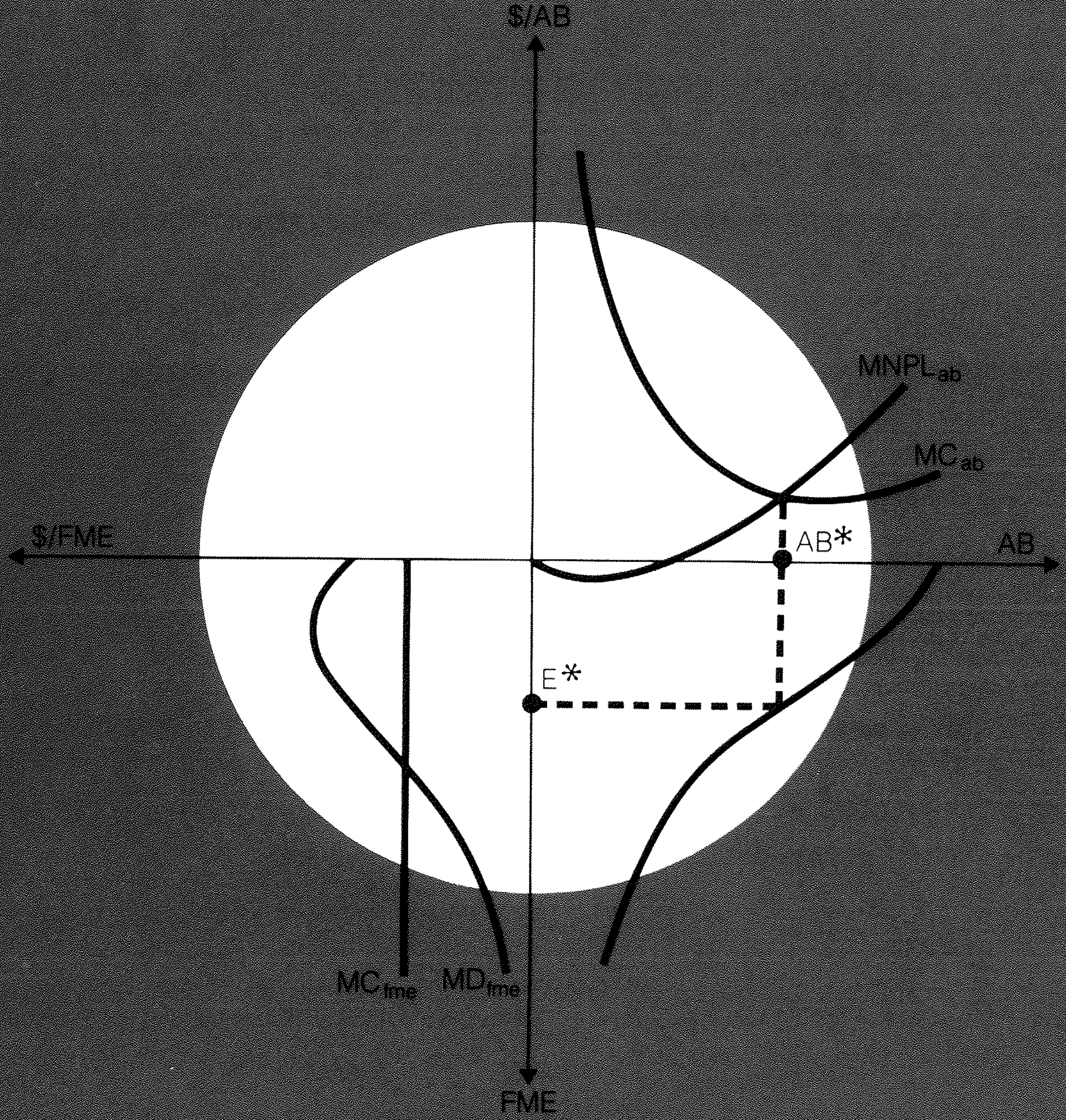
Wildland Fire Management:

The Economics of Policy Alternatives

A.J. Simard



WILDLAND FIRE MANAGEMENT: THE ECONOMICS OF POLICY ALTERNATIVES

by

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Résumé en français

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PREFACE

The purpose of this paper is to discuss the application of a few basic concepts from the field of economics to the field of wildland fire management. The paper is intended for management at the planning level as well as the academic community. Thus, many terms have been defined and numerous examples given to aid in understanding the presentation. Unfortunately, such an approach tends to lengthen a paper significantly. Better, however, a lengthy paper, where parts can be skimmed over, than a short paper, where understanding is adversely affected. For those with an interest in brevity, a summary has been provided.

Most of this paper is concerned with wildland fire management for control. A basic assumption of this aspect of fire management is that most uncontrolled fires result in undesirable impacts. If the impact of an uncontrolled fire could be placed in economic terms, the equation

$$NPV = B - D - C$$

where: NPV = net present value of the fire
D = damage (undesirable impacts)
C = suppression costs
B = benefits (desirable impacts)

would have a negative value. Hence losses exceed benefits, or net damage has occurred. This assumption is inherent throughout the first five sections of this paper. The case where NPV is positive will be considered in Section VI.

To readers with a reasonable background in economics, Sections II, V, and VI would probably be the main areas of interest in that they purport to present a new look at some old questions. Section I is included primarily as background. Sections III and IV are included primarily for the sake of completeness. Although the latter sections do not present any new concepts, their sporadic application in the fire management field suggests that a review is well worthwhile.

CONTENTS

ABSTRACT

The historical development of practical and economic wildland fire management policies is briefly traced. The main emphasis of the paper is on the economic approach. The economic theory is a function of three elements: cost, production, and net present loss. The production function is the key element of the theory.

Costs are classified into variable and fixed, the latter being further subdivided into short- and long-run. The need for using net present value with respect to the latter is discussed. As defined in this paper, there are three factors of production: fire occurrence, fire control, and fuel management. A theoretical procedure for determining the optimum mix of production factors is discussed. Net present loss consists of damage and benefits. There are three categories of damage, based on the person to whom the damage accrues: the owner, the user, and others. Actual value lost to each category is affected by substitutability and a risk premium. The importance of market processes in relation to damage assessment is also considered. Lastly, the effect of beneficial impacts of wildland fire is discussed.

RÉSUMÉ

L'auteur fait une brève récapitulation des mesures pratiques et économiques sur lesquelles se fonde la gestion des feux de forêt. Il appuie surtout sur l'aspect économique. La théorie économique, est fonction de trois éléments: les coûts, la production et la perte nette actuelle. La production représente l'élément clé de la théorie.

L'auteur classe les coûts en coûts variables et fixes, ces derniers se subdivisant à leur tour en deux catégories: à court et à long terme. Il discute de la nécessité de mettre en relation la valeur nette actuelle et les coûts fixes à long terme. L'étude mentionne trois facteurs de production, soit la fréquence des feux, la lutte contre les feux et la gestion des combustibles, et expose une méthode théorique permettant de déterminer la combinaison optimale de ces facteurs. L'ensemble des dommages et bénéfices constitue la perte nette actuelle. Les dommages se subdivisent en trois catégories établies en fonction de la personne qui les subit: le propriétaire, l'usager et les autres. La valeur réelle perdue varie selon les possibilités de remplacement et le coût de la protection pour chaque catégorie de dommages. L'auteur traite également de l'importance des procédés de mise en marché par rapport à l'évaluation des dommages et il discute, en dernier lieu, des effets bénéfiques des incendies forestiers.

WILDLAND FIRE MANAGEMENT: THE ECONOMICS OF POLICY ALTERNATIVES

A.J. SIMARD

I. THE FIRST 60 YEARS

The term "wildland fire management" is of sufficiently recent origin that a definition would be appropriate at the outset of this paper. Wildland fire management can be defined as:

> The application of management, physical, and ecological principles to the management of the wildland fire process so as to render the impact of wildland fire on the natural resource base, the ecosystem, and the environment consistent with the goals of the managing organization.

Wildland fire management includes the traditional fire control related activities (suppression, detection, etc.), as well as broader relationships between fire and wildland management, such as prescribed fire and fuel management.

A wildland fire management system, like any man-made system, functions most efficiently if it has an objective to guide its activities. Policy formulation is most effectively coordinated if it centers around a specific, measurable objective. This has been recognized since organized forest fire "protection" began around the turn of the century. It was in the formative years that two schools of thought concerning fire management objectives developed. The two schools can be referred to as the practical approach and the economic approach. Both approaches have persisted for more than half a century, and both are likely to persist for some time.

A. The Practical Approach

The practical approach to fire management encompasses a broad list of objectives and related policies. Their essential cohesive characteristic is that they are all, in some sense, operationally measurable. Thus one basic requirement of an effective objective is met. This characteristic is the strongest argument in favor of using the practical approach. It is so strong in fact that every fire management organization in North America today uses some form of practical objective to guide policy formulation and management plans.

The first objectives were very practical. Show and Kotok (1923) state that in the period from 1910 to 1915 the predominant objective was simply to reduce the area burned. Human and monetary losses from large, uncontrolled fires were enormous (Pinchot 1903). The initially huge disparity between the magnitude of the task and the resources available precluded the possibility of too much protection. Thus, the foregoing simple, open-ended objective was both adequate and appropriate for the conditions under which it was applied.

Dubois (1914) appears to have been the first to consider the amount of protection needed. This suggests that the fatal weakness of an unconstrained minimization of area burned (infinite resources are needed to reduce area burned to zero) had already become apparent.

By the early 1920's, the "acceptable annual area burned" objective had become firmly established, thus implying a limit on the amount of effort that would be expended. Its strongest supporters were Show and Kotok (1923, 1929), who published several articles advocating its adoption. In 1930 they modified the objective to include a subjective estimation of relative damage by fuel types, in an attempt to remove one of the most serious drawbacks of the objective (the assumption that all areas are equally susceptible to and damaged by fire). This modified version was proposed for adoption across Canada by Beall (1949), and remains today the major guide for fire management planning in Canada (MacTavish 1965). Perhaps the most significant weakness of this objective is that no basis exists for objectively establishing an acceptable annual area burned. The origins of the goal most commonly cited (0.1% of the protected area) are unclear, and at best cannot withstand any rigorous test of justification. The persistence of the acceptable annual area burned criterion, despite its serious drawbacks, suggests that the method has considerable practical appeal.

Headley (1943) states that the importance of aggressive speed in suppressing fires was first emphasized as early as 1915. The need for fast initial attack was decisively shown by Sparhawk (1925). Show and Kotok (1930) determined an elapsed time policy needed to achieve their recommended acceptable annual area burned objective. Arnold (1949) developed a more general fire control objective based on elapsed time between detection and initial attack. While elapsed time objectives might be considered superior to those discussed previously, they also have serious drawbacks. They do not consider the effect of fire size at the time of detection or the strength of the initial attack force. Despite these and other limitations, however, elapsed time criteria have a great deal of appeal because they can be used directly as management planning guides.

In the mid 1920's elapsed time objectives were expanded to include the entire control operation, thereby eliminating some of their major weaknesses. In 1935 the "10 o'clock" policy was officially adopted by the U.S. Forest Service, and it remains operational today. Additionally, this type of policy is often implied (though not necessarily stated) in the fire control plans of many suppression organizations throughout North America. Its strongest point is its relationship to fire behavior, in that large fires not controlled by morning are not likely to be controlled until the next night.

In essence, the 10 o'clock policy states that all fires will be controlled during the first few hours if possible. Failing that, an attempt will be made to control the fire by the end of the first work period. Lastly, "failing in this effort, the attack each succeeding day will be planned and executed with the aim, without reservation, of obtaining control before 10 o'clock of the next morning." While this objective has fewer faults than those discussed previously, it also has drawbacks. It implies the use of unlimited resources in an attempt to control escaped fires as quickly as possible - clearly not necessarily an efficient strategy. While the 10 a.m. control time may be a reasonable average, it certainly is not applicable in all situations. The policy tends to encourage excessive expenditures, which is as serious a failing as previous policies that simply ignored costs altogether. To quote Headley (1943)

> Discretion on the part of men in charge is relied upon to avoid applications of the policy when that would lead to unprofitable extremes. . .it is certainly not a happy state of affairs when. . .an important official policy. . .does not mean what it says but must be applied only when it is good judgement to do so.

A number of other objectives have been suggested from time to time, none of which has achieved major stature. Nonmeasurable goals such as "adequate fire control" or "to get the required coverage" can be dismissed without comment as their drawbacks are readily apparent. A selection of measurable objectives is presented below with brief comment. For a more detailed discussion, see Headley (1943), from whom these selections were made.

1. Complete fire exclusion, or no fires more than 1/4 acre. — There are some small, very high value areas (such as cottage sites and research forests) where this level of management is probably justifiable. It is generally recognized that, while this level of management is technically feasible, the cost would be prohibitive if even moderate-sized areas were considered.

2. Holding fires of 10 acres (4 hectares) or more to not more than 15% of the total number of fires. – This has two problems: the goal is arbitrary (why not, for example, 25 acres and 10%?); and how does the manager decide a priori which fires to reduce in size?

3. Catch every fire while still small. – This is similar to the fire exclusion objective and has the same faults.

4. A maximum size of 2,000 acres (800 hectares) for any fire. – Again, this requires an a priori determination of which fires require special attention. In addition, in some cases, a 2,000-acre fire could be devastating.

5. To carry out the fire control plan. – This suggests that once some effort has gone into developing a plan, the plan becomes the objective, rather than a means to reach a desirable objective. It might be suspected that as the degree of centralized control in an organization increases, the probability of encountering this policy also increases.

Finally, all these objectives and policies are lacking in that none consider the complete fire management system. Thus none of the foregoing policies could be expected to yield an optimal level of fire management. As previously mentioned, however, they have an enormous advantage in that they are measurable in practice. As a result, despite the lack of theoretical rigor of practical objectives, they are being universally applied by fire management agencies. This does not imply that economic criteria, such as costs and resource values, are being ignored today. It is not uncommon, for example, to see resource acquisition being related to some measure of costs and productivity, or resource allocation to a relative land valuation scheme. What is not done, however, is to relate the overall level of fire management to the benefits provided by the system.

Economic objectives for determining the intensity of fire management, while theoretically unassailable, currently have the drawback of not being measurable with sufficient accuracy to satisfy fire management policy-makers. Despite the current difficulties, economic objectives remain the ultimate goal. Thus they warrant a detailed discussion, which is the purpose of the remainder of this paper.

B. The Economic Approach

The economic theory of fire management is as old as limited practical objectives. Headley (1916) first proposed an economic approach to fire control objectives (Show and Kotok 1923). Examination of earlier literature suggests that costs and losses were an important consideration in the earliest days of fire protection. Pinchot (1903), in one of the earliest references calling attention to the need for forest protection, lists human and economic losses attributable to large uncontrolled conflagrations of the past. Stirling (1906) states:

> That it would be a paying business for states to invest in forest-fire protection does not need to be demonstrated here.

Greeley (1911) concludes:

> The patrol force which each national forest should carry and its intensity as between forests must be determined by a close analysis (1) of the relative values of the property at stake and (2) of the relative fire hazard.

It may be concluded from the above that at no time in the history of fire management was the importance of costs and losses unrecognized.

The economic or least-cost-plus-loss theory of fire control was formally presented by Sparhawk (1925). His classic diagram remains the standard reference today. Its essential form has been reproduced in Fig. 1.

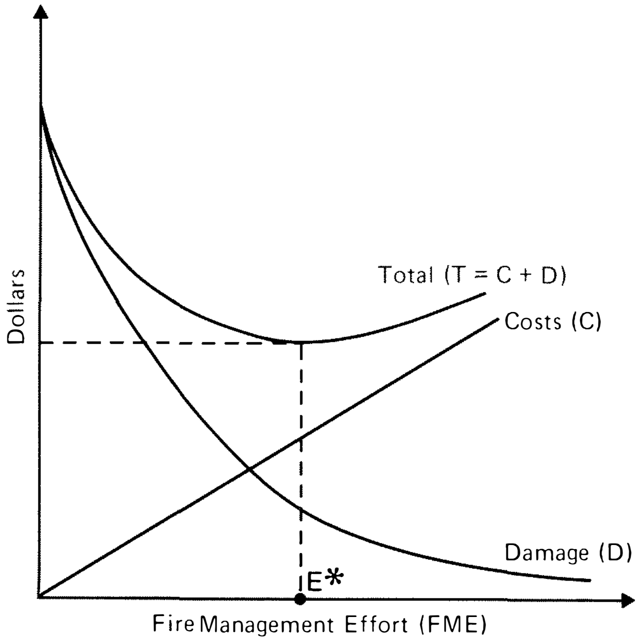

Figure 1. The least-cost-plus-loss (economic) theory.

In essence, the theory states that as fire management expenditures (C) are increased linearly, damage (D) decreases at a decreasing rate. Total expenditures (T) are simply the sum C + D. The optimum level of effort (E*) is at the point where T is minimized.

The theory is not without faults. McLean (1970) suggests that the economic theory "conceals more than it reveals about the derived demand for fire protection." This statement is more likely a reflection of the confusion resulting from the traditional method of presentation than a basic fault with the theory itself. Both costs and losses are typically shown as functions of some measure of fire management effort. Measurement units used to describe fire management effort include primary or presuppression expenditures, manpower (crew size, manpower equivalent), reduction in area burned, elapsed time to the start of suppression or control, and protection output. It is interesting that the diagram remains little altered regardless of how the horizontal axis is defined. To suggest that this can lead to confusion would appear to be somewhat of an understatement. Adding further to the confusion is the fact that costs and damage are related through a production function, which is somehow incorporated in the pair of curves, often without explicit definition.

Despite the potential for confusion, the strong appeal of such a simple yet seemingly ideal policy criterion is evidenced by the numerous references to it in the literature. Interestingly, most references deal with the desirability of applying the criterion rather than with attempts at application. None of the attempted applications were considered sufficiently successful to warrant field trials. Despite repeated frustrated attempts to solve the problem, research is continuing. The persistence of this line of research in spite of the obstacles is strong evidence of the desirability of applying such a goal to forest fire management policy formulation. The obvious question that follows is: why is the problem so intractable?

Initially, investigators were confronted with a paucity of data. Many felt that if enough good-quality data could be obtained, the problem could be solved. In the 50 years since Sparhawk's original 1925 article, considerable quantities of good-quality data have gradually been made available, yet the problem remains unsolved. Although it was concluded as recently as 1969 by Gamache that the data base is still insufficient, it was shown by Simard et al. (1973) that a great mass of suitable data can be made available by applying appropriate computer, data-processing, statistical, and analytic techniques to individual forest fire report data. This argument suggests that a lack of data is not the only problem.

Other difficulties were, in fact, recognized in the early years. For example, as pointed out by Show and Kotok (1923) in their criticism of the economic theory, so many factors have to be considered that, even if the problem could be solved for one forest, it is unlikely that another area would be similar enough for the original results to be applicable. This argument can also be applied to the measurement of fire danger rating. Yet with the use of appropriate tables, the fire danger in any area, regardless of its unique combination of circumstances, can be rated. This is so because, over the years, an understanding of the basic mechanisms has been developed. Thus, uniqueness is not the only problem.

The difficulties faced by early researchers led some to consider alternative methods for arriving at an economic solution. Flint (1924) and Coyle (1929) compared forest fire costs and losses with their urban counterparts. They both concluded that, per unit of value protected, forest fire control agencies spent about twice as much as their urban counterparts and suffered losses about twice as great. In retrospect, this is not suprising, considering the totally different environments within which the two systems operate. Urban fire departments have economies of scale (resulting from high value per unit of area protected) combined with an infrastructure (paved streets, fire hydrants, etc.), much of which is available at little or no cost to the urban fire service. Forest fire management organizations will never be blessed with these advantages.

If the costs of the infrastructure upon which the urban fire department is based were included as part of the calculations, a very different conclusion would probably be reached. Failing this, comparisons of the two operations are not likely to shed much light, particularly in a quantitative sense, on the problem of determining forest fire management objectives.

In all likelihood, the major stumbling block to determining a practical solution based on the economic theory was the lack of sophistication of the analytical techniques then in general use. The techniques simply were not sufficiently powerful to solve a problem as complex as the economic theory turned out to be. During the last decade, developments in systems analysis and operations research have found increasing applications in forest management. The power of techniques such as mathematical programming is orders of magnitude greater than earlier procedures. Simulation and systems dynamics can be used to analyze the most complex problems. Even though optimal solutions cannot be derived with the last two techniques, a great deal of understanding about a system can be acquired. Part of the power of the techniques stems from the fact that they are computer oriented, with the result that, even for massive problems, solutions can be computed with considerable speed.

A few other recent developments are of significance with respect to the economic theory. Parks (1963) expressed an economic fire management model in mathematical terms, which he then optimized with classical mathematical techniques. While his results are considered too theoretical to be applied, his approach is significant in that it was a major step in what appears to be the right direction.

In a separate development, Davis (1965) and Gamache (1969) demonstrated that the economic theory of fire management was compatible with production theory as applied in the field of economics. As a result, a well-developed body of knowledge from the field of economics can be brought to bear on the problem. Thus, for the first time it would appear that the final barrier to solving the economic theory of fire management has been removed, and that a practical solution is in fact obtainable.

II. THE BASIC ECONOMIC THEORY

In this section, we will consider the basic economic theory. It is referred to as basic at this point because only the damage portion of net present value is incorporated. This will suffice for the purpose of the present discussion. The complete theory will be presented in Section VI. We begin with a brief description of the three functions of which the economic theory is composed: damage, production and cost.

A. The Components

1. The Damage Function

It is generally agreed that as area burned increases, damage (undesirable impacts of fire) increases more than proportionally. Fig. 2 illustrates this behavior.

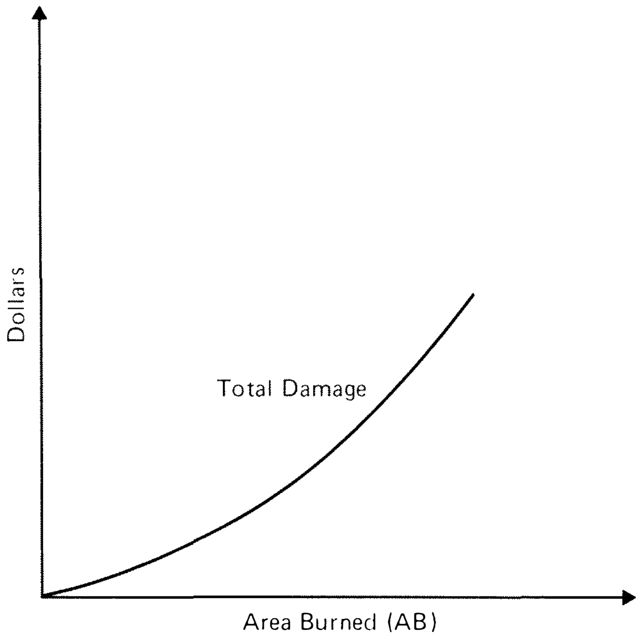

Figure 2. Relationship between damage and area burned (The Damage Function).

It can be intuitively argued that over a long term, area burned increases primarily as a result of an increased number of larger fires. Many decades of empirical observations indicate that, in general, large fires, owing to their tendencies towards higher intensities, cause considerably more damage than many smaller fires of equal total size. The form of the function is also supported by a second, completely different argument. From an economic point of view, there is decreased substitutability (and hence increased opportunity costs due to losses of value) as more and more acreage is damaged by fire. For example, a loss of 1 hectare out of a 1,000 hectare homogenous tract would be of little concern, as 999 other hectares would remain. If the hectare were the last one, however, and there were no comparable substitutes, the loss could be considerable. Thus, the above relationship appears to be reasonable. This function consists of a combination of technical and economic variables. Given that a fire has burned some area, the effects must be assessed (technical) and the market value of the effects must be determined (economic).

2. The Production Function

The production function relates the level of fire management effort to area burned. In terms of production theory, it relates the inputs, or factors of production, to system output. The production function incorporates productivity as well as the dynamic aspects of each production factor. In general, the production function can be written as:

(1) AB = f(FME)

where:
AB = area burned
FME = fire management effort

Classical production theory suggests that the relationship would be of the form shown in Fig. 3. Initially, increasing the fire management effort results in more than proportional returns to scale, in that combinations of factors can be used most effectively. Eventually, continued increases in fire management effort result in less than proportional returns to scale because resources remain idle for progressively longer periods.

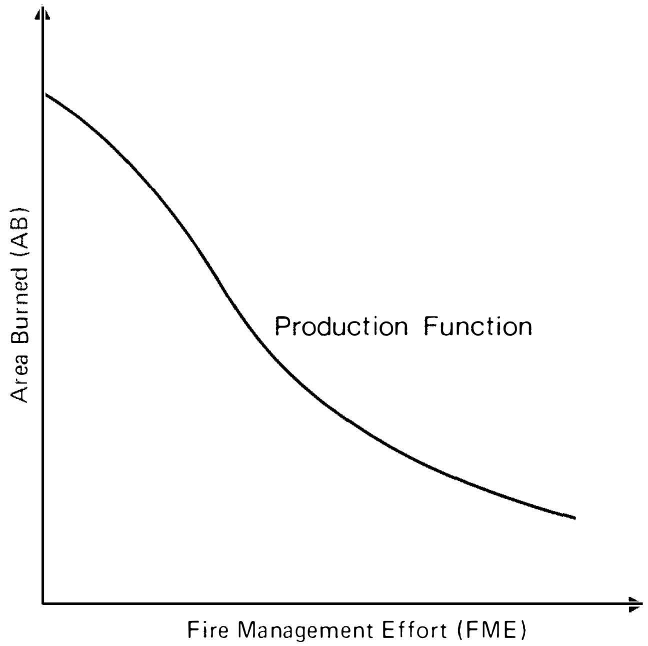

Figure 3. Relationship between fire management effort and area burned (The Production Function).

Intuitively, given a fixed fire load, the more resources that are brought to bear, the smaller will be the percentage of the total effort accounted for by each resource. Thus, in a sense the law of diminishing returns can be said to apply, even though all production factors are being increased simultaneously. The reason is that the fire load is fixed and that, like a plant, it imposes a limit on the productivity of continuously increasing factors of production. The only difference is that, in the case of manufacturing facilities, the limit results from overcrowding, whereas in the case of a fire management system, it results from a fixed work load. Another difference between Fig. 3 and the traditional production curve is that area burned is, in fact, the inverse of production. The usefulness of plotting Fig. 3 in this manner will be evident subsequently.

Before leaving the production function, a digression into units of measurement for FME would be in order. Elapsed time can be readily dismissed as it reflects only one aspect of the fire management system. Protection output and reduction in area burned are undesirable, because these are simply the inverse of area burned, the dependent axis of Fig. 3. Fire management expenditures, such as primary (presuppression) expenditures, have a similar weakness, in that they are directly related to the cost function. What is needed is a technical combination of the production factors that is not a measure of either area burned or costs.

Manpower (number of men, crew size, suppression force) is less than ideal, but it is a step in the right direction. The use of manpower alone is inadequate because it reflects only part of the suppression activity. This deficiency is alleviated somewhat by the use of manpower equivalent, on the assumption that it is possible to determine functions relating each type of fire suppression equipment to an equivalent productivity for manpower. Manpower equivalent has two drawbacks, however. First, it is a static concept applied to a dynamic problem. For example, how does one compare the effect of differences in travel time between two dissimilar suppression factors? A second drawback is that as traditionally defined, manpower equivalent is a measurement of the suppression activity only, and is therefore only part of the overall fire management effort. These deficiencies apply equally to elapsed travel time and time to control, as well as to a percentage of fires controlled at less than a predetermined size, or within a predetermined time interval.

The foregoing problems can be circumvented somewhat by modifying the derivation of manpower equivalent. To begin, consider measuring the level of fire management effort in units of resource availability rather than in resource productivity. Thus, it can be said that there are x units of manpower, y units of bulldozers, z units of airtankers, etc. The production function relates resource productivity, and hence the dynamic aspects of suppression, to system output. Thus, the need to consider time is transferred from the aggregation process to the production function.

It now remains only to establish a common unit of measurement. Man-years (months, days, etc.) will obviously suffice for manpower, and man-year equivalent can readily be used for other factors of production. By using an average wage, the cost of each factor of production can be equated to man-years. It should be emphasized that units of resource availability are being measured, and not costs. Costs are simply used to equate the various resources. This is an important distinction. The production function itself is entirely technical. It relates factors of production to output without consideration of costs.

The level of fuel management activities can be measured in terms of resource utilization. In other words, how much effort is being expended to manage the fuel complex? The number of man-years (and man-year equivalents) utilized can readily be computed. Thus, man-year equivalents can be used as a common unit of measurement for resource utilization as well as resource availability. Fire occurrence activities contain a mixture of components. Fixed components, contracted for the beginning of the season (towers, aircraft, prevention media presentations, etc.), can be related to resource availability. Variable components (detection flights, personal visits, etc.) can be related to resource utilization. Thus, fire occurrence activities present no additional problems of measurement.

Man-year equivalent is thus an appropriate measurement unit for fire management effort. With it, the availability or utilization of a wide variety of resources can be measured on a common scale, equated only on the basis of the cost of the resources.

3. The Cost Function

The last relationship needed to complete the economic theory of fire management is that between costs and the level of fire management effort. As can be seen in Fig. 4, total costs increase linearly with constant increases in fire management effort. The linear relationship does not imply no economies of scale, however. As pointed out by McLean (1970), forest fire management "is an excellent example of an 'industry' with increasing returns to scale over the entire range of demand." The apparent anomaly can be explained by noting that economies of scale relate productively to costs. In Fig. 4, we are relating resources to costs. Clearly the two are not equivalent. In theory, the function in Fig. 4 would curve downward slightly because at higher effort levels some resources would be acquired in sufficient quantities that discounts could be obtained. It is felt, however, that this would not have a major effect on the total cost function.

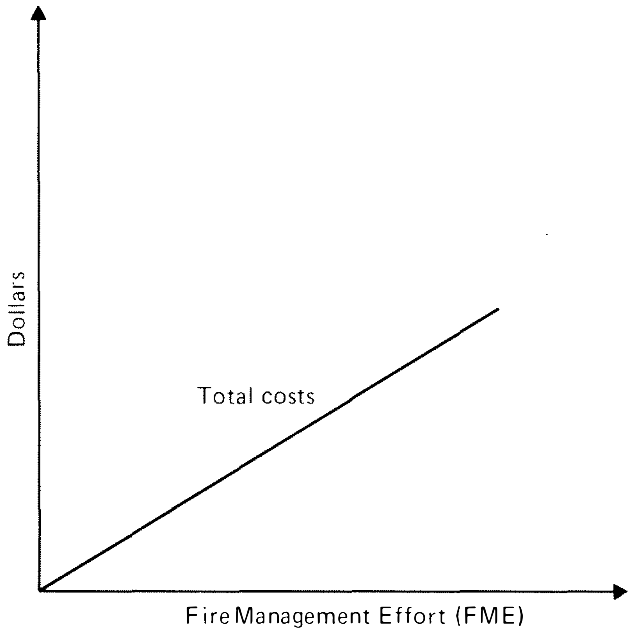

Figure 4. Relationship between costs and fire management effort (The Cost Function).

To summarize, fire management is essentially a production process composed of three functions:

1. Money is spent to acquire factors of production (cost function).
2. Factors of production are employed to produce an output (production function).
3. The output generates economic returns (damage function).

B. The Theory

In presenting three curves rather than the usual two, the preceding discussion departs from the traditional approach. A further departure will now be made in the manner in which the curves are combined. A number of authors have adapted techniques from other fields in an attempt to derive a workable solution to the fire management problem. One of the more interesting recent attempts was the comparison of flood control and fire management planning by MacTavish (1965). While he concluded that the technical difficulties facing the fire management planner were significantly greater than those faced by the flood control planner, his was a step in the right direction.

A well-known problem in which the economic aspects even more closely resemble forest fire management is that of pollution control. Both forest fires and pollution generate undesirable impacts (hence costs) on society. Both require the use of resources to reduce the level of undesirable impacts. In both cases, management system output is in the form of a reduction of impact rather than a physical product. In both cases, management costs should be balanced against the reduction of impact.

In terms of of technical complexity, the two problems are roughly comparable. In the case of fire, we are concerned with a single agent whose time and place of occurrence are only predictable on a probability basis. Further, the effects of fire are highly variable and difficult, if not impossible, to measure. In the case of pollution control, the problem of stochasticity is of minor importance, but there are many different agents, each of which can have a highly variable and difficult-to-measure impact. In both cases, the undesirable impacts involve externalities, conflicting interests, and political repercussions. They are thus not readily reducible through normal market processes. It seems reasonable, therefore, that some aspects of the economics of pollution control should be applicable to wildland fire management. To this end, portions of the following discussion are adapted from the work of Freeman et al. (1971).

Figs. 2, 3, and 4 are each seen to have one axis in common with one other. This allows the combination of all three functions in a single diagram, as in Fig. 5. Fig. 2 is in quadrant I, Fig. 3 is in quadrant II (turned 90 clockwise), and Fig. 4 is in quadrant III (flipped over). Quadrant IV contains a 45 line. All points along this line have equal costs and damages.

At this stage, Fig. 5 bears little resemblance to Fig. 1; yet all the information needed to equate the two is present. The production function in quadrant II is referred to as a "transform" in that, by using it, the costs in quadrant III can be transformed to quadrant I. Conversely, the damage function in quadrant I can be transformed to quadrant III. This has been done in Fig. 6. We now have costs (plotted on the same scale as damage) as a function of area burned in quadrant I. Similarly, we have damage (plotted on the same scale as costs) as a function of fire management effort in quadrant III. By summing the cost and damage curves in quadrant I, the total cost plus damage curve is obtained. Alternatively, the same can be done in quadrant III, which, as can be seen, contains the same information as quadrant I (flipped over). Quadrants I and III now contain the same information as the more traditional presentation shown in Fig. 1. For example, if quadrant III is turned 90 clockwise about the orgin so that FME is horizontal and then rotated to the right 180 about the cost axis so that quadrant III is superimposed on quadrant I, Fig. 1 will have been reproduced. The most important point of this discussion is the transform in quadrant II through which the combination of the two curves is possible. This is the key element of the theory, which has traditionally been overlooked.

In Fig. 6, the optimal effort level is E*. This requires an expenditure of C*, and results in an area burned B*, and damage D*. This level of effort results in the lowest total cost T*. Increasing the level of effort above E* results in proportionately greater increases in costs than would be compensated for by decreases in damage. Conversely, decreasing the effort level below E* results in proportionately greater increases in damages than would be compensated for by decreases in costs. Thus any shift in the level of fire management from E* will result in a nonoptimal solution.

The above arguments assume a continuous and deterministic world with perfect information, which, of course, does not exist. In the field, the manager is faced with several problems which require that he modify the basic economic theory as presented here.

(1) Indivisibility of resources. — To achieve administrative and operational efficiency, the manager normally dispatches standard size crews, even though a fire may warrant only one or two men.

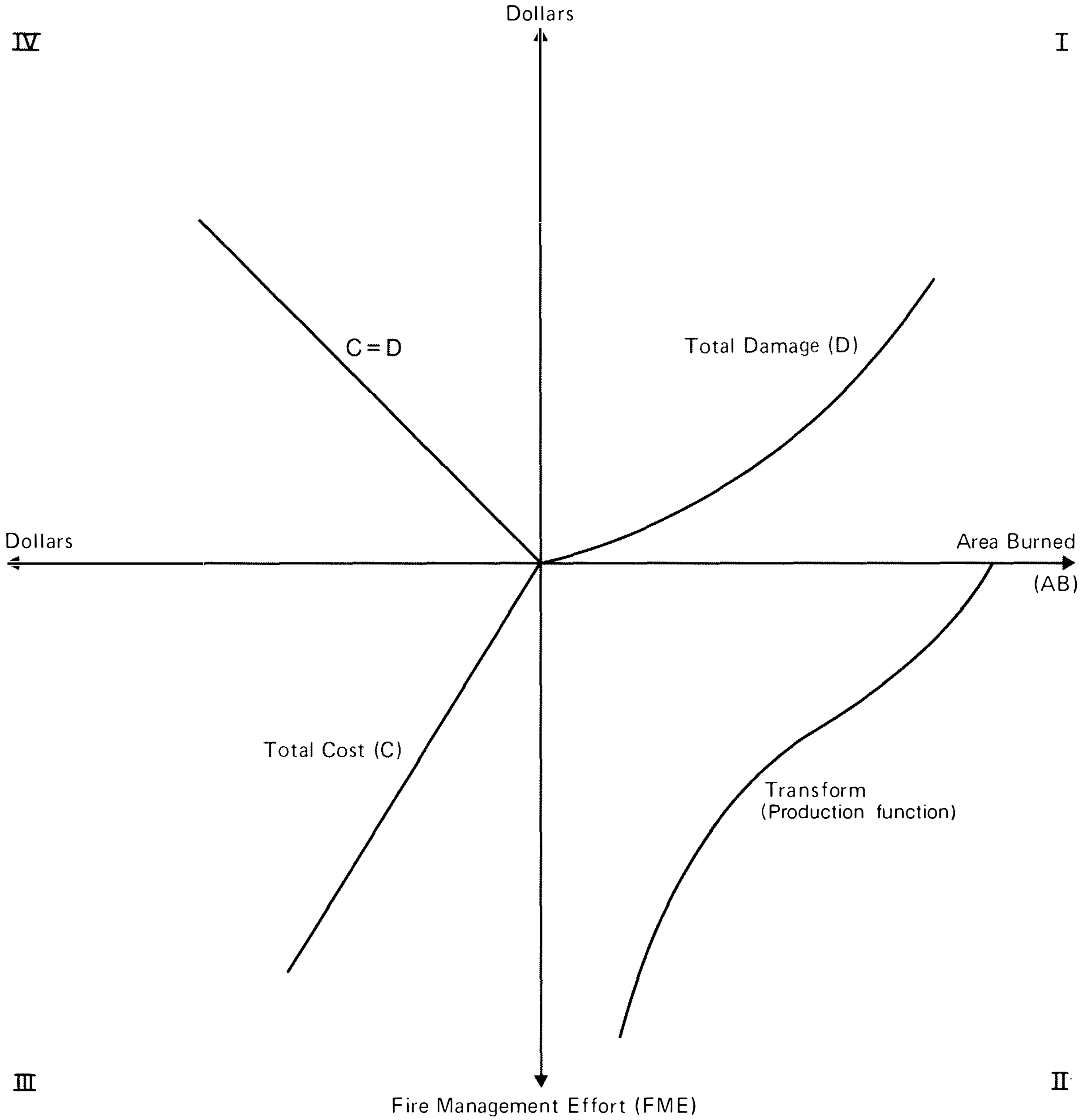

Figure 5. Combining the three components of the economic theory of fire management.

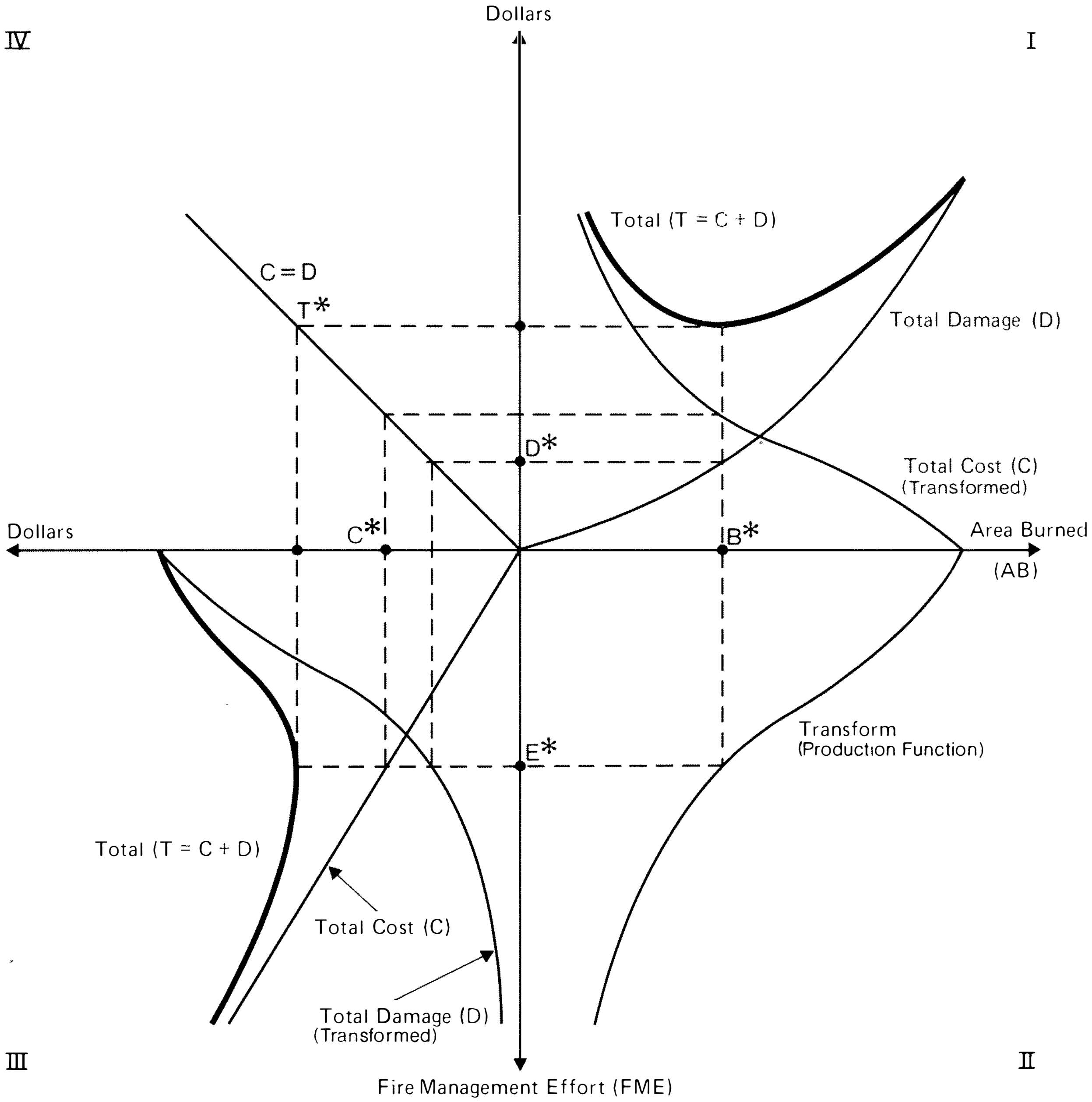

Figure 6. Transforming the cost and damage functions.

Similarly, he cannot dispatch half an airtanker or bulldozer. This implies that the functions are discrete step functions, as shown in Fig. 7.

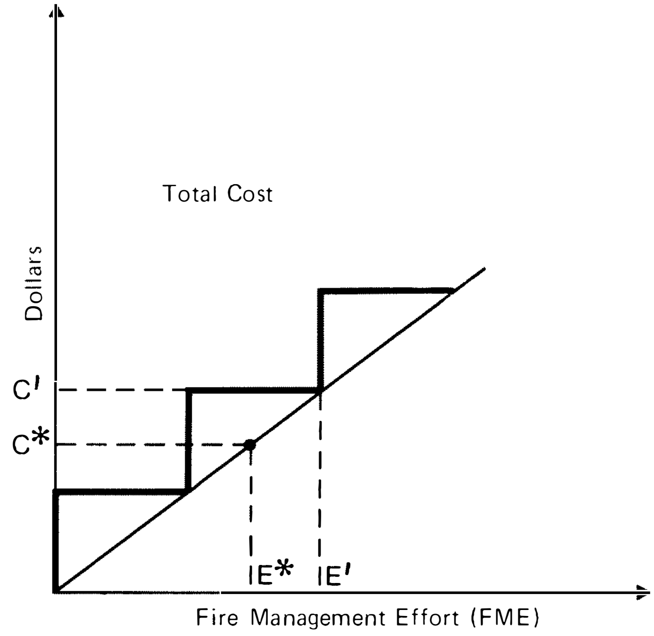

Figure 7. Discrete vs. continuous cost function.

If, for example, E* is the optimal fire management level, the manager will have to acquire two units of production at a cost of C' dollars to achieve at least that level. He will therefore spend C' - C* extra dollars. This is partially offset by the fact that a level of E' is achieved, thus providing additional benefits which are proportional to the difference E' - E*. By definition, however, if E* is the optimal effort level, the reduction in damage will be less than the increased costs, so that some inefficiency will result. Only in the case where E* = E' will there be no inefficiency. There is, of course, another option open to the manager. He could acquire only one unit which would result in a lower level of effort. Employing agruments similar to the preceding, there would still be some inefficiency, except that in this case the increased damages would exceed the reduction in costs. For very large administrative areas and long planning horizons, this problem can be almost negligible. For an individual fire, on the other hand, it can be of major consequence.

(2) Imperfect information. — At no time does the fire manager precisely know everything about a fire situation. The environment, the condition of the fuels, even the size and location of a fire are, at best, estimated on the basis of sketchy information. Consider a case where some factor of importance differs significantly from the estimated value. If the potential losses resulting from error equalled the potential gains, the rational manager would base his decisions on the expected value of the factor under consideration. In fire management, however, potential losses do not equal potential gains. If the state of nature is less severe than estimated, the manager could have saved some of the suppression cost. If, on the other hand, the state of nature is more severe than estimated, the fire may escape, with resultant suppression costs and damages that exceed the potential gains by orders of magnitude. Consequently, fire managers tend to assume the worst (based on available information) and make decisions accordingly. Thus, when faced with imperfect information, the manager bases his decision on the expected value of the outcome, not the decision variable. From both a theoretical and a practical point of view, this would appear to be a good strategy. The effect of such a policy is that, on the average, greater costs will be incurred than would be necessary if perfect information were available.

(3) ***Risk.*** – In addition to not knowing what is out there, there is a possibility that something unexpected will happen. This does not refer to changes such as a wind shift, which would have been predicted with perfect information. Rather, it refers to random phenomena, predictable only in a probabilistic sense. Events such as spotting, injuries to personnel, equipment breakdown, effectiveness of the suppression crew and so on are typically stochastic. The main difference between risk and imperfect information is that in the latter case (in theory at least) the phenomenon could be measured deterministically, given sufficient time, funds, and knowledge. In the case of risk, only the probability of an outcome can be predicted. In practice, the two situations may be lumped together because they are treated similarly. As in the case of imperfect information, the fire manager facing risk will assume the worst (for example by being overly conservative in his estimate of the expected rate of line construction) and make decisions accordingly.

The fact that, in practice, the fire manager will be forced to spend more than would be indicated by the economic theory does not invalidate the theory. It merely requires that these imperfections be taken into consideration in solving for the optimum level of fire management effort. On the assumption that these effects are incorporated in the solutions to be discussed in the remainder of this paper, we may proceed.

An optimal solution can also be found by using marginal analysis. Consider the total cost and damage curves shown in quadrant I of Fig. 6. To find marginal damage - MD(ab) - we simply determine the slope of the total damage function. Since total damage increases at an increasing rate throughout its range, the rate of change (marginal damage) will also increase at an increasing rate. This implies that for all values of AB the damage attributable to the loss of one increment of area is greater than the damage attributable to the loss of one less increment. The reason for the positive Y intercept for MD in Fig. 8 will be discussed in Section VI.

Similarly, marginal cost - MC(ab) - is the slope of the total cost curve. It can be seen that at low values of AB, total cost decreases at a decreasing rate, whereas at high values of AB, the decrease is at an increasing rate. Hence, marginal cost is initially negative, gradually becomes less negative (rises toward the zero axis), and eventually becomes increasingly negative again. Note that for quadrant I, the transformed rather than the original cost curve must be used. Interpreting the above, at low to moderate levels of AB, the cost per unit area of protecting one increment of area is less than the cost of protecting one less increment. At high levels of AB, however, the inverse is true. That is, the marginal cost of protecting additional increments is greater than the cost of protecting less area.

For the sake of convenience, MC is normally multiplied by minus one, making it positive. This step enables it to be plotted in the same quadrant as MD. This has been done in Fig. 8, where MC(ab) and MD(ab) are plotted as functions of area burned. The optimal solution (AB*) is at the point where MD equals MC, or in other words, the point where the absolute value of the slopes of the total cost and damage curves are equal. Intuitively, to the left of AB*, the cost of protecting a small unit of land is greater than the damage resulting from allowing it to burn. Therefore, total loss would be reduced if that unit were allowed to burn (increase area burned or move toward AB*). Conversely, to the right of AB*, the damage caused by allowing a small unit of land to burn is greater than the cost of protecting it. Therefore, it should be protected (decrease area burned or again move toward AB*). Any movement toward AB* decreases the net loss while any movement away from AB* increases the net loss. Thus, the point where MC equals MD must be the optimal solution.

It is also possible to apply marginal analysis to the total cost and damage curves in quadrant III, as has been done in Fig. 9. Since total cost was assumed to be linear, marginal cost - MC(fme) - is constant. This behavior reflects the assumption that the cost per unit of employing an increment of effort is the same as the marginal cost of one less or one more unit.

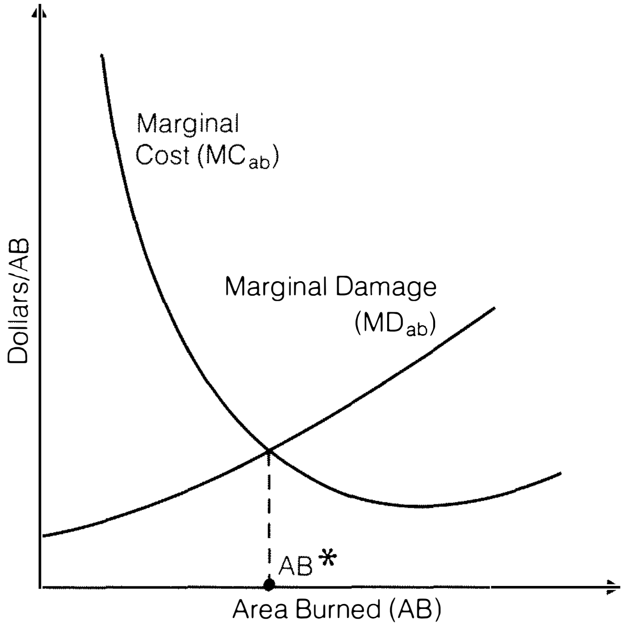

Figure 8. Marginal damage and cost as a function of area burned

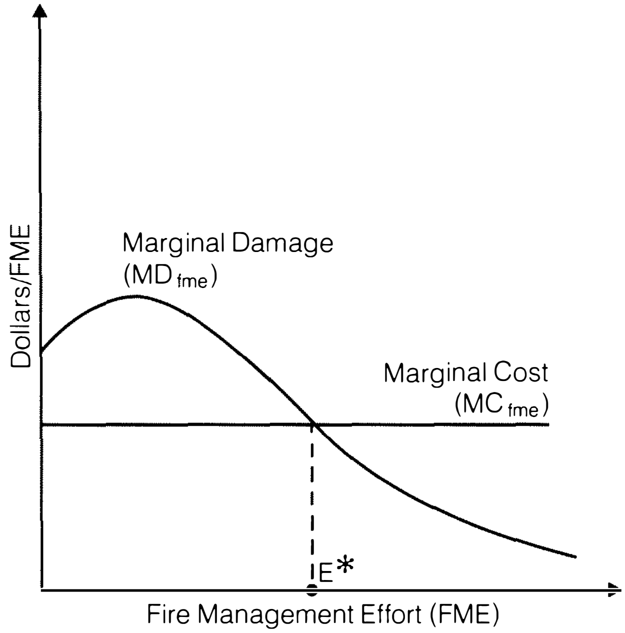

Figure 9. Marginal cost and damage as a function of fire management effort.

At low levels of FME, the transformed total damage curve (quadrant III of Fig. 6) decreases at an increasing rate. At moderate to high levels of FME, damage decreases at a decreasing rate. Thus, at low levels of FME, the marginal damage prevented by employing one increment of effort is greater than if one less increment were employed. Conversely, at high effort levels, the marginal damage prevented by employing one increment of effort is less than for the previous increment. Again, for convenience, marginal damage - MD(fme) - has been multiplied by minus one. As previously, the optimal level of effort (E*) is at the point where MD equals MC. Any deviation from E* results in some inefficiency.

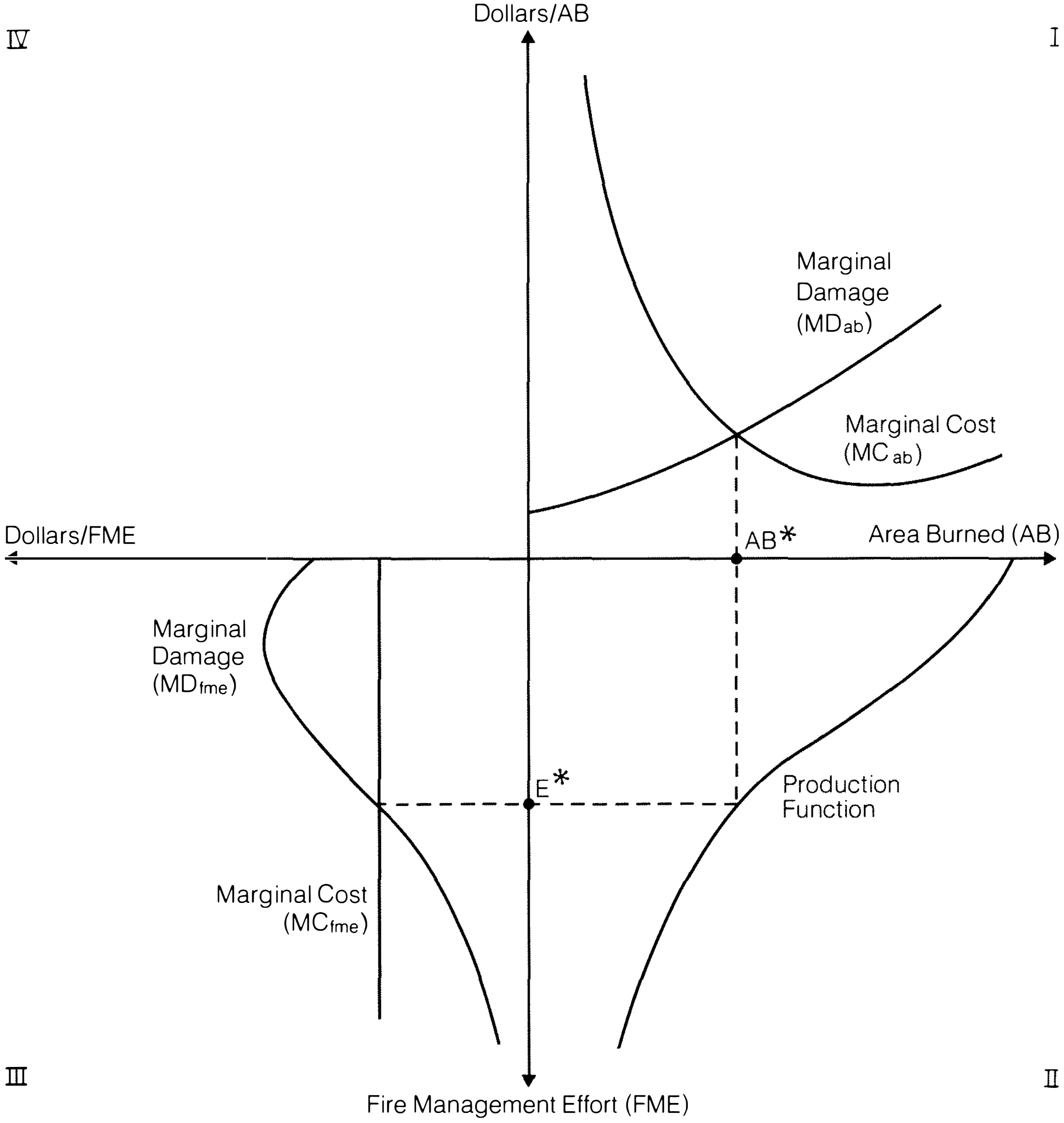

Figure 10. The optimal level of fire management effort.

In one case, we have an optimal solution in terms of AB, while in the other it is in terms of FME. While the manager is interested in knowing the optimal level of both FME and AB, he need only determine one set of marginal curves to find both solutions. To accomplish this, we add the transform in quadrant II to either set of marginal curves. In figure 10, for example, the curves shown in Fig. 8 have been plotted in quadarant I, along with the previously discussed production function of quadrant II. As can be seen, the vertical projection of AB* to the production function yields E*. Similarly, the marginal curves from Fig. 9 have been plotted in quadrant III. Again, the horizontal projection of E* yields AB*.

The solution is the same regardless of whether quadrant I or III is employed. Further, the optimal level of FME and AB will be the same whether marginal or total cost and damages are used. Both procedures involve about the same order of difficulty. When totals are used the sum of C + D is required, whereas in the case of marginal analysis, MC and MD must be determined. The marginal solution is easier to portray and visualize, however, as only two curves are required instead of three. For this reason, the remainder of the paper will employ marginal analysis whenever the economic theory is being discussed.

There are a few points to consider about the solution technique before discussing the implications of the economic theory.

First, it should be noted that quadrant IV is not used to obtain a solution when marginal analysis is employed. The two axes are different (dollars/FME and dollars/AB). They are, therefore, not equatable with a simple 45 line. We do know, however, that the projection of the intersections of the two sets of marginal curves must lie on the curve relating the two axes. The remainder of the function could be developed, but it is neither necessary nor would it convey any additional information.

Second, as long as the production function is defined, the absolute values of E* and AB* are independent of the units of measurement of either AB or FME. Changing either or both units of measurement changes the production function correspondingly, so that the solution remains the same in absolute terms.

Finally, there is an alternate procedure, which could be used to equate MC and MD. It is a reversal of the sequence in the preceding procedure in that MD and MC are calculated first and one or the other is then transformed. The transformation requires the determination of marginal productivity (MP) relative to the direction of the transformation, followed by multiplication of MP and either MC or MD (whichever is being transformed).[1] Since this more complex procedure eventually arrives at the same solution, it is recommended that the simpler procedure be followed. We are now in a position to interpret the economic theory.

The economic theory requires that all three curves be known - in other words, perfect information. Since we do not now have perfect information (in fact, none of the curves is currently rigorously defined in a quantitative sense), it is useful to consider the case of imperfect information. Again, the solution is analagous to that of the economics of pollution control.

What if, for example, in the absence of a damage curve, a policy simply specifies an acceptable area burned, one of the previously discussed practical objectives? This is comparable to specifying a tolerable level of pollution or concentration of residuals, which may not be exceeded. The effect of such a policy is shown in Fig. 11. In essence, such a policy implies that area burned below the objective results in no damage, while area burned in excess of the objective results in infinite damage.

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[1] This procedure is equivalent to taking the derivative of a composite function f(g(x)), which is given by the chain rule: f'(g(x)).g'(x).

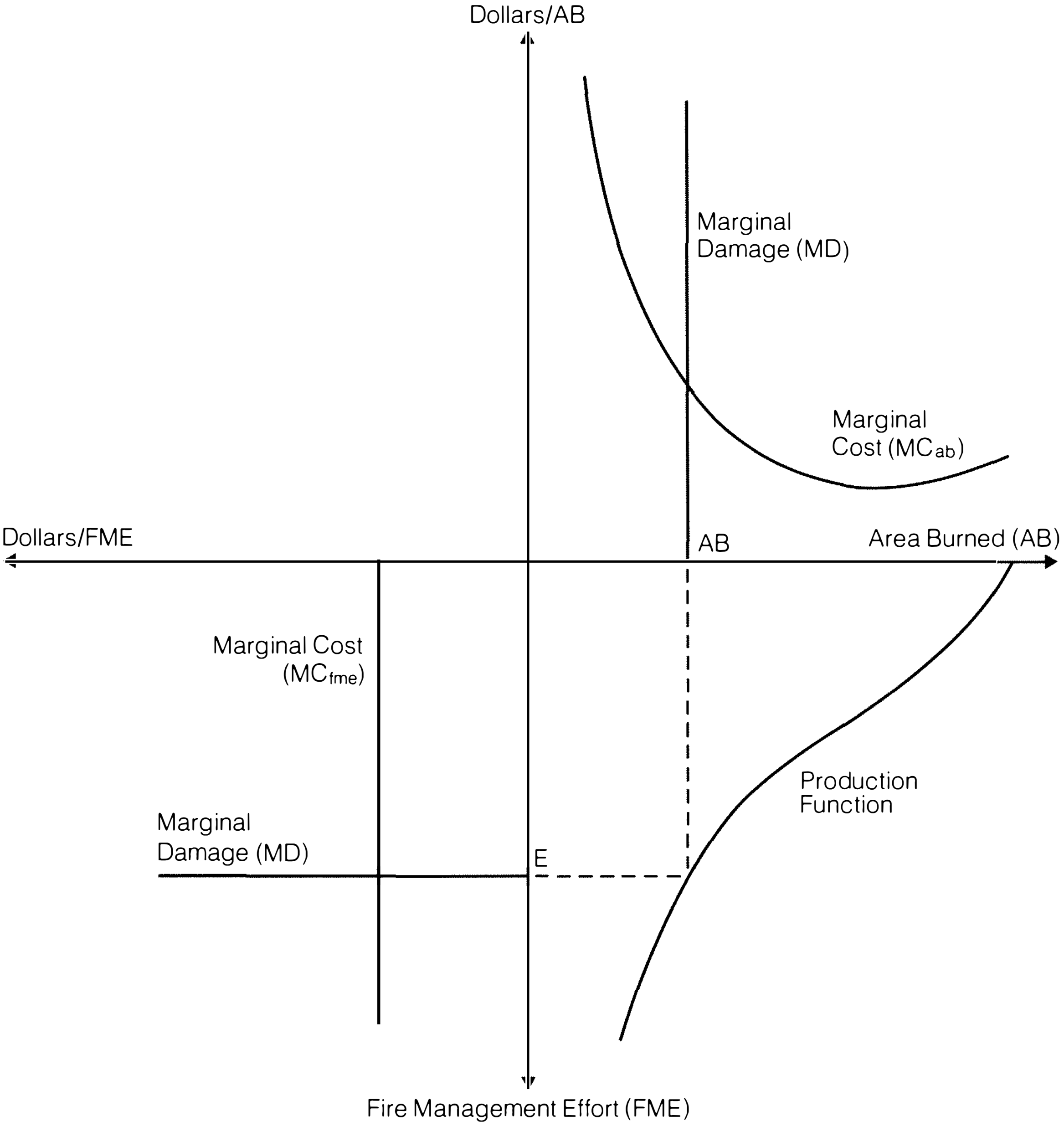

Figure 11. Effect of specifying an acceptable level of damage.

That the above accurately describes the actual effect of specifying an acceptable level of damage (or time by which fires must be extinguished), is strongly supported by the arguments against the 10 o'clock policy presented by Headley (1943). It will be recalled that in practice, field personnel applied a great deal of individual judgment in deciding whether or not to apply the policy. It was obvious that blind application in all cases would occasionally lead to costs far in excess of the savings incurred. Thus the most undesirable effect of the policy is ameliorated by what has to be considered judicious application.

It must be emphasized, however, that the preceding argument in no way justifies the use of noneconomic policies. To do so would be analogous to the argument that, because of internal checks and balances, the fire management system seems to function in a reasonable manner regardless of the guiding policies employed. Interestingly, as pointed out by the studies of Forrester (1968), this is common in all large systems, and seems to be a continual source of frustration to managers in their attempts to implement new policies. In response, management may well be tempted to simply select a convenient policy and let the system run itself. The obvious counter argument is that perhaps no policy at all is better than a poor policy.

The foregoing argument presents only one side of the problem. To correct deficiencies, management needs to be able to evaluate system performance. Practical objectives provide a mechanism whereby evaluation can be carried out. Until economic criteria can be made to provide similar effectiveness measures, they will be of little use as objectives. The economic theory is still useful, however, in that it dramatically points out the main deficiency of practical objectives. If it only serves to point out the need for judicious application of noneconomic objectives, it is useful.

In actual fact, the economic theory is considerably more useful than suggested above, even though only two of the functions might be known. With only the cost and production functions, it is possible to determine the level of effort needed to achieve the policy as well as the cost. Further, the function MC(ab) indicates the cost of all allowable area burned policies. MC(ab) in effect, provides management with a "cost-effectiveness" function. It can be used to select a level of AB at which management's subjective estimates of the value saved are commensurate with the costs. The cost-effectiveness procedure is based on the same concept as the social account approach (Kuhn 1962, in Davis 1965). The term cost-effectiveness is preferable in that it suggests the procedure without further definition. "Cost-benefit" would be a comparable term to describe the economic theory in its entirety.

It would be useful to consider the case where the damage function was defined, but expenditures, and hence the level of effort, were limited by a budget constraint. The budget level would presumably be determined by the availability of funds, which would, in turn, reflect administrative or political processes. As shown in Fig. 12, the effect of such a policy would be similar to a predetermined acceptable level of damage. The implication is that below the specified level of effort MC equals zero, while above the specified level MC equals infinity. Again, in practical situations, such a policy is mitigated by the procedures whereby it is applied. Typically, fire management funds consist of a capital budget and emergency funds. In the case of an ongoing fire, managers have available what almost amounts to a blank check. In general, they can spend whatever is necessary to bring the fire under control. Although this has often resulted in wasteful practices, no one has yet suggested stopping fire control efforts because of insufficient funds. It should be noted, however, that suppression efforts on large fires have been reduced or stopped in areas of low to nil land values. It would appear that large, uncontrolled fires are simply unacceptable to society, except in areas of very low values, regardless of suppression costs, or whether or not control efforts are having any beneficial effect. In fact, suppression resources have sometimes been dispatched for the sake of appearance on large fires with the a priori knowledge that they will be of little real value.

As was the case with an unspecified damage function, the economic theory provides useful, if incomplete, information. The function MD(fme) indicates the damage to be expected from various budget allocations. It provides the manager with a powerful argument for seeking further funds, if it can be shown that small increases will result in significant reductions in damages. Such a procedure would appear to be superior to current practices whereby legislators generally rely on the intuitive judgment of fire management personnel to determine the quantity of funds needed. There may be little difficulty if funds are readily available, but where competition is stiff, rigorous economic arguments cannot but help. As a corollary, the economic theory would also give an indication that perhaps budget allocations were excessive. Although such a problem has never been

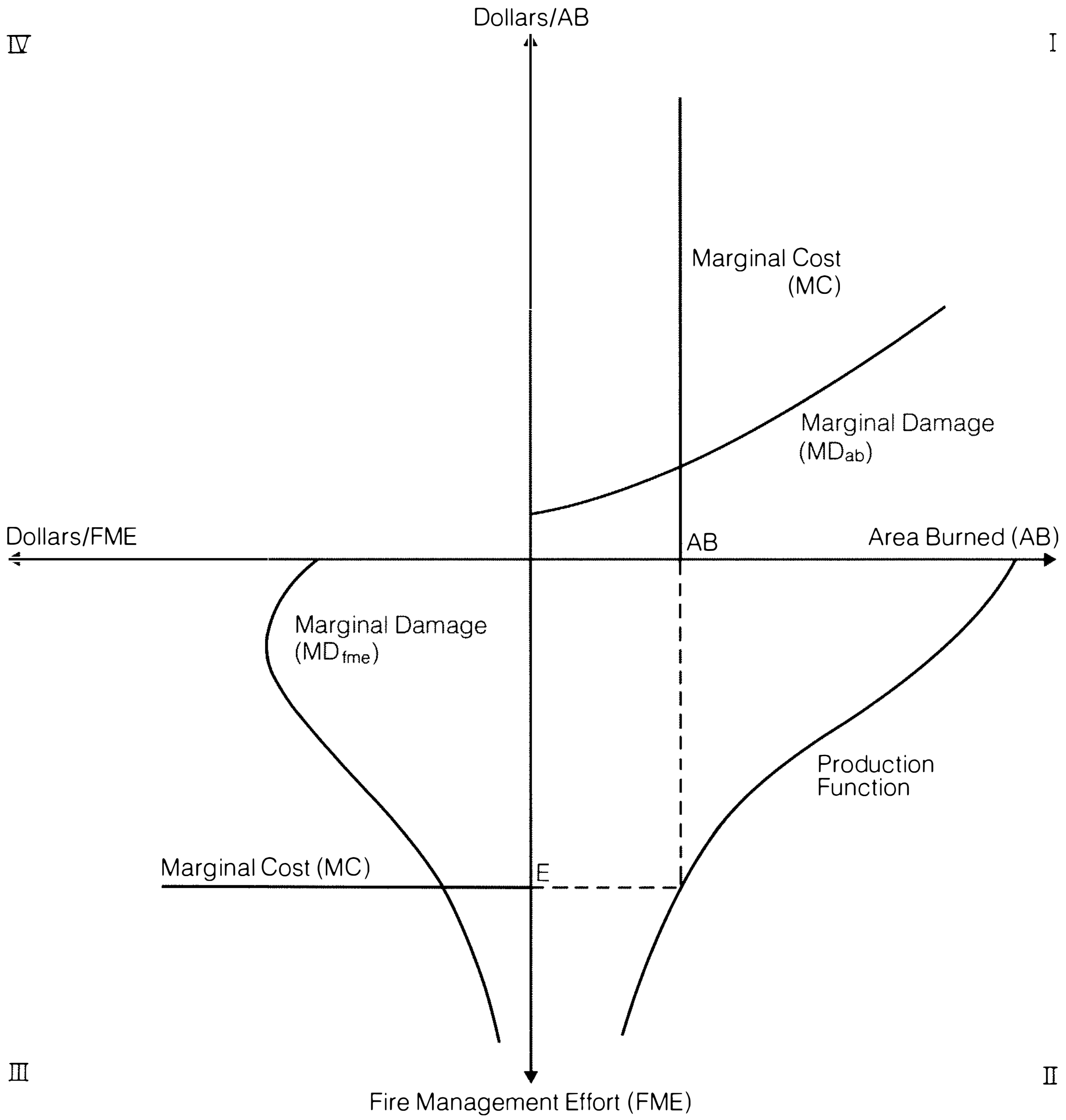

Figure 12. Effect of a predetermined budget level.

a source of complaint from fire managers, it should nonetheless be considered, in the interests of society as a whole, which fire managers, most of whom are public servants, should be concerned with. This process could be most appropriately described as an "effectiveness-benefit" procedure.

Another case of incomplete information must be considered. That is where the cost and damage functions are defined, but the production function is not. In this case, the theory yields no useful information, because it is simply not possible to transform either costs to quadrant I or damage to quadrant III. Without the transformation, costs and damage cannot be compared in any meaningful way. It can be seen, therefore, that the production function is the most critical component of the theory, for without it the theory yields no useful information.

Since the production function is the key to the economic theory, it would be useful to consider the situation in which it was the only defined function. Both cost and damage might be unknown or one unknown and the other prespecified. Note that it is not possible to predetermine both cost and damage at the same time. One limit may be set, but the other will be given by the transformation. Even in this limited case, however, some useful information can be obtained. Recalling Fig. 3, given a predetermined level of fire management effort, the expected area burned could be predicted. Conversely, given an acceptable area burned, the level of fire management effort needed to accomplish the goal could be determined. While such information is considerably removed from that which would be desired, it does provide a starting point for guiding forest fire management activities.

We have now arrived at a point where a more detailed discussion of the three components of the economic theory would be useful. These are the subjects of the next three sections. First we will consider costs, followed by production and damage.

III. THE COST FUNCTION

Traditionally, expenditures for fire management activities are divided into two categories – suppression and presuppression. Suppression expenditures are the variable costs of fire management. These costs increase as the number of fires and the difficulty of controlling them increases. Suppression expenditures are normally reported on the individual forest fire report form. Presuppression expenditures include expenses incurred by the organization for activities other than direct suppression. These are the fixed costs of fire management. The amount spent does not depend on the fire load at any given time but rather on the overall expected fire load over an extended period. Fixed costs are not normally included as part of the individual forest fire report form.

This framework poses some difficulties with respect to economic analysis. For example, standby is technically a presuppression activity, yet it is a variable cost in that it is only incurred when the fire danger is high. Similarly, prevention and detection have both fixed and variable cost components in that supplementary expenditures are normally incurred during times of high fire danger. In considering expenditures along traditional functional lines, anomalies such as these have to be either assumed not to exist or incorporated in some awkward manner.

It would be preferable to consider variable costs of fire management without reference to the activity involved. From both an economic and an operational point of view, there is a clear need to separate fixed and variable costs. For example, acquiring an airtanker (or its services through rental for a season), including hiring a pilot and mechanic, obtaining insurance, etc. are fixed costs. Once airtankers are acquired, the decision to dispatch them should be based solely on a comparison of variable costs (gas, oil, hourly maintenance, etc.) with the expected returns. Fixed costs are sunk and should not be considered at this stage.

Such a decision is comparable to the short-run and long-run shutdown points of a firm. In the short run, a firm will shut down only when average revenue (price) is less than average variable costs. Although they may operate at a loss, the loss will be less than it would be if they were to shut down, because the fixed costs still have to be paid. In the long run, a firm can terminate contracts, sell buildings, etc. Therefore, the long-run shutdown point is reached when average revenue falls below average total cost. This effect can be seen in Fig. 13. With respect to fire management, in the short run (one fire) the manager can dispatch an airtanker or not, on the basis of variable costs. In the long run (one or more seasons) the manager can terminate the contract for an airtanker if its total benefit does not equal or exceed its total cost. Clearly, these are two separate decisions.

Thus, the main difference between variable and fixed costs lies in the time period over which they are considered. Variable costs are compared with benefits on one or a few fires, while fixed costs are compared with benefits during one or more fire seasons.

There are two types of fixed costs that have to be considered by the fire manager: short-term (one fire season or less) and long-term (more than one fire season). Typical short-term expenditures are the hiring of seasonal personnel and 1-year airtanker contracts. Short-term fixed costs are incurred when they result in at least a commensurate reduction in total damage during the period to which they apply. In industry, dividing the total fixed cost by the quantity produced yields an average fixed cost. The average fixed cost can be added to the variable cost of production to yield total production cost per unit. Industry, however, has two advantages in this respect. First, it is not possible to determine a priori how many fires will occur in a fire season. Second, fires vary greatly with respect to their variable costs and damages. As a result, it is not possible to allocate an average fixed cost to every fire. Such a procedure would suggest that excessive amounts were being spent on the control of small fires and that large fires were less expensive to control (per unit of area burned) than small fires. Thus for the fire manager, the only valid accounting procedure to evaluate the level of fixed costs is to compare the total fixed cost with the total seasonal output of the fire management system, less the variable costs.

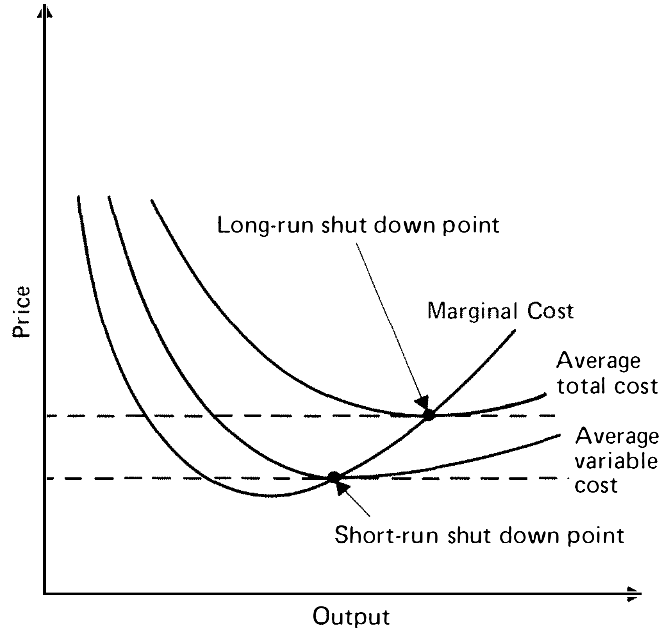

Figure 13. Long-run and short-run shutdown points for a firm.

Major equipment purchases, multiyear contracts, and fuel management activities typically involve long-term expenditures. The distinguishing characteristic is that the benefits from the expenditure will accrue over more than one season.[2] The importance of this characteristic is that long-term fixed costs are a form of investment. As a result, some elementary concepts from the field of finance must be considered. Specifically, we will deal with the net present value concept. It is interesting to note that despite the fact that the net present value concept is well documented in the fields of finance and economics and, closer to home, in the field of forest management, the first reference to the concept in the fire management literature of which the author is aware is Harrison et al. (1972). In all probability, application of the net present value concept in the field is even more limited.

Net present value incorporates two basic assumptions: (1) an individual (or firm) would prefer present consumption to future consumption, and (2) more consumption is preferable to less consumption. To induce an individual to forego current consumption, it will be necessary to compensate him by an amount equal to his rate of time preference. That is, he will have to receive at some future date more than he is currently foregoing. This premium is the interest he receives. Riskless investments (such as a savings account) require less interest than risky investments, for which the investor has to receive additional compensation to cover the possibility of losing some or all of his investment. A pure rate of interest (for a riskless investment) is often used to measure the rate of time preference. Determination of the interest rate is outside the scope of this paper. Suffice it to say that, at the present time, riskless investments are returning anywhere from 5% to 10%. The rate of time preference concept applies equally to individuals, firms, and society, although rates of time preference for each, and hence interest rates, are normally different.

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[2] This implies that the time value of money for periods of less than 1 year equals 1.0. This simplification is generally made in practical applications.

Mathematically, investing one dollar this year would yield \$1 + i next year where i is the interest rate. Conversely, if an investor were to receive \$1 next year, he would be willing to pay only \$1/(1 + i) this year. Thus, the formula for net present value:

$$\text{NPV} = \frac{B_o - C_o}{(1 + i)^o} + \frac{B_1 - C_1}{(1 + i)^1} + \frac{B_2 - C_2}{(1 + i)^2} + \text{-----} + \frac{B_n - C_n}{(1 + i)^n} \tag{2}$$

More concisely,

$$\text{NPV} = \sum_{t=o}^{n} \frac{B_t - C_t}{(1 + i)^t} \tag{3}$$

where:
B = benefits accrued in year t
C = costs incurred in year t
i = interest rate
n = life span of the project (in years)

It can be seen that as n increases, the denominator becomes progressively larger. As a result, the present value of a sum becomes progressively less as the length of time to its receipt becomes longer. In application, the numerator of the first term is generally negative owing to large capital costs. Note that the first term is not discounted (the denominator equals 1). If the investment is worthwhile, subsequent numerators will be positive (i.e. benefits greater than maintenance costs) by a sufficient amount that the sum over the life of the project will be positive. If the sum in equation 3 is negative, the investment is not worthwhile and should not be undertaken.

Failure to use the net present value criterion to evaluate long-term investments will yield inflated values to benefits received after the initial year of a long-term project. Other criteria for analyzing investment decisions which incorporate the concept of discounting future benefits, such as cost-benefit ratio and internal rate of return, have theoretical deficiencies which render them inferior to the net present value formulation.[3]

The above discussion is concerned with a method of cost accounting. The main purpose of the suggested procedures is to put costs in the proper form to permit a least-cost optimization of the production function. To optimize the mix of production factors in an economic sense, the price of each factor must be known, and it must be in the proper format. This leads to the next component of the economic theory, the production function.

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[3] This discussion is considerably abbreviated. For more information on the analysis of investment decisions related to public projects, see Hirschleifer, et al. (1969). For more information on financial investments in general, see Archer and D'Ambrosio (1972), or any general textbook in finance.

IV. THE PRODUCTION FUNCTION

The production function defines the relationship between fire management effort and the physical output of the fire management system. It is an aggregation of three factors of production (fire management activities) relating to fire occurrence, fire control, and fuel management. The following discussion considers the components and characteristics of each of the three factors of production.

A. The Factors of Production

1. Fire Occurrence

Fire occurrence related activities include prevention and detection. Prevention is principally concerned with reducing the number of fires which occur. Detection is concerned with reducing the time interval between ignition and discovery. As is the case for much of this paper, this grouping is at variance with traditional approaches. When examined in detail, however, these two activities have a great deal in common.

1) They are both related to fire occurrence. Prevention affects occurrence probabilities while detection responds to occurrence probabilities.

2) The occurrence of a specific fire cannot be predicted with regard to either time or place, necessatating the use of probability distributions for analytical work.

3) Both prevention and detection concern events occurring before the start of suppression.

4) The substitutability between prevention and detection is higher than between either of them and any other activity.

5) In application, the activities are not specific with regard to place, whereas they are specific with regard to time.

6) The level of either activity can be modified somewhat during the course of a season in response to variations in fire danger.

7) Both activities involve fixed (short- and long-run) and variable costs.

It can be seen, therefore, that grouping prevention and detection under the single heading of fire occurrence is not inconsistent with their characteristics.

2. Fire control

Fire control is concerned with suppressing the fires which occur in spite of the fire occurrence activities. There are two specific activities under the heading of control – presuppression and suppression. For purposes of this discussion, presuppression is defined as those activities directly related to suppression that take place prior to detection. Thus in the proposed framework, hiring seasonal crews and preparing a dispatch plan would be presuppression activities, whereas building a lookout and constructing fuel breaks would not. That suppression is intimately related to presuppression is beyond doubt. One cannot suddenly increase the number of smoke jumpers in response to a lightning "bust" even though it would be highly desirable to do so. Their availability is fixed by the number of men trained at the beginning of the season.

The primary fire control characteristics are listed below.

1) In theory, fire suppression is primarily deterministic, even though the mechanisms are not completely understood at this time. Stochastic events (such as variations in crew productivity

resulting from differences in leadership, training, esprit de corps, and prior activity) tend to be in the nature of random variations about expected values. In general, the variance tends to be small in relation to the expected value.

2. Analysis of suppression activities can be based on predicted outcomes for specific events.

3. Fire control activities are fixed with regard to both place and time.

4. Control activities concern events occurring both before and after a fire is detected.

5. Substitutability between presuppression and suppression is much greater than between either of them and any other activity.

6. Modification of the level of control activities in response to specific events is a major feature.

7. Presuppression involves all three cost elements, although variable costs are a minor constituent. Suppression involves variable costs only.

The intimate relationship between suppression and presuppression suggests that they form a natural grouping.

3. Fuel Management

This activity is primarily intended to aid the suppression effort. In certain instances, it also has the objective of reducing fire occurrence. It is sufficiently different from either of the other two activities to warrant separate classification. There is only one major activity under fuel management, with an infinite degree of variability possible. It is reasonable, however, to consider the two extremes of the activity separately, since operations in the midregions of the range are seldom, if ever, undertaken. The first, aerial management, involves prescribed burning, planting, and other techniques applied over large areas. The second, strip management, involves fuel breaks and hazard reduction along roads, trails, and ridge tops, with large untreated areas between strips. It is clear that as strips become very wide, the distinction loses its usefulness. In practice, however, there is normally a clear distinction between aerial and strip management.

Some of the characteristics of fuel management are

1) The activity occurs at a specific place, but its usefulness depends on the random occurrence of a fire. If a fire occurs at such a time and place that it is affected by the management effort, a benefit is provided. If a fire does not occur, or if the activity does not affect a fire, it has no direct fire management value.

2) It is a combination of deterministic and stochastic events.Thus analysis has to be of two forms. Given the time and place of the occurrence of a fire (the stochastic event), the effectiveness of the management effort can be calculated deterministically (in theory at least).

3) Fuel management activities occur before a fire is detected (backfiring is a suppression technique).

4) The level of the activity cannot be modified during a season in response to fluctuations in fire danger.

5) Fuel management contains fixed-cost elements only. There are both long-term (initial construction), and short-term (annual maintenance) costs.

From the preceding, it can be seen that fuel management differs fundamentally from the other two activities. Further, fuel management productivity depends on both occurrence and suppression. Separating fuel management from the other two activities minimizes their interdependence. Thus, a separate classification is warranted.

B. Optimizing the Production Function

We will now consider least-cost optimization of the production function. While the following discussion is at the level of the three major factors of production, the economic arguments can be applied to any level of the fire management system or subset thereof. We could, for example, consider the six activities of which the three production factors are composed (presuppression, suppression, detection, prevention, and aerial and strip fuel management). To do so, however, would needlessly complicate the discussion.[4]

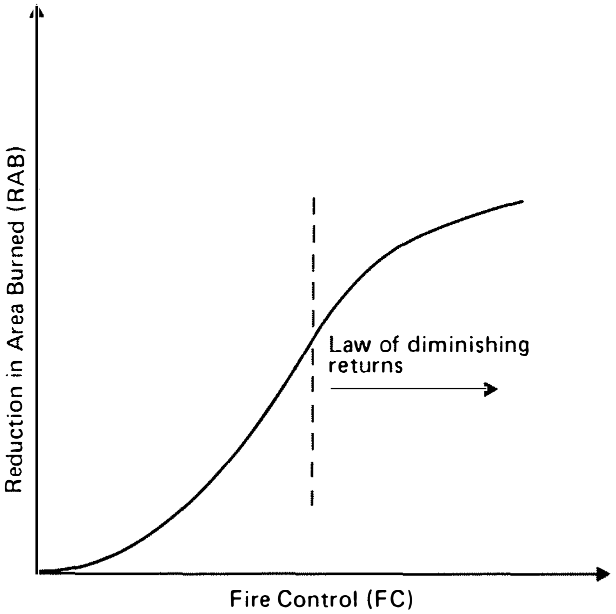

Figure 14. Total physical product

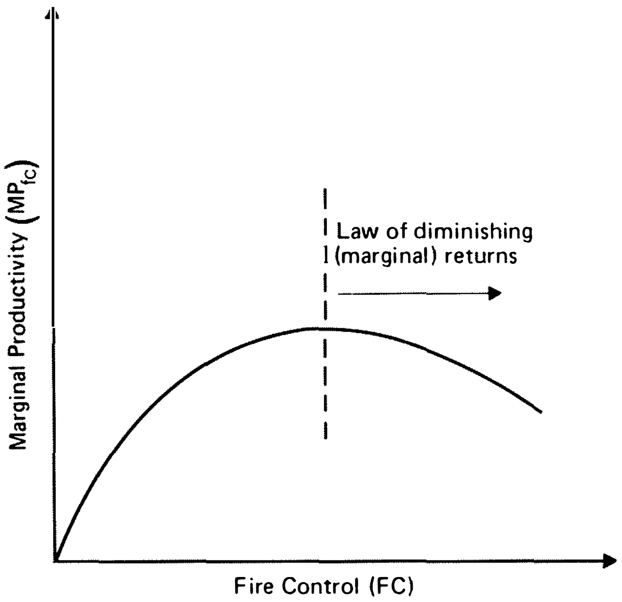

Figure 15. Marginal product

A brief discussion of production theory is necessary to develop the rule for determining the least-cost combination of production factors. Fig. 14 shows a typical total physical product curve (reduction in area burned RAB) obtained by holding all factors of production constant except one (for example, fire control -FC). Initially, increases in FC result in more than proportional increases in output because more efficient use is made of the other fixed factors. Eventually, however, the law of diminishing returns asserts itself, and continued increases in FC result in proportionally smaller and smaller increases in output. The slope of the total product curve is called the marginal product. It is shown in Fig. 15. Marginal product (MP) is the quantity of output per unit of input.

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[4] For more detail, see Gamache (1969) or any general reference in economics such as Gill (1970) or Dorfman (1972).

Considering two factors of production requires a three-dimensional graph. One axis is used for each factor, and the third for the level of output. Alternatively, a two-dimensional graph can be used with the production levels plotted as contours, known as isoquants, as in Fig. 16. Each curve shows the amounts of fire occurrence (FO) and fire control (FC) required to achieve various levels of production. The slope of a curve at any point is known as the marginal rate of technical substitution (MRTS). Mathematically,

$$(4) \qquad \text{MRTS} = \frac{\partial FO}{\partial FC}$$

Further, since the slope of the total product curve equals its marginal productivity,

$$(5) \qquad \text{MRTS} = \frac{MP_{fo}}{MP_{fc}}$$

Again, the law of diminishing returns can be seen to apply in that continuously decreasing one factor of production by constant amounts requires ever increasing amounts of the other factor to maintain a constant level of output. MRTS is equal to the ratio of the marginal productivities.

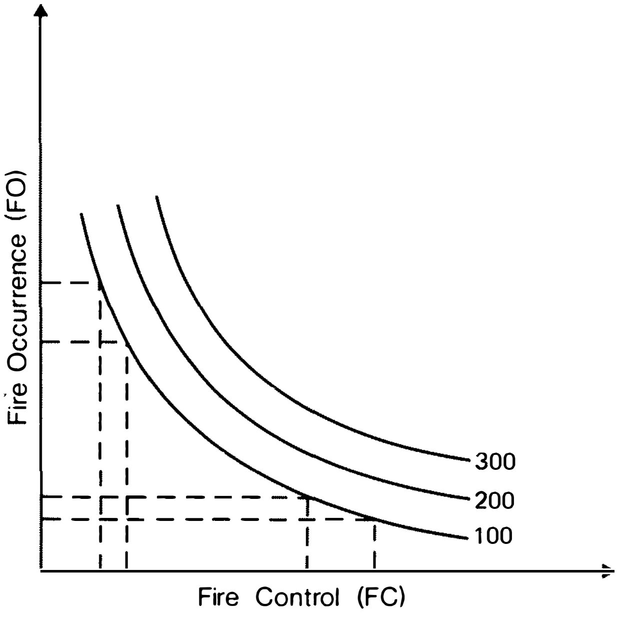


Figure 16. Isoquant map for FO and FC.

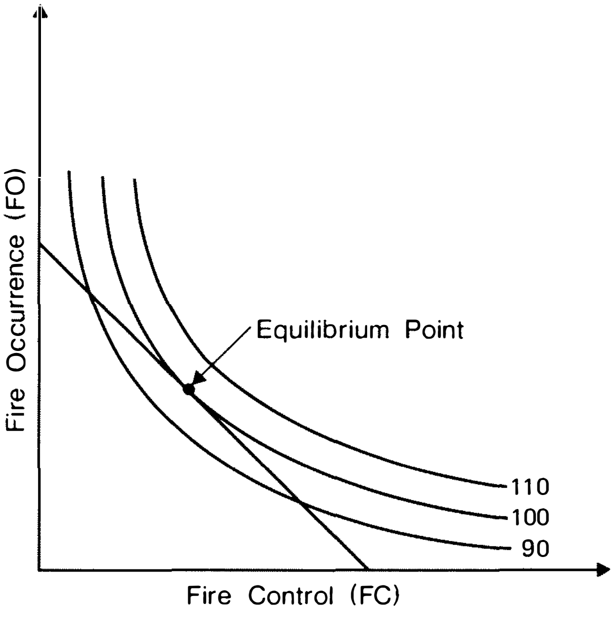


Figure 17. Least-cost combination of FO and FC.

In Fig. 17 a budget line has been added to the isoquant map. The slope of the budget line is equal to the ratio of the prices of the two factors. In other words, if $P_{fo}/P_{fc} = 1$, the prices would be the same. If $P_{fo}/P_{fc} = 2$, FO would be twice as expensive as FC.

Whereas in Fig. 17 only three isoquants were shown, there are, in fact, an infinite number of isoquants. There exists, therefore, an isoquant just tangent to the budget line at some point (the line for a production level of 100 in Fig. 17). Since higher isoquants represent greater outputs, the fire management system will naturally want to be on the highest possible isoquant (assuming that output maximization is one of the goals of the system). The highest possible isoquant is the one where the budget line is just tangent to an isoquant. If the system were on a lower isoquant, for the same budget, it would not be efficient. Since the system cannot be on a higher isoquant, the point of tangency must be the most efficient point.

At the point of tangency, the slope of the budget line and the slope of the isoquant are equal. Therefore,

$$\frac{P_{fo}}{P_{fc}} = \frac{MP_{fo}}{MP_{fc}} \tag{6}$$

is a mathematical expression indicating the least-cost combination for a given output, or alternatively, the maximum output possible for a given budget. In production theory, this is referred to as the equilibrium position for the competitive firm. The above expression indicates that the optimum combination of production factors is that combination where the ratio of the price for each factor equals the ratio of their respective marginal productivities.

The case of multiple production factors can readily be handled by rearranging the terms in equation 6:

$$\frac{P_{fo}}{MP_{fo}} = \frac{P_{fc}}{MP_{fc}} \tag{7}$$

and adding as many terms as necessary. Thus, a fire management system will be efficient if:

$$\frac{P_{fo}}{MP_{fo}} = \frac{P_{fc}}{MP_{fc}} = \frac{P_{fm}}{MP_{fm}} \tag{8}$$

Equation 8 indicates that the optimal position for a fire management system is achieved when the ratio of the price of every factor of production divided by its marginal productivity is equal to every other ratio. Note that equation 8 can be rewritten in a more general form to include the overall economic theory. If marginal productivity (MP) in each denominator were replaced with marginal damage (MD), the constraint of a predetermined budget or acceptable area burned would be removed, and an unconstrained optimal mix of production factors for the fire management system could be determined. This would be the same as the traditional two-function version of the theory.

An illustration of the three-variable case requires a three dimensional graph with one axis for each factor as shown in Fig. 18, which is adapted from Davis (1965). The line in Fig. 18 is an expansion path. It connects the optimal (efficient) point on every isoquant surface. Each isoquant surface represents a level of production, as did the curves in Fig. 17. Every point represents a different budget level. At every point on the expansion path, the equalities in equation 8 hold.

What does equation 8 mean in terms of the fire management production function? If the P/MP ratio for the fire occurrence factor is greater than the other two, either its price is too high, or its marginal productivity is too low in relation to fire control or fuel management. The fire management system would therefore increase its efficiency by switching enough of its budget from

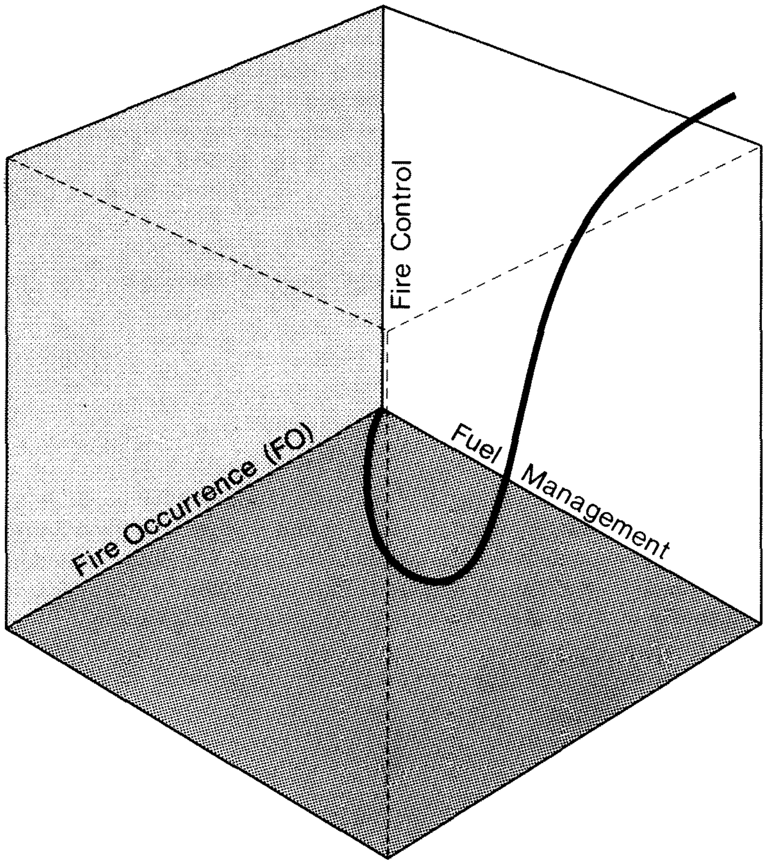


Figure 18. Expansion path for a hypothetical fire management system.

fire occurrence to one or both of the other two factors of production until the ratios were equal. Conversely, if the fire occurrence ratio was lower than the other two, it would pay to switch funds into fire occurrence, from the other two activities. Only when all three ratios are equal, implying that no reallocation can be made to improve overall productivity, would the fire management system be operating efficiently.

V. THE DAMAGE FUNCTION

Of the three components of the economic theory, the damage function is the most intractable. The main difficulties arise partly from a lack of knowledge of the nature of fire effects and the mechanisms whereby they occur, and partly from our inability to evaluate the effects.

For some types of damage, such as the loss of marketable forest products, forage, or improvements, market value provides an easily determinable measure of the value lost. For other types of fire-related damage, such as erosion, floods, and recreational opportunity losses, market values provide only an incomplete measure of the value lost. Lastly, for some types of damage, such as smoke pollution and loss of aesthetic values, hazard to life and health, and decreased security, there is no mechanism whereby the losses can be related to market processes.

Traditionally, estimates of damage have tended to concentrate on the more readily measurable aspects. In Canada, examination of the fire report forms used by various agencies indicates that losses to forest products are given by far the greatest significance. Nonforest losses rarely include anything other than improvements with a readily determinable market value. It is the current policy of the U.S. Forest Service to include as damages only values which can be documented well enough to stand up in court (U.S. Forest Service 1968). Some agencies make a conscious effort to include non-tangible damage but the tools provided them by reasearch are woefully inadequate.

Consequently, reported damage estimates tend to be lower than the actual damage. This difference is often cited as a reason for not applying the economic theory, in that the level of fire management effort that could be justified would be too low. The fault lies with the application, however, and not with the theory. If a complete measurement of damage could be arrived at, there would be no problem. We should not ignore the correct procedure because it fails in application. Rather, the applicability should be improved.

A. Damage Characteristics

There are three damage characteristics that will be considered in this section: (1) relative degree of substitutability, (2) relative importance of market processes, and (3) relative importance of a risk premium.

1. Substitution

Substitution with respect to damage assessment involves a combination of concepts discussed in Sections III and IV. The first was the rate of time preference (where future consumption was substituted for present consumption). The second was the marginal rate of technical substitution (where one production factor was substituted for another). It will be recalled that as more and more of one factor is employed, its substitutability for the other factor decreases. A similar argument can be applied to the consumer segment of the economy. Briefly, the consumer is assumed to always maximize his total satisfaction. Fig. 19 shows an indifference curve map with a budget line superimposed. The curves are also sometimes referred to as utility curves. The curves are loci of points of equal satisfaction. The individual is said to be indifferent about where he is along any particular curve. That is, any combination of goods placing him on the same curve yields equal satisfaction. The individual, however, does desire to be on the highest possible curve (on the assumption that more is better than less). Although indifference curves are not readily definable in a quantitative sense, they are useful for understanding the concepts involved.

The amount of one good that has to be substituted to compensate for the loss of one unit of another good to maintain the same level of satisfaction is known as the marginal rate of substitution (MRS). As before, this can be expressed as:

$$(9) \qquad MRS_{a,b} = \frac{MU_a}{MU_b}$$

where: MU = marginal utility

Bringing prices into the equation, the individual has maximized his utility when:

$$\frac{P_a}{P_b} = \frac{MU_a}{MU_b} \qquad (10)$$

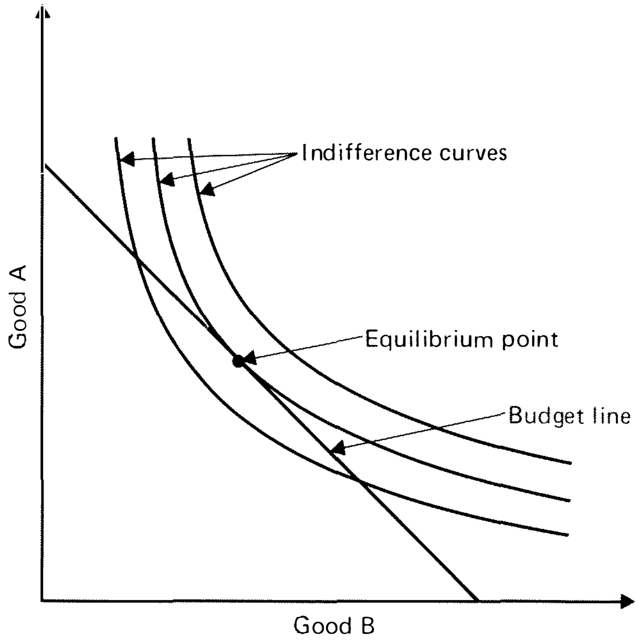


Figure 19. Indifference map.

The importance of substitution relative to fire damage assessment has been recognized for some time (Headley 1943, p. 99), although the concept has not been rigorously defined in economic terms. Its importance is second only to the actual loss of value. In theory a "rational" individual would always go to that place where his satisfaction is maximized. Note that the second visit to an area is worth less than the first to an individual who derives satisfaction from new experiences. Thus the incurrence of higher opportunity costs to visit new places whose satisfaction initally is less than that derived from the place first visited is not inconsistent with maximizing satisfaction. Repeat visits generally result in lower satisfaction than first visits. As long as the increased costs are less than the decreased value of repeated visits, the individual will visit new places.

A reduction in the value of a recreational experience resulting from a fire will move all persons who would have used the area to a lower indifference curve. They may have to travel farther to find a comparable area, or they may use the same area and receive less satisfaction. To the extent that the utility or satisfaction of the users of the area has been reduced, or the opportunity cost increased, the fire has caused damage.

The relative importance of this line of reasoning can best be demonstrated with the aid of an example. Consider first a large fire in a unique area such as Yellowstone National Park. Because of its uniqueness, substitutability and hence MRS would be low. This in turn implies a high cost of substitution or opportunity cost. In other words, it would require a great deal of alternate recreational experience to compensate an individual (or society for that matter) for the loss of Yellowstone. Thus, most of the value lost can be considered as damage.

Consider now the case of a small fire on an ordinary scenic hillside. Because there are many similar areas, and because the total impact would be small, substitutability and MRS would be high, implying a low cost of substitution. As a result, little of the value lost could be counted as recreational damage. Note that the size of the fire influences MRS. As area burned increases, MRS decreases because an individual may have to incur greater opportunity costs to find comparable areas. He may ignore a 1-hectare fire, but he would not ignore a 1,000-hectare fire. The effects of substitution are equally applicable to every type of fire loss: merchantable timber, forage, watershed values, and so on. If substitution is not taken into account, excessive damage will likely be recorded.

In addition, damage is dynamic. Damage, at any point in time after a fire, is a function not only of the negative impact but also of the time since the fire, in that the scar eventually heals itself to the point where damage equals zero. The time required may vary from a few weeks, in the case of a grass fire, to a century or more, in the case of the complete removal of a mature stand of timber. On the other hand, damage might well equal zero or even be negative before the original conditions return, in that a vegetative mosaic is often considered superior in aesthetic qualities to a uniform vegetative pattern. Essentially, if no relatively undesirable qualities are detectable, damage can be considered to equal zero.

A correct procedure for damage assessment requires that a net present value formulation be utilized, as in equation 3. The amount of damage realized each year after the fire, discounted to the present, is added to the immediate loss. In addition, future benefits resulting from the fire, such as a vegetative mosaic or a new stand of vigorous timber to replace an old decadent stand should be included.

2. Market Processes

Market processes are not applicable to damage assessment when 'public goods' are involved. Two characteristics of public goods are 'nonrivalness' of consumption and 'nonexcludability'. Nonrivalness refers to goods that are readily available to everyone. Clean air and pleasant scenery are nonrival goods in that anyone can enjoy them without impinging on anyone else's enjoyment. In theory, their consumption does not reduce their availability for anyone else. Thus, a price cannot be charged for nonrival goods, because they are freely available. Nonexcludability refers to an inability to prevent someone else from consuming a good. If others cannot be excluded, they cannot be charged for consumption. Fisheries, wild game, common oil pools and national defense are typical nonexcludable goods. Note that resources are nonexcludable only until captured. If property rights in a good can be acquired, it is not nonexcludable. In all the above cases, the commodity is classed as a public good, and as such is not subject to market processes. In theory, no one will want to buy the good, implying that no one will be able to sell it.

'Externalities' are another situation where market processes do not apply. Externalities refers to the imposition of a cost on an individual, firm, or society where the cost is not borne by the originator. Discharging wastes into the air or water imposes costs on all those who subsequently use these resources. Thus, an externality exists in the waste discharge process. There are many types of externalities. A fisherman catches a fish, or a hunter gets his deer, thereby reducing the number available for others. Driving a car imposes several externalities in terms of air and noise pollution and by increasing the time required by all other drivers to reach their destinations. Overcrowding at a recreation site poses externalities in the form of waiting lines and a reduction in the value of the experience. In general, externalities exist because the costs cannot be transferred to the originator through market processes. Some form of government intervention and regulation is generally necessary to achieve an equitable distribution of costs.

3. Risk Premium

The last factor to be considered here, risk premium, is related to the premium that an individual facing risk is willing to pay to reduce the risk. The insurance industry is based on the willingness of individuals and firms to incur small losses in order to avoid large losses. The key point is that a person is willing to pay more than the expected value of a loss to eliminate large losses. If this were not true, insurance companies could not pay administrative costs and make a profit. The larger the potential loss, the greater the difference between the expected value and the amount that a person is willing to pay. The concept is similar to the risk premium that an investor requires for risky investments. We can now consider the effects of the foregoing three damage characteristics on the evaluation of damage from wildfire.

B. Damage Evaluation

Harrison et al. (1972) distinguished between damage accruing three types of individuals: the owner of an affected area, the user, and persons other than the owner or user. Rather than simply a convenient classification scheme, the three categories are, in fact, fundamentally different in their relationships to the three damage characteristics. The remainder of this section will explore the nature of these relationships and the significant differences.

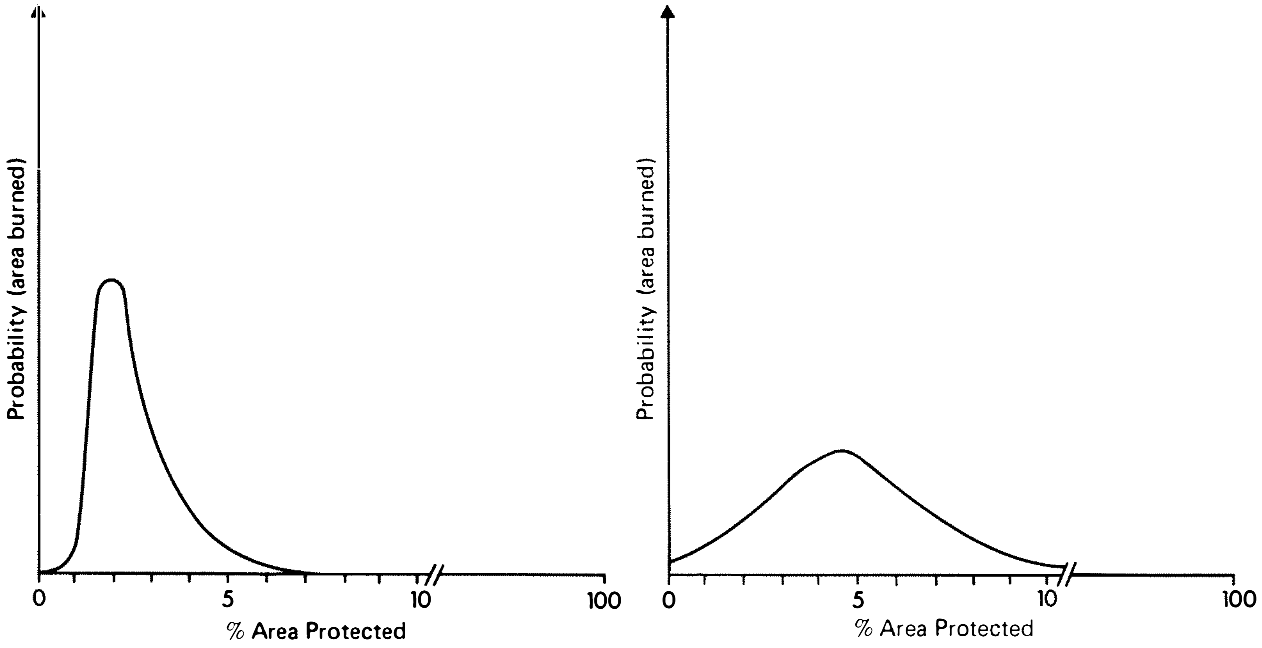
1. Damage Accruing to the Landowner

To the owner, the land represents a capital asset. He can suffer several types of losses from wildland fire. Detailed and fairly exhaustive listings of types of fire losses can be found in Headley (1943) and Harrison et al. (1972). These will not be repeated here. Direct losses to the owner (such as merchantable timber, topsoil, and improvements) can be aggregated under the difference in the market value of the land before and after the fire. Since land is readily bought and sold and has established market values, a comprehensive appraisal would provide a reasonable estimate of the direct market losses. Indirect market losses (such as grazing or recreation fees) can be readily calculated from the fee schedule and the reduction in use resulting from the fire.

To the extent that they are not included in the market value of the land, some nonmarket losses, such as scenic values and the owner's satisfaction derived from the prefire fauna and flora have to be tabulated under the owner's consumer surplus. Consumer surplus can be defined as the amount that the land was worth to the owner over and above its market value. Obviously, this will be more difficult to determine than market losses. Examination of land values suggests, however, that many apparently abstract amenities such as trees (for their scenic rather than commercial value), access to water, or a good view are, in fact, well represented by the premium prices that they command in real estate transactions. The landowner's consumer surplus may, in fact, be relatively small. If this is the case, most of the value lost to the landowner can be accounted for by market values.

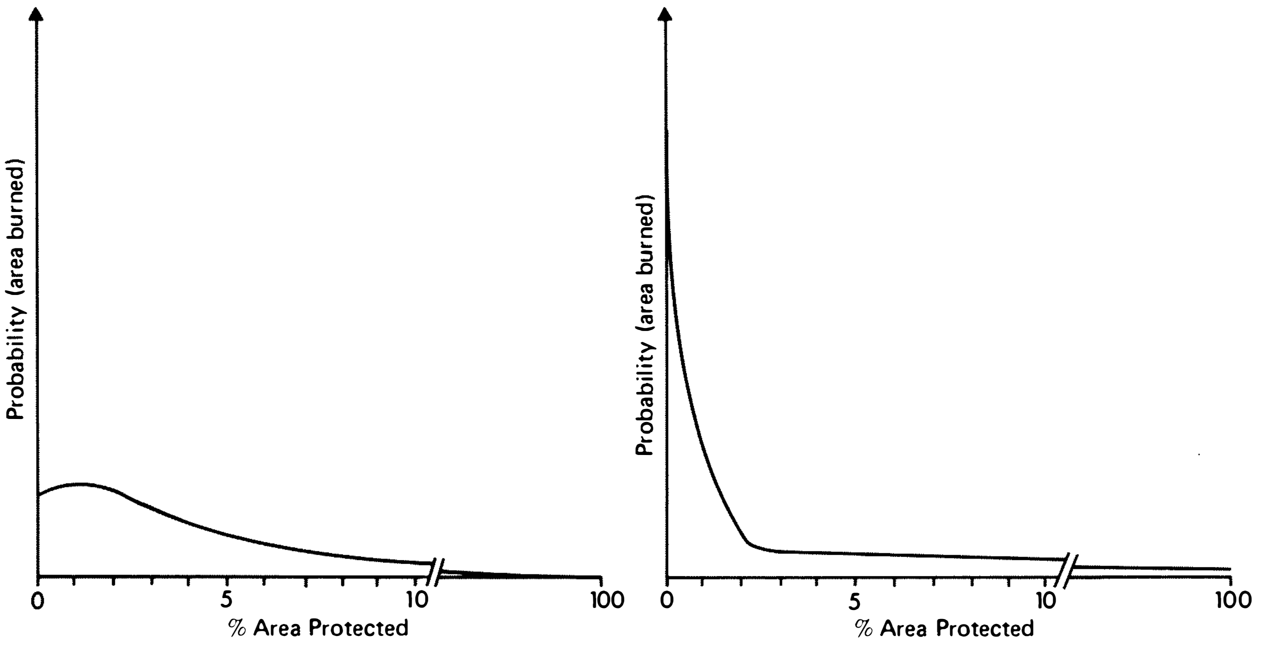
The degree to which the landowner can substitute for value lost as a result of a wildfire is severely limited. Reduction in market value, other than to improvements, through losses caused by fire, is generally not insurable. As a result, in most cases, the owner will not be able to substitute financial compensation for his losses. In addition, he may not be compensated for loss of fee revenue. Note that the fact that an owner can substitute financial compensation for a loss through insurance does not eliminate the loss. Rather, it becomes a loss to society through the insurance company rather than to the individual.

The degree to which the owner can substitute for the nonmarket values lost depends on the size of the fire in relation to the size of his holdings, and his mobility. If his entire property is destroyed, his substitutability for nonmarket losses is nil. Similarly, if the view from his living room window is ruined, there is little he can do. If the fire is relatively small, or the damage is light,



A. Large - 5 million hectares

B. Medium - 100,000 hectares or more.



C. Small - 5,000 hectares

D. Very small - 50 hectares or less.

Figure 20. Relationship between area protected and the distribution of the per cent of the area burned per year.

or his mobility is not limited (as would be the case for a picnic or fishing spot), his substitutability for nonmarket losses could be fairly high.

It should be noted that selling the land is not a form of substitution with respect to the losses. When the land is sold, the losses are written off through the owner's acceptance of a reduced price. Through the transaction the owner is substituting other goods for the damaged land. He is indicating that, whereas before the fire the land was worth at least the market price to him (because he did not sell), after the fire it is worth less than the devalued market price to him (because he is now selling). In general, for the landowner, substitution will be very limited, and damage will closely approximate the value lost on the site.

The importance of the risk premium to the landowner can be considered by examining the relationship between the distribution of annual area burned and size of protected area, as discussed by Davis (1965). Figs. 20 A through D show typical distributions of the percentage of the protected area burned per year that might be expected over an extended period for four different sizes of area protected. In the first case, (A) a very large landowner such as a public agency will experience a wide range of fire sizes but a relatively narrow range of percent of the total protected area burned per year. In a good year a few thousand hectares may burn, while in a bad year as much as half a million hectares might be lost. In the extreme, the distribution is only likely to span 10% of the total range, and the vast majority of the observations will lie between 0.5 and 2.0%. Hence, a very predictable outcome with relatively little variance. The agency could, in effect, act as its own insurer and pay no premium above the expected value of the losses.

In looking at B, it can be seen that as the size of the area protected is reduced, the probability of both smaller and larger percentages of area burned is increased. There is now a measurable probability that no area would be burned in a single season. There is also a measurable (but very small) probability that the entire area could burn in a single year. Further reductions in the size of the protected area continue the trend. In the smallest unit, there is a very high probability of no damage, and a significant (though much smaller) probability of total destruction. Clearly, in the last case, the landowner would be more willing to pay a premium to reduce the risk of a total loss than in the first case, even though the expected values were the same.

2. Damage Accruing to the User of the Land

The user of the land is in a significantly different position from the owner, in that he can move to another area not damaged by the fire. Thus, his substitutability is much higher than that of the owner. This does not imply, however, that the user of the land incurs no damage from a wildfire. To the user, the land represents either a factor of production or a consumer good. To the extent that, as a producer, he was using the least-cost combination of production factors prior to the fire, use of the land must have represented the lowest opportunity cost. Similarly, to the extent that, as a consumer, the individual was maximizing his satisfaction prior to the fire for a given budget of time and money, use of the land must also have represented the lowest opportunity cost. In either case, use of any other area will involve a higher opportunity cost. Conversely, use of the same area will result in lower productivity or satisfaction. Damage accruing to the user will therefore be measured by the difference between opportunity costs before and after the fire.

Harrison et al. (1972) suggests that damage incurred by the user will be measured by his consumer (or producer) surplus, i.e. the value of the land to the user in excess of the fee or rental charged by the owner. This will only be the case, however, when the user cannot profitably move to another location (or use the same area). Note that if there is no surplus, i.e. if the opportunity cost just equals the value of use, the user does not incur any losses from a fire. The rent or fee has already been attributed to the owner's loss. Thus, the consumer (or producer) surplus sets an upper limit on the damage that can accrue to the user. The effect of a fire with respect to the user is to reduce his surplus by an amount proportional to the value lost. As mentioned, this can be partially measured by differences in opportunity costs before and after the fire.

Changes in the productivity of the land (or value of the good), whether caused by the fire or by moving to a new location, also have to be taken into consideration. In addition, the cost of changing location must be considered. For a recreationist, this is likely to be close to zero, whereas for a cattle rancher the costs of moving may be significant. MP (or MU) could be either higher or lower after a wildfire. The above may be summed up mathematically for a producer:

$$VL = (OC_a - OC_b) + Q(MP_b - MP_a) + CM \tag{11}$$

where:
VL = value lost
OC = opportunity costs
Q = units of input
MP = marginal productivity
CM = cost of moving
a, b = after and before the fire, respectively

In the case of a consumer, the second group of terms would be written as $Q(MU_b - MU_a)$ where MU equals marginal utility. There is no restriction with respect to the size of either group of terms. For example, there could be a net decrease in opportunity cost resulting from a fire. This would have to be accompanied by an even greater decrease in productivity, however, if the assumption that the user had been maximizing his utility prior to the fire were to hold.

In some instances (as in the case of a cattle rancher) fire may improve productivity. In that case, the second term becomes negative, and since the user may not move, his opportunity costs could remain the same. The net result would be a negative value lost. Another way of looking at such a situation is that the fire resulted in a net benefit. The formula applies equally in either case. Equation 11 also applies if the user does not change location after the fire. In this case, CM equals zero.

The impact of the risk premium with respect to the user of the land would be inversely related to the importance of substitution. Since the user of the land is relatively mobile, he stands a much lower chance of total destruction than the owner of the land. The effect is much the same as for a large landowner. As a result, a premium for risk would be of relatively minor significance to the user of the land.

The last factor, the importance of market processes, is significant in that much of the use of the land involves nonmarket values. For example, how is a recreationist's consumer surplus measured? Whereas, in the case of the owner, the major portion of these values was reflected in the market price of the land, recreational user fees, on public lands, if they exist at all, are notoriously less than the value to the consumer. As a result, there is a large consumer surplus. Thus, market processes will likely fall far short of estimating values lost to users of the land. On the other hand, recreational use fees on private land tend to be significantly higher, thus considerably reducing consumer surplus.

3. Damage Accruing to Persons Other than the Owner or User

The effects of a wildfire on persons other than the owner or users involves externalities. The result is that the expected value of the losses borne by affected individuals will not be taken into consideration by the owner of the land, in the case of private ownership. In the case of public ownership, where maximization of social welfare is (or should be) the goal, the fire management budget should, of course, reflect external values.

In the case of external effects, the relative importance of substitution and risk premium depends on the nature of the damage. On the average, the relative importance will probably lie somewhere between that for the owners and users of the land. Consider the case of flood damage.

Affected individuals live in a fixed place, and moving in response to an increased flood threat can result in major costs. The threat is not immediate, however. Persons involved have time to plan ahead and exercise more substitution options than someone whose home is faced with imminent destruction by fire. Further, society normally has time to take steps to ameliorate the potential effects of flooding by seeding grass and other flood control measures. When preventative measures are employed, the costs of such measures would be substituted for the potential flood losses in calculating value lost attributable to the fire. Thus, for persons in the flood plain, the relative importance of substitutability and the risk premium will probably be moderate. For persons outside the flood plain, there is no damage attributable to flooding.

Consider now the case of smoke pollution resulting from a wildfire. Smoke is a temporary and generally (though not always) minor annoyance. Substitutability is high in that one can leave an area for a day or two at relatively little cost, if the annoyance becomes too great. Conversely, since there is little likelihood of a major loss from smoke, the risk premium is of little consequence.

The importance of market processes in measuring external effects is comparable to that for the landowner. The major losses accruing to other persons outside the protected area are in the form of direct destruction of improvements by the fire, flood damage, and in the case of large fires, possible loss of employment. These losses are all measurable through market processes. Losses such as air pollution and the emotional loss suffered when an area is ravaged by fire, even though it is not visited, are not accountable in the market place, but in all likelihood they are orders of magnitude less than the above losses.

The relative importance of the three characteristics with respect to each category of damage accrual is summarized in Table 1. It can be seen that, for the owner and others, market values give a reasonably good indication of value lost.

TABLE 1. Summary of the importance of damage characteristics.

Characteristic	Owner	User	Others
Substitutability	low	high	moderate
Risk premium	high	low	moderate
Market processes	high	low	high

For users, market values may not be well correlated with values lost through fire. It can also be noted, however, that substitutability is high for users, which suggests that losses would most likely be significantly less than those accruing to the other two categories. Much of the intangible damage (to recreation, wildlife, and scenic values) is attributable to this category. Additionally, much of the intangible loss of value accruing to the external sector is of a moderately substitutable nature. As a result, it is reasonable to wonder whether an assessment of damage that ignored intangibles would be as excessively low as has been repeatedly suggested in the literature ever since the first critical review of the economic theory by Show and Kotok (1923). It would be presumptuous to conclude that such was the case from the subjective arguments presented here. It would not be presumptuous, however, to suggest that a detailed analysis of such an intriguing possibility seems warranted.

VI. BENEFICIAL WILDLAND FIRES

A. The Benefit Function

In previous sections we have assumed that wildland fires result in negative net present value (NPV). Clearly, however, there exists a significant subset of fires that result in a positive NPV. In fact, as will be shown, all fires result in positive NPV immediately after ignition. Many of the concepts presented earlier apply equally to fires with positive NPV. Some of the functions are of a different form, however, and thus have to be redefined.

At this point an additional pair of functions is needed. Total net benefit (TNB) is defined as the cumulative positive net present value accruing as a result of the occurrence of wildland fire (whether accidental, natural, or deliberately caused). In other words, TNB is the difference between benefit and damage where the difference is greater than zero. Marginal net benefit (MNB) is simply the slope of TNB.

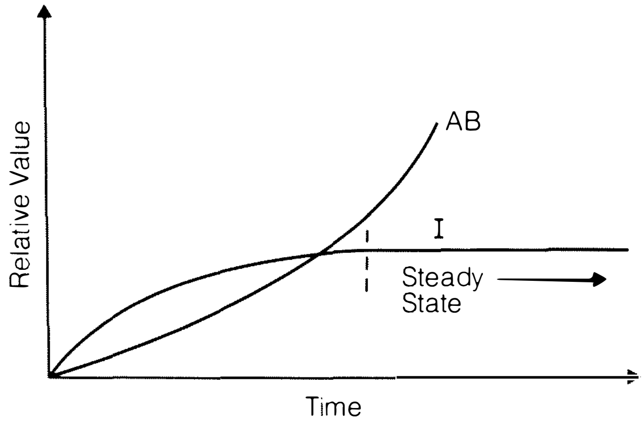


Figure 21. Relationship between area burned, fire intensity, and time since ignition.

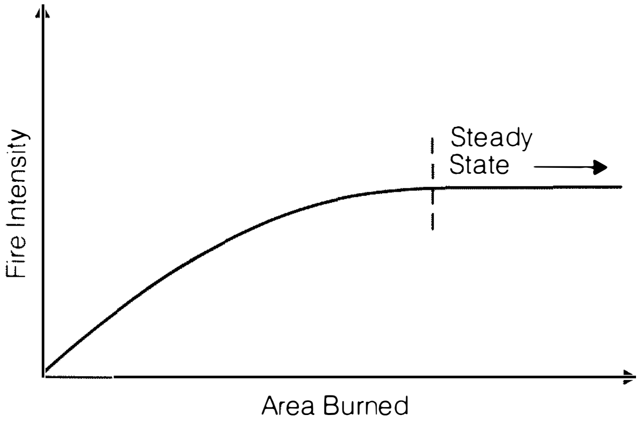


Figure 22. Relationship between area burned and fire intensity.

TNB and MNB can be defined by relating area burned to fire intensity. In addition, a set of assumptions relating beneficial impact to intensity are needed. The relationship between intensity and time since ignition is well defined in the literature. As shown in Fig. 21, intensity increases at a decreasing rate over time, particularly in the case of point ingition, which is the way fires start naturally. Eventually, a steady state is reached. The growth period could last from a few minutes to an hour or so. AB increases exponentially with increasing time since ignition. Thus, as shown in Fig. 22, during the growth period, intensity must be increasing with increasing area burned. After a steady state is reached, intensity is independent of area burned.

During every phase of a fire's history, both beneficial and undesirable impacts are being generated. A hypothetical relationship between these two and fire intensity is illustrated in Fig. 23. At low intensities, damage is likely to be nil and benefits slight to moderate. At moderate intensities, benefits tend to be maximized, while at the same time damage also increases somewhat. At higher intensities, benefits are likely to decrease, while damage begins to increase significantly, to the point where, at very high intensities, damage could exceed benefits by orders of magnitude.

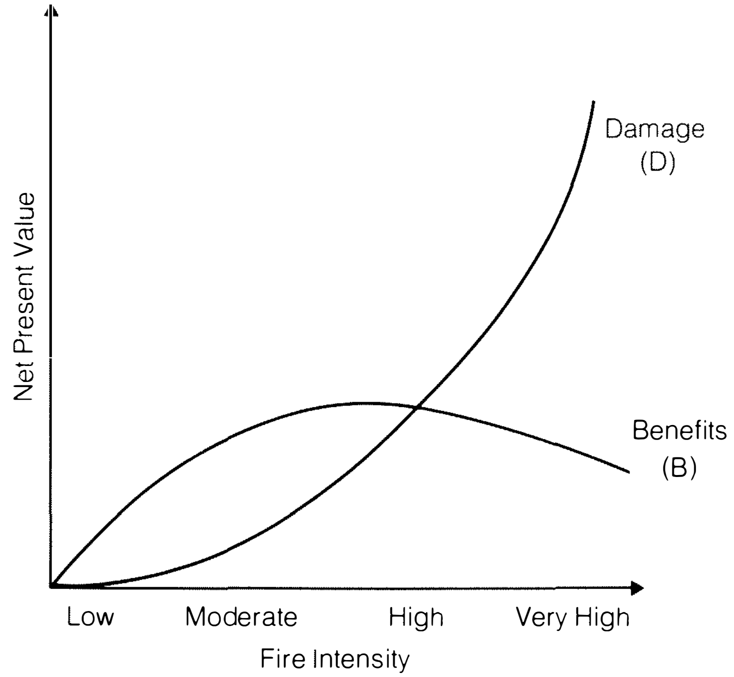


Figure 23. Hypothetical relationship between damage, benefits and fire intensity.

TNB, which is defined as the difference between benefits and damage, is plotted as a function of area burned in Fig. 24. At ignition (point A) TNB = MNB = 0. Clearly, if no area is burned, there can be no damage or benefit. MNB increases to its highest level as the difference between benefits and damage is maximized at moderate intensities (point B). Note that MNB(max) is not necessarily the point of maximum benefit, but rather the point of maximum positive difference between benefits and damage.

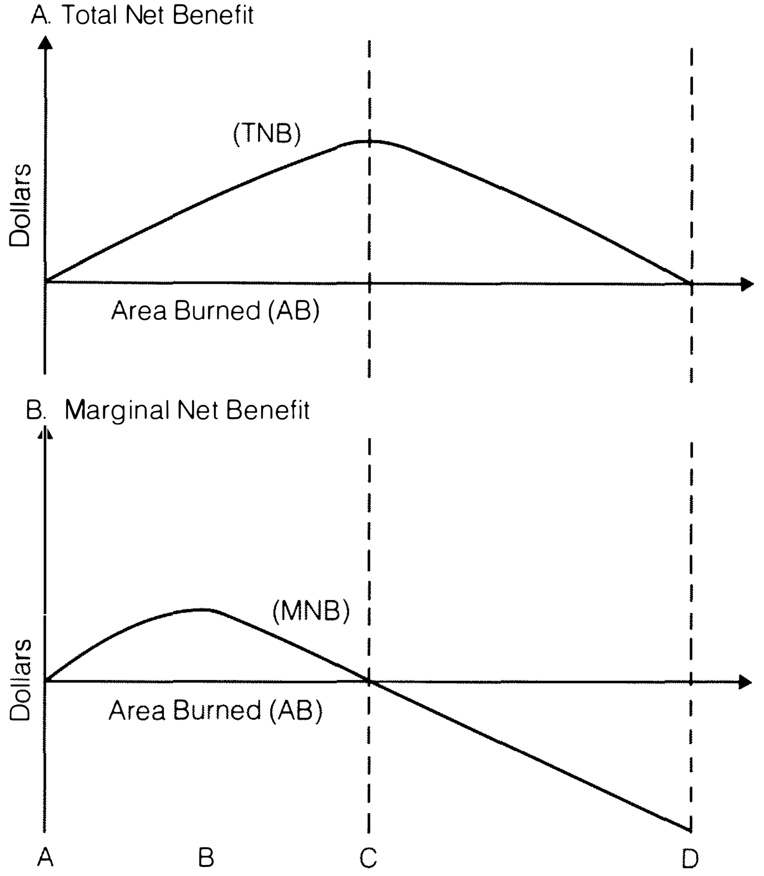


Figure 24. Total and marginal net benefit as a function of area burned.

Further increases in intensity (hence, also area burned) decrease the difference between damage and benefits to the point where MNB eventually equals zero (point C), indicating that damage equals benefits. This is the point of maximum total net benefit for the fire. Ideally, if a wildfire could be instantly extinguished at zero cost, this would be the optimum size and intensity at which it should be controlled. Continued increases in intensity (area burned) result in negative MNB or positive damage. Eventually, point D is reached, where the cumulative excesses of losses over benefits equal the previous cumulative excesses of benefits over losses and TNB equals zero. Mathematically, TNB = 0 when:

$$(12) \qquad \int_{A}^{C} MB \, \partial \, MB = \int_{C}^{D} MB \, \partial \, MB$$

The fire size (intensity) at which point D is reached will vary for every fire. It is a function of several variables, the most important of which are fire intensity, resource value, and susceptibility to damage. In the case of a fire attaining high intensity in a high value area, point D may be reached when the fire is only a few square feet in area. In the case of low intensity fires, point D may not be reached at all (within practical limits). It is clear, for example, that in the case of prescribed fires, the aim is to select burning conditions such that fire intensity attains a steady state level so as to generate MNB in the range between points B and C, and to maintain it at that level until the entire area to be treated is burned.

There are significant practical problems associated with applying the foregoing to wildfires. First, the point in the history of a wildfire where MNB changes from positive to negative must be identified. Second, the fire management system must be able to control the fire at that specific point in time. Third, suppression costs are not zero and they increase with increasing area burned. Finally, the variability of fire effects throughout the fire's history must be considered. Obviously, given the current state of the art and the numerous practical problems involved, the current practice of extinguishing wildland fires as quickly as possible is, and will continue to be, a good strategy for most fires. The gradual emergence of let burn policies in specific localities and under specific conditions, however, suggests that fire managers have already begun incorporating some of the above concepts in their planning process (Devet et al. 1974).

The benefit function is also applicable to a set of fires. In a randomly selected set of fires, most will be small and of low intensity, some will be of moderate size and intensity, while a few will burn a considerable area and be relatively intense. For a given region, a set of fires with a small total area burned will consist of a large proportion of small, low intensity fires and fewer large, intense fires. Conversely, if a greater area is burned in the same region the set will likely contain a smaller proportion of small fires and a higher proportion of large, intense fires. Thus, the benefit function should be of the same general form whether area burned in a single fire or total area burned by a set of fires is used as the independent variable. It is this property which allows beneficial impact to be incorporated into the economic theory.

B. The Complete Economic Theory

The production functions for fires with positive NPV differ somewhat from that for fires with negative NPV. The production function takes two forms, depending on whether the benefits result from the early stages of a wildfire or from a prescribed fire. In the case of wildfires, the production function shown in Fig. 3 is also applicable here. In the present case, however, the interpretation differs. In the case of fire where NPV is positive, the implication of Fig. 3 is that an increase in fire management effort decreases system output. This apparent contradiction is resolvable by noting that in the present case AB is the desired output of the system, whereas in the case of negative NPV a reduction in AB is the desired system output. As fire management effort is reduced, more area is burned and, in the case of positive NPV, the benefits are increased. Note that this cannot be an unconstrained objective in that at some point the fire will have to be extinguished. As fire size increases, the effort required to control it also increases, barring natural extinguishment. Thus a limit is imposed on the size that a fire can be permitted to achieve.

Applying the economic theory to wildland fires with positive NPV presents no significant difficulties. Fig. 25 illustrates the wildfire situation for three possible MNB curves. It is possible that a solution, other than the trivial one of $MC = MNB = FME = AB = 0$, does not exist. If MNB is less than MC(ab) throughout the relevant range (MNB_1), benefits are less than the costs of achieving them. In such cases, the benefit function, when considered by itself, has no meaning. It is still useful in combination with the damage function, however, as will be discussed subsequently.

In the case of MNB_2, the curve just touches MC(ab), thus ensuring one and only one solution: E_2^* and AB_2^*. Now consider MNB_3, which is greater than MNB_2 throughout the relevant range. In this case, two solutions are possible: (E_3^*, AB_3^*) and (E_3^{**}, AB_3^{**}). As in classical economics, whenever two solutions are possible, the optimum will always be at the intersection where MC is increasing. This can be easily demonstrated intuitively by considering a level of AB immediately to the right of AB_3^{**}. It can be seen that MC(ab) is lower and MNB_3 is greater than at AB_3^{**}. Since this is clearly more desirable, AB_3^{**} cannot be the optimum point. In contrast, by employing similar arguments, it is seen that any divergence from AB_3* results in an inferior solution. Hence AB_3* must be the optimum.

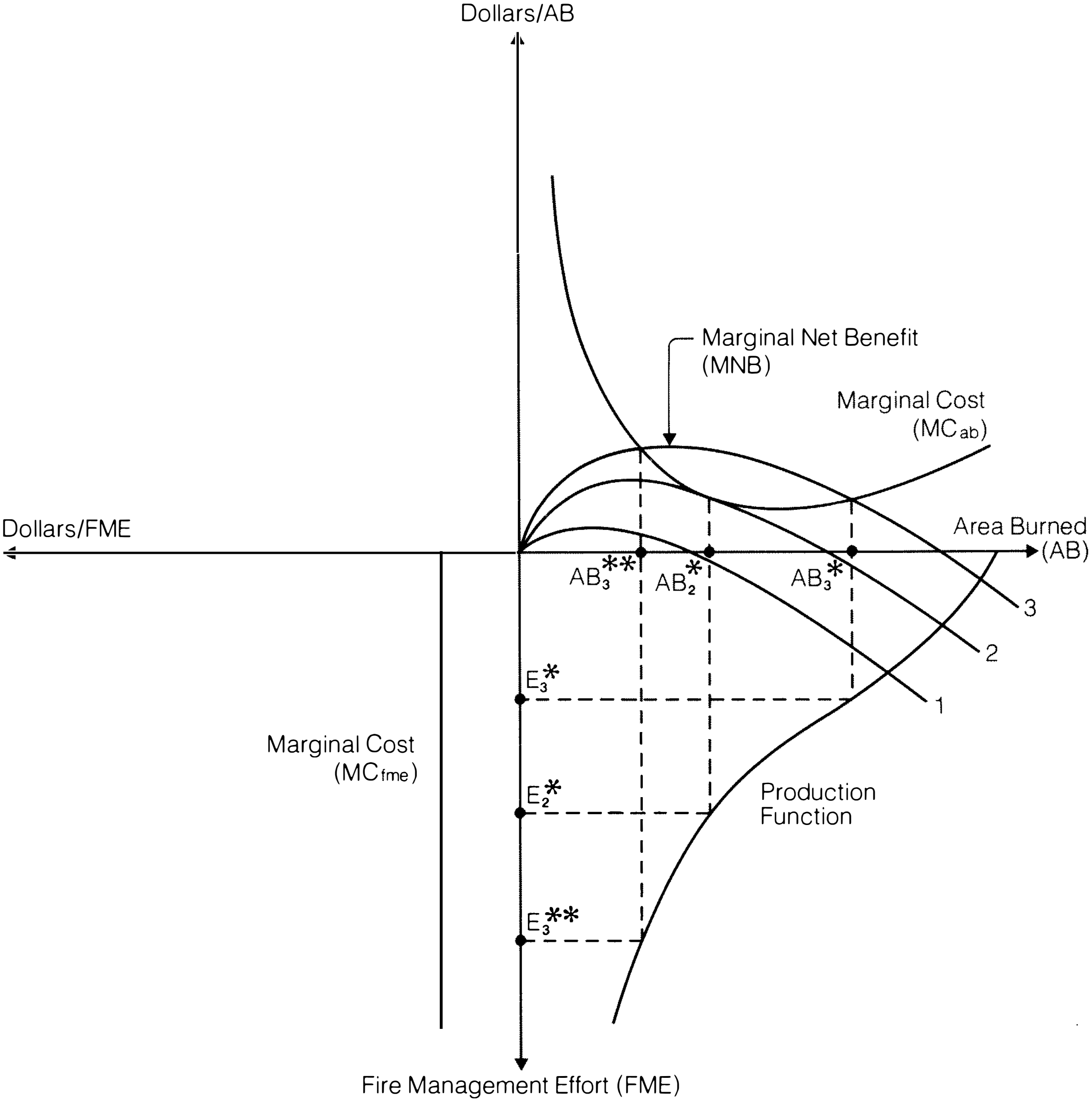


Figure 25. The economic theory applied to wildland fires with positive NPV.

In comparing MNB_2 with MNB_3, it can be seen that as MNB increases, the efficient solution is to allow more area to burn. This, in turn, allows a lower level of FME to be employed. This is what would be expected. If a fire is producing a greater net benefit, it should be allowed to burn longer (obviously not indefinitely as discussed previously). If a fire is allowed to burn, it follows that fewer resources are being used to control it.

The prescribed fire production function is of a different form than that previously discussed. Fig. 26 illustrates the classic form of production function. Since area burned is the output of prescribed burning, as opposed to being inversely related to output as in the case of fire control, the traditional presentation is appropriate. Fig. 26 shows initial economies of scale gradually superseded by diminishing marginal returns.

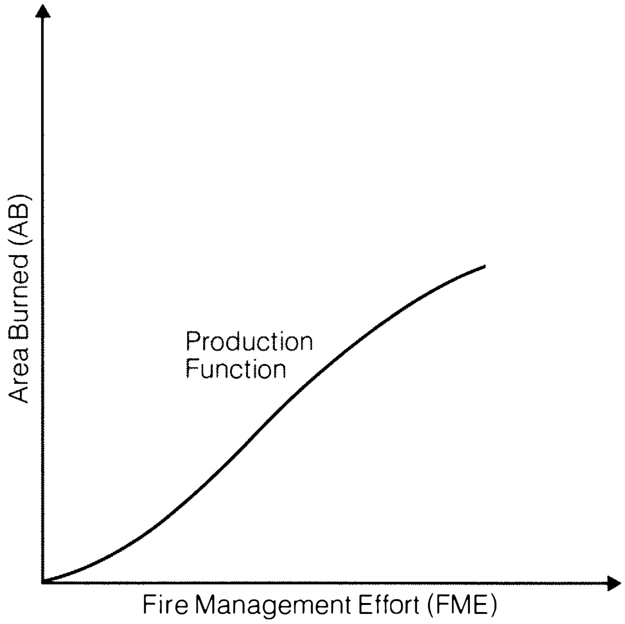


Figure 26. Production function for prescribed fires.

Application of the prescribed fire production function to the economic theory is illustrated in Fig. 27. The reader will note that MC(ab) in Fig. 27 is of the same form as that used previously, despite the fact that the production function (and hence the transformation) differs. This can be explained by the fact that the two production functions are complementary in form. That is, at low levels of FME, one rises at an increasing rate while the other falls at an increasing rate. At high levels, one rises at a decreasing rate while the other falls at a decreasing rate. The net result is that the transformed marginal costs are complementary in form with opposite signs. Thus, in the present case, MC(ab) is obtained directly from the transformation whereas in the previous case, it was obtained by taking the negative of MC(ab).

As in Fig. 25, a nontrivial solution may not exist as illustrated by MNB_1. The theory has a meaning in this case, however. The optimum solution is to set all four functions equal to zero, or in other words not to use prescribed fire, as costs are greater than benefits. In considering MNB_3, it can be seen that there also exists the possibility that an optimal solution may be beyond the relevant range of the production function (AB_3^*). Such a situation could result from a budget limitation which, in turn, limited the level of FME. In such a case, the practical solution would be to do as much prescribed burning as the budget would allow, as long as AB greater than AB_3^{**}

could be achieved. Since at effort levels below E_3** marginal cost is greater than marginal benefits, any prescribed burning at lower effort levels would result in a net loss. In the latter case, the best solution would be to undertake no burning at all.

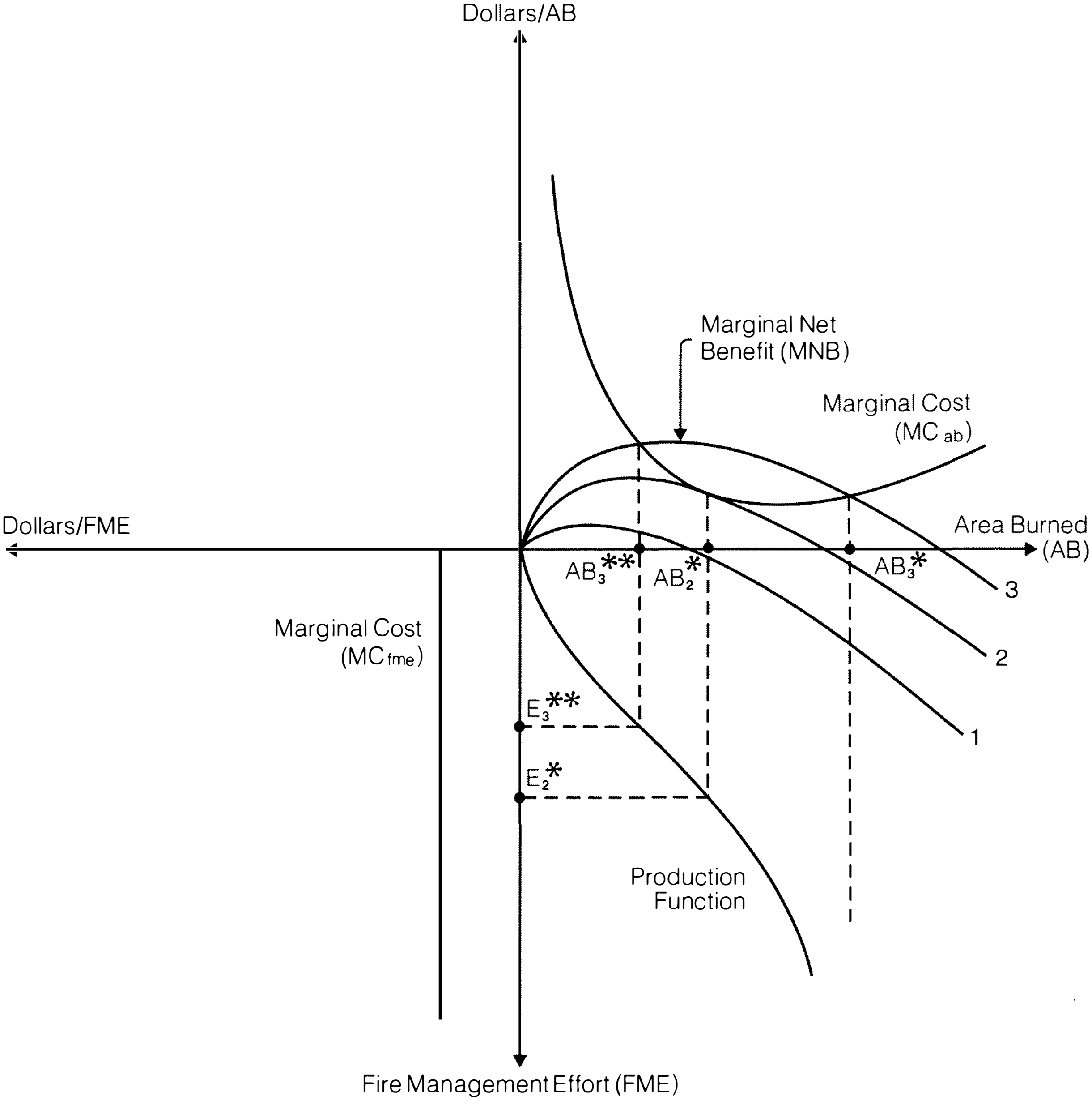


Figure 27. The economic theory applied to prescribed fires.

In most cases, however, MNB should fall somewhere between MNB_2 and MNB_3 with an optimal solution within the relevant range of the production function. It can be readily seen that as MNB increases, more prescribed burning will be undertaken. Conversely, as MNB decreases, less prescribed burning will be undertaken.

It now remains to consider the effect of the benefit function on the basic economic theory presented in Section II. To this point we have discussed the damage function (negative NPV) and the benefit function (positive NPV). It seems logical, therefore, to combine the two in a net present loss function (NPL). Net present loss is defined as the present value of the losses minus the benefits. The term loss is used rather than value, as we are interested in a function with a positive value when losses exceed the benefits. This is a useful property in relation to the economic theory. Hypothetical NPL and marginal NPL functions are illustrated in Fig. 28.

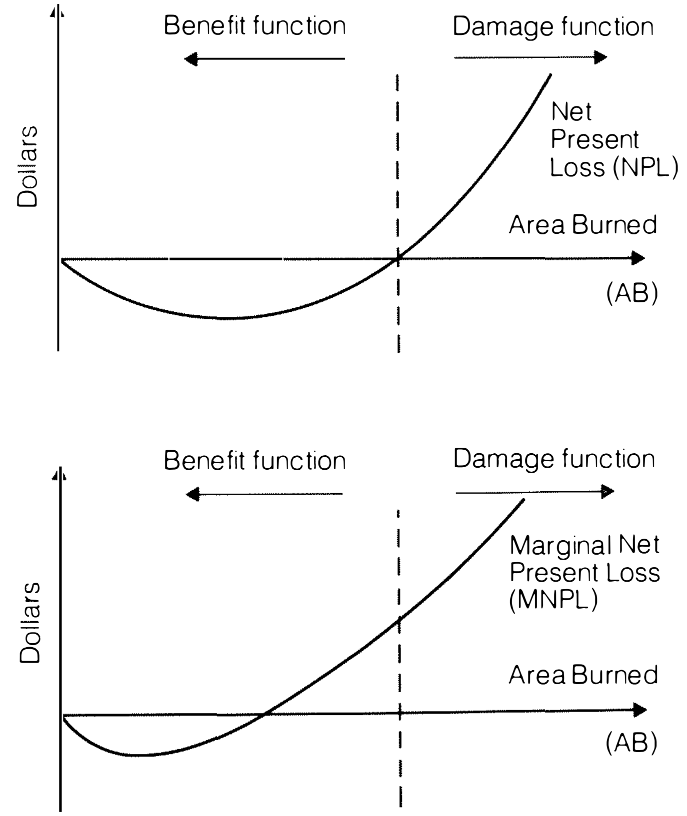


Figure 28. Hypothetical NPL and marginal NPL function.

It can be seen that positive values of the NPL function (to the right of the dotted line) are the same as the damage function shown in Fig. 2. It can also be seen that the negative portion of the NPL function (to the left of the dotted line) is simply the inversion of total net benefit as shown in Fig. 24(A). Values of MNPL, to the right of the dotted line, are equivalent to marginal damage shown in Fig. 8. Thus, the positive Y intercept for marginal damage, referred to in Section II, results from the incorporation of marginal benefit. Conversely, MNPL, to the left of the dotted line, is the inversion of MNB shown in Fig. 24(B).

In Fig. 29, the curves shown in Fig. 10 have been replotted with the addition of marginal NPL. It can be seen that MNPL(ab) will always be less than MD(ab). Therefore, an optimum based on equating MC and MD [E*(md) and AB*(md)] implies a higher effort level and lower area burned than an optimum based on equating MC and MNPL [E*(mnpl) and AB*(mnpl)]. In other words, to achieve an optimum solution when benefits attributable to wildland fires are incorporated into the economic theory, area burned will increase and the level of fire management effort will decrease.

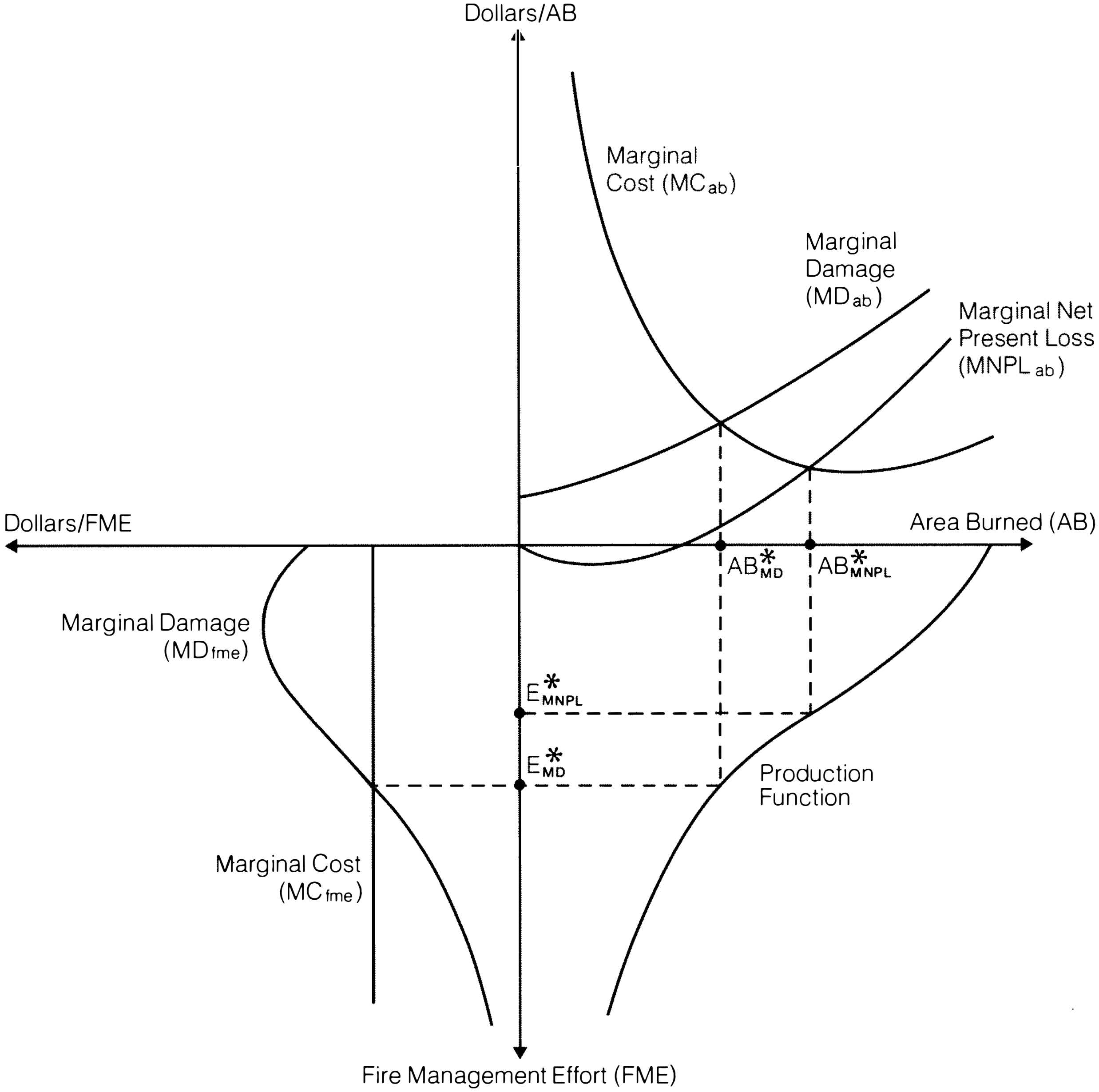


Figure 29. Effect of incorporating marginal net present loss in the economic theory of fire management.

In most wildfire situations, the negative portion of MNPL will be comparable to MNB_1 in Fig. 25. That is, the cost of achieving positive benefits probably exceeds the value of such benefits. Whether or not this is, in fact, the case can be determined by multiplying MNPL(ab) by minus 1. If the resulting curve crosses MC(ab) as in MNB_3 of Fig. 25, the benefit function should be used. If the curves do not cross, the overall economic theory as illustrated in Fig. 29 should be used.

The economic theory as presented in Fig. 29 is seen to include every significant aspect of the wildland fire management system. The use of net present loss is theoretically more defensible than the traditional damage function. The traditional approach tends to associate benefits with prescribed fires and losses with wildfires. This artificial segregation is a natural outcome of ignoring the beneficial aspects of wildland fires in assessing fire damage. Such a segregation is indefensible, however, in that in theory, every fire involves both benefits and losses. If a prescribed fire results in a net benefit, so also should a wildfire under the same conditions.

It is recognized that in the real world, practical problems may overshadow the preceeding arguments. For example, consider a fire which, on the day of origin, generates a net benefit, and on the second day generates a net loss. The theory suggests that the fire should be controlled at the end of the first day of burning. It is highly possible, however, that if the fire were allowed to burn unchecked for the full first day, it would be too large to control before the second day. Therefore, in practice the size at which the fire can be conveniently controlled becomes a dominant consideration.

From the point of view of the economic theory, the use of net present loss allows the manager to incorporate the beneficial as well as detrimental effects of wildland fire in setting goals for the fire management system. Given the current attitudes of environmentalists and recreationists, fire managers who fail to follow this course are likely to be taken to task, if in fact such has not already occurred.

VII. SUMMARY

Historically, there have been two approaches to establishing forest fire management policy. The predominant practical objectives are based on allowable annual area burned, elapsed time, or hour control criteria. The economic approach attempts to establish a level of fire management effort such that marginal costs equal marginal damage. The practical approach, while not denying the validity of the economic approach, refutes its applicability. While the validity of some of the arguments against the applicability of the economic theory is open to question, no major fire management organization in North America is currently using economic objectives in the cost-benefit sense. Further, while many agencies currently apply various economic criteria in highly constrained situations, the procedures used are often not entirely correct.

The economic theory of fire management is composed of three functions: costs, production, and net present loss. The use of three functions rather than the traditional pair of curves to describe the economic theory significantly increases its comprehensibility. Further, a reorganization of the three functions along generic rather than functional lines is useful from a theoretical, analytical, and operational point of view.

The cost function is an economic relationship linking costs and the level of fire management effort. As defined, marginal costs are constant with respect to the level of fire management effort. The production function is a technical relationship between the level of fire management effort (measured in units of man-year equivalents) and area burned. As the level of fire management effort increases at a constant rate, the area burned decreases at a decreasing rate, after initially decreasing at an increasing rate. Net present loss consists of damage and benefits. It is an economic-technical relationship between area burned and value lost. As area burned increases at a constant rate, marginal net present loss increases exponentially.

The production function, or transform, is clearly the key element of the theory, in that it links the cost and damage functions. This is of considerable significance when only limited information is available. The cost and damage functions, when considered in isolation, provide little useful information. The production function, on the other hand, even by itself provides some useful information, albeit incomplete. Addition of either the cost or the damage function to the production function provides management with a useful guide to policy determination even though the solution provided by the theory may be incomplete.

There are three types of fire management costs: variable costs, short-run fixed costs and long-run fixed costs. Variable costs increase in proportion to the number and intensity of fires and are charged against individual fires. Total fixed costs are compared with total benefits for an entire season (or relevant period). Short-run fixed costs are for periods of one season or less. Long-run fixed costs generally involve capital investments, the benefits of which are realized over two or more seasons. The net present value formulation must be used if valid comparisons with alternate fire management investments are to be made. The main purpose of the proposed classification scheme as opposed to the traditional functional breakdown is to permit a least-cost optimization of the mix of production factors.

There are three factors of production in a fire management system: fire occurrence, fire control, and fuel management. All fire management activities can be classified in one of these three groups. Fire occurrence activities (prevention and detection) involve predominantly stochastic phenomena. Fire control (presuppression and suppression) is predominately a deterministic process, and fuel management is a combination of the two. By incorporating elements of production theory, it is possible to determine the least-cost mixture of production factors for a predetermined budget or output level. The optimum mixture will be employed when the price of each factor divided by its marginal productivity is equal to the comparable ratio for every other factor.

There are three categories of damage, based on the type of individual (or firm) affected: the owner of the land, the user, or persons other than the owner or user. Measurement of damage accruing to each category is based on value lost adjusted by substitutability and a risk premium. Damage accruing to the landowner and others is, to a large extent, reflected in market values. Damage accruing to the user of the land is poorly reflected by market values. A high degree of substitutability in the user category, however, suggests that value lost may be small in relation to the owner and others. In all cases, the changes in net damage over time have to be considered through the use of a net present value formulation.

It was shown that fires with positive net present value can be analyzed by using a benefit function. The form of the production function for fires with positive net present value was discussed. The economic theory was shown to yield efficient solutions for both prescribed fires and wildfires. The concept of net present loss was defined as the present value of losses minus benefits. The use of net present loss was shown to be superior to the traditional damage function. Its incorporation in the economic theory will yield higher area burned and lower fire management effort levels than the damage function alone.

It has been the intent of this paper that the traditional economic theory, which has been with fire management for more than half a century, will be seen to be more comprehensible and yet richer than has been previously suggested in the literature. Its potential usefulness has never been questioned – only its applicability. It is without doubt a powerful tool that would be of great value to forest fire management policy makers. The potential payoffs for research on this topic are as high as those for any other endeavor in the fire management field. Now, more than at any previous time, there exists a distinct probability that the problems can be solved and the payoffs realized.

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