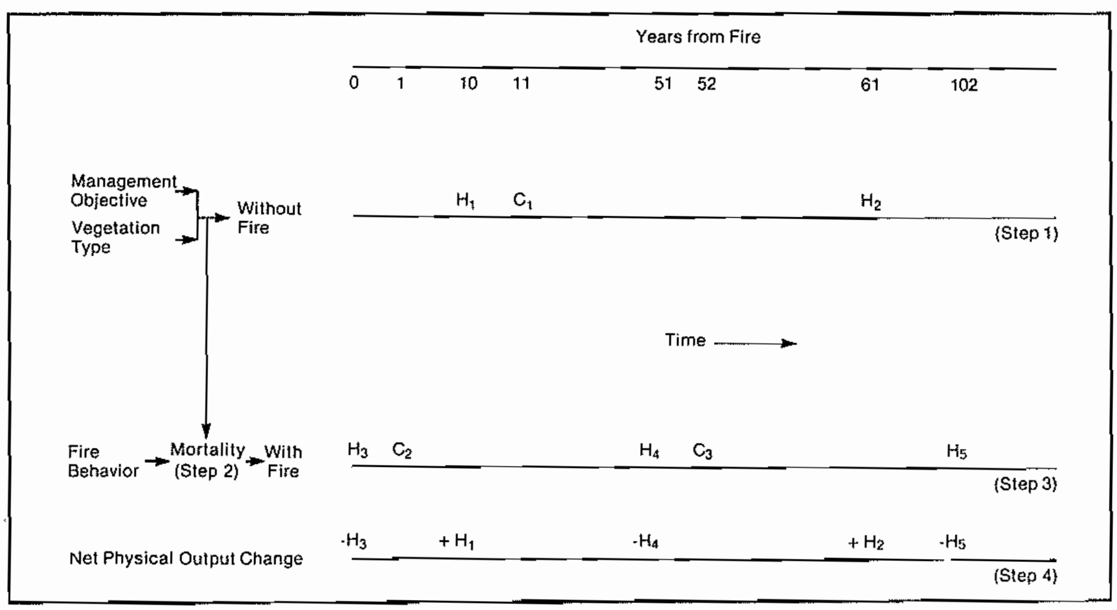

Figure 10—The calculation of timber net value change involves four steps.

immediate off-site effects.

- Estimate the "with-fire" time stream of per-acre management costs, resource output quantities, and revenues on the burned site.
- Estimate the net change in per-acre physical outputs between the "without-fire" and "with-fire" time streams. Include treatment costs, and then calculate the difference in the per-acre present net value of the two time streams. Multiply the per-acre values by the simulated expected value of acres burned in each fire size class to yield the net changes in physical output and net value change for the entire fire.

Net value change (NVC) is:

$$NVC = PNV^{o} - PNV^{f} \qquad (7)$$

where

PNV^{o} = present net value of the "without-fire" time stream of costs and revenues

PNV^{f} = present net value of the "with-fire" time stream of costs and revenues

The resulting net value change for the example in *figure 10* is:

$$NVC = \frac{H_1}{(1+i)^{10}} - \frac{C_1}{(1+i)^{11}} + \frac{H_2}{(1+i)^{61}} - H_3 - \frac{C_2}{(1+i)} + \frac{H_4}{(1+i)^{51}} - \frac{C_3}{(1+i)^{52}} + \frac{H_5}{(1+i)^{102}}$$

A more general form of the timber net value change computation can be found in Mills and Flowers (1985b, p. 974).

Defined this way, a negative net value change or physical output change is a "gain" or financial enhancement of the resource, and a positive net value change is a "loss" or detrimental effect. This seemingly reverse sign permits direct addition of the net value change to the fire program costs for the C+NVC efficiency criterion, thus maintaining consistency with the older "least-cost-plus-loss" criterion.

Since the net value change is the difference between two present net values, anything that affects the magnitude or timing of management costs, output levels, or per-unit values, in turn, affects the net value change. The fire's actual effect on the cash flow of the management costs and resource output returns within the management context of the individual fire situation is therefore reflected in the net value change. For example, if typical timber management practices would lead to a species conversion following a planned harvest, that species conversion is reflected in the with-fire time stream of costs and returns. Similarly, if there is a difference between fire size and planned harvest size in the absence of fire and that tract size differential leads to economies or diseconomies of scale in silvicultural treatment costs or timber prices, the entries in the cost and return time streams reflect those actual cost and revenue differences as well as possible.

The physical output changes reported here are the simple sum of output changes for 200 years after the fire. Two hundred years is long enough to encompass the one existing rotation and regenerated timber rotation. It is also long enough to cover essentially all of the net changes in the other resources. The net value change, just like the fire management program costs, was calculated at a 4 percent discount rate. Four percent is the estimated real rate of return on investments in the private sector (Row and others 1981) and is the rate used in Forest Service land management planning.

The probabilistic outputs from the suppression module (expression 6) provide the key inputs in the physical output change and net value change calculations. The probability of road access was added exogenously for the timber and water calculations as were the probabilities of site productivity classes for timber. Because of the lack of data on fire occurrence by roading and productivity classes, these two probabilities were based on their relative proportion of acres in the classes. All other occurrence frequencies are based on fire ignition frequencies rather than proportion of acres. The general functional form for physical output and net value changes is:

(Resource Output or Net Value Change)
=function of (SIZE,MORT,IPC,ACCESS,PROD)

The ignition-cause-dependent probability for each combination of input variables is expressed by:

$$P(SIZE,MORT,IPC,ACCESS,PROD,CAUSE) \qquad (8)$$

where

SIZE, MORT, IPC and CAUSE are as defined for expression (6).

ACCESS = access class (roaded or unroaded), used for timber or water only.

PROD = site productivity class (1-4), used for timber only.

The net value change per acre burned varied substantially among the resources and among the fire situations within each resource. Some of the resources had consistently positive values across all fire situations, e.g., recreation, or consistently negative, e.g., water yield. The net value change of other resources varied from positive to negative among fire situations, e.g., timber and range. The net value changes also varied substantially in magnitude, from approximately -$1,500 per acre burned (a gain) to $1,500 per acre burned (a loss). A substantial portion of the fire situations also had a zero net value change because the fire conditions had no net impact on net cash flow in the particular fire situation. The net impact of the several resources on the net value change for an FMS depends on the net value change estimates for separate fire situations combined with the relative fire frequencies among the fire situations.

Timber—After analysis of the sensitivity of the estimate to varying degrees of computational completeness (Mills and Flowers 1983), a fairly complete computational form of the timber net value change calculation was selected (Mills and Flowers 1985, 1986). Some of the simpler representations of the postfire cash flow sequence (for example, U.S. Dep. Agric., Forest Serv. 1982) yield quite different answers, one consequence being that they produce only positive net value change estimates, i.e., losses.

The tree mortality input to the net value change calculation was estimated for the scorch height classes in FEES for each timber fire situation using Peterson's (1983) generalized tree mortality model. It has the advantage of using mortality relationships that consider tree morphological characteristics, thus avoiding the need for species-specific mortality functions. Considerable additional tree mortality work is underway in the Climate Zone (Peterson 1984a, 1985; Peterson and Ryan 1984; Ryan and Peterson 1984) that could be used in future analyses.

The timber net value changes (Flowers and others 1985) varied substantially among fire situations, ranging from -$1,700 to $1,500 per acre burned. The timber estimates are generally higher values, per acre, in both the positive and negative directions, than are the estimates for the other resources.

The greatest losses were found in the moderate and high mortality fires in poletimber stands (*table 7*). High mortality poletimber fires often reduce stocking below that needed to retain the stand through the remainder of the existing rotation and yet the poletimber is often too immature to support a commercial salvage harvest. Postfire salvage partially offsets the loss of the existing stand.

Low- and moderate-mortality fires in most seedling and sapling stands, and in some poletimber stands, have a net value change of zero. Under our assumption that mortality is evenly distributed throughout the stand, these stands in the Climate Zone generally have enough stocking to absorb a low-mortality fire without any impact on the planned sequence.

The timber net value change was negative in 7 percent of the timber fire situations analyzed. These fire situations have a differentially large impact on the fire program performance, however, because of the high frequency of fires in ponderosa pine and Douglas-fir sawtimber stands and the relative large percentage of the acres that burn in large fires.

The timber net value gains occurred predominately in the large fire size class in Douglas-fir and ponderosa pine sawtimber stands. The gain results from two factors. First, the fire reduces stocking below the level required to retain a viable stand, thus truncating a rotation that exceeds the financially optimum rotation. Second, large fires stimulate economies-of-scale in salvaging the burned timber and in establishing the postfire stand when the fire is larger than the acreage of the normal management unit.

While these gains are really a partial reflection of the opportunity cost of the nontimber objectives for which the long rotations and small harvest areas were established in the first place, the gains accurately reflect the cash flow consequences of a fire in the public management setting in the Climate Zone. The nontimber losses resulting from shorter rotations and larger harvest areas should be considered in the fire management program decision, but they should not confound the timber net value change estimate. Instead, they should be incorporated in whatever resource category they occur. Unlike the constraint on the size of clearcuts in the National Forest Management Act Regulations, fire sizes cannot be legally enforced.

Rangeland Grazing—The range net value changes were drawn from the estimates developed by Peterson and Flowers (1984). The range net value changes are small relative to the timber estimates, generally varying from -$25 to $5 per acre burned.

Fires in mountain grassland situations result in net value change losses because grazing is withheld for a few years after fire to permit the site to reestablish (*table 8*). Even though the grazing yield is greater after the postfire rest period than without the fire, the complete loss of yield in the first few years is more of a financial loss than the small increase in yield in later years is a gain. Fires in timber types that permit grazing only during the seedling and sapling stage of the stand, such as Douglas fir, show small losses to fire, unless the mortality is high enough to lead to stand replacement. When the fire is severe enough to cause stand replacement, grazing in the early years after stand

Table 7—*Timber physical output change and net value change (1978 dollars) at a 4-percent discount rate for select fire situations in the Northern Rocky Mountain*[1]

Cover type	Cover type age class	Tree mortality	Fire size	Physical output change[2]	Net value change
		(Percent)	*(Acres)*	*(Ft³/acre)*	*(1978 dollars/acre)*
Douglas-fir	Seedling/sapling	30-59	1-99	0	0
Douglas-fir	Poletimber	60+	100+	600	293
Douglas-fir	Sawtimber	30-59	100+	800	-122
Ponderosa pine	Seedling/sapling	60+	1-99	0	219
Ponderosa pine	Poletimber	30-59	1-99	800	129
Ponderosa pine	Sawtimber	60+	100+	-6600	-206
Fir-spruce	Seedling/sapling	30-59	1-99	0	2
Fir-spruce	Poletimber	30-59	100+	4000	523
Fir-spruce	Sawtimber	1-29	1-99	-3600	-250
Lodgepole pine	Seedling/sapling	60+	1-99	0	141
Lodgepole pine	Poletimber	30-59	1-99	0	0
Lodgepole pine	Sawtimber	60+	100+	200	143

[1]All fire situations are for currently roaded sites of 50-84 ft³/acre/year, with productivity managed in a modified public timber management regime.
[2]The physical output change is the simple sum of the net changes in the 200-year period following the fire.

establishment is pulled forward in time from what would have occurred without the fire, thus leading to a gain. Fires in timber types that permit grazing throughout the rotation, such as ponderosa pine, generally have net value gains if the fire is of high enough intensity to remove some of the tree cover, thus permitting more forage production.

Water Yield—The water yield net value changes were drawn from the estimates developed by Potts and others (1985). Fire increases water yield by removing the vegetation that would otherwise transpire some of the water. The increased water yield was valued at the marginal value of irrigation water in the region, the same value used in Forest Service land management planning. We assumed that no flooding would occur from the increased water yield and that the increased flow could be captured for use in irrigation.

The water net value changes are about the same magnitude as the range estimates, varying from -$25 to $0 per acre burned (*table 9*). Unlike range, however, the water estimates are consistently negative. Therefore, the water net value changes do not partially cancel among the fire situations within the FMS as do the timber and range net value changes.

Sediment Yield—The net value change for the sediment yield stimulated by fire was drawn from the estimates prepared by Potts and others (1985). Although sediment yield is greatly affected by the presence of roads, it is affected very little by the presence of fire. The sediment net value change is consistently positive across the fire situations, but it is less than $0.01 per acre burned when sediment is valued as it is by the Forest Service for land management planning (-$7 per ton).

Recreation—The recreation net value change estimates were drawn from Flowers and others (1984). Using their computational procedure, which included substitution away from the burned site but not toward the burned site, the recreation net value changes are consistently positive. They vary from $0.13 to $4.74 per acre burned (*table 10*).

The recreation net value changes were estimated using the contingent valuation method (Vaux and others 1984) to measure fire impacts on recreation. Two photo series were compiled which showed the effects of fire on the vegetation over time after the fire. One photo series depicted a high mortality fire in a Douglas-fir sawtimber stand. The other showed an understory burn in a ponderosa pine stand.

Pairs of photos from different points in time were then shown to recreationists. The recreationists were asked to select the site they would prefer. A hypothetical bidding game was then conducted to estimate the recreationist's willingness-to-pay to use their preferred site.

The inability to estimate substitution of recreationists toward the burned site, which some recreationists preferred to the unburned site, is another problem with the recreation net value change estimates. As a result, these recreation net value changes probably overestimate the detrimental effect of fire on recreation. There is also debate about the hypothetical nature of the contingent market valuation method of estimating willingness-to-pay. The estimate is so low, however, it is unlikely that any reasonable assessment of the errors in the recreation estimates would affect the conclusion about the efficiency of the fire management program.

Fire Occurrence Module

The objective of the fire occurrence module was to estimate the probability of fire occurrences in each IPC. This was accomplished in two steps. First, the probability distribution of the total number of fires in the FMS was estimated (Bratten 1984a). Second, the relative frequency of a fire within an IPC is estimated given that a fire has occurred in the FMS.

The probability distribution of annual number of fires per million acres was derived by regressing the standard deviation of annual fire occurrence per million acres from the 26 National Forests in the Climate Zone against the mean fire occurrence per million acres in each Forest. The standard deviation of annual fire frequency per million acres was derived in each FMS by inserting the mean annual rate of fires in Ranger Districts representative of the particular FMS into this Climate Zone-wide regression equation. The resulting standard deviation and mean fire occurrence rates were used in a negative binomial distribution to describe the probability distribution of the annual fire occurrences in the FMS under study. The probability function for the annual fire occurrence rate was described as:

$$\text{Prob}(m \text{ fires/year/million acres}) = NB(m;n,p) \quad (9)$$

where n and p were parameters of the negative binomial (NB) distribution estimated from the mean number of fires/year/million acres specified for the FMS being analyzed and the standard deviation for the distribution. Illustrative mean and standard deviation of annual number of fires per million acres derived in this manner for the Douglas-fir FMS were:

Ignition cause	Mean	Standard deviation
	(Fires/million acres/year)	
Lightning	37.7	22.8
Human	14.8	6.8

Distinction between ignition causes is required in the fire occurrence distributions because fire behavior, fire size at time of detection, initial attack arrival times, and proportions of initial attack dispatch by fire management input are all differentiated by ignition cause.

The conditional probability of a fire in each IPC, given a fire in the FMS, was derived by simply stratifying the Individual Fire Reports (1970-1981) from the Ranger Districts that were representative of the FMS. These empirical data on fire frequencies were used directly to estimate the probabilities of occurrence in each IPC. Some of the IPC's had a zero fire frequency in the sample period. Those IPC's were assigned a zero probability in this study. Since several thousands of fires were analyzed for each FMS, we assumed with some confidence that the "zero" probabilities were in truth very small. The fire occurrence probabilities can be expressed as:

$$\text{Prob}(\text{Inferred parameter cell}) = P(\text{IPC};\text{CAUSE},\text{FMS}) \quad (10)$$

in which

Table 8—*Range physical output change and net value change (1978 dollars) at a 4-percent discount rate for select fire situations in the Northern Rocky Mountain-Intermountain Region*

Cover type	Cover type age class	Range rate	Tree mortality	Season	Physical output change[1]	Net value change
		(Percent)	*(Percent)*		*(AUM/acre)*	*(1978 dollars/acre)*
Douglas-fir	Seedling/ sapling	40	85	—	4.16	-26.69
Douglas-fir	Sawtimber	25	70	—	0.00	-10.68
Lodgepole pine	Poletimber	25	85	—	0.00	-12.17
Ponderosa pine	Seedling/ sapling	40	3	Summer	0.30	3.08
Ponderosa pine	Poletimber	40	60	Spring	-2.32	-8.47
Mountain grassland	—	40	—	Summer	0.74	7.06
Sagebrush	—	40	—	—	-2.48	-16.61
Pinyon juniper	—	25	—	—	-2.28	-6.79

[1]The physical output change is the simple sum of the net change in the 200-year period following the fire.
AUM = Animal Unit Months.

Table 9—*Water physical output change and net value change (1978 dollars) at a 4-percent discount rate for select fire situations in the Northern Rocky Mountains*

Aspect	Access	Tree mortality	Physical output change[1]	Net value change
		(Percent)	*(Acre ft/acre)*	*(1978 dollars/acre)*
North	Roaded	0-29	0	0
North	Roaded	30-59	-10.59	-24.21
North	Unroaded	30-59	-1.38	-2.94
South	Roaded	60+	-9.23	-21.25
South	Unroaded	30-59	-2.71	-6.31
South	Roaded	0-29	0	0

[1]The physical output change is the simple sum of net changes in the 200-year period following the fire.

IPC = one of 816 combinations of inferred parameter values.
(Parameters are: slope, aspect, elevation, cover age class, and time of year).

CAUSE = ignition cause class: 1—lightning, 2—human.

FMS = the fire management situation being analyzed.

The fire frequencies in the Douglas-fir FMS are heavily weighted toward sawtimber fires in the Douglas-fir and ponderosa pine cover types. Those two fire situations alone account for almost 40 percent of the fires in the FMS (*table 11*). This differential fire occurrence weighting has important implications for model results. Sawtimber stands, especially Douglas-fir and ponderosa pine, represent fire situations that often lead to negative timber net value changes in the public timber management regimes.

SIMULATION RESULTS

The economic efficiency and risk results of the simulations in the Climate Zone are multifaceted and interrelated, just like the fire management system. The several facets of the simulation results are unfolded sequentially below, starting with the economic efficiency results of the base program (IA(H,3),FT(H,3)) in the Douglas-fir FMS. The economic efficiency results focus on the expected value, which is the probability-weighted average of the probability distribution. The impact of variations in the initial attack program on efficiency are described next, followed by similar results of fuel-treatment program variations. The risk results from the Douglas-fir FMS simulation are presented next. They focus on the shape and width of the probability distribution around its expected value. The sensitivity of economic efficiency to hypothetical changes in large fire suppression and prevention program effectiveness and resource management objectives in the Douglas-fir FMS are then discussed, followed by a comparison of the ponderosa pine and fir-spruce with the Douglas-fir FMS simulation results.

Economic Efficiency

Base Program Option

The presuppression program level in the "base" program option (IA(H,3),FT(H,3)) of the Douglas-fir FMS was $662 thousand per million acres or $0.66 per acre protected (*table 12*). This total program level was composed of $396 thousand for initial attack, $126 thousand for fuel treatment, $86 thousand for detection, and $53 thousand for prevention. The prevention and detection program components are assumed constant in all of the simulations except the prevention sensitivity analysis. Elsewhere, effectiveness of prevention is reflected in historical fire occurrence frequencies and effectiveness of detection in historical fire sizes at time of detection.

The C+NVC at the base program option in the Douglas-fir FMS was dominated by the presuppression cost, i.e., the fire management program input into the fire management system (*table 12*). The expected value C+NVC was $764 thousand of which 87 percent was presuppression program cost, 13 percent was suppression cost, and less than 1 percent was net value change. The mean acres burned per million acres in the Douglas-fir FMS historically was 642 acres (1970-1981). The simulated area burned was 679 acres, a difference of less than 6 percent. The mean suppression cost in the simulation was $147 per acre burned, and the mean net value change was $3 per acre burned.

The Forest Service's nationwide suppression cost varies substantially from year-to-year, but is generally closer to 35 percent times as great as presuppression cost than the 25 percent simulated in the Douglas-fir FMS in the Northern Rocky Mountains and Northern Intermountain Fire Climate Zone. Given the high suppression costs in other Regions with heavy fuel loadings, such as western Oregon and Washington, and impact of Regions with prominent urban-wildland interfaces, such as southern California, the divergence between the national average and the simulated results in the Climate Zone is reasonable.

The simulated net value change summed across the entire FMS is low because the positive and negative net value changes among fire situations within the same resource partially cancel, and also because the positive and negative net value changes among the resource categories themselves partially cancel.

The timber net value change was only $4.3 thousand in the entire million acre FMS, or about $6 per acre burned. Even though the negative net value changes, i.e., the net gains, occurred in only 7 percent of the fire situations analyzed, those fire situations had relatively high fire occurrence frequencies. The negative net value changes occurred predominately in Douglas-fir and ponderosa pine sawtimber situations and in the large-fire size class (*table 7*). Almost 40 percent of the fire occurrences in the Douglas-fir FMS were in the Douglas-fir and ponderosa pine sawtimber situations (*table 11*), however, and 97 percent of all the acres burned in the Douglas-fir FMS were in the large-fire size class (100+ acres). The timber net value gains from those fire situations were almost enough to completely overcome the timber net value losses from the other fire situations. The total $4.3 thousand loss for the entire 679 acres burned is equivalent to the loss of only five acres of one of the highest loss individual timber fire situations.

The timber net value change computation in previous studies frequently resulted in much higher timber losses. Schweitzer and others (1982), for example, estimated a timber net value change of $493 per acre burned on the Deschutes National Forest, a Forest within the Climate Zone. If the timber net value change had been $493 per acre, the total timber net value change would have been $334 thousand, or 31 percent of the C+NVC, instead of the 1 percent of the C+NVC estimated here (*table 12*). The study reported here is the first major fire management analysis that included a timber net value change computation from which a net gain could be derived. The form of the timber net value change computation, therefore, does have potential implications for conclusions about the efficiency of the fire management program.

Although the primary reason for the differences between the timber net value changes estimated and those in earlier studies is thought to be the cash flow computational form, another

Table 10—*Recreation, physical output change, and net value change (1978 dollars) at a 4-percent discount rate for select fire situations in sawtimber age class in the Northern Rocky Mountains*

Cover type	Fire severity	Recreation use rate	Physical output change[1]	Net value change
		(RVD/acre/ year)	*(RVD/acre)*	*(1978 dollars/acre)*
Ponderosa pine	Understory fire, no tree mortality	0.13	0.183	0.3
		0.13	0.390	0.5
		0.28	0.8	1.3
Douglas-fir	100-percent tree mortality	1.02	0.183	1.1
		2.17	0.390	2.2
		4.74	0.856	4.6

[1]The physical output change is the simple sum of the net change in the 200-year period following the fire.
RVD = Recreation Visitor Days.

Table 11—*Fire occurrence probabilities in the Douglas-fir fire management situation, by cover type and cover type age class*[1]

Cover type	Recently cutover	Seedling/ sapling	Poletimber	Sawtimber	Total
			Percent of fires)		
Douglas-fir	2.53	1.23	4.00	15.56	23.32
Ponderosa pine	2.12	2.46	2.94	23.22	30.74
Western white pine	0.00	0.00	0.00	0.10	0.10
Fir-spruce	0.07	0.38	0.82	3.11	4.38
Hemlock-Sitka spruce	0.24	0.04	0.27	0.48	1.03
Larch	2.67	0.89	1.98	7.08	12.62
Lodgepole pine	0.48	0.75	4.04	5.13	10.40
Pinyon-juniper	—	—	—	—	0.62
Western hardwoods	—	—	—	—	0.44
Sagebrush	—	—	—	—	1.33
Mountain grass and meadows	—	—	—	—	6.84
Mountain shrub	—	—	—	—	1.74
Alpine	—	—	—	—	6.43
Totals	8.11	5.75	14.05	54.68	

[1]Pinyon-juniper through alpine do not have cover type age classes.

possible reason for the difference could be the mortality computation. The timber net value change used in FEES varies by mortality, as it interacts with existing stand stocking to yield a postfire stocking. The postfire stocking is in turn compared with a stand retention stocking minimum to determine if the originally planned harvest sequence for the stand is interrupted by the fire mortality. The National Forest timber inventory data show that many seedling and sapling stands are well enough stocked to absorb a low or moderate mortality fire with no disruption of the planned harvest. A higher timber net value change would have resulted if a higher proportion of the fires had been estimated to have high mortality rates.

The net value change for water yield (-$2.0 thousand) was about half as large as that for the timber total, but it was a net gain, rather than a net loss. The water yield net value changes for individual fire situations (*table 9*) were generally smaller than the timber estimates, but all of the water yield net value changes were negative so they did not partially cancel. There is often controversy over the appropriate per-unit value of water yield. The simulated water net value change is so small relative to the C+NVC, however, that there appears to be an adequate margin of confidence around the per-unit water yield value estimate used here. The sediment net value change rounded to less than $1 for the entire FMS.

The range and recreation net value changes over the entire FMS were also very low, $0.2 thousand (range) and $0.3 thousand (recreation). Just as the C+NVC would be affected little by changes in the per-unit value of water, it would also be affected little by changes in the per-unit value of recreation. Unlike the form of the timber net value change computation, debate over the hypothetical nature of the contingent market valuation method estimation of willingness-to-pay is of little concern for this fire management application of the value estimates.

The sum of the net change in physical output of the various resources for the 200-year period after the fire was also calculated. Those output changes were low relative to the already low net value changes. As Mills and Flowers (1986) found, the net value change is determined more by changes in the timing and the per-unit value of the resource output than by the absolute magnitude of the resource output changes within the 200-year period after the fire. The expected value change in output per million acres per year from the 679 acres burned was -60 thousand cubic feet of timber, -8 animal unit months of grazing, -209 acre feet of water yield, 0 tons of sediment, and 499 recreation visitor days of use. As in the net value change, a negative is a net gain over the 200-year period and a positive is a net loss.

Initial Attack Program Options

Recalling the marginal nature of the C+NVC criterion, no economic efficiency conclusions can be reached from studying the relationship between presuppression cost, suppression cost, and net value change at any one fire management program level. The relative efficiency among the program levels is signaled by their relative C+NVC. The program option with the lowest C+NVC, irrespective of its C+NVC composition, is the most efficient of those tested.

The efficiency of initial attack program options was tested first, while the fuel-treatment program was held at its base option (FT(H,3)). The C+NVC for all 15 combinations of program level and fire management mix of the initial attack program (IA(H-A,1-5)) was then simulated.

The simulated escape percent (percent of fires over 100 acres) in the historical fire management mix (IA(H,1-5)) increased as the initial attack program level was lowered (*fig. 11*), but the escaped fire percent did not increase dramatically. The simu-

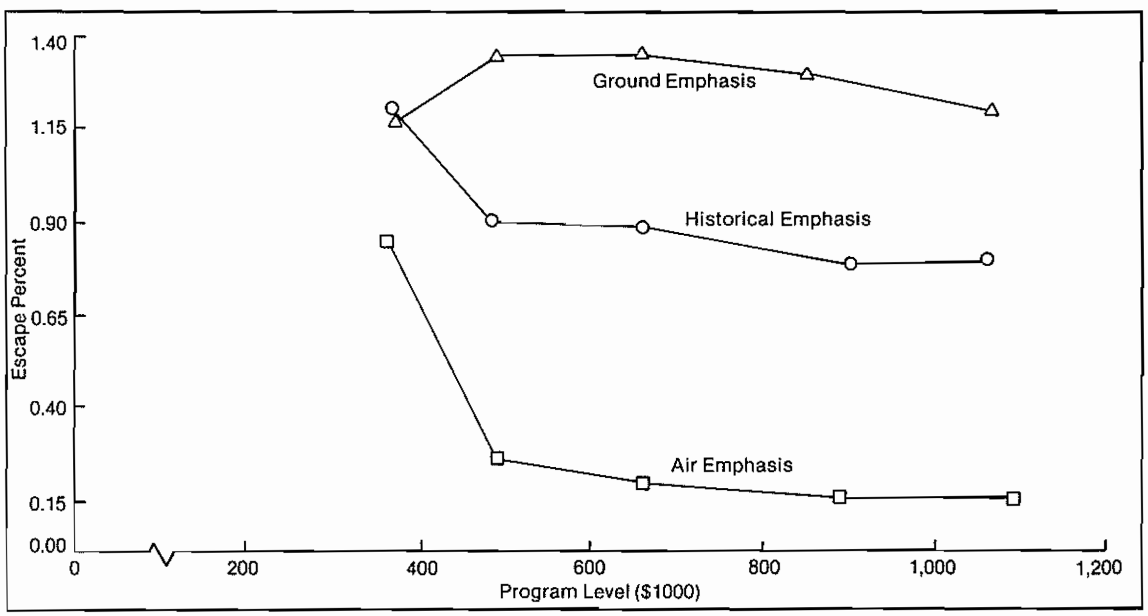

Figure 11—Simulated escape percent in the Douglas-fir fire management situation for the three initial attack program options, while holding the fuel-treatment program at its base option.

lated escape percents in the Douglas-fir FMS varied from 0.81 percent at the base-plus-100-percent program level to 1.22 percent at the base-minus-75-percent program level. While this is a 50 percent increase in escape percent, the fires that escape in the simulation are still a small percent of all fires.

To determine whether FEES underestimated the sensitivity of escaped fire percent to initial attack funding level, historical escape fire percents in the Forest Service Northern Region were compiled for the period 1940 to 1981 (*fig. 12*). There was a great deal of year-to-year variation in historical escape percents. Even the 10-year moving average fluctuates considerably. The escape percentage of 45 years ago was not substantially higher than today's, though. There is no statistically significant time trend to the historical escape percents. The mean escape percents for the 1940 to 1981 period (0.47 pct for lightning-caused and 2.08 pct for human-caused) were very similar to the 1970 to 1981 percents used for calibration in FEES.

There are some reasons for which the escape percents of 30 to 40 years ago were higher than they are today. The fire management program levels were much smaller then. There was less complete reporting of nonspreading fires which, in turn, would have increased the number of escaped fires as a percent of all reported fires. Road access was also far less developed then. There are also reasons for which the current escape percents would be higher. Human-caused ignitions have increased. Widespread timber harvesting and years of aggressive suppression have led to fuel accumulation. The simulated escape fire percents were well within the range of the historical data from the same general region. Escape fire percents did not increase dramatically when the program level was dropped in our simulation, just as escape fire percents are not materially lower now in the Northern Region than they were 40 years ago.

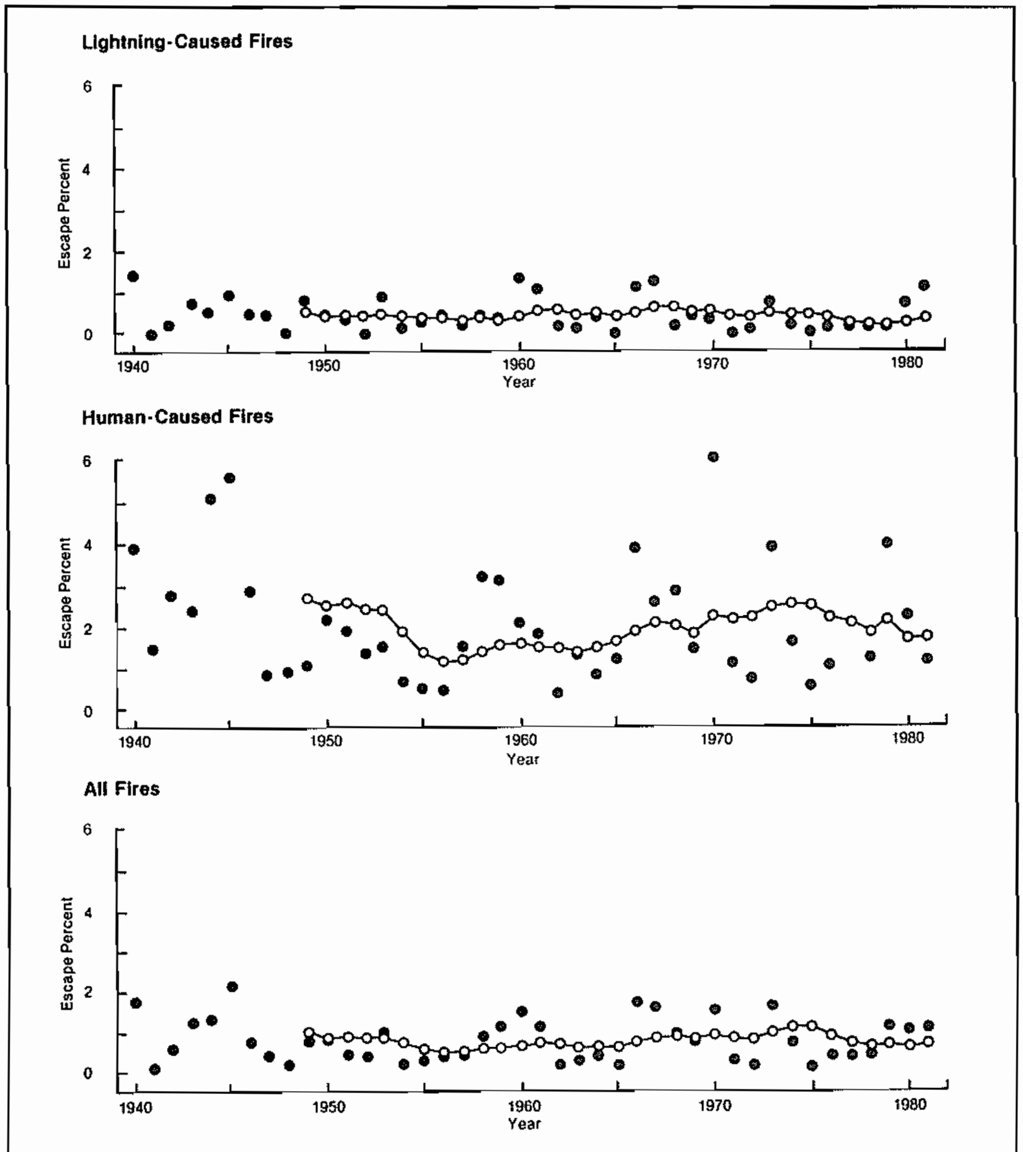

Figure 12—Percent of escaped fires in the Forest Service Northern Region, 1940 to 1981. (Open dots represent 10-year moving average; black dots represent individual years.)

Table 12—*Expected value C+NVC results for the Douglas-fir fire management situation, in 1978 dollars and acres burned per million acres protected per year*

Program option[1]	Presuppression costs			Suppression cost	Net value changes						C+NVC total	Burned acres
	Initial attack	Fuel treatment	Total[2]		Timber	Range	Water	Sediment	Recrea-tion	Total		
					(Historical Initial Attack Emphasis)							
IA(1)FT(3)	104,890	125,885	370,000	128,000	6,662	120	-3,237	0.0	497	4,042	502,000	970
IA(2)FT(3)	222,210	125,885	487,325	106,000	4,780	78	-2,444	0.0	375	2,789	596,000	740
IA(3)FT(3)	396,419	125,885	661,534	100,000	4,316	167	-2,008	0.0	314	2,789	764,000	679
IA(4)FT(3)	638,351	125,885	903,446	92,000	4,278	124	-1,886	0.0	295	2,811	998,000	625
IA(5)FT(3)	801,736	125,885	1,066,851	91,000	4,229	124	-1,865	0.0	292	2,780	1,160,000	623
					(Ground Forces Initial Attack Emphasis)							
IA(1)FT(3)	107,632	125,885	372,747	121,000	6,644	59	-3,271	0.0	499	3.931	498,000	943
IA(2)FT(3)	229,815	125,885	494,930	130,000	6,129	196	-3,210	0.0	500	3,615	629,000	1,020
IA(3)FT(3)	394,962	125,885	660,077	129,000	6,425	210	-3,197	0.0	497	3,935	793,000	1,003
IA(4)FT(3)	591,594	125,885	856,709	123,000	6,077	209	-3,037	0.0	473	3,722	984,000	962
IA(5)FT(3)	804,858	125,885	1,069,973	115,000	5,827	170	-2,986	0.0	461	3,472	1,189,000	907
					(Air Initial Attack Emphasis)							
IA(1)FT(3)	101,601	125,885	366,716	124,000	5,934	61	-2,418	0.0	370	3,947	495,000	729
IA(2)FT(3)	225,997	125,885	491,112	55,000	2,395	4	-888	0.0	134	1,645	547,000	267
IA(3)FT(3)	400,883	125,885	665,998	46,000	1,273	4	698	0.0	106	1,486	713,000	219
IA(4)FT(3)	627,623	125,885	892,738	40,000	1,761	23	-572	0.0	89	1,281	934,000	185
IA(5)FT(3)	826,648	125,885	1,091,763	39,000	1,723	24	-578	0.0	87	1,256	1,132,000	179
					(Historical Fuel Treatment Emphasis)							
IA(3)FT(1)	396,419	0[3]	535,649	101,000	4,316	169	-2,008	0.0	315	2,789	638,000	686
IA(3)FT(2)	396,419	62,988	598,637	100,000	4,316	168	-2,008	0.0	315	2,789	700,000	683
IA(3)FT(3)	396,419	125,885	661,534	100,000	4,316	167	-2,008	0.0	314	2,789	764,000	679
IA(3)FT(4)	396,419	188,827	724,476	99,000	4,316	167	-2,008	0.0	314	2,789	825,000	678
IA(3)FT(5)	396,419	251,854	787,503	99,000	4,316	165	2,008	0.0	314	2,789	888,000	675
					Prescribed Burn Fuel Treatment Emphasis							
IA(3)FT(3)	396,419	125,894	661,543	100,000	4,316	168	-2,008	0.0	314	2,789	763,000	682
					Equal Balance of Fuel Treatments (prescribed burn, mechanical pile and burn, hand pile and burn)							
IA(3)FT(3)	396,419	126,018	661,667	100,000	4,316	168	-2,008	0.0	314	2,789	763,000	682

[1]Original funding levels were as follows:

Initial attack (IA)
- *1—Base minus 75 pct*
- *2—Base minus 50 pct*
- *3—Base*
- *4—Base plus 50 pct*
- *5—Base plus 100 pct*

Fuel treatment (FT)
- *1—Base minus 100 pct*
- *2—Base minus 50 pct*
- *3—Base*
- *4—Base plus 50 pct*
- *5—Base plus 100 pct.*

[2]Includes $86,190 for fire prevention and $53,040 for detection.

[3]Program options include no fuel treatments for hazard reduction.

Stimulated by the changes in escape percent, the expected value of simulated acres burned varied in a similar manner, reaching a high of 970 acres at base-minus-75-percent and a low of 623 at base-plus-100-percent initial attack option (*table 12*). The tradeoff between presuppression costs and acres burned from the base to the base-minus-75-percent program level was $1,000 for each acre burned. That is, it required a $1,000 increase in presuppression costs to reduce total acres burned by 1 acre. The reduction in acres burned from increases in program level above the base level funding were even smaller, signaling diminishing returns to program expansions. The addition of $405 thousand in presuppression funding between the base and the base plus 100 percent, for example, reduced the simulated acres burned by only 56 acres. That presuppression program level increment corresponds to an increase in initial attack funding of $7,232 to reduce acres burned by 1.

Suppression cost changed in the same direction as acres burned, but the magnitude of the suppression cost response was less. At the base-minus-75-percent level, 43 percent more acres burned than at the base program level, but suppression cost was only 28 percent higher. The lower sensitivity to suppression costs results from the lower suppression cost per acre burned for large fires than for small fires (*table 5*). A larger share of the acres burned at the lower program level was in larger fires.

The net value change was relatively low at all of the initial attack program levels in the Douglas-fir FMS, from base minus 50 percent to base plus 100 percent. Just as at the base level, the positive and negative net value changes within and between the resource output categories largely canceled to produce a low total net value change. The total net value change across the FMS rose with the simulated areas burned, but even at the base-minus-75-percent program level, the net value change was only 1.3 percent of the total C+NVC.

The net result of the simulated changes in suppression cost and net value change across the presuppression program levels was that the most efficient initial attack program level tested was base minus 75 percent (IA(H,1)). Although the C+NVC curve was beginning to flatten as the funding was reduced (*fig. 13*), it was still declining. Program levels below base minus 75 percent were not tested because data within FEES, such as the initial attack arrival times, become less valid as the test program level deviates farther from the historical program level from which the data were derived.

Simple sensitivity analysis can demonstrate how much the simulation results would have to change to affect the efficiency conclusions. One sensitivity test was applied to the combined suppression cost and net value change.

The combined suppression cost and net value change per acre burned were $136 at base minus 75 percent and $147 at base minus 50 percent. These combined suppression cost and net value change "losses" per acre would have to be over five times greater before base minus 50 percent could become the most efficient program level. While there are data and computational weaknesses in the FEES model, it is doubtful that they translate into a fivefold error in the combined suppression costs and net value change estimate.

Another sensitivity test was applied to acres burned. The simulated acres burned was 970 acres at base minus 75 percent and 740 acres at base minus 50 percent. Assuming that the original suppression cost and net value change estimates are accurate, the original 230-acre differential in acres burned between the two program levels would have to expand to a differential of over 920 acres before base minus 50 percent would become the most efficient level. That required 920-acre differential between the two program levels is almost as large as the original estimate of 970 acres burned at the base-minus-75-percent level. While the number of actual acres burned at the base-minus-75-percent level could well be greater than the number of simulated acres burned, it is doubtful whether the acres-burned differential between the two program levels is in error by a factor of 4.

The economic efficiency results from the other two fire management mixes tested, the ground and the air emphases, were similar to the results from the historical mix in the shape of the C+NVC curve at different program levels and in the composition of the total C+NVC. The most economically efficient program level for the other two alternative mixes was also the lowest program level tested, base minus 75 percent (*table 12, fig. 14*). Suppression costs and net value changes were a similarly small percentage of the C+NVC.

Efficiency is affected by fire management mixes as well as the program level. The air emphasis was consistently the most efficient fire management mix at all fire program levels tested because it consistently produced materially lower estimates of acres burned (*table 12, fig. 14*). The actual difference between the C+NVC among the three mixes was small, however, because the C+NVC in all three emphases was dominated by the presuppression cost.

Acres burned may be an important decision parameter in some situations. At the base program level, the number of acres burned in the air emphasis was 219 acres, as opposed to 679 acres in the historical emphasis at the same program level, and 1,003 acres with the ground emphasis. Only one fire management input, e.g., one handcrew or engine, was dispatched to the vast majority of the fires in the initial attack simulation, and that one fire management input was able to contain the fire. There are fewer input units in the air emphasis than in the ground emphasis at a given program level, because the per-unit cost of the air inputs is relatively greater. The faster arrival times of the air units apparently are more than enough to make up for the infrequent times that an inadequate number of firefighting units are available for dispatch in the air emphasis, however. The jump in acres burned in the air emphasis from 267 to 729 acres (*table 12*) between the base-minus-50-percent and the base-minus-75-percent program levels may indicate that the advantage of faster arrival time is beginning to be outweighed at base minus 75 percent by the times when more inputs are needed for dispatch than are available.

Fuel-Treatment Program Options

Alternative fuel-treatment program options were then tested while the initial attack program was held at its base level (IA(H,3)). The impact of fuel treatments was registered within FEES through adjustments in the translation from fuel models in

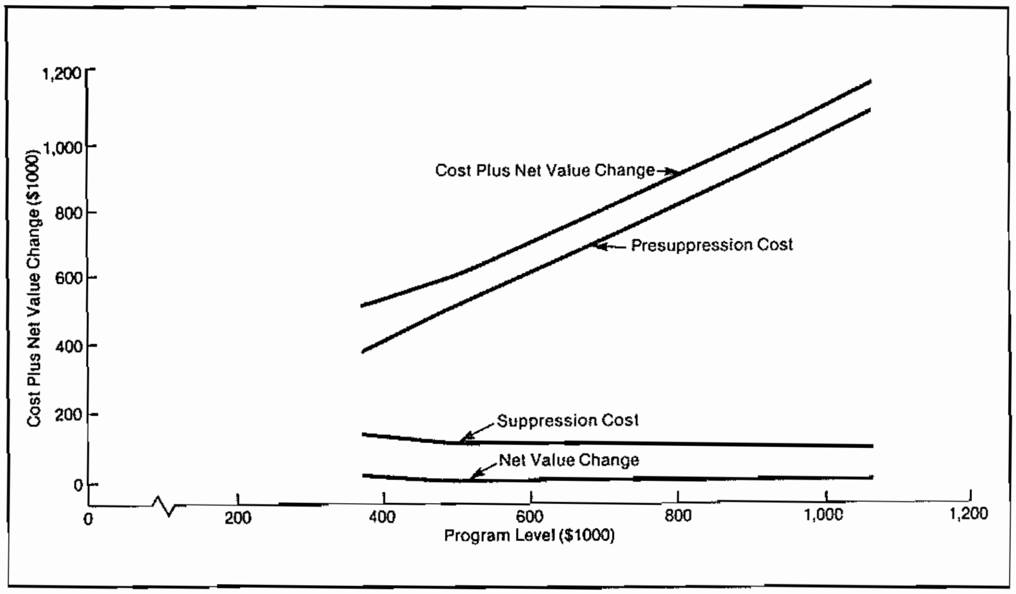

Figure 13—Expected value C+NVC components in the Douglas-fir fire management situation for the "base" program for both initial attack and fuel treatment (IA(H,3),FT(H,3)).

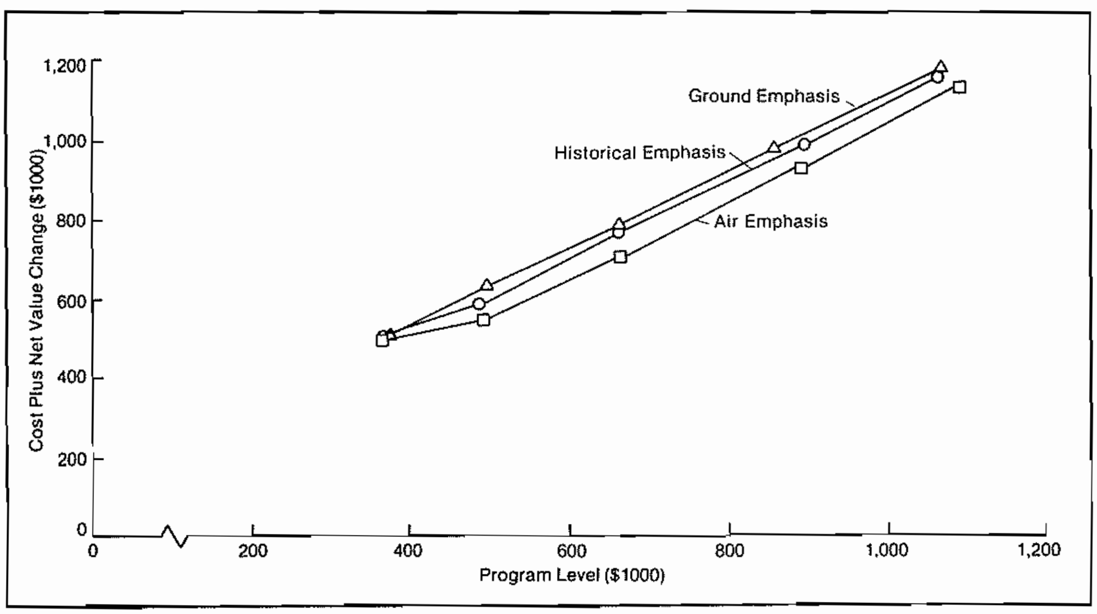

Figure 14—Family of expected value C+NVC curves in the Douglas-fir fire management situation for the three initial attack program options (IA(H,G,A,1-5)), while holding the fuel-treatment program at its base option.

the fire behavior module to cover types in the fire occurrence and fire effects modules. Fuel treatments, therefore, shift fire occurrences from fuel models that have more severe fire behavior toward fuel models with less severe fire behavior. Although this approach is less direct than changing the number of acres in the different fuel models, the net effect of the fuel treatments is the same. The fuel treatments were targeted toward the slash fuels to give the greatest reduction in fire severity.

Changes in funding of the historical emphasis fuel-treatment program had essentially no impact on the simulated acres burned, the suppression cost, or the net value change (*table 12*). Even complete elimination of the fuel treatment program had no material impact on the simulation results. The zero program level was the most economically efficient program level tested. The two alternative fuel-treatment mixes—the burning emphasis, and equal balance of treatments—also had no impact on the suppression costs or the net value changes. The same efficiency results occurred when fuel-treatment options were tested in combination with the ground and air initial attack emphases.

Fuel treatment only shortens the time period over which slash fuels are most hazardous. Treatment of up to 1,128 acres within the 1-million-acre FMS, twice the historical rate of treatment, has insignificant impacts on the fire system behavior beyond what is already accomplished by natural fuel deterioration. Fire ignitions are apparently too infrequent in the Douglas-fir FMS to provide an economic return to the fire system from a shortening of the time window of greatest fuel hazard by treatment.

This lack of economic efficiency is consistent with results of other studies of fuel treatments on National Forest lands. Wood (1978) estimated very low returns for fuel-treatment projects in a study area in the northern Rocky Mountains. Hirsch and others (1979) estimated similarly low returns on a study area in the Southwest, and so did Barrager and others (1982) on a study area in the Pacific Northwest. While slash fuel treatments might be an effective means of accomplishing some objectives, such as site preparation for planting, it appears that they do little to improve efficiency.

Risk Results

Base Program Option

The economic efficiency conclusions are all drawn from the expected value C+NVC. The width and symmetry of the probability distribution surrounding the expected value C+NVC provides one measurement of the risk associated with a particular fire management program option. The risk consequences of a program selection are separable from expected value economic efficiency. How the two parameters are incorporated into the decision calculus is a function of their relative utility to the decisionmaker or the public served by that decisionmaker. It is not the program analyst's or fire program modeler's role to integrate the relative importance for risk directly into the computational procedures themselves as has sometimes been done.

The entire cumulative distribution for acres burned is shown in *figure 15*, for suppression cost in *figure 16*, for net value changes in *figure 17*, and for C+NVC in *table 13*. Various ratios of the values at the 5th and 99th percentile points on the cumulative distribution to the expected value are used to describe distribution width. The percentile point on the cumulative distribution where the expected value lies is used to describe the symmetry of the distribution. As will be shown, the form of the display of the probability results could affect the decisions reached with the risk results.

The probability distribution of acres burned for the base level program option, IA(H,3),FT(H,3), has two prominent characteristics: it is wide and asymmetrical (*fig. 15*). The simulated acres burned at the 5th percentile point on the cumulative distribution is 141 acres per year per million acres protected; i.e., there is a 5 percent probability that the acres burned in any one year will be 141 acres or less. The number of acres burned at the 99th percentile is 7,766 acres per year per million acres protected; i.e., there is a 99 percent probability that the acres burned in any one year will be less than 7,766 acres or, alternatively, a 1 percent probability that the acres burned in any one year will be greater

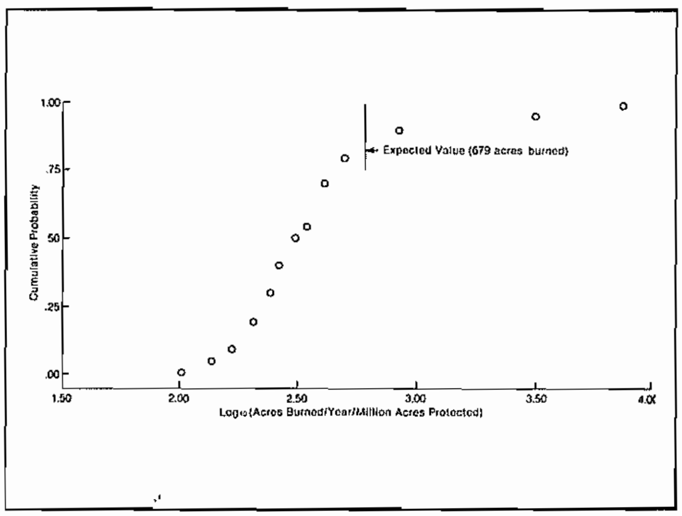

Figure 15—Cumulative probability distribution of acres burned in the Douglas-fir FMS to the base program options for both initial attack and fuel treatment (IA(H,3),FT(H,3)).

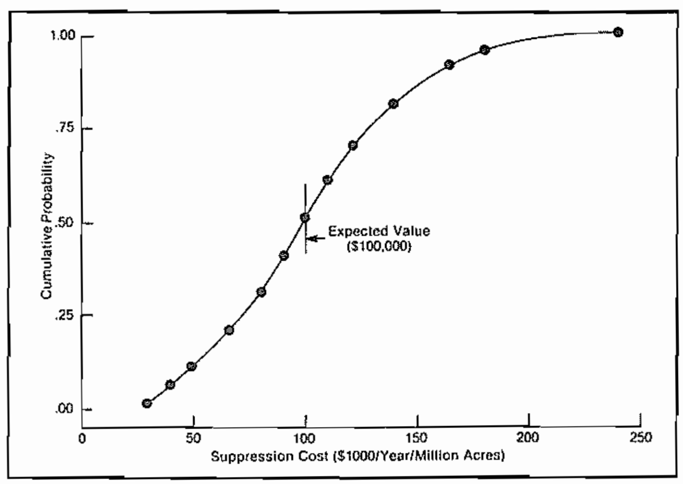

Figure 16—Cumulative probability distribution for the suppression cost in the Douglas-fir fire management situation for the base program options for both initial attack and fuel treatment (IA(H,3),FT(H,3)).

than 7,766 acres. The ratios of percentile values to the expected value are 0.21 (5th percentile) and 11.43 (99th percentile). That is, there is a 1 percent probability that the acres burned in any one year will be more than 11 times greater than the expected value of 679 acres burned per million acres protected per year. The width between the 5th and 99th percentile points, expressed as a percentage of the expected value, is 1,123 percent for the base program option. For convenience, this measurement of distribution width is referred to here as "risk percent."

The "tail-heavy" nature of the fire management system is apparent in the heavily skewed probability distribution of acres burned. The expected value acres burned lies between the 80th and 90th percentile points on the distribution. The few years with high numbers of acres burned have such high values that they even affect the expected value or mean acres burned across all years.

When the acres-burned distribution is translated into a suppression cost distribution, using the cost-per-acre-burned computations (expression 6), the resulting suppression cost probability distribution is much narrower and more symmetrical than the acres-burned distribution (*fig. 16*).

The ratios of percentile points on the suppression cost distribution to the expected value are 0.42 (5th percentile) and 2.27 (99th percentile). Stated differently, there is only a 1 percent probability that the suppression cost in any one year will be greater than 2.27 times as large as the expected value suppression cost, $100 thousand per million acres per year. The expected value lies close to the 55th percentile point on the suppression cost distribution.

These distributional differences occur for the same reason that expected value suppression cost increased less than did expected value acres burned when fire management program

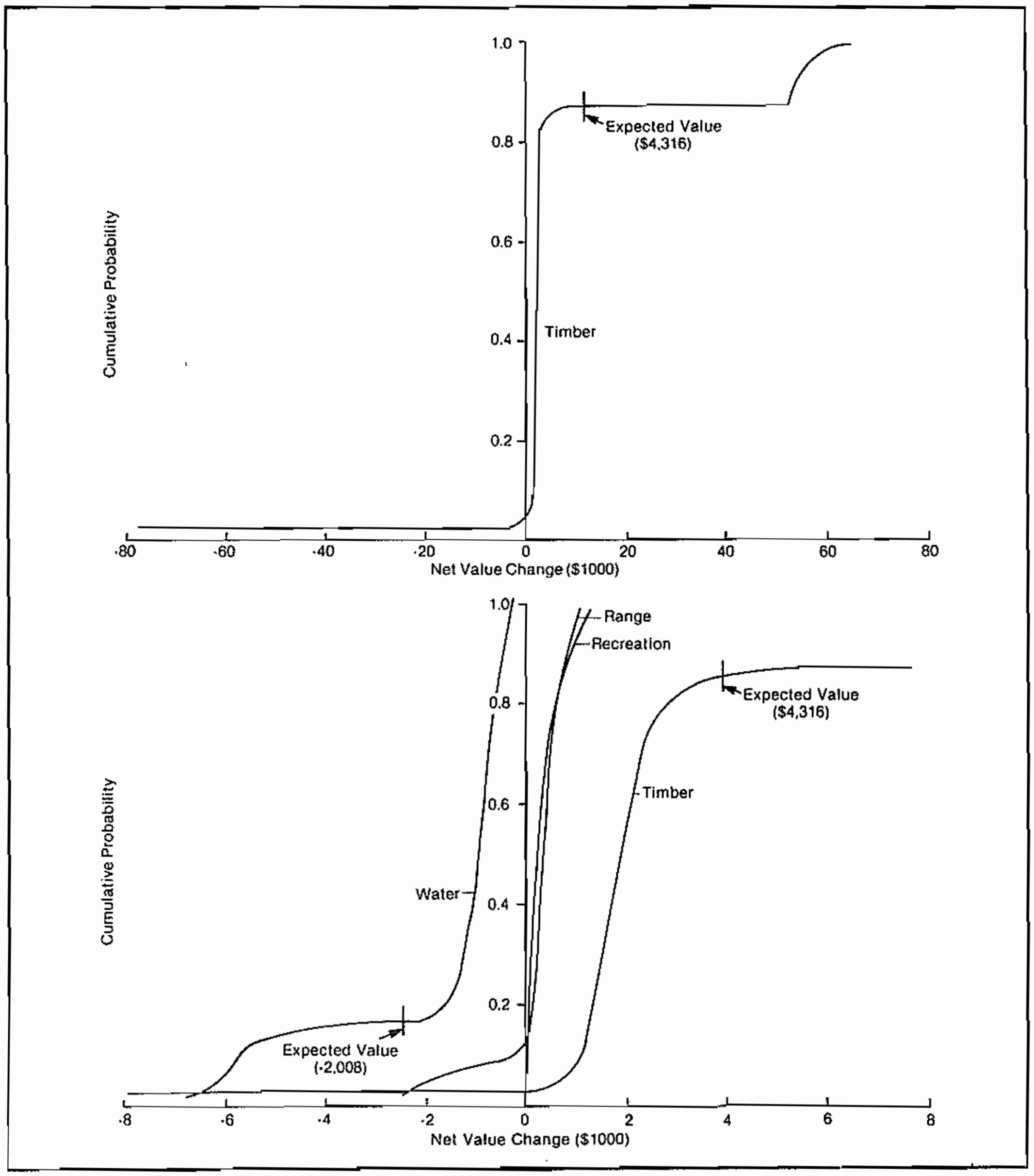

Figure 17—Cumulative probability distribution for the net value changes by resource in the Douglas-fir fire management situation for the base program options for both initial attack and fuel treatment (IA(H,3),FT(H,3)).

levels were reduced (*table 12*). The years with higher numbers of acres burned have a higher proportion of large fires, and suppression cost per acre for large fires is materially less than that for smaller fires (*table 5*). That economy-of-scale in suppression costs materially counterbalances the "tail-heavy" character of the acres-burned distribution.

The distributions of net value change for the separate resources are wide relative to their expected values, but the absolute width of the distributions of net value changes is generally so narrow as to be unimportant (*fig. 17*). The only exception to this observation is the timber net value change distribution, which is wide and skewed, just as was the acres-burned distribution. There is a 2 percent probability that the timber net value change for the Douglas-fir FMS is -$147 thousand, a net gain that exceeds the expected value suppression cost. There is also a 10 percent probability that the timber net value change is $54 thousand, a net loss that is one half as great as the expected value suppression cost and over 12 times larger than the expected value timber net-value-change. Even though the possible net gain is larger than the possible net loss, the 10 percent probability of a large loss outweighs the 2 percent probability of an even larger net gain. As a result, the expected value is a net gain that lies between the 80th and 90th percentile points on the distribution. However, the range in dollar values from the top to the bottom of the timber net-value-change probability distribution is still small relative to the total $764 thousand C+NVC.

The suppression cost and net value change distributions are the only sources of variation in the C+NVC. The presuppression program cost is a fixed input at any one program level. Since the net value change and suppression cost are relatively small percentages of the C+NVC at the expected value, 13 percent, the C+NVC distribution is also narrow relative to its expected value. The risk percent of the base program option, i.e., the 5th and 99th percentile distance expressed as a percentage of the expected value, is only 0.36 for C+NVC. The ratios of the percentile points on the C+NVC distribution to the expected value are 0.91 (5th percentile) and 1.26 (99th percentile). That is, there is only a 1 percent probability that the C+NVC in any one year will be more than 25 percent larger than the expected value.

This relatively narrow C+NVC distribution is a substantial contrast to the comparable acres-burned distribution where there is a 1 percent chance that the acres burned in any one year could be over 11 times greater than the expected value. The effect of the acres-burned variability is dampened substantially when acres burned is translated into its suppression cost and net value change contributions to C+NVC variability. Its effect is dampened for the same reason that suppression cost changed less within program level than acres burned did. The C+NVC distribution is also very symmetrical. The expected value falls between the 50th and 60th percentiles.

Initial Attack and Fuel Treatment Program Options

One of our hypotheses was that the C+NVC probability distribution would narrow with increasing program levels. We further hypothesized that the shape of the distribution would lead a risk-averse decisionmaker to select a higher program level than a risk-neutral decisionmaker. Probability distributions were developed from simulations of all initial attack program options, IA(H-A,1-5),FT(H,3), and all program levels of the historical fuel-treatment option, IA(H,3),FT(H,1-5), to test these hypotheses.

The acres-burned distribution was wide at the base program option, IA(H,3),FT(H,3), but it was similarly wide at the other program levels (*fig. 18*). The difference between the 5th and 99th percentiles expressed as a percent of the expected value acres burned declined with increasing program levels. The difference in acres burned between those percentiles, however, was the same at the lowest program level as it was at the highest program level tested, even though the expected value for acres

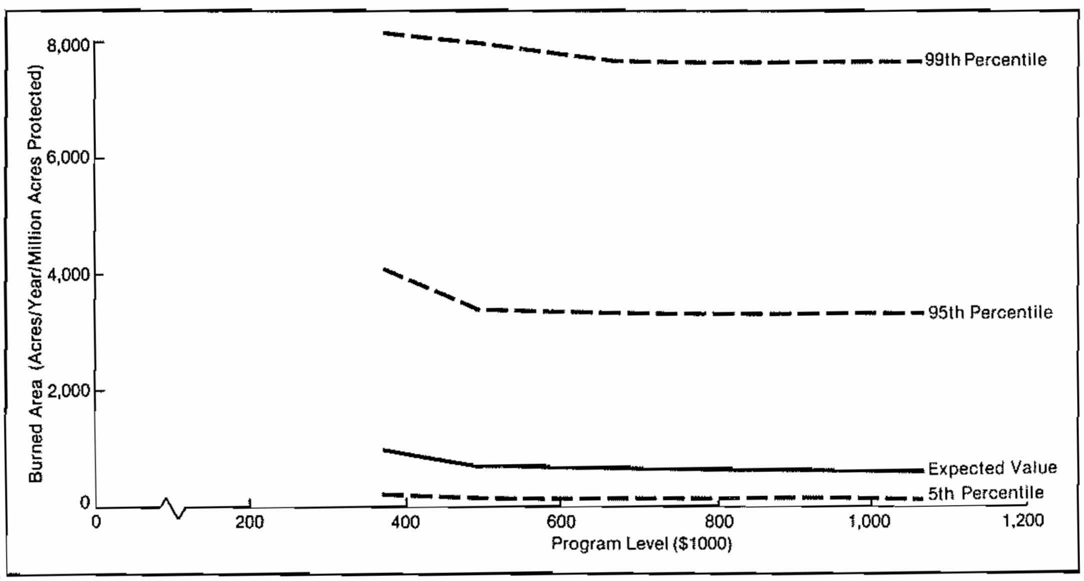

Figure 18—Probability envelope about the expect-ed value acres burned in the Douglas-fir fire management situation for the historical initial attack program option, while the fuel treatment was held at its base level (IA(H,1-5),(FT)H,3)).

burned declined as the program level increased. Therefore, increases in the funding of the initial attack program will not materially reduce the probability of large burned areas in individual years.

Unlike the acres-burned distribution, the width of the C+NVC probability distribution narrows with increasing initial attack program levels (*fig. 19, table 13*). The C+NVC narrowed with increasing program levels primarily because of the economies-of-scale for suppression costs on large fires. The C+NVC distribution can narrow then even if the acres-burned distribution does not. For example, the C+NVC risk percent dropped from 71 percent at the lowest initial attack program level tested (IA(H,1),FT(H,3)), to 22 percent at the highest program level tested, (IA(H,5),FT(H,3)). The absolute C+NVC dollar difference between the two percentiles also decreased over the same program level span from $347,000 to $248,000.

The width of the C+NVC distribution was also affected by the initial attack emphasis or fire management mix. The C+NVC probability distribution for the air emphasis was narrower than the distributions for the other two initial attack emphases at all program levels tested. Just as the air emphasis appeared to encounter diminishing returns at the lowest program level tested, though, the C+NVC distribution for the air emphasis widened more between the base-minus-50-percent and base-minus-75-percent program levels than did the other initial attack emphases.

These simulation results do not in themselves demonstrate how the tradeoff between risk and economic efficiency might affect the decisionmakers' selection of a fire management program option. Program selection is also affected by the decisionmakers' relative utility between efficiency and risk. Research has also demonstrated that the form in which the risk dimension is displayed can affect the decisions reached in other risk situations (Fishchoff and others 1980; Slovic and others 1982; Tversky and Kahneman 1981a,b).

The economic efficiency and risk tradeoffs are displayed here in two ways. Those two displays show that the fire management program selection may also be affected by how the C+NVC probability distributional information is presented.

The first display is typical of how risk has been viewed by fire managers. Concern over the tail-heavy nature of the fire system has often led fire managers to design fire management programs for above-average fire severity conditions. The Forest Service's 1972 fire management planning process, for example, was designed to build a fire management program capable of performing successfully against the 90th percentile burning index in the fourth worst year of the last 10 years. Similarly, the National Fire Danger Rating System is based on weather readings taken at midafternoon on exposed southwest slopes. Both of these representations describe more severe fire conditions than occur at the expected value. The hypothetical probability envelope about the C+NVC expected value (*fig. 4*) is a risk dimension display that is consistent with this traditional view of fire system risk.

Mirroring this traditional approach to fire system risk, Schweitzer and others (1982) estimated the C+NVC performance of four initial attack program levels in six National Forests against 3 historical years of varying fire severity. Although the simulated suppression costs and net value changes were higher in the more severe fire years, the most economically efficient program level was unaffected by fire-year severity in five of the six National Forests tested. The exception was the Willamette National Forest in western Oregon which has high-value, old-growth timber. The increased initial attack program expenditures did not lead to greater than offsetting reductions in suppression costs and net value changes even in the severe fire year. Except in that one Forest, then, it was not efficient to increase the initial attack program level even if there had been advance knowledge that a given fire year was to be more severe than average.

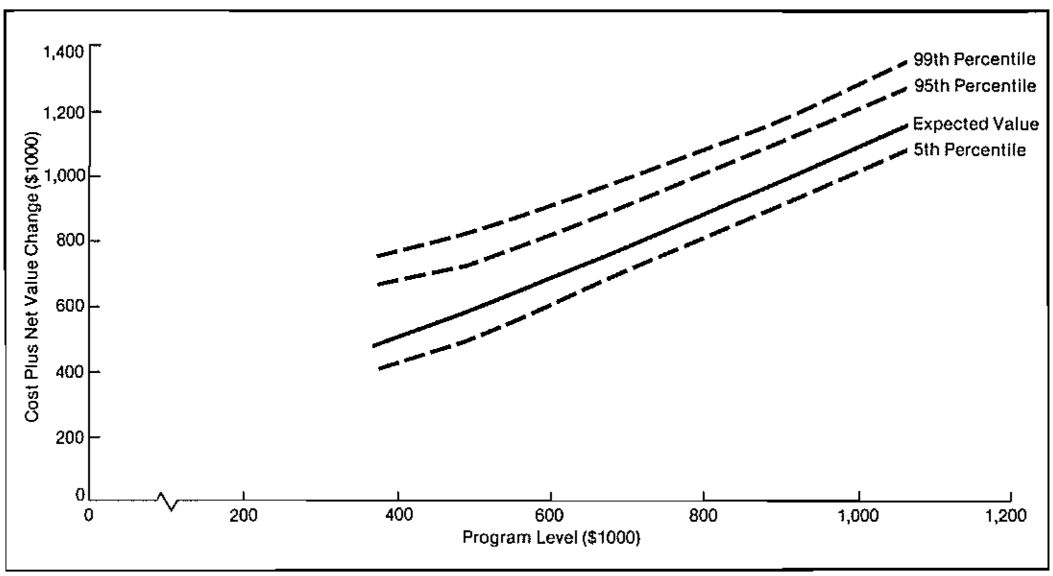

Figure 19—Probability envelope about the expected value C+NVC in the Douglas-fir fire management situation for the historical initial attack program option, while the fuel-treatment program was held at its base (IA(H,1-5),FT(H,3).

Our attempt to display the risk dimension in this traditional fire manager's view was to develop C+NVC curves for different points on the C+NVC probability distribution. If a fire manager is interested in planning a fire management program for the worst year in 20, the C+NVC curve that connects the 95th percentile points on the C+NVC probability distributions shows the C+NVC consequences of alternative program levels in that worst year. The program level that minimizes the C+NVC is the most efficient for that level of fire severity. Similarly, a manager interested in identifying the most efficient program level for the worst year in 10 would find the program level that minimizes C+NVC on the C+NVC curves that connect the 90th percentile points on the C+NVC probability distributions.

The probability envelope in *figure 19* shows the C+NVC curves for the 99th, 95th, and 5th percentile points on the C+NVC distribution for the historical initial attack emphasis, IA(H,1-5),FT(H,3). We found that the program level that minimized C+NVC was the same at the 99th and 95th percentile as it was at the expected value, similar to the results of Schweitzer and others (1982). Therefore, the program level that is most economically efficient at the expected value is also the most efficient in the worst year in 10 or 20 years. The program level that was most efficient at the expected value was also most efficient at any point on the C+NVC probability distribution *(table 13).* The same conclusion was reached for the air and ground emphasis of the initial attack program and across program levels in the historical fuel-treatment emphasis.

A second form of risk display that is more common in the general risk literature is a parameter preference model that compares the mean outcome of a program selection with the variance of that outcome (Blattenberger and others 1984). Program opportunities that have higher mean returns also often have higher variances about that mean return. By comparing the decisionmakers' utility for mean versus variance against the production possibility surface, the program option with the highest utility can be identified.

Our formulation of the parameter preference model in *figure 20* differs from the traditional parameter preference display in two minor ways. First, a lower mean C+NVC is more efficient than a high mean C+NVC. Second, the risk percent, i.e., the difference between the 5th and 99th percentile C+NVC as a percent of the expected value C+NVC, replaces variance as the measurement of variability. Perhaps more clearly than the C+NVC probability envelope in *figure 19, figure 20* shows that a more economically efficient fire management program can be gained only at the expense of greater variability in C+NVC outcome.

The potential consequences of this parameter preference display of risk dimension are clear from the hypothetical utility functions in *figure 20.* The risk-neutral decisionmaker, whose utility function is described by line AB, would select the program option with the lowest expected value C+NVC irrespective of the variability about the expected value. The risk-neutral decisionmaker would, therefore, select the air emphasis initial attack option funded at the base-minus-75-percent program level.

A hypothetical utility function for a risk-averse decisionmaker, line CD, shows that the decisionmaker will accept a program option of lower mean efficiency only if that option has less variability about the mean. A decisionmaker with this hypothetical utility function would select the air emphasis at the base-minus-50-percent program level. The air emphasis funded at the base minus 75 percent would be at a lower level of utility.

Sensitivity Analysis

Changes In Resource Management Objectives

What are the efficiency implications of applying the same fire management program options to private lands in the Climate Zone rather than to public lands? Is the most economically efficient fire management program level higher on the commodity-oriented private lands than on the relatively noncommodity-oriented public lands? Since timber net value is substantially affected by management objectives (Mills and Flowers 1983), even for the same fire severity and vegetation characteristics, the most economically efficient program levels could differ.

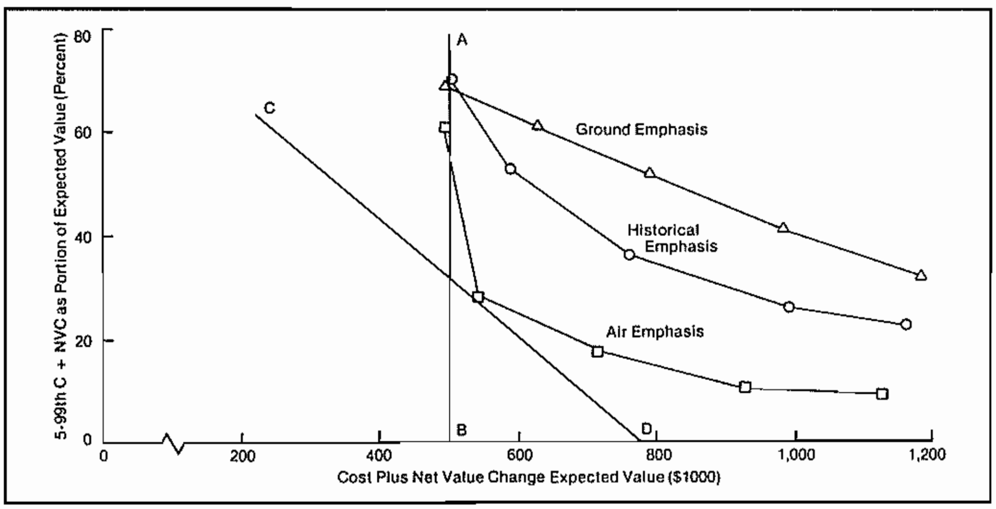

Figure 20—Parameter preference model for economic efficiency versus risk in the Douglas-fir fire management situation by initial attack fire management emphasis and program level (IA(H-4,1-5)), while holding the fuel-treatment program at its base level(FT(H,3)).

Table 13—*Cumulative probability distribution for C+NVC in thousands of 1978 dollars per million acres per year for the Douglas-fir fire management situation*

Program option[1]	C+NVC expected value	Cumulative probabilities *(percent)*											
		5	10	20	30	40	50	60	70	80	90	95	99
						Historical Initial Attack Emphasis							
IA(1)FT(3)	508	406	419	439	456	474	492	513	537	568	618	664	766
IA(2)FT(3)	602	514	524	541	556	571	587	605	626	654	698	740	832
IA(3)FT(3)	769	689	699	714	728	742	756	772	791	816	855	892	972
IA(4)FT(3)	1002	929	939	953	966	978	991	1006	1023	1045	1080	1113	1185
IA(5)FT(3)	1165	1092	1101	1116	1128	1141	1154	1168	1186	1208	1244	1277	1349
						Ground Forces Initial Attack Emphasis							
IA(1)FT(3)	503	405	417	436	453	470	487	507	531	561	610	655	755
IA(2)FT(3)	634	526	539	560	578	596	616	638	664	698	753	804	916
IA(3)FT(3)	798	688	701	721	740	759	779	801	829	865	922	977	1097
IA(4)FT(3)	989	882	894	913	931	950	969	992	1018	1054	1111	1166	1286
IA(5)FT(3)	1194	1094	1105	1123	1140	1157	1175	1196	1221	1254	1307	1358	1469
						Air Initial Attack Emphasis							
IA(1)FT(3)	501	410	423	442	458	473	489	506	527	553	594	632	713
IA(2)FT(3)	552	508	514	523	531	538	546	555	565	578	599	618	660
IA(3)FT(3)	715	679	684	691	697	703	709	717	725	736	754	770	806
IA(4)FT(3)	936	907	911	917	922	927	932	938	944	952	965	977	1002
IA(5)FT(3)	1134	1103	1107	1113	1118	1123	1129	1135	1142	1152	1167	1181	1211
						Historical Fuel Treatment Emphasis							
IA(3)FT(1)	643	563	573	589	602	616	630	646	665	690	729	766	846
IA(3)FT(2)	706	626	636	652	665	679	693	709	728	753	792	829	909
IA(3)FT(3)	769	689	699	714	728	742	756	772	791	816	855	892	972
IA(3)FT(4)	832	752	762	777	791	805	819	835	854	879	918	955	1035
IA(3)FT(5)	895	815	825	840	854	868	882	898	917	942	981	1018	1098
						Prescribed Burn Fuel Treatment Emphasis							
IA(3)FT(3)	769	689	699	714	728	742	756	772	791	816	855	892	972
						Equal Balance of Fuel Treatments (prescribed burn, mechanical pile and burn, hand pile and burn)							
IA(3)FT(3)	769	689	699	714	728	742	756	772	791	816	855	892	972

[1]Program funding levels correspond to those given in *table 12*, footnote 1.

The Douglas-fir FMS simulations for the five program levels of the historical fire management emphasis were rerun with net value changes representative of private management practices in the Climate Zone. All of the simulation inputs except the net value changes, such as the fire occurrence level and the large-fire size probabilities, were unchanged.

The timber net value changes for the intense private timber management objectives reported by Flowers and others (1984) were used in this sensitivity analysis. The private timber management regimes have rotation ages that approximated the maximization of present net value and planned harvest sizes that approximated practices in the area. The private rotation ages were therefore shorter than the public rotations. For example, the private management rotation age for existing Douglas-fir poletimber stands on moderate sites was 75 years. The comparable public management rotation age was 115 years. The planned harvest sizes were larger in the private management option. For example, the size of moderate site Douglas-fir clearcuts in the private management option was 100 acres versus 30 acres in the public management option. These differences reduce the advantage of fire-induced truncations of uneconomically long rotations and the fire-induced economies-of-scale in salvage harvests and postfire stand establishment costs. As a result, the private timber net value changes are greater losses than the comparable public timber net value changes, and there are few timber net value gains.

To better reflect a private resource management scenario, the range net value changes reported by Peterson and Flowers (1984) that correspond to higher intensity range use were used in place of the lower intensity range use levels. The intensity of recreational use was also reduced to reflect private land use levels more closely, leading to lower net value changes for

Table 14—*Expected value C+NVC results for the private management sensitivity analysis in the Douglas-fir fire management situation in 1978 dollars and acres burned per million acres protected per year at historical initial attack emphasis*

	Presuppression costs				Net value changes							
Program option[1]	Initial attack	Fuel treatment	Total[2]	Suppression cost	Timber	Range	Water	Sediment	Recrea-tion	Total	C+NVC total	Burned acres
IA(1)FT(3)	104,890	125,885	370,000	128,000	22,423	99	-3,237	0.01	209	19,494	518,000	970
IA(2)FT(3)	222,210	125,885	487,325	106,000	16,761	62	-2,444	0.0	158	14,537	609,000	740
IA(3)FT(3)	396,419	125,885	661,534	100,000	14,116	149	-2,008	0.0	134	12,391	774,000	679
IA(4)FT(3)	638,351	125,885	903,446	92,000	13,405	109	-1,886	0.0	125	11,753	1,007,000	625
IA(5)FT(3)	801,736	125,885	1,066,851	91,000	13,180	109	-1,865	0.0	124	11,548	1,170,000	623

[1]Program funding levels correspond to those given in *table 12*, footnote 1.
[2]Includes $86,190 for fire prevention and $53,040 for detection.

private recreation (Flowers and others 1984). The water yield and sediment yield net value changes were not adjusted.

The net value change at the base program level for the historical fire management emphasis, 1A(H,3),FT(H,3), of this private management analysis was $12.4 thousand, substantially higher than the $2.8 thousand when the public resource management objectives were used to calculate the net value changes (*table 14*). Essentially all of the difference was in the timber net value change. It was $14.1 thousand in the private management simulation and $4.3 thousand in the public management simulation.

The mean timber net value change in the private management analysis ($21 per acre burned) is over three times larger than the timber net value change under the public management formulation of the FMS ($6 per acre burned), but it still falls far short of the $493 per acre burned estimated by Schweitzer and others (1982) for the Deschutes National Forest. Even though the private timber regimes had rotation ages that approximate a maximum present net value, the present value of the foregone planned harvest was calculated by discounting the anticipated future revenue to the time of the stand age at the time of the fire. The computational form used by Schweitzer and others (1982), as well as the U.S. Department of Agriculture, Forest Service (1982), implicitly assumes that a fire in a "mature" timber stand occurs at the same age as the planned harvest.

Even with the simulated increase in net value change in the private management analysis, the total net value change still contributed only 1.6 percent of the total C+NVC. The suppression cost was the same with the private as with the public management option, 13 percent of the C+NVC.

As would be expected from the small C+NVC contribution from the net value changes, the relative economic efficiency of the various fire management program levels is the same with the private management objective as it was with the public resource management objective. The financial losses to fire were greater when the resource management was more heavily oriented toward commodity outputs, but the dollar value of the increased losses was not enough to justify higher fire management program levels on grounds of economic efficiency. The base-minus-75-percent level is still the most economically efficient of those tested using the historical fire management emphasis.

Changes in Prevention Program Effectiveness

The FEES model is not capable of directly evaluating prevention program effectiveness. Production functions that relate number of fire ignitions and dispersion of those ignitions among weather, terrain, and vegetation conditions to the funding and configuration of the prevention program are generally unavailable. Most prevention program analyses are based on subjective estimates of how fire occurrence rates are affected by changes in the prevention program, rather than on the results of mathematical simulations of the production relationships, such as in the initial attack module of FEES.

One way to approach such a subjective prevention analysis is to determine how much C+NVC changes in response to hypothetical changes in the fire occurrence rate. The change in C+NVC defines the break-even prevention program funding increment that can be spent to achieve that change in fire occurrence without affecting the net economic efficiency of the fire management program. For example, if C+NVC drops $10 thousand when fire ignitions are reduced 20 percent, any prevention program increment that can achieve the 20 percent reduction in ignitions for less than $10 thousand will be an economically efficient prevention program increment. That break-even estimate provides a much more structured arena within which prevention specialists could make subjective estimates of prevention effectiveness.

The prevention program sensitivity was analyzed while holding the initial attack and fuel-treatment program components at their base options, IA(H,3),FT(H,3).

The original expected value number of human-caused fires in the Douglas-fir fire management situation was 14.8 per million acres protected per year. Four sensitivity tests of the prevention program were described by the following percentage changes in the mean number of the human-caused fires:

Prevention sensitivity *(Percent change in human-caused fires)*	Human-caused fires *(Fires per million acres per year)*
Base minus 50 percent	7.4
Base minus 25 percent	11.1
Base plus 25 percent	18.5
Base plus 50 percent	22.5

The entire probability distribution of human-caused fires was shifted similarly to the mean. The relative frequency of fires among the IPC's was assumed constant at each of the four fire-occurrence levels, rather than changed to simulate a prevention program targeted toward the high-severity and high-loss fire locations. If the prevention program activities were targeted toward the IPC's that have the greatest losses per ignition, the impact of the various fire occurrence changes on C+NVC would be greater than estimated here. An alternative way to interpret these results is the sensitivity of C+NVC to errors in the fire occurrence input data or changes in fire occurrences caused by other than the prevention program, e.g., changes in population density.

The expected number of lightning-caused fires was held constant at 37.7 fires per million acres per year. This implicitly assumes that the prevention program does not affect the natural lightning process nor the ignitions that result from lightning strikes.

The impact of these prevention program sensitivity options on the expected value C+NVC was:

Prevention scenario *(Percent change in human-caused fire)*	C+NVC *(Thousand 1978 dollars)*	C+NVC change from base scenario *(Thousand 1978 dollars)*	*(Percent)*
Base minus 50 percent	735	-28	-3.7
Base minus 25 percent	750	-13	-1.7
Base	763		
Base plus 25 percent	780	+17	+2.2
Base plus 50 percent	796	+23	+4.3

If a 50 percent reduction in the number of human-caused fires can be accomplished by a $28 thousand increase in prevention program funding per million acres per year, then the efficiency of the overall program remains unchanged. If the increased prevention activity costs less than $28 thousand, the prevention program increment is economically efficient. If the increased prevention activity costs more than $28 thousand, the prevention increment is not efficient. The other prevention program scenarios are similarly interpreted.

The Fiscal Year 1979 funding for the prevention program on Forest Service land across the Climate Zone was $86 thousand per million acres per year (1978 dollars). The $28 thousand C+NVC increment represents a 33 percent increase from this 1979 prevention program funding level. Therefore, a 33 percent increase in funding must accomplish a 50 percent reduction in human-caused ignitions to be economically efficient. Conversely, if a reduction in prevention program funding from $86 thousand to $63 thousand (a 37 percent decline) would lead to an increase in fire occurrence of less than 50 percent, the prevention program would be more efficiently funded at $63 thousand per million acres per year.

Changes in Suppression Program Effectiveness

It was not possible to estimate the effectiveness of changes in the large-fire suppression component of the fire management program within FEES for the same reason that it was not possible to directly evaluate changes in the prevention program: production functions that relate changes in large-fire suppression activities to changes in acres burned are not generally available. It was possible to measure the sensitivity of C+NVC to hypothetical changes in the large-fire suppression effectiveness, however, and thus provide a convenient break-even benchmark against which expert estimates of large-fire suppression effectiveness can be compared.

The probability distribution of large fire sizes (1970-1981) and suppression cost per acre (1964-1974) (*table 5*) were derived from National Forest data in the Climate Zone. The relatively aggressive 10 a.m. fire suppression policy was in force during most of those years. It was generally expected that the 1978 revision of the fire suppression policy on Forest Service lands would lead to relatively less aggressive suppression. This could, in turn, lead to lower suppression costs per acre burned and to larger fire sizes. The historical large fire sizes and suppression costs per acre used here reflect no material impact from implementation of that policy.

Two large-fire sensitivity simulations were performed to show the possible consequences of hypothetical changes in the mean size of large fires and the suppression cost per acre burned. Both sensitivity analyses increase the mean size of escaped fires by 10 percent, from 1608 to 1769 acres. This was accomplished by similar percentage changes in the expected value fire size in each of the large-fire size classes in *table 5*, leading to the values in *table 15*.

The increased large fire size was combined in one sensitivity simulation with a reduction in the expected value large fire suppression cost per acre burned of approximately 15 percent, from $105 to $86 per acre burned. This suppression sensitivity was labeled the "lower cost savings" simulation. A "higher cost savings" option was defined by the same 10 percent increase in large fire sizes combined with a reduction in mean large fire suppression cost per acre of approximately 25 percent, from $105 to $76 per acre burned. The "higher cost savings" option implies that eventual size of escaped fires is relatively less affected by suppression actions than does the "low cost savings"

Table 15—*Large fire suppression sensitivity analysis input of conditional probabilities for large fire size classes given an escape, expected value acres-burned per fire, and suppression costs per acre (1978 dollars) for the Douglas-fir fire management situation*

Program option	Large fire size classes *(acres)*					
	100-300	300-1000	1000-3000	3000-10,000	10,000+	Mean
Base input:						
Conditional probability[1]	0.4997	0.2906	0.1249	0.0573	0.0276	—
Expected acres burned/fire	173	541	1,696	5,262	30,018	1,608
Suppression cost/acre	600	268	129	66	25	105
Lower cost savings:						
Conditional probability[1]	0.4997	0.2906	0.1249	0.0573	0.0276	—
Expected acres/fire	190	595	1,865	5,788	33,019	1,769
Suppression cost/acre	511	228	109	56	22	86
Higher cost savings:						
Conditional probability[1]	0.4997	0.2906	0.1249	0.0573	0.0276	—
Expected acres/fire	190	595	1,865	5,788	33,019	1,769
Suppression cost/acre	451	201	97	49	19	76

[1]The probability of the large fire size class is conditional on a fire escaping initial attack, i.e., exceeding 100 acres.

Table 16—*Expected value C+NVC results for the Douglas-fir fire management situation, in 1978 dollars and acres burned per million acres protected per year at historical initial attack emphasis resulting from hypothetical changes in large fire suppression effectiveness*

Program option	Presuppression costs			Suppression cost	Net value changes						C+NVC total	Burned acres
	Initial attack	Fuel treatment	Total[1]		Timber	Range	Water	Sediment	Recreation	Total		
Base input	396,419	125,885	661,534	100,000	4,316	167	-2,008	0.0	314	2,789	764,000	679
Lower cost savings	396,419	125,885	661,534	95,000	4,632	183	-2,200	0.00	344	2,959	759,000	742
Higher cost savings	396,419	125,885	661,534	87,000	4,632	183	-2,200	010	344	2,959	751,000	742

[1]Includes $86,190 for fire prevention and $53,040 for detection.

Table 17—*Mean historical number of fires and acres burned in the Douglas-fir, ponderosa pine, and fir-spruce fire management situations per million acres protected per year (1970-81)*

Fire management situation	Acres burned			Number of fires		
	Lightning	Person	Total	Lightning	Person	Total
	Acres burned/million acres/year			*Fires/million acres/year*		
Douglas-fir	255	387	642	38	15	53
Fir-spruce	107	305	412	35	16	51
Ponderosa pine	524	176	700	56	25	81

simulation. For example, the higher savings simulation implies that the eventual size of large fires is relatively more affected by natural factors, such as weather and fuels, than does the low cost savings simulation. Both sensitivity simulations were performed using the base program option, 1A(H,3),FT(H,3).

The lower savings simulation was more economically efficient (*table 16*) than the historical large-fire suppression effectiveness reflected in *table 5*. The net value change increase from $4.3 to $4.6 thousand was more than offset by a reduction in suppression cost from $100.0 thousand to $95.0 thousand. The sum of suppression cost and net value change is 5 percent lower, $98.0 thousand, in the lower savings simulation than in the historical suppression strategy, $102.8 thousand. The efficiency gains are even greater in the higher saving simulation.

Therefore, if a less aggressive large-fire suppression strategy that leads to a 10 percent increase in the mean size of large fires will result in at least a 15 percent reduction in large-fire suppression costs per acre burned, the change in strategy is economically efficient. Actually, the efficiency break-even point on necessary suppression cost savings is something less than 15 percent. Repeat simulations are required to locate the actual break-even point because there are two variables changing in the suppression sensitivity: mean large fire size and suppression cost per acre burned. Just as in the prevention sensitivity analysis, these large-fire sensitivity analysis results can be compared with expert estimates of large-fire suppression effectiveness to determine if those fire-size and cost-saving combinations are possible.

Ponderosa Pine and Fir-Spruce Fire Management Situations

The ponderosa pine and fir-spruce FMS's were evaluated to determine how much impact the vegetation, terrain, and management objective characteristics of an FMS had on the efficiency among the fire management program options tested. The two FMS's represent a substantially different fire situation from the Douglas-fir FMS in the Climate Zone.

The ponderosa pine FMS has a higher historical level of fire occurrence (81 fires per million acres protected per year) and acres burned (700 acres per million acres protected per year) than the Douglas-fir FMS (*table 17*). The greater fire system "severity" indicated by the historical ignitions and acres burned has the potential to affect the economic efficiency of the fire management program options, possibly leading to a higher economically efficient program level than in the Douglas-fir FMS.

There was a stronger relationship between simulated acres burned and fire management program level in the ponderosa pine FMS than there was in the Douglas-fir FMS. The simulated acres burned in the ponderosa pine FMS increased 55 percent or 528 acres between the base and the base-minus-75-percent program levels, from 952 to 1,480 acres burned per year per million acres protected (*table 18*). The simulated acres burned in the Douglas-fir FMS increased 43 percent or 291 acres, from 679 to 970 acres burned, over the same program level increment. The economies-of-scale to suppression costs, however, affected the impact of this increased acreage burned in the ponderosa pine FMS just as it had in the Douglas-fir FMS. As a result, the suppression cost increased proportionally less than did the acres burned in the ponderosa pine FMS.

Perhaps the greatest difference between the ponderosa pine and Douglas-fir FMS's was in timber net value change. The overall timber net value change in the Douglas-fir FMS was small, but it was a net loss. The overall expected value timber net-value-change in the ponderosa pine FMS was a net gain, which was over twice as large as the expected value loss in the Douglas-fir FMS.

National Forest inventory data were used in the timber net value change calculations for the individual fire situations. The ponderosa pine stands in the inventory, especially the sawtimber and poletimber stands, have a stocking that is only marginally above the acceptable retainable stand stocking level. As a result, even a moderate mortality fire leads to nonretention of the postfire stand. This, in turn, leads to a potential salvage harvest and stand reestablishment, with the associated efficiencies that result from truncation of an uneconomically long rotation and economies-of-scale in the stand establishment and salvage harvest if the fire is larger than the planned harvest. When the net value gains in those individual fire situations are combined with the relatively high fire occurrence rate in Douglas-fir and ponderosa pine poletimber and sawtimber stands in the ponderosa pine FMS, the result is a net gain in the fire-induced present net value of the timber stands in the FMS.

The net timber gain leads, in turn, to a total net value gain when all of the resource output categories are added together. The effect of a net value gain on fire management program efficiency is predictable. The most efficient program level is the lowest program level tested, base minus 75 percent.

The ground emphasis of the initial attack program simulated more acres burned (1,321 acres) at the base program level than the historical emphasis (952 acres). The air emphasis simulated fewer acres burned (371 acres). This is the same relative impact of fire management emphasis on acres burned that was found in the Douglas-fir FMS, but here the acres-burned differential between the fire management emphases is even greater. The more rapid initial attack arrival times accomplished by the air attack forces were even more important in the higher rate-of-spread fuels that are more predominant in the ponderosa pine FMS.

Once again, however, sizable differences in acres burned do not affect the economic efficiency outcome. The base-minus-75-percent program level is still the most efficient in the ponderosa pine FMS, irrespective of the fire management emphasis.

The fir-spruce FMS is representative of higher-elevation, cooler, moist sites in the Climate Zone than are typical of the Douglas-fir FMS. That difference is reflected in the smallest historical acres burned, 412 acres per year per million acres protected, of the three tested FMS's (*table 17*). In spite of this indication of a correspondingly lower fire system severity in the fir-spruce FMS, the efficiency results from the fir-spruce FMS (*table 19*) were very similar to the results for the Douglas-fir FMS (*table 12*).

Table 18—*Expected value C+NVC results for the ponderosa pine fire management situation, in 1978 dollars and acres burned per million acres protected per year*

Program option[1]	Presuppression costs			Suppression cost	Net value changes						C+NVC total	Burned acres
	Initial attack	Fuel treatment	Total[2]		Timber	Range	Water	Sediment	Recreation	Total		
					(Historical Initial Attack Emphasis)							
IA(1)FT(3)	104,890	125,885	370,005	127,000	-11,504	-179	-6265	0.0	1,224	-16,724	480,000	
IA(2)FT(3)	222,210	125,885	487,325	114,000	-12,020	-151	-4909	0.0	965	-16,115	585,000	1,201
IA(3)FT(3)	396,419	125,885	661,534	97,000	-10,133	-78	-3537	0.0	706	-13,042	745,000	952
IA(4)FT(3)	638,351	125,885	903,466	87,000	-8,965	-89	-3137	0.0	628	-11,563	978,000	858
IA(5)FT(3)	801,736	125,885	1,066,851	88,000	-10,547	-94	-3100	0.0	625	-13,116	1,141,000	874
					(Ground Forces Initial Attack Emphasis)							
IA(1)FT(3)	107,632	125,885	372,747	121,000	-12,062	-258	-6,451	0.0	1,261	-17,510	479,000	1,506
IA(2)FT(3)	229,815	125,885	494,930	130,000	-12,187	-166	-5,853	0.0	1,153	-17,053	598,000	1,441
IA(3)FT(3)	394,962	125,885	660,077	129,000	-9,554	-111	-5,628	0.0	1,099	-14,194	758,000	1,321
IA(4)FT(3)	591,594	125,885	856,709	123,000	-9,664	-98	-5,288	0.0	1,034	-14,016	950,000	1,253
IA(5)FT(3)	804,858	125,885	1,069,973	115,000	-11,361	-119	-5,657	0.0	1,102	-16,035	1,161,000	1,303
					(Air Initial Attack Emphasis)							
IA(1)FT(3)	101,601	125,885	366,716	135,000	-4,082	-114	-4,627	0.0	902	-7,921	494,000	1,086
IA(2)FT(3)	225,997	125,885	491,112	66,000	-1,485	-25	-2,022	0.0	388	-3,144	554,000	453
IA(3)FT(3)	400,883	125,885	665,998	55,000	-1,094	-23	-1,598	0.0	309	-2,406	719,000	310
IA(5)FT(3)	826,648	125,885	1,091,763	47,000	-658	-18	-1,378	0.0	264	-1,790	1,137,000	305
					(Historical Fuel Treatment Emphasis)							
IA(3)FT(1)	396,419	[3]0	535,649	97,000	-10,133	-78	-3,537	0.0	706	-13,042	620,000	954
IA(3)FT(2)	396,419	62,988	598,637	97,000	-10,133	-78	-3,537	0.0	706	-13,042	683,000	952
IA(3)FT(3)	396,419	125,885	661,534	97,000	-10,133	-78	-3,537	0.0	706	-13,042	745,000	952
IA(3)FT(4)	396,419	188,827	724,476	97,000	-10,133	-78	-3,537	0.0	706	-13,042	808,000	952
IA(3)FT(5)	396,419	251,854	787,503	97,000	-10,133	-78	-3,537	0.0	706	-13,042	871,000	955
					Prescribed Burn Fuel Treatment Emphasis							
IA(3)FT(3)	396,419	125,894	661,543	97,000	-10,133	-78	-3,537	0.0	706	-13,042	746,000	952
				Equal Balance of Fuel Treatments (prescribed burn, mechanical pile and burn, hand pile and burn)								
IA(3)FT(3)	396,419	126,018	661,667	97,000	-10,133	-78	-3,537	0.0	706	-13,042	746,000	952

[1]Program funding levels correspond to those given in *table 12*, footnote 1.
[2]Includes $86,190 for fire prevention and $53,040 for detection.
[3]Program options include no fuel treatments for hazard reduction.

Table 19—*Expected value C+NVC results for the fir-spruce fire management situation, at historical initial attack emphasis, in 1978 dollars and acres burned per million acres per year*

Program option[1]	Presuppression costs			Suppression cost	Net value changes						C+NVC total	Burned acres
	Initial attack	Fuel treatment	Total[2]		Timber	Range	Water	Sediment	Recreation	Total		
IA(1)FT(3)	104,890	125,885	370,005	127,000	4,866	246	-2,032	0.0	454	4,534	500,539	747
IA(2)FT(3)	222,210	125,885	487,325	103,000	3,529	199	-2,629	0.0	319	2,629	592,954	542
IA(3)FT(3)	396,419	125,885	661,534	97,000	3,150	299	-2,356	0.0	303	2,356	760,890	544
IA(4)FT(3)	638,351	125,885	903,466	91,000	3,256	196	-2,435	0.0	277	2,435	996,901	515
IA(5)FT(3)	801,736	125,885	1,066,851	90,000	3,259	193	-2,424	0.0	300	2,424	1,159,275	5,179

[1]Program funding levels correspond to those given in *table 12*, footnote 1.
[2]Includes $86,190 for fire prevention and $53,040 for detection.

Table 20—*Changes in expected value C+NVC that result from incremental changes from base initial attack program level for the Douglas-fir, ponderosa pine, and fir-spruce fire management situations, in 1978 dollars per million acres protected per year*[1]

Program option[2]	Program level	Program level increment	C+NVC change per dollar program level increment from base program		
			Douglas-fir	Ponderosa pine	Fir-spruce
	($/million acres/year)				
IA(H,1)FT(H,3)	370,005				
		117,320	-0.80	-0.89	-0.79
IA(H,2)FT(H,3)	487,352				
		174,209	-.97	-.92	-.96
IA(H,3)FT(H,3)	661,534				
		241,932	+.97	+.96	+.98
IA(H,4)FT(H,3)	903,466				
		163,385	+.99	+1.00	+.99
IA(H,5)FT(H,3)	1,066,851				

[1]Program level changes and C+NVC results are for the historical initial attack emphasis and the base-level fuel treatment program options, IA(H,1-5),FT(H,3).
[2]Program funding level corresponds to those given in *table 12*, footnote 1.

The timber net value change was somewhat lower than in the Douglas-fir FMS, but it was not a net gain as it was in the ponderosa pine FMS. The expected value of suppression costs were somewhat lower, consistent with the lower number of acres burned, but suppression cost responded to changes in program level changes in the same manner as it had in the Douglas-fir FMS. The base minus 75 percent was the most economically efficient fire management program level of those tested, just as it was in the other two FMS's. Simulations for the ground and air emphases were not performed for the fir-spruce FMS because the historical emphasis initial attack results were similar to the Douglas-fir results.

The similarity in the expected value economic efficiency results among the three FMS's was surprising. The differences in fire behavior and net value change among the individual IPC's were substantial, but apparently the probabilities of fire occurrence between the different IPC's among the FMS's were similar enough to generate similar efficiency results. The terrain, vegetation, fire occurrence, fire behavior, and acreage-burned differences between the FMS's are usually used to differentiate areas into different fire severity classes, with corresponding differences in fire management program funding.

The C+NVC estimates from the three FMS's provide an opportunity to demonstrate how a constrained budget could be allocated among competing areas if the objective is to maximize the economic efficiency of the combined fire management budget. The difference in C+NVC between program levels equals the change in the present net worth of the fire management program (Mills 1979). Since the program level increments tested here are not of equal dollar intervals, the change in C+NVC between program levels must be expressed in terms of change in C+NVC per dollar of program level change to standardize for scale differences.

The changes in C+NVC from the base program level for the historical initial attack emphasis are shown in *table 20* for the three FMS's tested. The base program level of the historical fire management emphasis is not the most economically efficient of those tested. Therefore, if the original budget was set at the base level, the first increment of reduced funding would be allocated to the FMS with the greatest reduction in C+NVC. That allocation achieves the greatest increase in economic efficiency of the combined fire management program across all of the FMS's.

Using these three fire management situations as an example, the first $174,209 of reduction would be allocated to the Douglas-fir FMS. The combined present net value of the fire management program would increase $168,983. The next $174,209 of reduction would be allocated to the fir-spruce FMS, since that increment has the next largest change in C+NVC per dollar of program level increment from among those increments that can be selected. The program level in any one FMS could not be dropped to base minus 75 percent until it was first dropped to base minus 50 percent in that FMS, even if the base-minus-75-percent increment achieved a greater reduction in C+NVC. Conversely, if the starting program level was the most economically efficient of those tested, the first $117,320 of increased funding would be allocated to the fir-spruce FMS because that would reduce the combined economic efficiency by the least amount.

While illustrative, the actual differences in the incremental C+NVC's among the FMS's tested here are small. Decision parameters other than efficiency impacts would, therefore, probably weigh heavily in the allocation of budget increments.

DISCUSSION

There are several problems with any current model of the fire system performance. Some problems result from sparse data, and some are caused by the lack of important behavioral relationships. Sensitivity analyses help place these problems in perspective. We think that these simulation results are robust enough to yield economic efficiency and risk information sufficient to test our hypotheses in the Northern Rocky Mountain and Northern Intermountain Fire Climate Zone.

To permit the reader to more fully appreciate these modeling problems and to help other people avoid some of them in the future, we discuss the major problems and our solutions below. We then discuss the tests of the hypotheses that were proposed at the beginning of the paper.

Modeling Problems and Solutions

Two types of modeling problems were encountered in developing the FEES representation of the fire system. Some problems anticipated during model development were later revealed to be manageable or of minor consequence, an outcome that was difficult to foresee in the complex and interactive fire system. Other problems were eventually managed with only marginal success because of shortcomings in state-of-the-art system components. Many of the problems in this second group could be the focus of productive future research.

Problems That Were Easy To Solve

An example of an anticipated but manageable problem is the development of the probability distribution for fire size at the time of detection. The detection size input was difficult to develop because data on size at detection were sparse. The only substantial empirical data set was over 10 years old. The sensitivity analysis reported by Salazar and Mills (1984), however, demonstrated that considerable shifts could be made in the detection size distribution with almost no impact on the initial attack results. The detection size input should be described as a distribution, as opposed to a point estimate, and the probability of the large size-at-detection classes must be developed with care. At least for evaluations of initial attack program options, however, the remainder of the detection size distribution apparently can be satisfactorily developed from available data.

The recreation net value change is another example of the first type of problem. Considerable effort was devoted to tailoring a contingent market valuation method study of fire's impact on recreation. The resulting recreation net value changes were so small that they were of little importance to the economic efficiency of the fire management program.

Initial attack arrival time input into the initial attack module is yet another example of an item that proved to be less troublesome than originally expected. Sensitivity analysis demonstrated that changes in arrival times within the expected range of variation had relatively minor impact on initial attack module output (Smith 1984). If model results were more sensitive to arrival time, it would have been necessary to make the entire model design more site-specific and to stratify the arrival time data by additional parameters, such as elevation and time-of-year.

The estimation of timber net value changes is another example of the first type of problem, but one that required more effort to overcome. Development of the timber net value change computation and collation of the diverse input data were difficult. Timber net value change also had the potential to materially affect the fire management program efficiency results because of the magnitude of the net value change for individual fire situations. The only major question remaining in the timber net value change calculations, however, is a philosophical one: Should the management objective or policy implied in measuring fire effects on the "fire site only" or the "entire management unit" be used in fire management program planning?

Development of the economic cost estimates is another example of a problem. Substantial effort was required to develop the estimates of hourly costs for initial attack inputs, mopup costs, and fuel-treatment costs. Because the costs required for an economic efficiency analysis are not typically computed in accounting systems, considerable collection of original data was required. As with the timber net value changes, the cost estimates had the potential to materially affect the calculated fire program efficiency. The methods developed to derive the cost estimates, however, were fully satisfactory.

Problems That Were Difficult To Solve

Modeling problems in the second group were largely overcome, but some elements of the problems persisted.

Developing Fire Behavior Distributions—There were particular difficulties with developing fire behavior distributions for the full population of fire ignitions, the initial attack dispatching process, the fire occurrence probability distributions, and full model validation. In terms of responsiveness of the fire system to variations in the initial attack program, fires can be categorized into three groups (*fig. 21*)—(A) those that can be suppressed by even a minimal initial attack force, (B) those that are beyond the capabilities of even a large initial attack force, and (C) those that are in a rate-of-spread range in which their containment during initial attack is a function of the size and composition of the initial attack program. Only the portion of the fire population in group C is relevant to evaluations of initial attack effectiveness.

Considerable effort was spent in developing input data to the Rothermel fire behavior model, such as probabilistic weather input and ratios for mixing the stylized Northern Forest Fire Laboratory fuel models. Even when the fire behavior distributions from the Rothermel model were tempered with the addition of nonspreading fires, the simulated percentage of escaped fires was higher than it has been historically. This was true especially for lightning-caused fires. It was necessary, therefore, to calibrate the fire behavior distribution in two places, once through shifts in the Climate Zone's probability distributions for spreading fires and once through adjustment of the simulated percent escape in each FMS. The historical percentage of escaped fires by cause was the calibration target. The calibration adjustments and the percentage of nonspreading fires were greater for lightning-caused than for human-caused fires, indicating that the fire behavior distributions for the two causes are different.

There are at least three ways to adjust the fire behavior input and to calibrate fire behavior. All three calibration methods yield fire behavior distributions that simulate percentages of escaped fires that match percentages of historical fires when the initial attack model is run with historical initial attack program levels and program emphases. There is strong reason to believe, however, that the three calibration methods will materially affect the proportion of escaped fires in group C and, therefore, produce far different degrees of sensitivity to changes in the initial attack program level. Bias in the percentage of escaped fires will lead to bias in the suppression cost and net value change estimates which, in turn, will bias the estimate of the most efficient initial attack program level.

One calibration method merges the distribution of spreading Rothermel fires from the fire behavior model with nonspreading fires and then adjusts the percentage of nonspreading fires in the distribution to accomplish calibration. We tried this calibration method but found that the percentage of fires that were nonspreading had to be raised from the historical percentages shown in *table 2* to 97 percent before calibration could be achieved. The percentage of nonspreading fire had to be raised that high because of the relatively large percentage of the uncalibrated spreading fires from the Rothermel model that are in group B. The consequence of this calibration method is to reduce the number of fires in group C to a low percentage—to probably a far smaller number than occurs in reality. The end result of this calibration method would be to underestimate the responsiveness of the percent of fires that escaped to changes in the initial attack program, and through that the suppression cost and net value change. That lack of responsiveness would, in turn, bias the C+NVC minimum toward a lower presuppression program level.

A second calibration method ignores the presence of nonspreading fires and instead assumes that the entire population of fires is represented by the Rothermel fire behavior distribution for spreading fires (U.S. Dep. Agric., Forest Service 1982). Calibration is then accomplished by shifting the spreading fire distribution toward less severe fire behavior. This method may underestimate the percentage of fires in group B by producing a considerable downward shift of the high-spread-rate portion of the distribution. Of more importance, this calibration method will probably lead to a much higher proportion of the fires in group C. The high percentage of historical fires that are essentially nonspreading (*table 2*) indicates the amount of overestimation that could result. Overestimating the number of fires in group C will result in overestimating the responsiveness of escape percent and, in turn, of suppression cost and net value change to presuppression program level changes. The net result is probably a corresponding bias in the C+NVC minimum toward a higher presuppression program level.

The calibration method used in this study is yet a third alternative. The final fire behavior distribution was a combination of the Rothermel spreading fires and the nonspreading fires. Calibration was accomplished by shifting only that subset of the fire behavior distribution represented by the spreading fires. This third approach is between the other two calibration alternatives in its effect on the percentage of fires in group C and, we feel, is less likely to yield biased results.

The primary objective behind the design of state-of-the-art fire behavior models was real-time fire behavior prediction of individual fires. They appear to perform quite well for those fires. Brown (1972) validated the rate-of-spread predictions from the fire behavior model in Douglas-fir and ponderosa pine by logging slash fuels on sample plots with zero slope under conditions of low wind and low fuel moisture. The fire behavior model predictions compared favorably with observed rates-of-spread for those spreading fires.

The design objective for existing fire behavior models was not unbiased estimation of the fire behavior probability distribution for the full population of fire ignitions. Yet the full population of ignitions is relevant in fire management calculations. Relatively minor adaptations of available fire behavior models did not prove wholly satisfactory. This is especially true when those fire behavior modeling problems are combined with errors and simplifications embodied in the individual fire reports, weather data, and initial attack containment model. Future research effort should be devoted to developing fire behavior distributions appropriate for the full population of fires for two reasons: (1) the lack of reliable empirical fire behavior data for the full population of fires leaves us unsure about how unbiased any calibrated fire behavior distribution might be, and (2) the form of the final fire behavior distribution has a material impact on the efficiency results. Since even advanced fire behavior models are likely to require some form of calibration, research on the implication of alternative calibration procedures is also needed.

Simulating Initial Attack Dispatching—Simulation of initial attack dispatching is another example of a very difficult modeling problem. Dispatching was initiated in FEES with historical data using the proportions of dispatch by type of fire management input. An alternative dispatching criterion might have been to dispatch the force with the shortest arrival time. Historical dispatching proportions were used instead because they

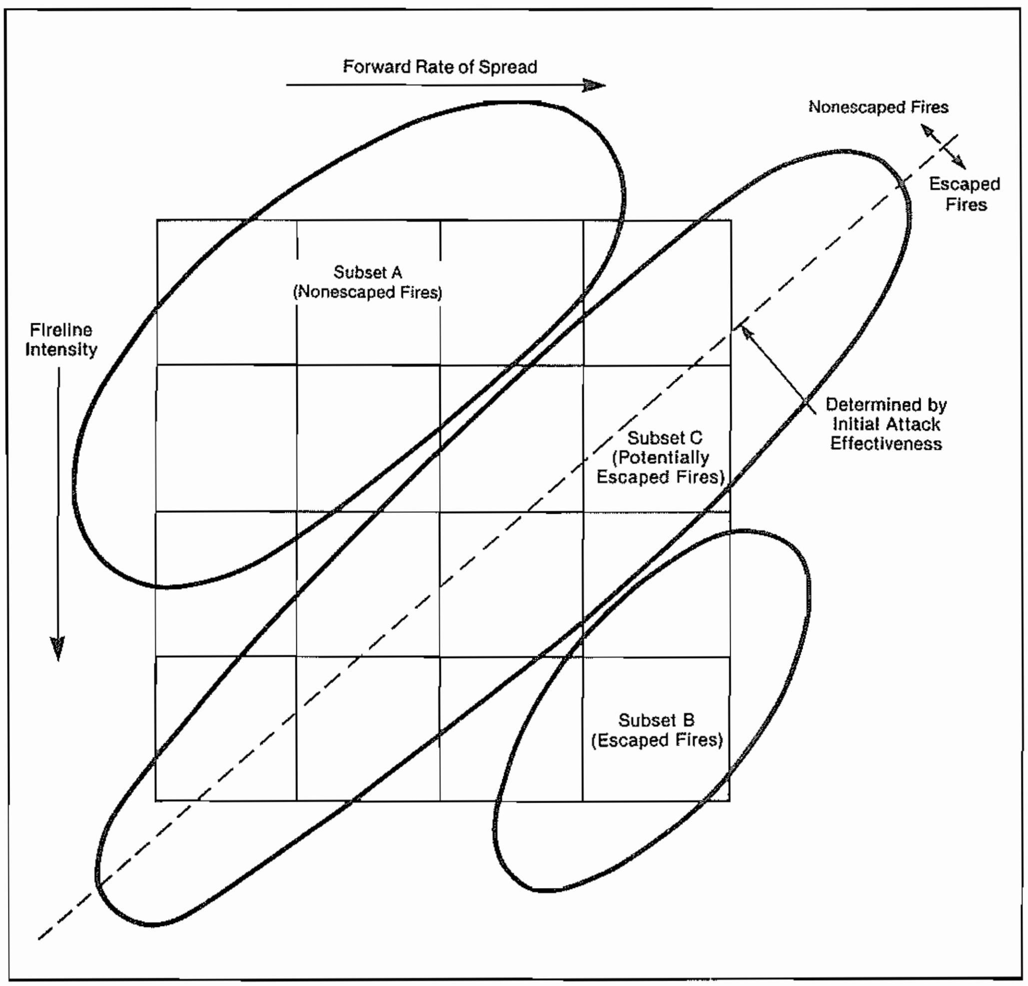

Figure 21—Hypothesized relationship between rate-of-spread and fireline intensity and the sensitivity of escape probability to the size and composition of the initial attack program.

consolidate diverse dispatching decisions into a simple model input that mirrors historical dispatching patterns.

Dispatching proportions and arrival times were adjusted as the amount and composition of the fire management input list was changed. The random number stream in the initial attack Monte Carlo simulator was standardized between fires to remove random variation between initial attack program options. In spite of these precautions, the percentage of escaped human-caused fires increased, rather than decreased, in a few instances when the initial attack program level was increased. Base minus 75 percent of the ground emphasis (*fig. 12*) is an example. The source of the problem may lie in the adjustments of the dispatch proportions or arrival times, or in the restrictions set by the rate-of-spread/rate-to-line construction criterion for terminating dispatch.

A related initial attack dispatching issue, dispatching under conditions of multiple fires, was handled by assumption. Arrival time data reported by Hunter (1981) showed that up to six simultaneous multiple fires had little effect on arrival times under initial attack program levels that existed in the study area in the 1970's. Therefore, all fires were assumed to occur one at a time in the initial attack model. The arrival times might deteriorate under multiple fire conditions at program levels as low as the base-minus-75-percent level tested here. If that is true, the simulated increase of the percent of escaped fires to major reductions in the initial attack program level was underestimated. Dispatching of initial attack inputs that are shared between FMS's is a similar issue. Although the arrival times were increased, as the share of the pool financed by the FMS dropped to reflect the wider spacing of the initial attack forces, all fires serviced by those pooled attack forces were assumed to occur independently. Both multiple fires and the sharing initial attack input should be reflected in the model through adjustments of the arrival time distributions and the proportions of input types dispatched.

Modeling Fire Occurrence Distributions—The highly stochastic character of fire occurrences also created a modeling problem. The 1970 to 1981 sample period from which fire occurrence data were drawn for this study is really only a sample of a high variable population of occurrences. Even for a sample period of this length, an upward trend in the number of human-caused fires was discovered in some of the data sets for individual National Forests (Bratten 1984a). A longer sample period would overlap major changes in the underlying structure of the fire occurrence system, caused by factors such as increased road access and timber harvesting. The dilemma is how to achieve a fire occurrence sample large enough to capture the full variation of fire occurrences while not overlapping major changes in the structure of the fire occurrence process.

This problem was addressed here by statistically fitting the fire occurrence data to a Weibull distribution to smooth the high occurrence tail of the frequency distribution where data were sparse. Fire occurrence data from all areas within the Climate Zone that were representative of each FMS were also pooled. The fire occurrence probabilities were derived from that pooled data rather than from the much more limited data set that would have been available for each individual area. Without this pooling of data into FMS sets, separation of the occurrence data into strata would have been infeasible. The fire behavior and fire effects in the fuel model, time-of-day, and slope class strata, for example, are too important to ignore. The fire occurrence sample size available from a site-specific approach would have been inadequate. While productive, these measures may still not capture the full variability of fire occurrence.

Validating the Model—Model validation is another modeling problem that is caused by the highly stochastic nature of the fire management system and its annual cycle. Empirical observations of the behavior of the full system can only be generated once a year. Wherever possible, input data were developed directly from empirical data. The fire occurrence frequencies, the large fire size classes, and costs per acre are examples. It was also possible to compare the simulated escape fire percents and simulated acres burned against historical data. The simulated escaped percents and acres burned are within the range of historical data. Similarly, the simulated relationship between the presuppression and suppression costs was consistent with the historically observed ratio. More detailed suppression cost validation was hampered by the lack of detailed historical cost data and changes in the Forest Service accounting procedures on the differentiation of firefighting time between presuppression and suppression cost charges. In the absence of empirical data, it was impossible to empirically validate the simulations of fire behavior, fire effects, and net value changes.

Perhaps more troublesome, there appears to be no good way to empirically validate the C+NVC and risk output of the model. There is no historical data on either the expected value C+NVC or its probability distribution against which the simulation output can be compared. Even if a particular fire management program option were implemented in a selected area and data were collected, the stochastic fire management system would simply yield one point estimate that would surely fall on the simulated probability distribution. Without repeated annual observations, however, there would be no way to estimate a historical probability distribution that could be compared to the simulated distribution or from which an expected value could be estimated. If data over a long enough time period of observation were collected, they would likely show that the underlying structure of the fire management system in the test area would have changed.

Hypothesis Test Results

First Hypothesis

Our first hypothesis was that economic efficiency in the fire management system is affected by both the funding level of the fire management program and the type of fire management inputs that are bought with the funds. Since different fire management program emphases have different production functions, the acres burned and resulting suppression costs and net value changes are likely to be affected by changes in both program funding and program emphasis. Those differences, in turn, would lead to differences in economic efficiency.

Simulated acres burned were quite sensitive to changes in initial attack program level and program emphasis. Major changes in the number of acres burned translated into much smaller changes in suppression cost and net value changes, however, primarily because of the economies-of-scale in both suppression cost and net value change with larger fire sizes. The suppression cost and net value change consequences of those acres-burned differentials were therefore relatively minor. When combined with the relatively small contribution of suppression cost and net value change to the total C+NVC, the C+NVC was almost exclusively controlled by the cost of the presuppression program itself.

The air emphasis of the initial attack program component consistently resulted in the lowest number of acres burned and was marginally the most efficient, but its margin of efficiency over the other initial attack emphases was small. When viewed as a vehicle for hazard reduction alone, differences in program level and emphasis of the fuel-treatment program had essentially no impact on the simulated acres burned or on the suppression cost and net value change. While the program level greatly affected economic efficiency, program emphasis did not. Therefore, these results only weakly support our hypothesis.

Second Hypothesis

Our second hypothesis was that risk, where risk is measured by the width of the probability distribution about the expected value C+NVC, would be less at high fire management program levels than at low levels. There is a wide distribution about the expected value acres burned, but the width of that distribution of the absolute acreage burned was essentially unaffected by substantial changes in program level. The C+NVC distribution did narrow with increasing initial attack program levels, but the reduction in risk was relatively minor.

The effect of program level on risk was minor primarily because the suppression cost and net value change were such a small portion of the total C+NVC. Suppression cost and net value change are the only contributors to C+NVC variation. While minor, the air emphases of the initial attack program did consistently have lower levels of risk than the historical or ground initial attack emphases just as they had marginally higher economic efficiency. The fuel-treatment program options had essentially no impact on the width of the C+NVC distribution. These results, therefore, only weakly support our second hypothesis.

We also hypothesized that the tail-heavy character of the fire system would yield an expected value C+NVC that lay close to the severe end of the C+NVC distribution; however, these results yielded a fairly symmetrical C+NVC distribution, which does not support our hypothesis.

Third Hypothesis

Our third hypothesis was that the relationship between efficiency and risk would lead the risk-averse decisionmaker to select a higher program level than a risk-neutral decisionmaker. The traditional fire management approach to risk is to select a fire management program that is most efficient at an above-average level of fire severity. Using that risk representation, the most efficient program level for the risk-averse decisionmaker is the same program level that is most efficient for the risk-neutral decisionmaker.

On the other hand, if risk is represented as it is in the general risk literature, as a parameter preference model for mean versus variance, these study results indicate that the risk-averse decisionmaker could select a higher program level than the risk-neutral decisionmaker. How much higher is a function of the shape of the utility function between risk and efficiency.

Implications of Hypothesis Tests

These results do have implications for the use of an economic efficiency justification for fire management programs on public lands in the Northern Rocky Mountains and Intermountain Fire Climate Zone that are typical of the FMS's tested here. These results lend very little economic efficiency justification for initial attack or fuel-treatment program levels that approach the base-level funding. The lowest program level tested for the initial attack program, base minus 75 percent or $0.10 per acre protected per year, and the lowest program level for the fuel treatment program, $0 funding, were consistently the most efficient program levels in all three FMS's. Results from the sensitivity analysis on resource management objectives indicates that the same conclusion is probably also true for the fire management program on private lands in the Climate Zone representative of the FMS's. Selection of a program level as high as the base-level funding must therefore be justified on decision criteria other than economic efficiency.

Return to a more natural fire regime has often been advocated for wilderness areas (e.g., Lotan and others 1983). The most economically efficient fire management program in this study is one that would provide the low level of fire control that might be readily accepted by environmental interest groups.

These risk results have an implication for the justification of fire management programs on public lands in the Climate Zone typical of the FMS's tested just as the economic efficiency results have. They give little risk justification for a high fire management program level.

Whether risk should even affect the program selection at all is also a point of debate. Arrow and Lind (1970) argued, for example, that public agencies should be risk-neutral because public risks are spread among a large number of events, i.e., the public can be self-insured because any one loss is small relative to the total public investment. Any one wildfire is small relative to the total public investment in natural resources in the study area. Unlike the potential catastrophic consequences of nuclear energy or chemical accidents, wildfires are natural ecological events that do not produce irreversible consequences.

The public's attitude toward risk is also important in determining whether the public decisionmaker should be averse to risk since, after all, it is the public's resources that are involved in the fire management decision. Recent studies have demonstrated that the public's attitude toward risk within the fire management system might be more tolerant than many managers have previously thought. Gardner and others (1985), for example, in a survey of 1,646 members of nine organized resource-oriented groups, such as the Soil Conservation Society of America and the Sierra Club, found that 58 percent of those interviewed favored the use of prescribed fire as a management tool even if an occasional fire would escape control. In a similar study of 1,200 adult residents of the Tucson metropolitan area, Cortner and others (1984) found that 72 percent approved the use of prescribed fire, even knowing that escapes were possible.

Concern for risk has entered debates about fire management policies and operating procedures for decades, but only recently has there been an ability to model risk consequences of program alternatives. Currently available models permit us to replace simplistic proxies for fire system risk, such as number of fires over 10 acres in size or extremes in total acres burned, with performance parameters, such as expected value economic efficiency and the probability distribution about that expected value, which integrate far more into one measurement. Risk analysis of the fire system requires probabilistic data inputs and probabilistic models, both of which are expensive. Until more is known about the risk character of alternative fire management programs, however, additional research should be directed toward understanding the risk response surfaces in the fire management system.

Just as the tradeoffs between risk and efficiency must eventually be integrated within the decision calculus by the decisionmaker, the results of this study must be carefully placed within three additional dimensions of the decisionmaking context for the fire management program.

First, neither the numerical input to our model nor the behavioral relationships within the model that manipulate the numerical input during the simulation are, nor ever could be, totally accurate. The complexity of the fire management system is too great to permit complete modeling accuracy. The sensitivity analyses presented here provide a partial indication of the consequences of data and model errors, but no sensitivity analysis can ever be fully successful in depicting the potential consequences of deficiencies in data and models.

Second, there is a true uncertain facet to fire system performance, using Knight's (1933) classic definition of uncertainty as an outcome to which no probability can be assigned. Fire occurrence levels and the size of large fires are examples. The simulation model input for these two factors was derived from historical data, but there is no certainty that the future levels of fire occurrence will not be higher or the large fires larger.

Third, our study was restricted to fire management program inputs and outputs that could be assigned dollar values. While we think that our measurements of fire consequences reflect the dollar-measured cash flow impacts on the fire site as clearly as possible, there are certainly other consequences of fire than cannot be assigned a dollar measurement. Potential fire impacts on threatened animal species and archeological sites are examples.

Just as the decisionmaker must integrate the risk and efficiency tradeoffs into the decision calculus, the decisionmaker is also responsible for incorporating these three additional dimensions. While the efficiency and risk results of this study help measure the opportunity cost of alternative integrations of these diverse factors, they in no way dictate an answer.

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Three hypotheses about fire system performance were formulated: (1) economic efficiency is affected by both the dollar amount of the fire management budget and the mix or emphasis of the fire management inputs purchased with the budget; (2) risk in the fire management system, where risk is measured by the probability distribution about the expected value economic efficiency, decreases with increasing fire management funding levels; and (3) the most efficient funding level for a risk-averse fire program manager is higher than for a risk-neutral manager. These hypotheses were tested on selected public lands in the Northern Rocky Mountains using the Fire Economics Evaluation System (FEES). Study findings show that efficiency is strongly affected by the fire management program level but relatively little by changes in the fire management mix or emphasis. The most economically efficient initial attack program level was the lowest from among those tested, 75 percent below the base level funding for the study period. When only hazard-reduction benefits are credited to fuel treatments, the zero program level was the most economically efficient. The level of risk does decrease with increasing program levels, but the decrease in risk is relatively minor. Whether there is justification for a higher program level for the risk-averse than the risk-neutral decisionmaker is a function of how the risk/efficiency tradeoff is displayed.

Retrieval Terms: cost plus net value change, fire behavior, fuel treatments, initial attack, fire suppression, fire effects, resource values, probability modeling, risk analysis