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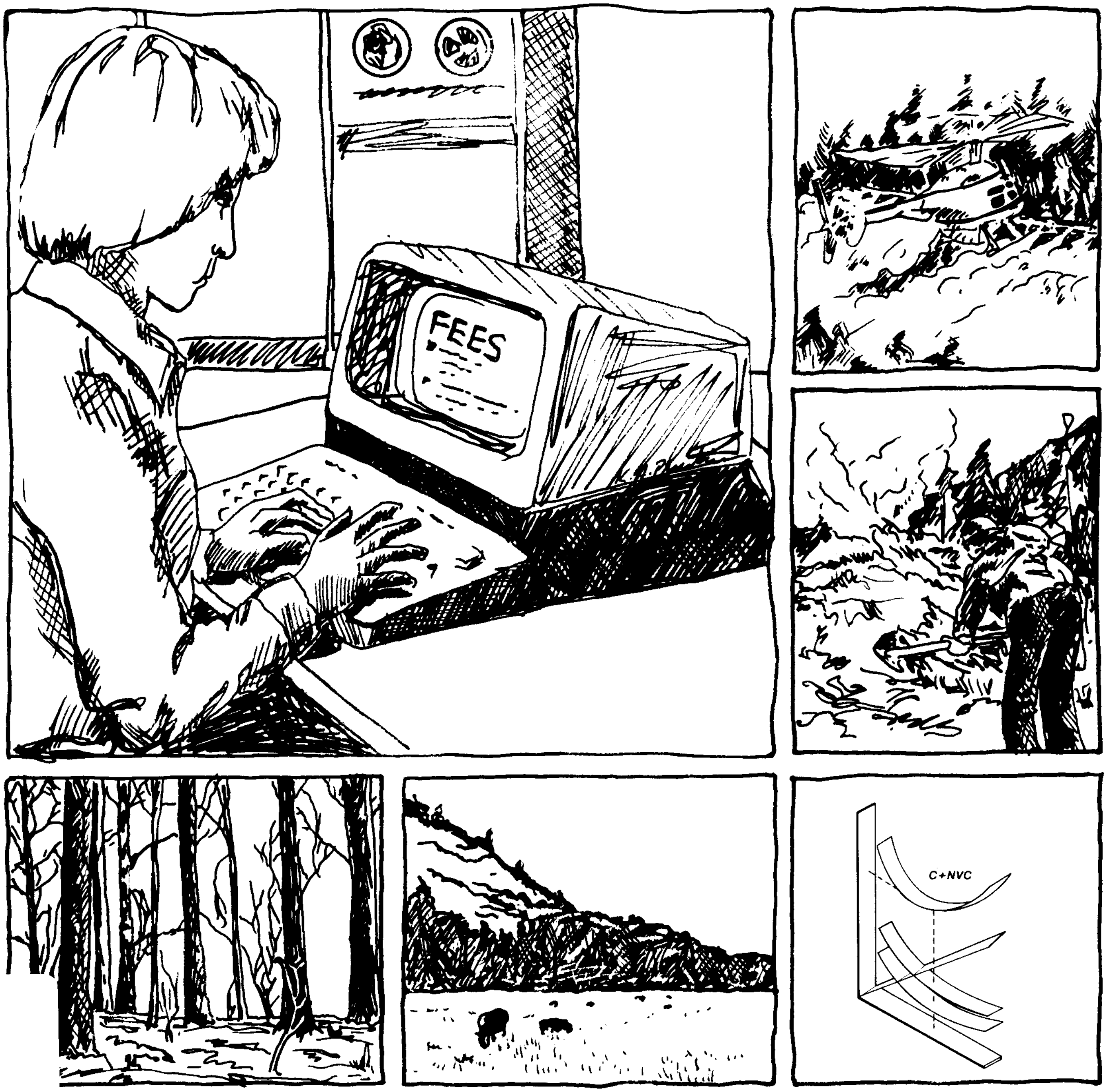
FEES: design of a *F*ire *E*conomics *E*valuation *S*ystem

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



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IN BRIEF...

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Currently available procedures for analyzing fire management program options are significant improvements over the analysis capability which existed a decade ago, and they provide important information for fire program planning. Major expansion and refinement of the existing capability is necessary, however, to cope with the persistent questions about public program efficiency.

In particular, a subregional-resolution analysis system is needed which can estimate the economic efficiency, fire-induced change in resource outputs, and risk consequences of a broad array of fire management program options. That subregional analysis would act as a screening step for subsequent high-resolution analyses which are more site- and time-specific. The high-resolution, and generally higher cost, analyses should be restricted to that narrow range of fire program options which show promise of high performance. As a minimum, the fire program options evaluated in the subregional analysis system should include alternatives with fuel treatment, initial attack, and large fire suppression program components. Each program option should be further defined by dollar program level, fire management mix or program emphasis, and large fire suppression strategy.

The *F*ire *E*conomics *E*valuation *S*ystem (FEES), the conceptual design of which is described in this report, can provide that subregional-resolution analysis of a broad range of fire program options. This simulation model is designed to evaluate situation-specific fire management situations or "kinds of areas" that have no site-specific delineation except that of regional fire climate zone. There is no reason to repeatedly apply a site-specific model to different areas if the characteristics of the area which influence fire program performance are essentially the same. The fire program option evaluated in FEES embodies all of the fire management inputs applied to the fire management situation rather than just those contributed by a single agency. The question of who should pay for the fire program cannot be logically answered until a total fire program option has been selected. FEES can be used by any public agency with wildland fire management responsibilities.

Development of an operational system that fulfills this conceptual design should proceed with a prototype version of the system applied to one area of the country, the Northern Rocky Mountain and Intermountain fire climate zone, for example. Once the prototype model has been subjected to extensive sensitivity analysis and validation tests, it should be applied to another study area, such as the Pacific Northwest fire climate zone. Different factors are important to fire program performance in different parts of the country. For example, timber losses are relatively more important in the Pacific Northwest, sharing of fire management inputs and multiple fires are relatively more important in southern California, and the many influences o complex terrain are relatively more important in the Northern Rocky Mountains. Even the first prototype version of FEES must recognize these differences so that subsequent expansion of model capability is easy to accomplish.

Once FEES is completed, it is proposed that the system be operated at a central location to produce a FEES guidebook of model output which can then be used directly by local fire program planners. Centralized operation of FEES would greatly reduce the training costs over the alternative of direct application of the FEES computer software by the fire program planner, and centralized operation would greatly increase the consistency of model results, thus enhancing the ability to make funding allocations on the basis of FEES results. Centralized processing is not synonymous with centralized decisionmaking. The relative weights among the decision criteria must still be assigned by a local decisionmaker who has an understanding of the ramifications of a fire program selection on the other management programs.

No simulation model is a substitute for a decisionmaker, and FEES is no exception. A decisionmaker must still weigh and assimilate a large number of relevant factors, many of which cannot be measured in common units or even be measured quantitatively at all, and must place the fire program within the context of other management programs and institutional constraints. FEES simply quantifies some of the factors which are relevant to fire management program planning and traces the interaction of relationships too complex and numerous for a person to easily follow. FEES is designed to show some of the costs of imposing institutional constraints. While many of those constraints are valid, their costs must always be considered.

FEES contains many of the parameters important in fire management program planning but others are left out; fire effects which cannot be measured in dollars, for example. It is essential that a decisionmaker, who is knowledgeable about the setting within which FEES results will be applied, fully understand these limitations of scope.

Wildfire is such an awesome and frightening natural phenomenon that funding for wildland fire management programs was relatively easy to obtain in the past. This was particularly true immediately after a severe fire season, when funding levels often rose quickly, only to erode away before the next severe fire season occurred. They were seldom scrutinized as closely as those of other land management programs.

This view of fire programs has progressively changed in the last decade, however, in response to the sheer size of fire program budgets, to greater appreciation of fire's natural role in the environment, and to recognition that fire management activities should be evaluated on the basis of their impact on resource outputs, just like any other land management activity. A symptom of the change was a request in 1975 by the U.S. Office of Management and Budget that the Forest Service, U.S. Department of Agriculture, estimate the real cost of its fire management program and identify the "best" fire management practices (U.S. Dep. Agric., Forest Serv. 1977). The best practices were to be identified through an evaluation of appropriate costs and returns.

Another symptom of change was the concern expressed by the U.S. Senate Appropriations Committee during review of the fiscal year 1979 budget request for the fire management program on National Forest lands. The Committee observed that "presuppression costs have risen dramatically in recent years, but the Committee is unable to discern any marked benefits stemming from these expenditures" (U.S. Senate 1978). The Committee requested that the Forest Service "conduct a cost-benefit analysis of both presuppression and suppression activities" as a basis of future budget requests. In simple terms, what benefits are being generated that justify the ever larger fire program funding levels?

Revisions in the land management planning process on National Forests, and their implications for fire management analyses, are other symptoms of the change. Regulations that implement the National Forest Management Act of 1976 require fully integrated analysis of all land management planning activities, formulation and evaluation of a range of feasible management alternatives, and selection of one alternative on the basis of explicit criteria (U. S. Dep. Agric., Forest Serv. 1979a, 1979b, 1982c). The fire program can no longer be evaluated in isolation from other land management programs.

The fire program on the National Forests is not the only fire program being scrutinized more closely. Funding for the Forest Service's Cooperative Forest Fire Program, which coordinates activities among the fire programs in the States, was reduced from $30.5 million in 1978 to $19.9 million by 1981 and is under continually closer scrutiny. Fire management programs are also being more closely studied by legislatures in many States--California and Oregon, for example.

In response to this changing attitude, the Forest Service made a major policy change in 1978 by requiring that the fire management program be cost-effective and become a part of integrated land management (Nelson 1979). The policy language was further refined in 1981 to state that economic efficiency and probability of success are important criteria for selecting among fire suppression actions (U.S. Dep. Agric., Forest Serv. 1981).

Economic efficiency case studies of the fire program options have been completed in progressively greater rigor (Oregon State Dep. of Forestry 1972; Schweitzer and others 1982; U.S. Dep. Agric., Forest Serv., 1980, 1982a; Winkworth and others 1981). Similarly, improved analysis procedures have been developed to implement policy changes (Calif. Dep. of Forestry 1979; U.S. Dep. Agric., Forest Serv. 1982a). Recent analysis procedures are great improvements over our past capability, and they provide valuable information for some fire program decisions. But important refinements in the fire program planning and evaluation capability are necessary.

Fire programs should not be viewed solely as a support function in the land management planning analysis even though protection of life and property is a goal of the program. Fire management activities influence resource outputs just as other land management activities do, and should be evaluated in the same manner, in terms of program cost increments compared to the changes they bring about in resource outputs. Fire suppression increases timber output above the unmanaged output level just as tree planting does. The fire program options should, therefore, be considered at the same time as other means of accomplishing land management objectives. The fire program *contributes* to the accomplishment of the land management objectives, it does not simply *support* other activities.

This paper identifies the information required for long-term fire program planning decisions and discusses its implications for design of a system to evaluate fire program options. On this basis, and recognizing recent advances in fire program analysis methodology, it describes the design of a particular *F*ire *E*conomics *E*valuation *S*ystem (FEES) capable of providing the required information. An improved operational system can be developed from this design. Fire program managers and economic analysts should also find the design useful in their attempts to interpret output from currently available fire management analysis models.

FIRE MANAGEMENT PROGRAM DECISIONMAKING

Information Requirements

Ideally, at least three types of analytical information should be developed for each fire management program option evaluated: dollar estimates of economic efficiency, quantitative estimates of effects on resource outputs, and assessments of the risk associated with these values. This information is especially relevant in the screening of fire program options early in the planning process.

Concerns about *economic efficiency* are apparent in the questions raised by the Office of Management and Budget and the Senate Appropriations Committee. These are the same cost-benefit questions that have long faced Federal water projects, questions addressed in the description of procedures for economic analysis by the Water Resources Council (1979). Economic efficiency is also a planning criterion in the National Forest Management Act regulations.

The minimization of the sum of fire program costs and the dollar value of net resource output changes which result from fire is a correct economic efficiency criterion (*fig. 1*). It leads to the same program selection as more commonly used economic efficiency criteria, such as present net worth maximization. The criterion of minimizing cost plus net value change (C + NVC) is more convenient than others to apply to fire control programs because the primary objective of the control activity is to reduce the losses from fire. The C + NVC criterion recognizes that resource output gains, as well as losses, sometimes result from fire. Other than that distinction, it is an only slightly modified version of the criterion of least-cost-plus-loss, first applied to fire programs by Headley in 1916 (Baumgartner and Simard 1982, Gorte and Gorte 1979). Simard (1976) refined the C + NVC concept for fire management analyses by using conventional economic theory principles of marginality, and Herrick (198 1) applied the same procedure to an analysis of insect control programs. The difficulty has not been the lack of an appropriate economic efficiency criterion, but rather the lack of a model from which the cost and net value change relationships could be derived.

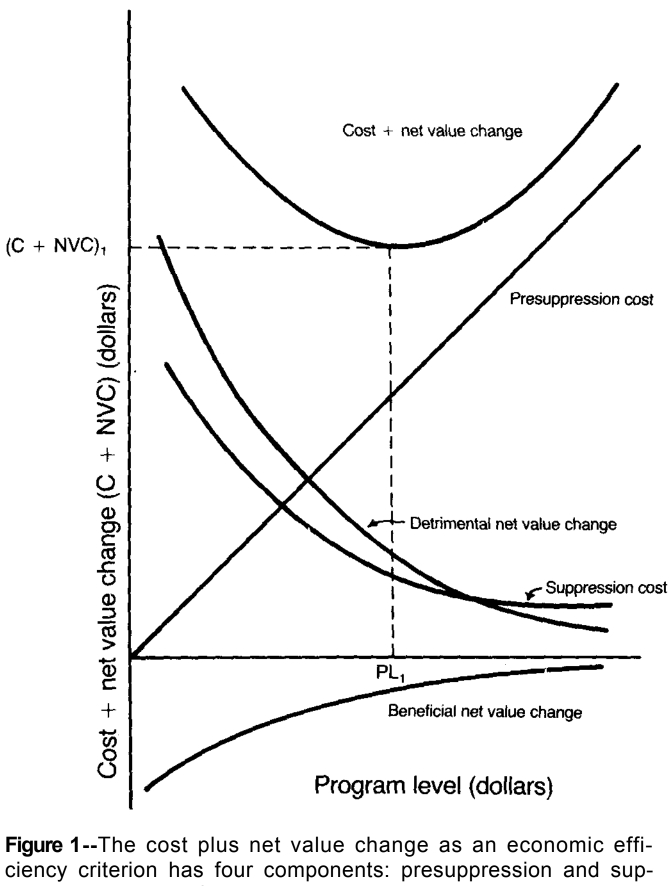

Figure 1--The cost plus net value change as an economic efficiency criterion has four components: presuppression and suppression costs, beneficial and detrimental net value changes.

Some fire program inputs and resource output consequences cannot be readily measured in a common denominator of dollars. Fire effects on cultural sites, rare and endangered species, and air quality are examples. These effects should not be forced into an economic efficiency analysis. As a result, C + NVC is not a holistic measure of economic efficiency and is not a sole decision criterion. Instead, C + NVC must be considered in combination with other effects which cannot be readily measured in dollars.

The second relevant decision criterion is the *change in resource output* levels over time. Although all changes in those resources that can be measured in dollar units are included in the net value change computation, the timing and magnitude of the output changes are often treated as decision criteria themselves. The repeated attention that the Office of Management and Budget and Congress gives to National Forest timber harvest levels and the perennial debate over nondeclining even flow of timber harvests are examples of the importance placed on quantitative resource output effects themselves.

The *risk level* inherent in the fire program option is a third important decision criterion. By risk, we mean the variability in fire program performance which can result from the application of a single program. The severity of the fire season often changes dramatically from year to year, reflecting variations in fire weather and fire occurrence. The pervasive stochastic character of the fire system has generally been recognized in program evaluation procedures through adjustments of the analytical process itself rather than by treating risk preference as a separable decision criterion. The 1972 fire planning process that was applied to National Forests, for example, evaluated fire program performance against effects of fires burning in weather conditions typified by the 90th percentile burning index in the fourth worst fire year of the previous 10 years (U.S. Dep. Agric., Forest Serv. 1972). If only one point on the distribution of possible fire conditions can be measured, there may be some logic in measuring a severe condition, because the greatest suppression costs and damages occur then.

A more complete risk representation is possible, however, with the calculation of probability distributions about the other two decision criteria--economic efficiency and resource output changes. Those probability distributions display the range of possible consequences of a fire program option because of the inherent variability of the fire system. The probability distribution and the expected value (the probability-weighted average that can be calculated from the distribution) permits the decisionmaker to apply specific weights to efficiency, resource outputs, and risk consequences of each fire program option. The importance of risk should be assigned by the decisionmaker, not by the analyst through some adjustments or selective use of empirical model input. Since some public program decisions are not risk-neutral, the expected value outcome should be accompanied by a display of potential variability about the expected value.

Analysis Resolution

The range of time and space resolutions appropriate to fire management analysis is wide. The information needed for highly time- and site-specific attack decisions on individual fires, for example, must be more detailed than that needed to determine the most efficient size and composition of the long-term fire program in a geographic region. This requirement influences system design. It is probably much more efficient to construct an interrelated set of two or three fire management analysis models, each one tailor-built to answer the questions relevant at the different levels of analysis resolution, than to build one larger model capable of addressing all possible levels (Mills 1982). High-resolution models demand large amounts of data, so they should be preceded by low-resolution models that screen potential fire program options down to that subset which warrants further investigation in greater detail. Very detailed, site-specific analysis should only be applied to the small subset of program options that can contribute most to management objectives.

Given the wide range of potential fire program options, two outcomes are possible if a preliminary low-resolution model is not used. The high resolution model, with its associated higher cost, could be applied to all potential fire program options. This would lead to high analysis costs. Alternatively, the high-resolution model could be applied to a small subset of the potential fire program options, leading to suboptimization. The cost of an errant decision through suboptimization could be greater than the higher analysis cost of the first possibility.

Where should the low-resolution analysis start? Probably the best place is at the point where a wide array of fire programs are being evaluated for subregional areas, areas of 1 to 3 million acres in size. Areas of this size are large enough to require a mostly self-contained fire management program, yet they still retain a large amount of resources and topography homogeneity. It is difficult to model the heterogeneity of larger areas, but the modeling trade off for these smaller areas is that some fire program inputs, such as hand crews and air tankers, are shared with other areas. This subregional analysis is not only a useful first step in evaluating programs for a given planning unit, the results can also be used in the development of national- or state-level fire program aggregates.

The size of the area to which the fire management program is applied influences optimum model form, a point sometimes overlooked in the rush to site-specific land and resource management planning. For example, a fire management program option composed of prevention specialists, fire detection personnel, initial attack crews, and fuel treatment specialists is not designed to manage fire on a 1000-acre parcel, but rather an area composed of a substantial number of such parcels.

The most crucial information required for a low-resolution evaluation of fire management programs is a description of the area, specifying characteristics that influence the performance of the fire management program options, such as resource management emphasis and vegetation. How the fire program performs on a certain kind of area is more important in the low-resolution analysis than "where" that area resides within the overall fire management area.

Once a fire management program option has been selected, the "where" and "when" to use individual fire program inputs is a central focus of operational planning. Site-specificity is very important at that planning stage. Before that stage, site-specificity within the fire management area is excess baggage in a modeling sense, and very expensive baggage to carry.

Earlier Studies

Several fire management analyses at approximately the same level of resolution addressed here have been completed. None of the studies meet the scope requirements outlined above, but all provide valuable insights into the most efficient design of FEES.

A number of historical series studies of fire management programs compare program funding levels to program performance indicators, such as acres burned. Fedkiw (1965) compared fire program expenditure levels from 1945 to 1964 to acres burned across the entire nation. Years were separated into two classes: those with more than 90,000 acres burned and those with less. Marginal cost curves which showed the added fire program cost per acre of reduced burning were calculated from the data. Winkworth and others (1981) compared the increases in fire program funding in North Carolina to reductions in the timber value lost to fire. The 4 years analyzed were all severe fire seasons that were adjusted into closer comparability using the average burning index for the year. Benefit-cost ratios were calculated from the cost and net value changes. The Oregon State Department of Forestry (1972) conducted a similar study based on a comparison of fire program funding levels to changes in the net value of resource outputs caused by fire. The C + NVC or cost-plus-loss criterion was used in that analysis.

These historical studies have a strong appeal because they stand on true empirical data which, with all of its reporting weaknesses, have certain advantages over simulation model results. They have two important weaknesses. First, a large number of important parameters, such as fire weather and fire occurrence levels, cannot be controlled because they vary within a year and between years. Fire program funding is not the only variable. Even with the adjustments for burning index or the stratification of areas by acres burned, too many important parameters are still uncontrolled. The difference in acres burned cannot be attributed to changes in fire program funding alone.

Second, the historical analysis is restricted to fire program funding levels and program compositions which have actually occurred in the past. This is a limited subset of the potential program options that should be evaluated, yet there is little basis in the historical models to extrapolate the results to other fire program options or to other fire years. The historical approach may provide a rough approximation of the efficiency of past expenditures, but it is insufficient for the broad-scope screening of future fire program options.

There have been studies of separate components of the fire management program, such as fuel treatment or initial attack, but few attempts to incorporate all major fire program components into the same model. Without that integration, trade-offs cannot be evaluated. Trade-off analysis is a major function of the screening process in a broad resolution fire economics evaluation system.

Fuel treatment program options were studied by Hirsch and others (1979) in the Southwest and by Barrager and others (1982) in the Pacific Northwest. Both of these studies used a decision-tree approach. Nodes on the tree reflected the probabilities that various fire behavior conditions would occur and that certain fire sizes would result. Wood (1978) studied fuel treatment programs in the northern Rocky Mountains. The effectiveness of fuelbreaks has been evaluated by Davis (1965) and Omi and others (1981).

The FOCUS model was designed to evaluate alternative initial attack programs (Bratten and others 1981). Although it was constructed for a more site-specific or location-specific application than is best for the low-resolution, subregional analysis, certain of the design characteristics of FOCUS are relevant to lower-resolution models. Modifications of FOCUS which reduce its site specificity can be made by replacing the transportation network and historical fire data with direct travel time estimates to sample or representative fire locations (Lehto and See 1981). This reduces the cost of FOCUS implementation, but retains the rigor of its fire containment simulation. The study of initial attack fire programs on six National Forests by Schweitzer and others (1982) used FOCUS to assess initial attack options. Procedures for fire effects and resource value considerations were added to derive the net value change for each program option. The stochastic nature of the fire system was recognized by evaluation of three historical fire years which varied in fire season severity.

The study of the fire program on 41 National Forests (U.S. Dep. Agric., Forest Serv. 1980) is the most complete subregional analysis of fire management program options to date. The analysis model used in the 41-forest analysis was refined and is now contained in a draft fire planning handbook for use on all National Forests (U.S. Dep. Agric., Forest Serv. 1982a). The resolution of the handbook model is higher resolution, especially more site-specific, than the subregional-resolution being considered here. The fire effects and resource valuation procedures in the handbook are similar to those used by Schweitzer and others (1982), but the initial attack evaluation process is quite different. Fire program performance in the handbook model is evaluated against "representative" fire locations rather than each historical fire location. Most of the major behavioral relationships, such as fire effects and fire behavior, are assumed to be homogeneous over the area assigned to the representative location, which has been as large as 18,000 acres in some applications. The handbook model was also applied to several state protection areas throughout the country (U.S. Dep. Agric., Forest Serv. 1982b).

Although the fire planning handbook is well suited to answer some program planning questions at fairly high-resolution levels, it is primarily designed to evaluate the initial attack component of the fire program using an expected value analysis. Fuel treatment alternatives are not fully included in the analysis model nor are escaped-fire suppression alternatives. The latter omission is particularly important because the differences in cost among suppression alternatives can be high enough to outweigh changes in the presuppression program cost. Failure to evaluate suppression alternatives can lead to selection of a larger-than-optimum presuppression program.

These past fire planning efforts contribute greatly to the design of a fire economics evaluation system for subregional analyses. No existing model, however, provides the information needed at the targeted analysis resolution. The capability of calculating risk consequences, in particular, is missing. Risk is not adequately displayed in expected value analyses or in the analysis of selected historical years that have varying fire season severity but unknown probability of occurrence in the future. Yet, the concern over low-frequency severe events greatly influences fire program decisionmaking. The capability to evaluate trade-offs between major fire program components, especially fuel treatments, initial attack, and escaped fire suppression, is also largely missing from currently available models. Another weakness in current models is reliance on an overly generous homogeneity assumption in the description of the fire program areas. This in turn ignores important variability in fire behavior, suppression effectiveness, and fire effects, all of which are critical in the selection of a fire management program option.

These conclusions do not imply that past studies and exisiting [sic] models are not useful for the purpose toward which they were directed. They do not, however, fulfill all of the needs of a subregional fire management analysis that can screen a wide array of fire program options to identify a subset that warrants high-resolution analysis.

OVERVIEW OF FEES

The proposed Fire Economics Evaluation System (FEES), once it becomes operational, will meet most of the fire management analysis information needs at the subregional level of resolution. The subregional resolutions correspond to the fire management analysis Level I as described by the Fire in Land Management Planning Task Force (U.S. Dep. Agric., Forest Serv. 1979a) and Mills (1982), the broadest resolution analysis relevant to an individual land and resource planning unit. A brief overview of the system is provided here to place the detailed description that follows in better perspective.

FEES is a simulation model, an appropriate format because empirical data are not available to evaluate all of the fire management programs that should be investigated. The limited empirical data that are available are used to construct the basic behavioral relationships within the model. Those underlying behavioral relationships are then interrelated in different combinations to simulate the performance of a fire management program option that may never have been applied to a particular fire management situation.

The eventual user of FEES will be a program analyst or fire program planner who will provide two types of input (*fig. 2*). One input is a general description of the *fire management situation;* that is, the characteristics of the subregional area that influence fire program performance. The other is a general description of the *fire management program options* being evaluated for that area.

The output from FEES for each fire program option evaluated meets all the major information needs described earlier. Two FEES outputs are the expected value C + NVC and expected value physical change in resource outputs by resource category. The third output is the probability distributions about each of the two expected value outputs. The probability distributions permit an assessment of risk.

To produce these outputs, the user inputs are translated within the FEES model into (1) descriptions of strata within the fire management situation, and (2) a list of the pool of fire management inputs. The more detailed strata are needed to drive the behavioral relationships found within the simulation components or modules internal to FEES. The model simulation then progresses through these modules for each fire management situation stratum, from estimating fire behavior through the assignment of per-unit resource values. The outcomes are then weighted for each stratum by the probability of fire occurrences in that stratum and summed together to yield the results for the fire management situation as a whole.

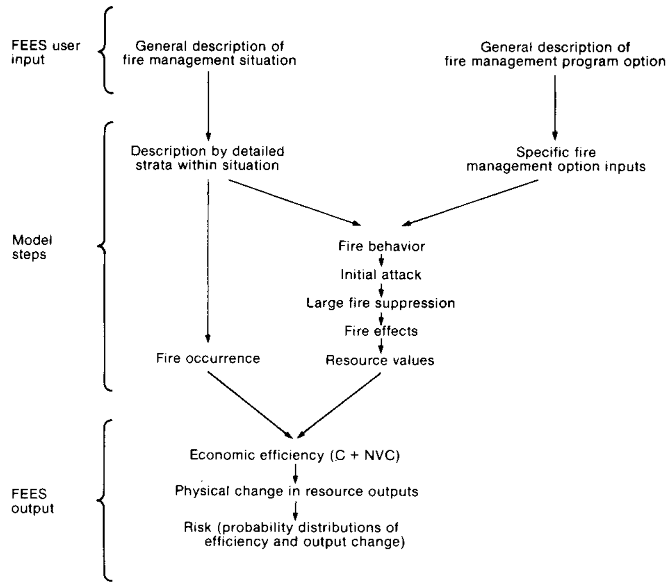

Figure 2--The Fire Economics Evaluation System diagrammed to simplified form shows model input, primary processing steps, and output for one subregional area.

The inputs supplied by the user to FEES are described in more detail in the next section, which is followed by a discussion of the actual output FEES will yield. The input and output are discussed together, before the actual structure of the simulation model is described, because in large part they determine the functions the model must perform.

INPUT SUPPLIED BY USER

As indicated earlier, the two major user-supplied inputs to FEES are descriptions of the fire management program option being evaluated and the fire management situation to which the program is being applied. These user-supplied inputs are different than those supplied by the model builder. The model builder provides all behavioral relations within the model, such as the fire growth and fire containment algorithms, and all data relevant to that fire management situation, such as per unit resource values and fire occurrence frequencies.

Fire Management Program Options

FEES includes the capability to evaluate alternatives of three major components of the fire program--fuel treatment for hazard reduction, initial attack, and large fire suppression. Together, these account for the vast majority of fire program funding, approximately 80 percent on National Forest land in fiscal year 1979 and similarly high proportions in other Federal and State wildfire organizations. Two of the three selected program components, fuel treatment and initial attack, are part of the planned or presuppression funding, and the other component, large fire suppression, is usually funded on an emergency basis.

The fire prevention and fire detection program components are not evaluated in FEES because it is difficult to estimate their influence on overall program performance. Both components are funded at relatively low levels. In using empirical data on fire occurrence frequencies and fire size at time of detection, the past performance of the two components is assumed to be constant.

If desired, prevention and detection could be evaluated with a break-even analysis. For example, the maximum increase in prevention funding that would be justified by a 10 percent reduction in fire ignitions could be determined. This break-even information would permit a fire program specialist to judge whether the fire ignition reduction could be accomplished for less than that break-even increase in funding.

Only fuel treatments undertaken for hazard reduction are included in FEES. Fuel or vegetation management treatments applied primarily for other objectives, such as wildlife habitat improvement and site preparation, should be evaluated with those respective programs rather than with the fire program. This is a boundary condition in the design of FEES rather than a land management planning constraint. The results of all programs should be combined and analyzed again in an integrated land management planning model like FORPLAN (Johnson and others 1980).

Each fire program option is described by three parameters--presuppression program funding level, presuppression program mix or composition, and large fire suppression strategy. Presuppression *program level* is the total dollar amount available to build the program and is expressed as true economic costs rather than budgetary dollars. Accounting systems were established for accountability rather than for tracking true economic costs yet economic costs are required in the estimation of economic efficiency. The costs of all fire management inputs are annualized, even the durable inputs that are purchased with a single year's appropriations. If the cost of durable inputs were not annualized, the fire program selection would be biased toward inputs with a useful life of 1 year or less. The program level should encompass all presuppression inputs available for the entire area rather than only the inputs supplied by any one agency. The relevant point at the subregional resolution level of FEES is identification of the optimum total fire program, however optimum is defined.

The presuppression *fire management mix* describes the composition or emphasis of the program constructed with the program level. For example, one program mix may emphasize initial attack with ground crews while another may be more heavily weighted toward broadcast fuel treatments. Each of these fire management programs has a different and unique production function, or influence on program outcome, so each must be evaluated separately. One approach which might be followed to implement the fire management program mix notion is to describe mix as the proportion of total dollars allocated to each type of fire management input, such as smokejumpers and engines (Hunter 1981a).

In the past, fire program analyses have not included a rigorous evaluation of fire program mix as such. As a result, fire program descriptions have tended to be too general or too detailed. There has been an apparent assumption that the most efficient program mix was obvious and that finding the most efficient program level was the only problem. Since it is our contention that the most efficient mix is no more obvious than the program level, it is an important dimension of the FEES design.

Consistent with FEES' subregional resolution, the fire management inputs available for initial attack are described by a few categories in FEES (Gonzalez-Caban 1981). For example, all engines are described by three size classes and hand crews are generally described either as Category I or Category II-IV The fire program inputs in each category are described by the average cost and production rates for the class. A finer distinction among inputs is not justified at this level of resolution.

A note on terminology-the entities which construct fireline or accomplish fuel treatments are termed "inputs" here rather than "resources" even though the latter is the term more commonly applied by fire program personnel. The term "inputs" is used to distinguish them from natural resources, such as timber and livestock grazing.

The total pool of program inputs available for large fire suppression is essentially limitless. Within the constraints of delivery time, fire suppression inputs can, and are, literally drawn from all over the country and from inputs commonly used for other land management activities, such as timber inventory or brush disposal. The relevant question then is not how many suppression inputs should be made available, but rather how many should actually be requested and how should they be used in large fire suppression? In short, what is the most efficient *suppression strategy*?

Both the presuppression management mix and large fire suppression strategy can and should be treated as variables for a given fire management situation. For any one overall mix and strategy evaluated, however, it may be necessary to apply them differentially by strata within the fire management situations. These differences in fire management input use can be reflected through internalized rules for dispatching personnel and equipment to fires.

Fire management inputs should only be used for large fire suppression if they lead to a more than offsetting reduction in the fire-induced net value change in resource outputs, provided economic efficiency is the objective. If suppression input use is not evaluated on this basis, an overly aggressive suppression strategy will lead to unsupportably high suppression costs for all large fires. If suppression strategy is overly aggressive, the presuppression program funding could be elevated above the optimum level simply to avoid high suppression costs. In the last analysis, the cost of all fire program inputs must be compared with the changes induced in the net value of resource outputs, not simply the reduction in other program costs.

Since presuppression fire management mix and suppression strategy have a major influence on the program's underlying production function, and therefore the C + NVC relationships, they are included in FEES. Each program option is defined by a specific combination of these three parameters supplied by the user. Those combinations must be varied systematically to trace out the full set of relevant options.

Fire Management Situation

The fire management situation evaluated in FEES is not a real area in the site-specific or location-specific sense. It is not an actual piece of land. Rather, it is a hypothetical area which is representative of a group of real areas. The fire management situation is a "kind of area." It captures the essence of the real areas in the parameters which describe the fire management situation. Only those characteristics which influence fire program performance are embodied as parameters to distinguish one fire management situation from another. They are very much "situation-specific" then, even if they are not site-specific.

This type of abstraction permits us to accomplish the low-cost screening of fire program options without sacrificing knowledge of planning area characteristics which influence fire program performance. The data required in the fire management situation model building may be taken from samplings of the real areas but this approach avoids the wholesale duplication of data collection and analysis of real areas even though they are in essence the same, i.e., they show similar performance patterns. Ownership delineations are ignored in the fire management situation just as agency delineations are ignored in the fire management program option. Basic questions about program performance must be addressed at this first low-resolution analysis. The incidence of benefits and costs should be addressed later.

The situation-specific nature of a fire management situation is really no different from the development and use of timber yield tables. The most important independent variables in yield tables, such as site index, species, and age, are identified in a data set drawn from some sample area and the yields corresponding to each combination of those variables are estimated. Those yield results are then extrapolated to any area which is similar in the describing parameters of site index, species, and age.

The seven parameters that describe a fire management situation are fire climate zone, acreage, resource management emphasis, topography class, vegetation class, person-caused fire occurrence level, and lightning-caused fire occurrence level (Bratten 1981b). Fire climate zones are contiguous geographic areas which have similar synoptic weather types associated with critical fire weather (Schroeder and others 1964). There are 14 climate zones in the United States, varying in size from the smallest in southern California to the largest in the Southeast, which includes seven States and portions of several others. The climate zone is the only fire management situation parameter that indicates geographic location. It also is an important index of weather conditions. The other parameters are situation-specific only.

The fire management situations are all assumed to describe hypothetical areas of 1 million acres but once FEES is operational, it will include an algorithm to adjust results for larger and smaller areas. Economies related to scale, as well as the indivisability [sic] of some of the high-cost fire management inputs, will require some form of nonlinear scale adjustments.

Resource management emphasis is framed broadly, for example, to distinguish a commercial timber management objective from a wildlife habitat and dispersed recreation objective. The resource management emphasis class is the vehicle by which the land and resource management objectives are addressed within FEES. The management emphasis, in combination with the vegetation class, is linked to decision rules within FEES, such as timber rotation ages, livestock grazing levels, and action taken in response to sedimentation problems. The without fire time stream of resource outputs is a much more direct articulation of resource management objectives than a transformation of that output objective into an acreage burn standard.

There is a long history of resource management on both public and private lands. Private management actions can be observed even if the objectives behind those management actions are difficult to determine. Observed management actions permit the selection of a resource management emphasis class in FEES.

Topography and vegetation can be described by any one of a number of available classification schemes. The fire occurrence level provides a partial measure of fire program workload. This design produces a FEES which evaluates fire program options for individual fire management situations. Most National Forests or State protection areas are probably composed of several fire management situations. The correct way to join the situations and their respective optimum fire programs is beyond the scope of this design, but it is largely a question of how to model the sharing of fire management inputs between areas.

Time Horizon

Two time horizons are relevant in FEES--one for fire program planning, another for the time over which fire effects are measured. The program planning horizon is 10 years. This 10-year horizon is addressed in FEES by repeating the 1 year fire program performance for 10 years. Because weather and fire occurrences are treated as probability distributions, the simulation of the first year's fires is actually a simulation of all possible combinations of fires that could occur in 1 year. The results from that first-year analysis are valid for the planning area as long as the characteristics of the program option and fire management situation remain unchanged. Those characteristics are assumed unchanged for 10 years in FEES. If, on the other hand, the underlying makeup of the fire management situation changes, the optimum fire management program changes in turn, and a separate analysis must be made. It is easier, and probably adequate for most purposes, to apply FEES to the changed situation when it occurs rather than construct a dynamic model that simulates the changes over time.

The time horizon for the fire effects calculation is long enough to encompass all of the net change in resource outputs that results from the fires that occur in the single simulated year. This period is only a few years for range output effects, since postfire grazing levels quickly approach the prefire level after a fire of moderate intensity. The time horizon of timber effects is probably the longest. The change in timber output from the loss of an immature timber stand does not occur until the time when the burned stand would have been harvested, some 60 to 100 years in the future for some species, sites, and ownerships.

OUTPUT PRODUCED BY FEES

FEES produces output on three separate decision criteria: economic efficiency, change in resource output due to fire, and risk. This output is displayed in such a way that program planners using FEES can also draw inferences about the incidence of program costs and benefits. The output includes data that can be used in consistency checks between the FEES analysis at the subregional resolution and subsequent higher resolution analysis, using more site-specific models. Each of these classes of output is developed for each program option applied to each fire management situation.

Economic Efficiency

FEES provides C + NVC estimates for each program option evaluated. Recall that C + NVC is the sum of presuppression costs, suppression costs, and the net fire-induced change in the value of resource outputs. The minimization of C + NVC is a correct economic efficiency criterion and leads to the same program selection as present net worth maximization. The application of C + NVC differs, however, from that used for economic efficiency criteria. Accordingly, the data required for the C + NVC calculation and interpretation of the C + NVC values also differ.

Typically, benefit-cost ratio or present net worth calculations for a total resource management program compare the costs and benefits of the *program* to the costs and benefits of having no management program at all. This "with" versus "without" program calculation is not feasible for fire management, because it is not possible to estimate how large and damaging fires would become if no fire management program existed.

Instead, with the C + NVC criterion, the resource outputs with the fires are compared to those without the fires. The net value change is calculated by subtracting the present value of the estimated time stream of resource outputs without the fires from the present value of the resource outputs assuming fire occurrence corresponding to a particular program option:

$$\text{net value change} = \sum_{i=1}^{n} (Q_{1i} - Q_{2i})V_i$$

where

Q_1 = resource output without fires
Q_2 = resource output with fires
V = per unit value
i = resource category

The net value change, therefore, corresponds to the net "loss" in the value of resource outputs. The "without fire" time stream of output provides a common benchmark for comparison. There is no implication that the without-fire benchmark is any more desirable than any other, nor that exclusion of all fires is even feasible. The net value change is a margin between two time streams of resource output, but it is not a margin which results from adding an increment of program input.

The cost component of C + NVC, on the other hand, is the total economic cost of the particular program option being evaluated and not the incremental cost between the program level and the cost of a program which would exclude all fires. Therefore, the C + NVC criterion is not a marginal efficiency criterion in a strict sense since a single C + NVC calculation does not estimate the efficiency of a marginal change in the program.

One implication of this C + NVC nature is that a single C + NVC calculation provides no efficiency information (Mills 1979). The C + NVC of successive program options must be compared; the program option with the lowest C + NVC is the most efficient. The increase in the present net worth associated with the incremental change in the fire management program equals the difference in the C + NYC's. Thus, a true marginal efficiency measurement can be derived by comparing separate C + NVC calculations even though efficiency conclusions cannot be drawn from individual C + NVC estimates.

Defining a program option as a composite of program level, fire management mix, and suppression strategy implies that instead of a single C + NVC curve, as shown in *fig. 1*, there is a whole family of C + NVC curves. If suppression strategy is held constant and program level and fire management mix are varied, a family of curves result, such as the hypothetical set shown in *fig. 3.* The objective of the efficiency analysis is to trace the loci of minimum points shown by the dashed line. The production function of the fire program for each fire management mix eventually encounters diminishing returns as the program level is increased and another fire management mix becomes more efficient. If the suppression strategy is varied too, each of the C + NVC curves for separate fire management mixes in *fig. 3* further expands into a family, one curve for each suppression strategy and fire management mix combination.

The foregone present net worth of a fire program budget constraint can be derived from these curves. If the fire program level is constrained at PL_2 (*fig. 3*), the foregone present net worth of a program planning horizon application of the fire program option is $(C + NVC)_2 - (C + NVC)_1$. Similarly, if PL_3 and fire management mix 3 are selected to achieve environmental benefits to which dollars are not assigned, the implied minimum value of the environmental outputs is $(C + NVC)_3 - (C + NVC)_1$.

The three descriptors of the fire management program (program level, fire management mix, and suppression strategy) are incorporated in the FEES design because of the hypothesis that, under certain conditions, each influences economic efficiency. There is limited empirical evidence to date to test this hypothesis because there are only a few studies in which the fire management mix was varied at all and none in which the suppression strategy was systematically varied as well. The fire management analysis on 41 National Forests (U.S. Dep. Agric., Forest Serv. 1980b) contained program level variations but relatively small fire management mix changes. No consideration was given to alternative large fire suppression strategies.

Holding suppression strategy constant for the sake of illustration, four possible C + NVC relationships can be hypothesized. First, both program level and fire management mix may influence the shape of the C + NVC family and, therefore, the fire program efficiency (*fig. 3, 4A*). Second, program level may be important while program

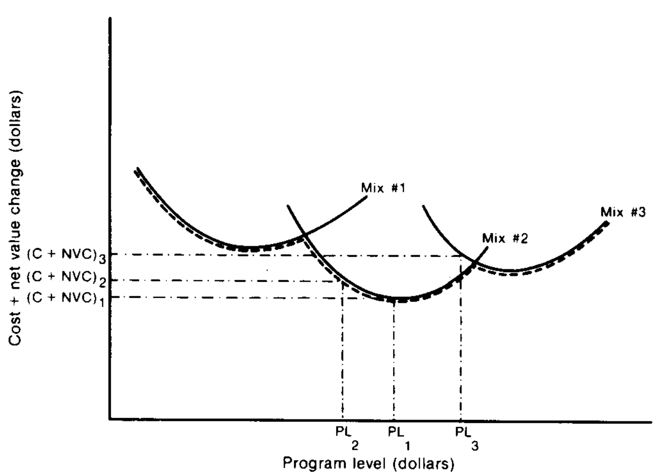

Figure 3--A family of cost plus net value change curves might result from various fire management mixes.

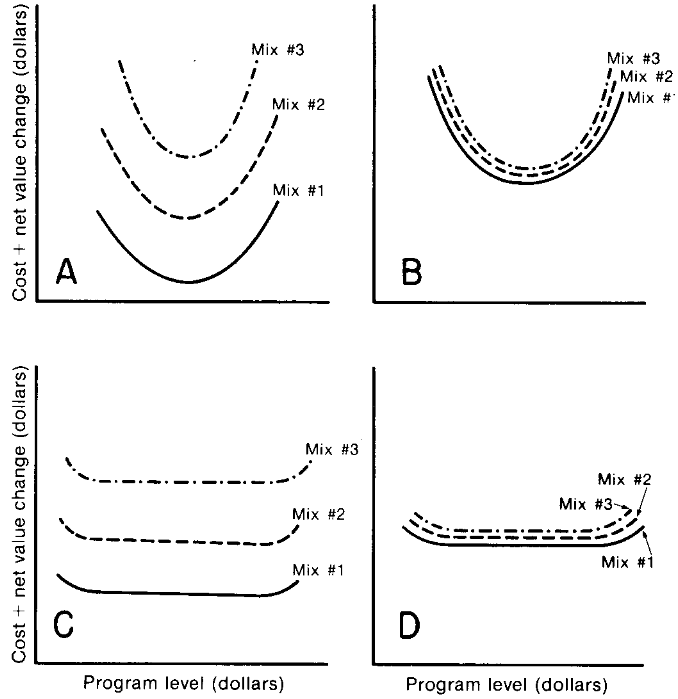

Figure 4—Curves for cost-plus-net value change are shown for four hypothetical conditions: *A*, both program level and fire management mix influence economic efficiency; *B*, program level influences economic efficiency but fire management mix has a minor impact; *C*, fire management mix influences economic efficiency but program level has a minor impact; and *D*, neither fire management mix nor program level have a major impact on economic efficiency.

mix is not (*fig. 4B*). Third, program mix may be important while program level is not (*fig. 4C*). Finally, there may be situations where neither has a major influence on economic efficiency (*fig. 4D*). The limited evidence available from the 41-Forest analysis lends support for all four hypotheses for different areas of the country. If the hypothesized conditions depicted in *fig. 4B and 4C* are substantiated for a given area through the FEES analysis, the subsequent site-specific analysis conducted with a high-resolution model can center even more closely on the important variables. If the conditions in *fig. 4D* are substantiated, a more detailed site-specific analysis is not needed unless changes in resource outputs or risk are differentially affected by the program level or mix. Since we cannot determine, at this time, which condition will fit a particular fire management situation, FEES is designed to evaluate variations in all three program descriptors.

Resource Output Changes

FEES provides estimates of fire-induced changes in resource outputs over time for each program option tested. The net change is the resource output "without" the fires minus the output that will occur "with" the fires simulated to occur with that program option. For example, if the net change (net loss) in timber output with program option A is

10 million board feet and with program option B is 7 million board feet, the marginal increase in timber output achieved in moving from fire program A to B is 3 million board feet.

FEES provides net output change estimates for timber, range, water, wildlife and fish, recreation, and improvements--all of the outputs to which dollar values are assigned in the net value change calculation. The C + NVC calculation is actually built from an even finer resource stratification since fire effects and resource values vary considerably within these broad resource categories. The time stream of the net change in output is needed for discounting in the net value change calculation, so the time stream of output change is reported separately.

Risk Assessment

The risk embodied in any program option is displayed through the probability distributions about the expected values of C + NVC and resource output changes. The sources of the variability are mostly fire weather, fire occurrence levels, and the location of fire occurrences (Bratten 1981a). Additional variability originates in estimates of fire size at time of detection (Salazar 1981), elapsed time between detection and first arrival of initial attack (Hunter 1981a), and large fire suppression effectiveness (Hunter 1981b).

Risk exists if an outcome is variable, but the outcomes vary with a known probability distribution (Knight 1965). Uncertainty exists if the variable outcome cannot be described with a probability distribution. An example of risk is fire occurrence, which varies significantly from year to year, but the probability can be fairly well predicted from historical fire occurrence frequencies. The probability distributions for the major fire system variables can be similarly defined empirically. This is an example of a risk situation. The distributions of other important variables, however, such as large fire suppression effectiveness, are much more difficult to derive. They interject an element of true uncertainty. Although probability distributions about the FEES model outputs are treated if they are known, an unmeasurable amount of uncertainty remains.

Program options which minimize the expected C + NVC lead to the greatest long-run efficiency. Decisions based on expected values are valid if the estimated net value change accurately reflects the disbenefit associated with infrequent but very severe fires and if all of the probability data accurately reflects the likelihood of those severe fires.

If, however, the survival of society itself were at stake, the appropriate per unit value for the net change in resource outputs approaches infinity rather than the per unit resource value which is used in FEES. Under that situation, a risk-averse selection is justified on the implied assumption that there is measurement error in the FEES per unit resource values. A risk-averse selection is also justified if the fire-induced loss is large in relation to the total size of the society, that is, if there is a cash flow problem. If the probability of the severe event is thought to be underestimated, the decisionmaker may also make what appears to be a risk-averse decision. In reality, the decisionmaker is acting under conditions of uncertainty rather than risk. Expected-value decisions are also not proper if the group that the decisionmaker represents is not risk-neutral. Furthermore it is doubtful that wildfire has a truly "catastrophic" nature which would threaten society (Blattenberger and others 1982).

Whatever the risk preference may be, the extent of risk embodied in a fire program must be explicit. The degree of risk preference should not be embedded in the analytical procedures themselves, such as through model builder adjustments of discount rates, or some subset of the total variability in an important parameter, such as the 90th percentile weather. The probability output of the FEES model permits the decisionmaker to measure explicit trade-offs among the economic efficiency, resource output change, and risk consequences of each fire program option so as to treat risk as a separate decision criterion.

There are several ways to display the risk dimension. One way is to describe the expected value C + NVC curve for a particular fire management mix and also the curves that trace the 90th percentile probability band or envelope about the expected value *(fig. 5).* Our hypothesis is that the C + NVC probability distribution narrows about the expected value as the program level increases. Greater initial attack and large-fire suppression capability is available at higher program levels to more completely control severe fires when they occur:

Another way to display risk is to calculate the difference in C + NVC between the expected value and the top end of the 90th percentile probability band, D_1, in *fig. 5* at PL_1. That difference could be shown as a percentage of the expected value C + NVC for that program level, $(C + NVC)_1$, in *fig. 5.* The "risk percentage" R for PL_1, in *fig. 5* is then:

$$R_1 = \left[\frac{D_1}{(C + NVC)_1}\right] 100\text{percent}$$

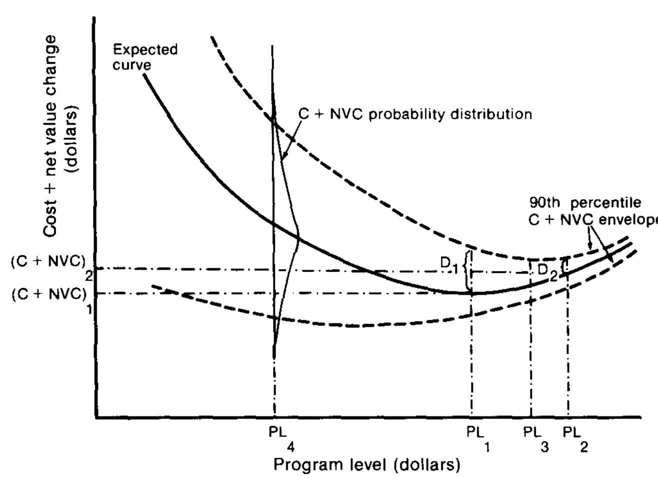

Figure 5--Trade-off between economic efficiency and risk is diagrammed at four program levels.

A risk-averse decisionmaker may choose PL_2 instead of PL_1. This could result from a conscious decision that the reduction in risk from R_1 to R_2 is more valuable than the foregone efficiency, $(C + NVC)_2$ minus $(C + NVC)_1$. This simple difference between the two C + NVC's is the risk premium, the reduction in efficiency that the decisionmaker must pay to achieve a lower risk level.

A more complete way to display the risk is to select points from the cumulative distribution of C + NVC (*fig. 6*). A hypothetical cumulative C + NVC distribution is shown in *fig. 6*, with an expected value of $(C + NVC)_{ev}$. Three additional C + NVC values can be calculated in relationship to the expected value--one 50 percent as large, $(C + NVC)_1$, one 150 percent as large, $(C + NVC)_2$, and one 200 percent as large, $(C + NVC)_3$ as the expected value. The corresponding values from the vertical axis show the probability that a C + NVC of that size or smaller would result from the application of the fire program option which was evaluated--P_1, P_2, and P_3 in *fig. 6.* Another way to display risk is to compare the mean and variance of any program outcome with the parameter preference utility function of mean-variance trade-off (Blattenberger and others 1982).

The FEES probability output can be used to identify the most efficient program option in a high- or low-severity fire year. As Schweitzer and others (1982) found in their analysis of six National forests, the most efficient fire program level in a high-severity year is sometimes larger than in a low-severity year. In our hypothetical example in *fig. 5,* the most efficient program for the high-severity end of the 90th percentile band is PL_3, that is, the program level with the least C + NVC. The most efficient at the low end of the probability band is PL_4. If reliable estimates of the current year's severity could be made, this information could be used to adjust the presuppression programs during a fire season.

The probability information may also help distinguish between the occurrence of a low frequency but severe fire

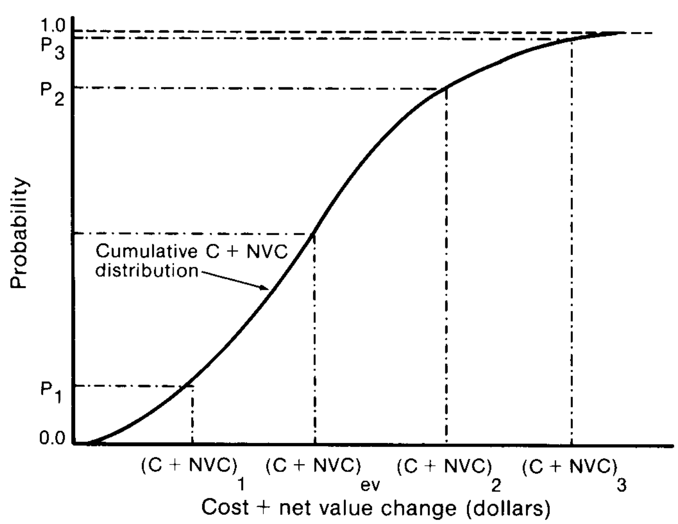

Figure 6--Risk can be displayed by selected points on the cumulative probability distribution of cost plus net value change.

season from a poor program decision, that is, to distinguish bad outcomes from bad decisions. High fire losses do not necessarily mean that someone made a program mistake any more than a severe earthquake does. Some severe fire conditions are beyond our technological capability of control and our ability to predict.

Inferences About Program Effects

It is possible to infer from the FEES output certain information that is not produced directly or in detail. The incidence of fire program effects--the number and kind of people who are affected--can be inferred from the C + NVC components, which indicate how much each group pays for or benefits from the program. The new value change component also shows the incidence of the program on user groups, such as the timber industry and recreationists. The fire program planner could also estimate the program-induced employment and income change by applying appropriate multipliers to the estimates of resource output changes.

Some of the FEES output also permits a fire program planner to draw inferences about environmental effects that are not valued in dollars. One intermediate model output, the probability distribution of fires by fire size and fire intensity classes for each fire program option, indicates whether such effects are likely. Long-term effects on soil productivity, for example, may be positively correlated with fire size and fire intensity in certain soils and slopes, and air quality deterioriation [sic] may be related to the same parameters. Inferences about the extent of these effects are possible even though the FEES output does not include complete data.

Output Display

A full display of the major decision parameters provided by FEES would be large and difficult for the fire program planner or decisionmaker to assimilate. A full display would contain C + NVC and resource output change estimates, both as probability distributions and over time, and the probabilistic fire size and intensity for each program option evaluated.

One solution to this overabundance of information is to display only a subset of the decision criteria. The abbreviated FEES output contains the expected values for all components of C + NVC; the expected change in resource output by resource category; the 90th percentile risk percent; and selected points on the cumulative probability distribution of C + NVC (*table 1*). The probability distributions for the resource output changes and the time dimension can be shown separately (*tables 2, 3*) along with the results on fire size and fire intensity (*table 4*).

A second solution to the output display problem is to include full output sets in a simple linear programming or goal programming optimization module, where the output parameters could be assimilated into one objective function. The optimization module would help the decisionmaker understand the implications of the relative weights

Table 1--*Economic efficiency, risk, and changes in resource output per million acres from applying selected fire management program options for 10 years in:*

Fire management situation________________________________

Fire management program option			Cost-plus-net value change									Change in resource outputs[4]								
Program level (Dollars/ million acres)	Fire management mix	Suppression strategy	Expected[1] value				Cumulative probability for expected value fractions[2]				Risk[3]									
			A	B	C	Total	≤0.50	≤1.00	≤1.50	≤2.00		D	E	F	G	H	I	J	K	L
			Thousand dollars								*Pct*									
PL_1	FMM_1	SS_1																		
.	.	.																		
.	.	.																		
.	.	.																		
PL_n	FMM_n	SS_n																		

[1]A = Presuppression cost
B = Suppression cost
C = Net value change
[2]Probability that cost-plus-net value change less than or equal to the various proportions of the expected value of cost-plus-net value change will actually occur.
[3]Difference between 90th percentile cost-plus-net value change and the expected value of cost-plus-net value change as percent of expected value of cost-plus-net value change.
[4]Net change in output without fire minus output with fire; therefore, positive net changes are "losses" and negatives are "gains." Outputs are:
D = Timber (thousand cubic feet)
E = Range (thousand animal unit months)
F = Water (thousand acre feet)
G = Recreation (thousand visitor days)
H = Wildlife (thousand visitor days)
I. = Fisheries-sport (thousand visitor days)
J = Fisheries-commercial (thousand pounds)
K = Improvements-public (number of structures)
L = Improvements-private (number of structures)

Table 2--*Probabilities of net changes in resource outputs and net value change in resource output per million acres for a 10-year program*[1]

Fire management situation =______________________________
Program level/ million acres =______________________________
Fire management mix =__________________________________

Probability	Timber[2]		Range		Water		Recreation		Wildlife		Fisheries		Improvements Public		Improvements Private	
(proportion)	(MCF)	($)	(MAUM)	($)	(MAF)	($)	(MRVD)	($)	(MRVD)	($)	(MRVD)	($)	(Units)	($)	(Units)	($)
0.25																
0.50																
0.75																
0.90																
Expected value																

[1]Net resource output is calculated from (output without fire) - (output with fire) so a positive net change is a "loss." A net output change less than or equal to the number shown in the body of the table will occur with the specified probability.

[2]See *table 1*, footnote 4, for definition of units.

Table 3--*Expected net changes in resource outputs overtime per million acres for a 10-rear program*[1]

Fire management situation = ______________________________
Program level/ million acres = ____________________________
Fire management mix =__________________________________

Time periods	Timber[2]	Range	Water	Recreation	Wildlife	Fisheries	Improvements	
							Public[5]	Private[6]
(year)	(MCF)	(MAUM)	(MAF)	(MRVD)	(MRVD)	(MRVD)	(Units)	
1-5[3]								
6-10								
11-20								
21-30								
31-40								
41-50								
51-100								
101-150								
151-200								
Total[4]								

[1]Change in net resource output is calculated from (output without fire) - (output with fire) so a positive net change is a "loss."
[2]See *table 1*, footnote 4 for definition of units.
[3]Average net change during the time period.
[4]Total net change over the 200-year period as a result of applying the specified fire management program for 10 years.
[5]"X" percent of the losses resulted from fire. "l-X" percent of the loss was from resulting flooding or sedimentation.
[6]"Y" percent of the losses resulted from fire. "l-Y" percent of the loss was from resulting flooding or sedimentation.

among the decision parameters and the implications of program selection constraints. Steuer and Schuler (1978), for example, describe a multiple-objective linear programming model for forest management which was designed to assist the decisionmaker in selecting a program. Schuler and others (1977) also describe some of the characteristics of goal programming and the type of problems it can most efficiently address. For example, the C + NVC of a program option could carry a relative weight of 1.0 in the objective function and the change in recreation output of 2.0. The risk could be handled as an element in the objective function or treated as a constraint to the solution. This is the same mental process the decisionmaker will follow in evaluating FEES model output anyway. An optimizing routine would simply assist in the program option comparison.

Table 4--*Average annual probabilities of fire size and fireline intensity and expected values for number of fires and acreage burned*

Fire management situation = ________________________.
Program level/ million acres = ______________________.
Fire management mix = ____________________________.

Fire size (acres)	Fire line intensity (BTU/ft)[1] 0-99	100-499	500-999	1000+
	X Y Z	X Y Z	X Y Z	X Y Z
0.25				
0.25 - .9				
1.0 - 9.9				
10.0 - 99.9				
100.0 -999.9				
1000.0+				

[1]X = Probability of that fire size and fire intensity occurring
Y = Expected value (EV) of number of fires/million acres/year
Z = Expected value (EV) of acreage burned/million acres/year

DESIGN OF THE FEES MODEL

The FEES model simulation starts with the user-specified fire program option and a fire management situation. The program option is transformed within FEES into a list of fire management inputs for the fuel treatment and initial attack components of the presuppression program. The fire management situation is similarly subdivided within FEES into homogeneous strata, defined here as "inferred parameter cells." The inferred parameter cells are described by the parameters, such as slope and cover type, which are needed to determine fire program performance. The simulated progress of fires within each homogeneous cell is traced from the time of fire detection through each one of an interrelated set of behavioral modules until suppression costs and net value change are estimated. FEES contains separate modules for fuel treatment, fire behavior, initial attack effectiveness, large fire suppression effectiveness, fire effects, resource values, and cost calculations. Probabilistic results for each inferred parameter cell are then weighted by the fire occurrence probability in that cell. Similar results from all the cells are summed across the fire management situation, providing the model output for one program option.

One execution of the model for a given fire program option produces one C + NVC point on the family of curves and one line of FEES output for the abbreviated display in *table 1.* Systematic changes of the program option and repeated executions of the FEES simulation trace the full family of C + NVC curves and the full display of model output for one fire management situation.

FEES is designed in a modular fashion. The modules are quasi-independent sets of computations (*fig. 7*). The modules all interact with an underlying probability model that passes inputs and outputs between the various modules, condensing output where appropriate. This model structure permits the model builder to refine behavioral relationships in one module (initial attack effectiveness, for example) without forcing major modeling changes in other modules or in the underlying probability model. Each module receives specified input from the probability model. Using that input, each module performs the necessary calculations to yield the output information required for the next step in the model simulation. The transformation from input to output within each module is largely unencumbered by the rest of the model structure.

Inferred Parameter Cells

The parameters used to describe the fire management situation are kept to a minimum (seven) to simplify the fire program planners' interaction with the FEES model. Areas of 1 million acres are not homogeneous in all the variables that influence fire program performance, however, even if they are fairly homogeneous in the fire management situation parameters. Additional parameters are needed within the FEES model to reflect the heterogeneity within the fire management situations and to drive the behavioral relationships in the modules.

FEES accomodates [sic] this heterogeneity internally by stratifying the fire management situation into "kinds of fire sites," termed inferred parameter cells because their composition is inferred from characteristics of the fire management situation. Examples of the parameters that distinguish between inferred parameter cells include slope, aspect, elevation, time of year, time of day, cover type, and cover type age class. Fuel characteristics are inferred from cover type and cover type age class. The net change in timber output and the stumpage price, for example, are much more easily calculated from the cover type inferred parameter than from the more aggregative vegetation class parameter of the fire management situation.

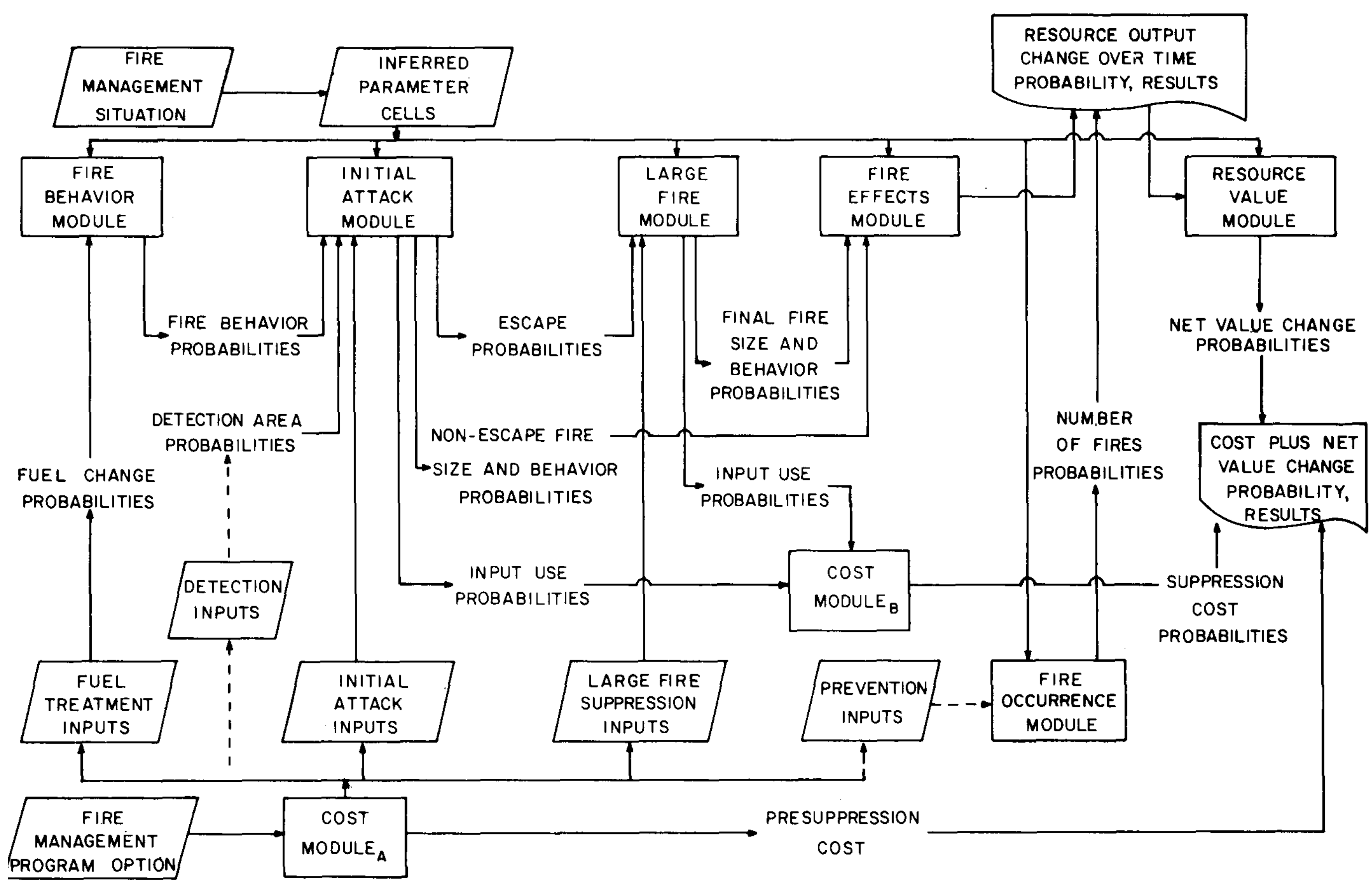

Figure 7--Detailed schematic of FEES shows the modules of this simulation model and their interactions.

An important modeling trade-off is related to the size of the fire management situation. Small fire management situations are more homogeneous. The number of inferred parameters, and classes for each parameter, needed to fully describe the areas for modeling purposes are in turn small. On the other hand, the proportion of the fire management inputs that are shared between fire management situations increases as the fire management situation shrinks. Modeling the probability that shared fire management inputs are available when needed may be as difficult as retaining more heterogeneity in the area description. The optimum modeling size of the fire management situation is related to the true amount of heterogeneity in the area, the amount of fire management input sharing, and difficulty in modeling both of these factors.

The relative frequencies of fires in the various inferred parameter cells within a fire management situation are derived from historical fire occurrence data. The fire occurrences for each cell can be drawn from individual fire reports for actual areas that represent the fire management situation in the fire climate zone. Those same fire occurrence probabilities can be applied to all other areas which have the same fire management situation parameter values. The fire occurrence probabilities for inferred parameters that are not recorded on the fire reports must be inferred from other sources, for example, from acres of certain cover types that are managed for timber production.

The inferred parameter cells, just like the fire management situation itself, are not location- or site-specific but instead are situation-specific. They are hypothetical fire locations just as fire management situations are hypothetical segments of a fire program planning unit. They condense the essence of real fire locations into abstract "kinds of fire locations." They describe homogeneous areas within which "kinds" of fires are simulated from time of detection through containment and on to an assessment of fire effects and resource values. In an actual planning unit, examples of an inferred parameter cell may occur at several locations. This causes no modeling problems, as long as all segments are serviced by the same fire program inputs.

The correct criterion for determining which parameters are needed to distinguish between inferred parameter cells, and therefore kinds of fires, is whether that parameter influences performance of the fire management program. Slope, for example, affects fire behavior, the rate of fireline construction, the cost of silvicultural treatments, timber stumpage prices, peak water discharge, and sediment yield. Similarily [sic], cover type influences fuel model, fireline construction rates, timber yields, stumpage prices, grazing yields and a host of other factors which enter into the C + NVC calculation. Which inferred parameter cell descriptors are finally included in FEES and how many classes are used to represent each parameter is eventually a question of sensitivity of program performance to their exclusion. The logic used above for slope and cover type was used to set the preliminary design of FEES.

The question of site specificity is relevant in this context too. Geographic location is only one parameter that describes a kind of fire. If the behavior of a fire, effectiveness of fire suppression, and fire effects can be determined by the characteristics of the fire site, site specificity provides no additional information for long-term planning. For example, initial attack arrival time is an important input item in the simulation of initial attack effectiveness but it can be drawn empirically from fire report data rather than map locations of fires and initial attack bases.

The output from the respective modules are accumulated and combined at appropriate points through underlying probability computations within the main FEES model. The FEES model produces similar information for each cell. Once joined together by fire occurrence probabilities, that common output provides the output for the whole fire management situation.

Fuel Treatment Module

The amount of fuel treatment activity, by practice or treatment class, is specified in the fire management input list. The fuel treatments are identified by three parameters: pretreatment fuel model, post-treatment fuel model, and method of treatment (Salazar 1981). The Northern Forest Fire Laboratory fuel models (Albini 1976), or groupings of the fuel models if sensitivity analysis demonstrates that the resulting fire behavior does not differ significantly among individual fuel models, are used in FEES. The fuel treatment-induced change in the fuel model "shifts" the treated area from one inferred parameter cell to another based on the change in fuel model. This shift registers within the model through a change in the fire occurrence probability associated with the affected inferred parameter cells. The method of treatment classes are needed for treatment cost estimation.

Only broadcast or broad area fuel treatments, such as the removal of logging slash through mechanical or prescribed burning methods, are included in FEES. Fuelbreak analysis requires juxtapositional information not easily included in a nonsite-specific model. Only fuels management activities directed primarily at hazard reduction are evaluated, although almost any vegetation manipulation has an impact on fire behavior. The total treatment cost should be allocated among the various objectives of the treatment, even though any such allocation rule is arbitrary. Only that portion charged to fire hazard reduction is included in FEES.

Fuel treatments, especially when the method is prescribed burning, do not always produce the targeted post-treatment fuel loadings. In recognition of this variability in fuel treatment performance, the probability of achieving various post-treatment fuel models by means of a given treatment method are included in FEES. A less rigorous modeling approach would be to list only the expected post-treatment fuel model rather than the distribution of actual fuel model outcomes.

Fuel treatments are the only fire management activities that have a major impact on the inferred parameter cell composition of the fire management situation. Many long-term fuel treatment programs can be evaluated within the 10-year program time horizon, but not by repeating the 1-year results for 10 consecutive years. Under certain simplifying assumptions about the nature of the C + NVC change from the initial fire management situation to the situation which exists when all fuel treatments are completed, the efficiency of a multiyear fuel treatment program can be constructed from a sequence of 1-year analyses of different fire management situations.

Fire Behavior Module

The fire behavior module estimates the probabilities of values for the set of fire behavior parameters that are required in the initial attack and fire effects modules (Salazar 1981). The fire behavior parameters required for the initial attack module are forward rate of spread, length-to-width ratio, and fireline intensity. The fire effects module needs scorch height.

The fire behavior values are estimated from inferred parameter cell descriptors and weather variables. The mathematical fire behavior model is adopted from Rothermel (1972) and Albini (1976). Important inferred parameters for fire behavior prediction are slope, aspect, time of day, time of year, and fuel model. Important weather parameters are windspeed and fuel moisture. Since the weather variables are described as probability distributions, the estimated fire behavior parameter values are similarly probability distributions rather than arithmetic means for each inferred parameter cell. This weather variation leads to different "kinds of fires" within each cell.

Fire behavior is simulated from the time of detection until such time as the fire behavior model assumptions of homogeneous fuel, weather, and topography are violated. The fire is assumed to be burning in a steady state at time of detection. The distribution of fire sizes at time of detection are empirically derived from individual fire report forms from the 1960's and then adjusted using data on changes in fire detector classes to reflect subsequent changes in fire detection programs. Use of these historical detection size distributions implicitly assumes the fire detection program is fixed at its historical level and its performance is reflected in the fire size distributions.

When the homogeneity assumptions of the fire behavior model are violated, the fire is identified as "escaped." The fire size at which escape occurs will vary with fuel model and fire climate zone. For example, the contiguous areas of grass fuels are generally larger than areas of slash fuels so the "escape" size is correspondingly larger. The appropriate fire size and burning time homogeneity thresholds can be derived empirically from field studies of the size of homogeneous fuels and terrain, and from homogeneous weather parameters, respectively.

Initial Attack Module

The majority of all fires are contained when they are small, but the few fires which escape initial attack account for almost all of the suppression costs and net value change in resource outputs. The primary objective of the initial attack module then is to estimate the number of escaped fires rather than to model initial attack for its own sake. The initial attack module, as well as the initial attack program, is based on the hypothesis that the percentage of escapes is a function of the size and composition of the initial attack organization. If it were not, the highly dispersed initial attack organization should be disbanded in favor of a more centralized, but highly mobile, large fire suppression organization.

Our hypothesis is that fires can be separated into three subsets by forward rate of spread and fireline intensity. Fires with low spread and intensity can be contained by almost any initial attack organization (subset A) (*fig. 8*). This includes the majority of all fires. Conversely, a smaller set are of such high spread and intensity that they are beyond the technological capability of almost any initial attack organization (subset C). Whether the fires of intermediate spread and intensity (subset B) escape or not is a function of the performance of the initial attack organization.

The initial attack module is constructed to concentrate modeling effort on subset B (Hunter 198la). Fires in subset A are assigned negligible fire sizes and those in subset C are passed directly onto the large fire suppression module. The proportion of all fires which fall into each subset and the relationship between the initial attack program and escape probability will probably vary by fire management situation.

Using fire behavior input, selected inferred parameter cell values, and the list of the fire management inputs, the initial attack module provides output useful in the fire effects, large fire suppression, and cost modules (Hunter 1981a). The module output is joint probability distribu-

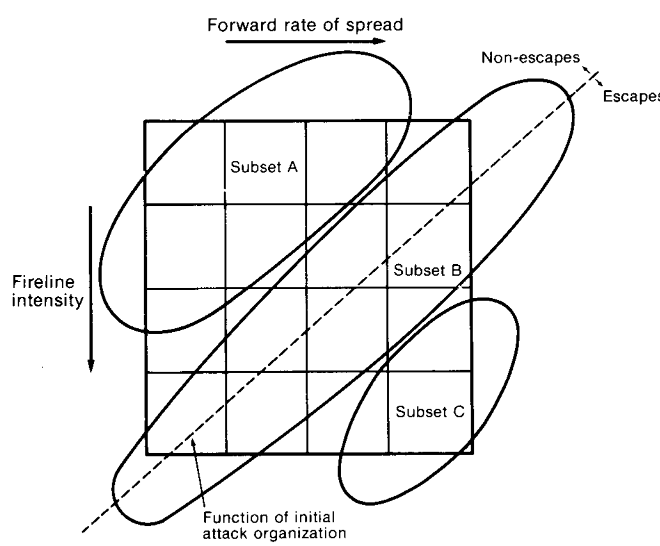

Figure 8--Hypothetical subsets of fire escape potential as a function of forward rate of spread and fireline intensity.

tions of fire size and fire behavior parameters, for the fire effects module; the probability of escape and the fire characteristics at the time of escape, for the large fire suppression module; and the probability of the time that each fire management input is used in initial attack, for the cost module.

The arrival time of attack forces is represented by cumulative distributions of arrival time by fire management input class and fire cause (Hunter 198lb). The arrival time distributions are derived from individual fire report forms (Mees 1981). These empirical arrival time distributions are consistent with the nonsite-specific design of the fire management situation, since information on the juxtaposition between fires and initial attack bases is not required in the derivation or use of the distributions. Historical arrival time distributions are representative of future distributions as long as the location of initial attack bases relative to fire locations does not change over time or with different program options. The arrival time distributions for individual fire management situations can be drawn from a sampling of geographic areas representative of the respective fire management situations.

Rules for dispatching initial attack inputs to fires are drawn from existing preplanned dispatch records and expert opinion. Fireline production rates for various fire management input classes can be adapted from past studies. Because of the wide variability in line production rate estimates (Haven and others 1981), the production rates may be represented as probability distributions rather than point estimates. The distributions can be subjectively derived from an amalgamation of past study results.

One of the more difficult design elements of the initial attack module is the sharing of initial attack inputs among fire management situations or even among competing multiple fires within a single fire management situation. Queuing analysis may provide a method of addressing this problem.

The initial attack module is constructed as a Monte Carlo simulation model. Initiating fire behavior parameters, arrival, times, and line production rates are randomly drawn from their respective distributions. Fires which will obviously be small (subset A) or will obviously escape (subset C) are allocated at this point to avoid a detailed computerized simulation of fire containment. The initial attack containment is then simulated mathematically for the remaining fires (subset B) by using a simplified version of the FOCUS containment algorithm (Bratten and others 1981). Repeated draws from the distributions and subsequent containment simulations are made until a sufficient frequency distribution of module output is achieved.

Large Fire Suppression Module

Once a simulated fire burns out of the inferred parameter cell, the homogeneity assumptions of the fire behavior module are violated. The fire is identified as escaped and is evaluated in the large fire suppression module (Hunter 1981b). Mathematical models which simulate large fires require much data, especially on very heterogeneous fuels and topography, and empirical data from past large fires are too fragmentary to allow construction of an empirical module of large fire suppression effectiveness. Recent attempts using expert opinion gaming to evaluate large fire suppression effectiveness have led to questionable results (Joseph 1981), possibly because the escape fire scenario was described in such general terms that the experts actually perceived different situations and, therefore, provided different answers.

Hunter (1981c), by refining Schultz's (1964) approach, proposed to evaluate large fire suppression effectiveness by using a modified version of expert opinion gaming. The experts are only asked to estimate fire behavior and suppression effectiveness for relatively homogeneous time segments of an escaped fire, rather than for the entire fire. The time segments are described by initiating conditions, such as fire size and contained perimeter. Environmental conditions, such as weather, terrain, and fuel model, are also specified and assumed homogeneous throughout the time segment. Given data on the initiating conditions and available suppression forces, the experts provide probabilistic estimates of suppression force usage and end-of-period fire characteristics, such as fire size and contained perimeter.

This expert opinion gaming process, just like the initial attack module, must be exercised using hypothetical "kinds of fires" to remove the dependence on a location parameter. For example, the experts are asked to game burning event scenarios described by a set of representative photographs and maps.

The gaming results from the time segments are then joined together within the large fire module into complete fires from time of escape through containment time using transition probabilities. These are estimates of the probability that the environmental conditions of one time period will change into some other set of environmental conditions for the next time period, for example, the probability that windspeed will be 10 mi/h in period t+1 if it was 5 mi/h in period t. These probabilities can be drawn empirically from weather records and samples of the size of contiguous area of homogeneous fuel and topography areas.

The outputs of the large fire module are probabilistic estimates of fire size at time of containment and fire behavior throughout the fire, both of which are needed in the fire effects module. The module output also includes probabilistic estimates of suppression force usage which are needed in the cost module.

Cost Module

The cost module performs two functions (Gonzalez-Caban 1981). First, it transforms the fire management program option into the list of fire management inputs available for fuel treatment and initial attack activities. Second, it calculates the suppression costs incurred above the cost of inputs already funded through the initial attack portion of the program level.

Although the cost module includes estimates of the true economic cost of the fire management inputs, rather than the costs from a particular accounting system, not all accounting-like rules can be bypassed. This is especially true in the separation of suppression costs from the cost of actions already funded in the initial attack program. This suppression cost separation is important because one objective of FEES is to measure the trade-off between the initial attack and suppression components of the fire program.

Most public agencies fund their initial attack program from beginning-of-year appropriations, and their suppression actions from emergency, supplemental appropriations during the year. Until we can better predict the severity of the upcoming fire season or until the suppression appropriations are treated as a multiyear revolving account, the suppression activities should continue to be financed through supplemental appropriations rather than beginning-of-year appropriations. Since the various public agencies do have different rules for allocating costs among program components, however, a procedure is needed to transform FEES program level into corresponding budgetary estimates.

The major building block for the cost calculations is the per unit cost of each class of inputs. All costs are allocated to the fire program inputs that actually accomplish the fire management activity. For example, the per hour cost of a Category I hand crew is composed of cost components for salary, supplies, training, facilities, and overhead (McKetta 1981). Other inputs, such as smokejumpers, have additional special training cost. The overhead cost is composed of general administrative overhead (GA) and the cost of the fire program management staff. These overhead costs are equally allocated to each fireline personnel. An annualized cost of all facilities is calculated that reflects the true opportunity cost of the input. The annualized cost calculation includes the initial capital cost, useful life, salvage value, and discount rate. Large fire costs resulting from the onsite fire overhead team, mop up, and demobilization are also included as separate entries in the cost module.

Fire Effects Module

The fire effects module provides estimates of the fire-induced change in resource outputs over time from the fires which occur in each inferred parameter cell (Peterson 1981). Inputs to the module include values of the inferred parameters, such as vegetative cover, slope, and management objective, and the fire behavior characteristics, such as fire size, fireline intensity, residence time, and scorch height.

There are important scope restrictions in the FEES fire effects module that have only been alluded to so far. Only resource outputs which can be reasonably valued in dollars are included. Recreational use is included, for example, but fire effects on rare and endangered plant and animal species are not. The resource actually valued is the one affected by fire and used by humans. Wildlife impacts, for example, are registered as changes in the number of days of consumptive and nonconsumptive use of the wildlife resource, rather than as changes in acres of wildlife habitat or changes in wildlife populations. The wildlife populations or habitat are much more difficult to value than user days. Effects on the fire site and direct offsite effects are included, but secondary effects on local employment and income are not. Fire effects are estimated for various categories of timber, range, water, wildlife and fish, recreation, and improvements (*table 5*).

The fire effects calculation progresses through a four-step process. In the first, the resource output levels over time that would have occurred in the absence of the simulated fires are estimated. The direct physical and biological effects of the fire on each resource are estimated in the second step. For example, tree mortality and the stream flow changes are estimated.

In the third step, the resource output time stream that results from the direct fire effect is estimated, such as the future time stream of timber yields and recreation usage. Management objective or intended resource use plays an important part in determining the postfire resource output levels. This calculation requires establishment of assumptions about rehabilitation actions, such as reseeding grass, that influence the postfire costs and output levels. These assumptions are internally linked within FEES to resource management emphasis. The rehabilitation decision is separable from the fire program decision, and inefficient rehabilitation decisions can influence which fire program is most efficient. Nonetheless, the consequences of the rehabilitation treatment must be reflected in FEES, since they influence the resource output time stream.

In the fourth step, the resource outputs in the presence of fire (step 3) are subtracted from the output level in the absence of fire (step 1), yielding the net change in resource outputs over time for that fire. Since the entire probability distribution of fire behavior characteristics is available as input into the fire effects module, the probability distribution of net change in resource outputs is calculated within the module.

The four steps in fire effects calculation are illustrated in a hypothetical timber example (*fig. 9*). The without-fire

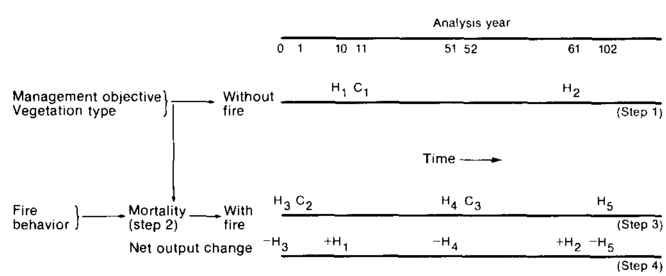

Figure 9--Illustrative net change in timber output shows the effect of fire on the magnitude and timing of costs and harvests.

Table 5--*Resource categories and units of measure used in the FEES fire effects calculations*[1]

Resource and resource elements	Effects	Physical units
Timber:		
Roundwood output[2]	Change in production	Thousand cubic feet
Range:		
Livestock grazing	Change in carrying capacity	Animal unit months
Recreation:		
Developed	Change in use	Recreation visitor-days
Dispersed	Change in use	Recreation visitor-days
Wilderness	Change in use	Recreation visitor-days
Wildlife:		
Hunting	Change in hunter use	Recreation visitor-days
Fishing-Commercial	Reduced take (catch)	Pounds
Fishing-Sport	Change in angler use	Recreation visitor-days
Water:		
Yield usable		
Domestic	Change in quantity	Acre-ft
Agricultural	Change in quantity	Acre-ft
Improvements:		
Public-buildings	Destroyed or damaged	Number of structures
Public-other improvements[3]	Destroyed or damaged	Number of structures
Private-buildings	Destroyed or damaged	Number of structures
Private-other improvements	Destroyed or damaged	Number of structures

[1]Includes only fire effects to which dollar values can be assigned; relative importance of the resources vary by area and characteristics of the simulated fire.

[2]The timber output category is further stratified by cover type. Source: Peterson (1981).

[3]Such as bridges, fences, or catchment basins.

time stream (step 1) would have started with a final harvest of the existing timber stand in 10 years (H_1). That would have been followed by a stand establishment cost (C_1) in analysis year 11 and a subsequent second rotation harvest (H_2) after a 50-year rotation in analysis year 61.

Through consideration of vegetative type, such as tree species and tree size, and fire behavior parameters, such as scorch height, tree mortality is estimated (step 2). Tree mortality, in combination with information about the management objective, such as stand stocking standards, is used to estimate the postfire salvage harvest (H_2). The salvage is followed by a stand establishment cost (C_2) in analysis year 2 and a future harvest (H_4) in analysis year 51. C_2 is the cost of the "rehabilitation" practice in this example. In keeping with the economic efficiency dimension of FEES, only rehabilitation practices that pass a minimum economic efficiency test are included in the FEES time stream. A second rotation starts in analysis year 52 with stand establishment (C_3) and ends in year 102 with final harvest (H_5).

The step 4 estimation at the bottom of *fig. 9* is the harvest time stream witohout [sic] the fire minus the stream with the fire. Entries in the with- and without-fire time streams need to be traced into the future until their corresponding discounted net value change is negligible. Even if harvests H_1, H_2, H_4, and H_5 are of equal volume and the stand establishment costs C_1 and C_3 are of equal magnitude, they will generally occur at different points in time. They must therefore all be included separately, because their discounted values will be different.

The "loss" in this fire effects calculation is the foregone future harvest (H_1) or rather difference in the timing of the harvest. The stand establishment cost which led to H_1 is irrelevant. That past cost is sunk and cannot be recouped, whether there is a fire or not.

Because only those resource output changes on the fire site and direct offsite effects are included, substitution of unburned timber at another location for the burned timber on the fire site is not accounted for, whether the substitution occurs this year or in the future. Alternatively FEES could have been designed to evaluate the fire site resources within the context of the entire planning unit and the administrative policies which regulate resource uses on the planning unit. If this alternative design were pursued, the substitution, otherwise termed "allowable cut effect" (Schweitzer and others 1972, 1973; Lundgren 1973), would lead to a much lower net value change in timber output and a reduced efficiency of the fire management program (Bell and others 1975). Van Wagner (1979) argued for this approach to estimating wildfire effects on timber output. Inclusion of the substitution assumption is pervasive in land management planning analyses on public lands, and it has been used in some individual investment analyses (for example, Sassaman and others 1972). It is a fact which affects the cash flow on public lands managed under an even flow policy where "excess" old-growth timber exists.

These substitutions were not included in FEES because we believe, following Teeguarden's (1973) arguments, that investment funds should be allocated in relationship to inherent productivity of the site affected by the management action rather than site productivity and the institutional setting within which the site lies. Excluding substitution yields a more unencumbered reflection of inherent productivity than does including institutionally induced substitution. The design of FEES is consistent on this point with the fire program analyses reported by Schweitzer and others (1982) and the U.S. Department of Agriculture, Forest Service (1980), but is inconsistent with the operation of land management planning models, such as FORPLAN (Johnson and others 1980).

Resource Value Module

The objective of the resource value module is to estimate net value change by applying per unit resource values to the net physical change in resource outputs and by discounting the resulting net value changes to the present. The present value is an estimate of the net value change from the simulated fires in that one inferred parameter cell.

The correct per unit resource value is the value of the resource actually affected by the fire, for example, stumpage rather than lumber. Where available, appropriate real value changes over time should be considered since the resource output should be valued at the time the output would actually occur. For example, Haynes and others (1980) estimate that real stumpage price changes will occur in the future. To be consistent with the fire program costs, the values should reflect true value to society, rather than any particular land owner.

Faced with these design criteria, we decided that the bases for resource valuation in FEES should be marginal willingness-to-pay (Althaus and Mills 1982). The margin, across which willingness-to-pay is measured, is the change in resource outputs caused by the fire. The marginal willingness-to-pay can be approximated by the prefire per unit value *if* the demand function is very elastic *or* the change in output caused by the fire is small.

Row and others (1981) suggested using a 4 percent real discount rate for long-term forestry investment analyses, but it is doubtful if the longstanding controversy over discount rates is over. Different rates might also be appropriate for different agencies. FEES is, therefore, designed to permit easy modification of the discount rate used in the present value calculation of the net value change and in the estimation of the annualized cost of fire management inputs that have a useful life of greater than 1 year.

The effect of discount rate changes on fire program efficiency may be opposite of its impact on timber growing activities (Blattenberger and others 1982). A reduction in the discount rate improves the economic efficiency of the timber growing activity, but it may decrease the efficiency of the fire program. Consistent with the fire effects calculation procedure, a fire delays future harvest rather than irrevocably removing it. The harvest delay is less important if the interest rate is low.

Per unit values are needed for all the harvest volumes as of the point in time when they occur (*fig. 9*). The net value change (NVC) for this example equals:

$$NVC = -(H_3)(V_3) + \frac{C_2}{(1.04)^1} + \frac{(H_1)(V_1)}{(1.04)^{10}} - \frac{C_1}{(1.04)^{11}}$$

$$\frac{(H_4)(V_4)}{(1.04)^{51}} + \frac{C_3}{(1.04)^{52}} + \frac{(H_2)(V_2)}{(1.04)^{61}} - \frac{(H_5)(V_5)}{(1.04)^{102}}$$

The net value change may be negative (beneficial effect) even if the fire leads to a physical loss in output; that is if H_1 is greater than H_3. This can occur if the salvage value (V_3) approaches the green timber value (V_1), if the mortality loss (H_1 - H_3) is small, and the without fire harvest occurs far in the future. These conditions are approximated whenever the without fire timber rotations are far longer than the financial maturity rotation.

Fire Occurrence Module

The modules discussed to this point simulate fires which occur in one inferred parameter cell. Estimates of the suppression cost, fire-induced changes in resource outputs, and the present value of the net value change are available at this point in the model. The variable fire weather, initial attack arrival times, fireline productivity rates, and large fire suppression effectiveness which entered the various modules influenced the model output for each inferred parameter cell. The output is in the form of probability distributions rather than point estimates or expected values alone.

The last stochastic input, the probability of fire occurrence, is incorporated in the fire occurrence module through a two-step calculation (Bratten 1981a). First, the probability distribution of annual fire occurrences for the whole fire management situation is derived empirically from summarized fire report statistics. The distribution of occurrences in the fire management situation is derived as a function of mean fire occurrence level. The mean occurrence level is one of the seven parameters that define the fire management situation. Second, given one fire in the fire management situation, the probability that it will occur in each of the inferred parameter cells is derived from individual fire reports. The resource change and net value change probabilities for each inferred parameter cell are multiplied by the corresponding fire occurrence probabilities in each cell and summed over the cells to get total probabilities for the fire-induced changes, given a fire in the fire management situation. The numbers of fires and their probabilities are then combined with the change probabilities to yield the FEES outputs for one line in the abbreviated output display (*table 1*).

Probability Calculations

The underlying probability model combines the probability distributions produced by the various modules at appropriate points in the simulation to provide inputs for subsequent modules. The probability computations are continued until the distributions for C + NVC and resource output effects are derived. *Fig. 10* shows the major proba-

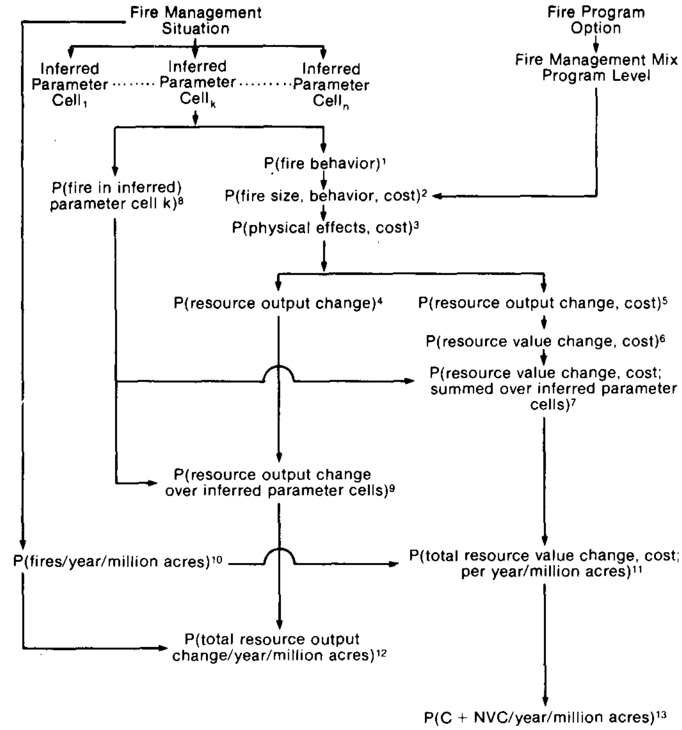

Figure 10--Sequence of combining probability distributions within the FEES model begins with the selection of fire management situation and program option.

bility functions used and the computational flow from the model inputs (Fire Management Situation, Fire Management Mix, and Program Level) to the outputs (Resource Changes and Cost plus Net Resource Value Changes). The functions and relationships shown in *fig. 10* are discussed briefly here, referring to the parenthetical numbers in the figure. A more complete development and discussion is given by Bratten (1981a).

The fire behavior probability function (1) is produced by the fire behavior module. The variables used to describe fire behavior are forward rate of spread and fire intensity which are needed in the modeling of fire spread and suppression force effectiveness. Fire behavior values, such as tree crown scorch height and fire residence time, are needed to model fire effects on forest resources. That is, P (fire behavior) gives the probabilities of sets of values for fire spread rate, intensity, scorch height, and other conditions, for a fire in a given inferred parameter cell of the fire management situation. An inferred parameter cell is a set of values for parameters for a fire location needed to calculate fire behavior and fire effects on land resources given the behavior and results of fire suppression action. Other probabilities are used within the fire behavior module. Weather and fuel probabilities for the inferred parameter cell and fire management situation, for example, are derived from various data sources and used within the module as inputs to a fire behavior model to generate the fire behavior probabilities (Salazar 1981).

The fire behavior variables and their joint probabilities are used as inputs to the initial attack and large fire suppression modules which produce probability function (2) (Hunter 1981c). Probabilities of final fire sizes and suppression costs are calculated by using an initial attack model and, for fires which escape initial attack, the large fire suppression model. Probabilities of fire behavior are then passed on from (1) in the initial attack model or generated in the large fire analysis procedure.

Fire size and fire behavior variables are used to calculate the physical effects of fires on forest resources in the fire effects module. Direct physical effects are measured with variables such as tree mortality, tons of grass burned, and acres of wildlife habitat destroyed. Since each set of values for fire size and behavior has an attached probability (2), the probabilities (3) for the resulting fire effects can be calculated. In some cases, probabilistic models may be used along with the inputs to generate function (3).

Costs have been carried forward from (2) to (3). However, the left-hand branch to (4) in *fig. 10* concerns only resource changes. Costs are not needed. A simple summation of function (3) on costs provides the simplification. Physical effects of fire are translated into changes in forest resource outputs over time. These changes are summed over time, and probabilities are appropriately combined to give probabilities of total resource changes from a fire. Resource changes include variables, such as volume of stumpage, animal unit months of grazing, and recreation visitor-days. These changes are total values calculated by summing all changes (positive and negative) in the time stream following a fire.

In function (5), costs are carried along because this branch of the calculations is concerned with the economic consequences of the fires. The resource changes described above for (4) are the same in (5). Resource changes are translated into dollar value changes, and probabilities are transformed to give function (6). Here, the time stream of value changes is appropriately discounted to give present net values.

All calculations described above (functions 1 to 6) are completed for the fire set in. each inferred parameter cell. The range of outputs of the various modules encompasses the results which might occur (with appropriate probabilities) for any fire in a given inferred parameter cell. Up to this point, results for each cell have been analyzed without considering the liklihood [sic] that a fire might occur in such circumstances. Fire occurrence probability is introduced by function (8).

Functions (4) and (6) in *fig. 10* are conditional probabilities (c.f. Feller 1960). Expression (4) canoe interpreted as "the joint probability of resource changes x_1, x_2, . . . for the various resources is . . . , given that a fire occurs with inferred parameter value set k." When this function is multiplied by function (8) for that cell, the result is the joint probability that a fire has occurred with parameter value k and that the resource changes are x_1, x_2, ... These joint probabilities are then summed over the inferred parameter cells to give total probabilities (9) of resource change values, given a fire in the fire management situation.

The reasoning for function (7) is similar to that given above for function (9). The difference is that suppression costs are carried along in function (7).

We want to produce results from the FEES model which are standarized [sic] for time span and land area. That is, we want quantities of resource change or dollars per million acres for the 10-year planning horizon and the time span of fire effects. These standards are achieved by using numbers of fires per year per million acres in the fire management situation being analyzed. The form of probability function (10) is developed by analysis of historic fire occurrence data. The scale is set by some of the fire management situation parameters, namely, expected numbers of fires per year per million acres for the various fire types.

Functions (7) and (9) are defined, given a fire in the fire management situation. What if there are more than one fire, say N fires? Assumptions are made that the N fires are independent and that the fire consequences are additive. The independence assumption implies that each of the N fires can be assigned to one of the sets of resource change values of function (9), governed only by the probability values. An assignment of all N fires results in a distribution of the N fires over the sets of change values, say n_1 in set 1, n_2 in set 2, etc. The n_1's must add up to N. Mathematically, the probability of a set of n_1's is given by a multinomial probability distribution. The total resource changes for any set of n_1's are calculated, using the additive assumption, by multiplying the change values in set i by n_i and summing over i. Repeating this process for all, or a large sample, of the possible n; sets and summing both of the resource changes and associated probabilities over the sample gives the desired results for N fires. Multiplying by the probability of N fires, function (10) in *fig. 10*, gives the final results (12) for this branch of the model. A strictly analogous process for resource value changes and costs, in place of resource changes, results in function (11) and the final result, function (12).

Sensitivity Analysis and Model Validation

This design of FEES describes a particular level of model sophistication, but it is very difficult to determine *a priori* the most appropriate level of model detail and input data accuracy, especially in a system with many complex interrelationships. The data requirements for FEES are extensive and diverse, ranging from probability distribution estimates of fire weather and fireline productivity to point estimates of tree mortality and recreation value. The cost of tabulating existing data, such as fire occurrences, is fairly low but it is much more costly to generate new data, such as fireline productivity estimates, to refine existing data. Similarly, the cost of constructing the model is sensitive to model detail, especially in the fire behavior, initial attack, and large fire suppression modules. Those costs of data collection and model construction should be balanced against the cost of an errant decision caused by inaccurate FEES output.

Final decisions on the most appropriate model detail and data accuracy will flow from a structured sensitivity analysis conducted with a prototype version of FEES. The sensitivity of the final model output, and fire program selection in turn, is the sensitivity that should influence these decisions. It may not be important for example, that fire behavior is sensitive to windspeed, if the final model output is not highly sensitive to fire behavior.

The detail built into some dimensions of this conceptual design of FEES is less than has been built into some fire planning models, FOCUS for example (Bratten and others 1981), and more than was built into others, for example, the fire planning handbook model constructed for use on National Forests (U.S. Dep. Agric., Forest Serv. 1982a). The level of detail built into the FEES design, at this point, is based on our judgment about how an operational version of the model will perform. We have tried to err on the side of greater detail because it is easier to reduce model detail than to determine from the performance of an aggregative model where more detail is needed. The modular design of FEES will permit selected changes in calculations without major disruptions elsewhere in the model.

Fortunately, there are reasons to believe that the model output is fairly insensitive to some errors. The accuracy of the per unit resource value is important, for example, only if the corresponding resource output is materially affected by fire and if the net change in output occurs soon enough after the fire that its value is not all dissipated through discounting to a present value (Althaus and Mills 1982). The net value change calculation itself tends to cancel out similar errors in the with and without fire time streams of resource output. Similarly, since the C + NVC is a marginal criteria of sorts, errors in one C + NVC are partially canceled [sic]when two C + NVC's are compared. Timber and capital investment improvements were generally the resources affected most in previous fire program analyses (Schweitzer and others 1982; U.S. Dep. Agric., Forest Serv. 1980, 1982b). Wildlife and water impacts were generally small and therefore, errors in their per unit value estimate would have little impact on model output or fire program selection.

Model validation is also important and validation must be distinguished from sensitivity. Validation is the determination of whether model output for a particular fire program option corresponds to what would happen in the real world. Complete analytical validation is particularly difficult to achieve with a model of a highly stochastic process. Even if a FEES fire program option was applied for a year, the only empirical data generated would be for that year's unique combination of weather, fire occurrences, fireline production rate, and large fire suppression effectiveness, that is, only one point on the joint probability distributions. By the time enough years had passed to validate the full probability distribution of model output, secular changes in population and technology will have changed the underlying structure of the system.

With model validation in mind, we designed FEES around empirical relationships whenever possible. Simulation is only used when empirical data are sparse or nonexistent and expert opinion is only proposed when a mathematical simulation is not practical. The fire occurrence, fire weather, most fireline productivity rates, most fire effects. fire program costs, and resource value relationships are empirically derived. The fire behavior, initial attack, and parts of the fire effects modules are largely simulation models even though some of the input data are empirical. Many of the relationships in the large fire suppression module are based on expert opinion.

Attention will be focused on validating the output of individual modules of FEES where the validation task is tractable. If the model pieces are valid, the whole should be valid as well. The empirical modules, such as fire occurrence and resource values, can be validated with standard statistical procedures. The mathematical fire behavior simulation model which underlies the fire behavior module has already been validated in selected circumstances (Salazar 1981). For example, Brown (1972) validated the rate of fire spread predictions in Douglas-fir and ponderosa pine logging slash fuels on sample plots with zero slope under conditions of low wind velocity and low fuel moisture. He concluded that the model-predicted rates were reasonably close to observed rates in the test fires.

The initial attack module can be validated by comparing the actual results of real fires with the model-predicted outcome on similar individual fires. The attack forces which were dispatched in the real fire can be duplicated in the initial attack module and the fire size results can be compared. The large fire suppression module can be similarly validated by comparing the historical record of actual large fires with the expert opinion results from a similar hypothetical large fire.

While short of a complete mathematical validation of the model, these steps, in addition to reasonableness checks by knowledgeable people, is probably all the validation that is possible. If enough empirical data were available to completely validate the model analytically, there would be enough data to design an empirical version of FEES rather than a model which relies on simulation and expert opinion modules.

APPLICATION OF FEES

The FEES design to this point could be applied in a number of ways and still meet its objective of providing a first screening of fire management program options at the subregional level of resolution. One alternative is to provide a computer software package to fire program planners. The program planner would then collect all the necessary model input data, such as resource values and fireline productivity rates, and operate the model. This is the alternative which was followed with FOCUS (Bratten and others 1981) and FORPLAN (Johnson and others 1980). This approach is justified if the program planner has unique data and the necessary expertise to operate the model. A disadvantage of this approach is the cost of preparing all the necessary user software material and the cost of training. Another possible outcome is inconsistent data collection or model operation among planning units. Inconsistencies in model use could influence the allocation of fire program funding among competing fire planning areas.

A preferable alternative is the collection of data and operation of FEES at a central location for a wide range of fire management situations and fire program options. The results of this centralized model operation would be printed as a *FEES Guidebook* containing pages of output similar to *table 1.* This alternative has lower training costs; the consistency of data and model operation would improve; and the local program planner could still make interpretations of the output for a particular area.

Once completed, the FEES system output would contain fire program information and analysis procedures to assist the program planner and decisionmaker select a fire program option. The system would contain (1) a key for sorting among the fire management situations to locate the one which most closely resembles a given portion of the planning unit; (2) separate sets of FEES model output for each fire management situation; (3) optimization procedures which would assist in the selection among competing program options using relative weights set by the local deci-

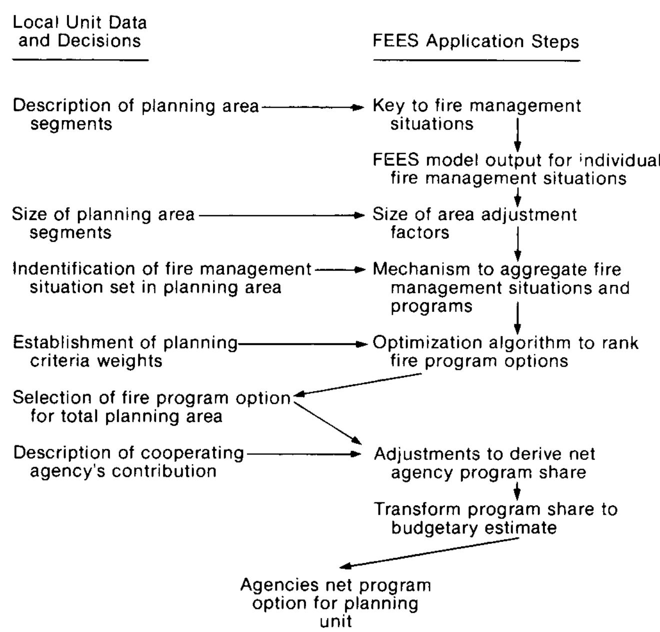

Figure 11--Steps in the application of FEES to identify the fire program for a planning unit of a particular agency.

sionmaker; (4) procedures for scaling results from the standard 1-million-acre fire management situation size to the acreage of the actual planning unit segments; and (5) instructions on how to combine the fire management situations into a cohesive fire program for the planning unit (*fig. 11*). The program level and fire management mix would then be adjusted by the net program contributions of cooperating agencies, and the economic program costs would be converted into budgetary figures relevant for the particular agency. These same steps would apply for any of the public agencies with fire management responsibilities.

Centralized data collection and operation of FEES should not be confused with centralized fire program decisionmaking any more than centralized development of timber yield tables means that timber management decisionmaking is centralized. The FEES output must still be interpreted at the local level and the relative weights among the various outputs must be assigned by someone familiar with the local ramifications of a particular fire program selection. FEES is not designed to be a total decisionmaking model. It simply provides some of the information which is relevant to fire program selection.

The institutional setting within which FEES is used is an important consideration in the interpretation of the output. Management constraints should be the *output* of natural resource program planning rather than an *input* to the planning process.

FEES will estimate economic efficiency, resource output change, and risk relatively unfettered by most institutional constraints. For example, the net change in timber output is estimated by considering only the timber on the fire site. Substitution of unburned timber at another location for burned timber on the fire site is not included in FEES design. Substitution, both temporal and spatial, is relevant only if the fire program analysis is fully submerged within the institutional setting of a planning unit. Similarly, a legislative mandate in some States to suppress all wildfires, irrespective of cost or potential net value change, is excluded from the FEES design. That constraint would artificially restrict the range of technologically feasible initial fire program options evaluated.

Some constraints are included in portions of the FEES design, however. Currently applied rehabilitation practices are included, for example, subject to an economic efficiency screening. Similarly, the timber rotations included in the timber net value change calculations are set by the predominant rotation age in the particular climate zone. That rotation age, if drawn from public lands, more closely approximates the age when mean annual timber increment is maximized than when financial maturity occurs and the rotation age is influenced by the timber even flow constraint.

There are several reasons why the minor management constraints were not excluded from the FEES design. First, the scope of the FEES model had to stop at some point. Including an economic efficiency evaluation of postfire rehabilitation options within FEES, for example, would have led to a model of unmanageable size. The constraints or management directions that were retained were the minor ones which will probably have a small impact on fire program efficiency if they are subjected to an approximate efficiency test.

The final fire program selection may well be other than the most economically efficient program as identified by FEES results. Whether the final fire management program selection is the result of institutional constraints or the consideration of additional fire system effects, at least the FEES output will display the foregone efficiency and risk consequences of those considerations and other effects.

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The Forest Service, U.S. Department of Agriculture, is responsible for Federal leadership in forestry. It carries out this role through four main activities:

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Mills, Thomas J.; Bratten, Frederick W. **FEES: design of a *F*ire *E*conomics *E*valuation *S*ystem.** Gen. Tech. Rep. PSW 65. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1982. 26 p.

The Fire Economics Evaluation System (FEES)--a simulation model--is being designed for long-term planning application by all public agencies with wildland fire management responsibilities. A fully operational version of FEES will be capable of estimating the economic efficiency, fire-induced changes in resource outputs, and risk characteristics of a range of fire management program options. Risk is described by the probability distributions of economic efficiency and resource output changes that result from annual variation in factors such as fire occurrences and fire weather. Particular attention is given to the fuel treatments, initial attack, and large fire suppression portions of the fire management program. FEES evaluates the performance of fire management program options as they are applied to particular fire management "situations," described by parameters which influence program performance, such as vegetation, topography, resource management objective, and fire occurrence levels. Location is addressed only through the regional fire climate zone. The situation-specific design, as opposed to location- or site-specific design, was chosen to avoid duplication of data collection and analysis costs. Duplication costs occur when site-specific planning models are applied independently to planning areas even though the characteristics of the area which influence fire program performance are essentially the same.

Retrieval Terms: economic efficiency, risk, fire suppression, probability model, fire effects