CHAPTER 18

TOWARD A UNIFIED ECONOMIC THEORY OF FIRE PROGRAM ANALYSIS WITH STRATEGIES FOR EMPIRICAL MODELING

Douglas B. Rideout, Yu Wei, Andrew G. Kirsch, and Stephen J. Botti

1. WHY A UNIFIED THEORY

Recent United States federal wildland fire policy documents including the 2001 policy update (US Department of Agriculture and US Department of the Interior 2001) call for integrated approaches to the national fire program. An important theme of these inter-agency policies is to encourage planning and budgeting across the major fire program components (e.g., suppression, fuels, prevention) in a consistent way. This means, for example, that planning and budgeting for the fuels (suppression) component is informed by the planning and budgeting of the suppression (fuels) component. In this chapter we specify the economic structure of a planning and budgeting system, as opposed to a component-by-component analysis. This structure shows, for example, that budgeting a federal system by program component is unlikely to promote efficiency. The structure also shows that the components can be managed in concert to capitalize on the complementary impacts they are likely to have on each other.

Implementing a unified theory in planning constitutes a major challenge across uncharted waters. Current planning approaches are largely based upon component specific models and budgeting is often executed as incremental adjustment to precedent. This chapter reaches beyond by deriving the essential principles of an integrated fire system in support of cost effective planning and budgeting. While some of our analytics used to derive the principles are complex, we do not intend to imply that budgeting systems need to reflect such complexity: only the essential principles.

Previous planning and budgeting models have focused on individual program components such as fuels management, suppression, or prevention with no direct or simultaneous consideration of the other components. This means that managing and budgeting the system of components in concert has been largely unattainable. Current models were not intended to directly address how the plans for initial attack (fuels treatment) are affected by a simultaneous consideration

T. P. Holmes et al. (eds.), The Economics of Forest Disturbances: Wildfires, Storms, and Invasive Species, 361–380.

of the plans for fuels treatments (initial attack). For example, the initial attack models used in the U.S. such as the National Fire Management Analysis System (NFMAS) and the California Fire Economics Simulator (CFES2) are specific to initial attack. Fuels models including advances designed by Hof and Omi (2003) are not intended to directly incorporate initial attack or suppression effects. In some instances these component-specific models can use the output from one component as input to another. This sequential approach to program interaction has serious limitations that can be improved upon by a fuller development of a system level analysis that attempts to more holistically address the problem.

While previous conceptual models (such as the least cost plus loss or cost plus net value change) address the balance between damage (net value change) and fire program level (preparedness), this chapter addresses wildland fire management at the system level by specifying each program component as part of a unified system. For further development of current management approaches, see other chapters in section IV of this book. Section two provides critical background on the fire program components and the key ways that they interact. Section three develops the core analytics of the unified theory at the system level. This structure serves as a potential foundation for addressing the principles of management and budgeting of the fire program components within a cohesive and unified system. For example, we show how the productivity of the fuels component changes the productivity of the suppression component. This section concludes with an application of the envelope theorem revealing a potentially refutable proposition regarding program cost effectiveness. In the last section, we identify alternative modeling approaches. These approaches inform the balance between the advantages of the unified theory and the pragmatic concerns of viable modeling and implementation. Implementation of a truly unified approach is perhaps impractical, but development of the theory will identify important principles, conditions, and implications related to policy analysis, budgeting and program implementation. We start by establishing the structure of the key relationships between the program components.

2. RELATING THE PROGRAM COMPONENTS

In this section, we review the three basic kinds of interactions among the program components:

- the *budgeting* process,
- *cost* structures,
- physical interactions among the *productivity* of the components.

In *budgeting*, funds allocated to one component often reduce funds available for another component. For example, allocating more funding to prevention may reduce funding available for suppression. This form of interconnectedness directly reflects scarcity through the fire program budget and appropriation processes. The economic principle often used to address budget scarcity across the components is to require equal improvement in each component per additional dollar spent. This is an application of what economists refer to as the equi-marginal principle (for example, Samuelson and Nordhaus 2001). While this is an important consideration, it does not provide a singularly compelling reason for developing a unified economic theory. The reason for this is that a common budget does not directly affect the underlying benefit or cost structure of the program. Separate program component levels could be independently adjusted up or down to conform to the equi-marginal principle[1].

Cost analysis by component is complicated and often frustrating because fire management resources (engines, aircraft, personnel, etc.) are interrelated through the cost function. A fire management resource, such as an engine, is often used to support multiple program components. For example, the purchase cost of an engine used in both fire protection and in fuel management would be joint, making it impossible to logically divide the purchase price of the engine between these two program components. In economics this is the well-known problem of joint cost allocation. Such cost considerations are not well addressed through a separate, or sequential analysis of program components. It is unlikely that a separate consideration of the program components will enable the planning or budgeting process to take advantage of the cost savings available in fire resources that are common across components. This can lead to redundant funding.

Interconnectedness in the *productivity* of the components has been long recognized, but it has not been well analyzed. For example, a major rationale for hazardous fuel reduction is to positively affect suppression efforts by reducing flame lengths, slowing fire growth rates, and enabling faster fireline construction. Budgeting and physical interactions among fire program components enjoy both a longstanding and consistent recognition. Sparhawk (1925) recognized the interaction between preparedness and suppression for fire management planning. More recently, Pyne et al, (1996, page 386) stated

> *"All of these activities and all these levels of management require planning. Especially as fire management enters a period of consolidation, plans by which to integrate program with program, agency with agency, region with region will assume ever greater importance."*

The most widely used fire economics model for planning and budgeting, known as least cost plus loss, or cost plus net value change, was not intended to address multiple program components. While numerous fire management models have been designed to address individual fire program components (McGregor 2005), none of those designed for U.S. federal lands have directly attempted to integrate multiple fire program components into an overall unified system. Additionally, advances in geographic information systems (GIS) and computing

[1] This would require the potentially awkward enumeration of a full set of funding levels for each program component, each to be compared to select the optimal mix of component levels.

resources applied to fire (Miller 2005, Finney 1998) enable a fresh look at the problem of system-wide resource allocation across the various fire program components.

The next section takes a philosophical departure from traditional approaches to fire management economics to provide the core analytics of a unified system.

3. A UNIFIED PROBABILISTIC ECONOMIC MODEL

To formulate a unified economic model of fire program analysis we assert that federal managers exhibit behavior consistent with cost minimization. While such behavior may not always reflect reality, this assertion has withstood the test of time for modeling purposes and we suggest that modeling such behavior is desirable at least as a benchmark of comparison to alternative behavior. The cost minimization assertion also aids in understanding and in recognizing a cost-effective fire program.

We begin by specifying a series of important conditions and assumptions. First, while recognizing that fire program management involves a full suite of program components, we develop our analysis with just two: hazardous fuel treatments and suppression. We will discuss prevention in this context without a substantive development. We define suppression broadly as the activities involved in extinguishing wildland fires while recognizing that for pragmatic purposes, suppression may be separated into initial and subsequent attack categories such as "large fire." Focusing our discussion and analysis on two components greatly simplifies and improves our ability to illustrate the underlying economic relationships. Expanding the analysis to include additional components such as fire prevention and ecologically based fuel treatments for site condition improvement is straightforward.

Our second assumption represents a major departure from many previous approaches. Here, we recognize that program planning and budgeting is performed in the context of managing for future fires and fire seasons that are *unknown* with respect to fire incidence, intensity, size, etc. The usual assumption that specific individual fire events expressing a future fire season workload can be modeled from historic events has been widely used and appears in models such as the Interagency Initial Attack Analysis system (IIAA) and in CFES2 (Fried et al. 2006). It has also been customary to model placement of fuel treatments based upon assumed ignition locations such as the Monte Carlo simulations of Hof and Omi (2003) or as in FlamMap (Finney 2005). The Monte Carlo simulations and the FlamMap application both use stochastic processes to establish the location of modeled fires. However, once the locations are established, even if they are established using a stochastic process, they become a "known" set or distribution of fires and all information on the likelihood of having a fire in a given location is lost. The "known fire" assumption introduces two important challenges. First, assuming knowledge of the ignition point plays an important role in affecting the solution as to placement of fuel treatments (Hof et al. 2000). Second, modeling individual known ignitions suggests, or may require, tactical management and modeling of the individual fire event(s).

Event-based modeling introduces a potential philosophical inconsistency between program-level and the tactics of event-level analysis. For example, current event-based models require management of individual fire events that belong to a set of events. This potential inconsistency can be overcome by incorporating a probabilistic production function. Although future fires and fire seasons are unknown, we assume that the probability of fire occurrence by intensity and location can be estimated using established probabilistic methods. For example, recent research such as that by Prestemon et al. (2002) introduced econometric approaches to wildland fire occurrence that also focused on probabilistic functions. For a fuller development of how to model disturbances at broad spatial and temporal scales using a probabilistic framework, see chapter 3.

Abstracting to a probabilistic production function eliminates the potential philosophical inconsistency of modeling individual events to analyze an entire program and it better conforms to the scale of analysis often needed to address the wildfire program. Abstraction to a probabilistic production function introduces new challenges regarding the availability of information. We therefore assume that there is (or could be) the technology and resources to generate credible information regarding the probability of fire incidence and behavior to create spatially explicit "probability" maps of burn probability across the landscape.

Our fourth assumption is that the productivity of each fire program can be represented by changes to the landscape probability map. Representation of program productivity is essential to any production based economic analysis; it is unavoidable. Because our probabilistic approach abstracts away from the individual fire event, it symmetrically abstracts away from the individual fire resource. Our intent is to focus on the fire program and its relation to the program components. We therefore concentrate on how changes in each program component would, in principle, change the unifying probabilistic production function that would ultimately be represented as a landscape map.

Finally, we recognize that spatial and temporal interrelationships are important. Spatial relationships are important because the probability of fire at a given location is influenced by conditions at neighboring locations. For example, the probability of fire in a given location (e.g., a geographic information system (GIS) raster cell) is a function of that cell's fire producing attributes and of the attributes of neighboring cells. Recent advances in GIS technology and in fire applications of GIS technology reflect this concept well (Finney 1998 and Miller 2005). Temporal considerations have historically been associated with fuels management because investments in treatments provide returns over time and they affect the structured pattern of optimal treatments over time. Other program components including suppression often provide benefits or impacts for many years and thus are equally well suited for temporal analysis. For example, aggressive suppression is commonly asserted to have led to a long-term accumulation of fuels.

While a probabilistic production function enables a more robust integration of the spatial and temporal interactions, we use a static model as a simplifying first step[2] because our focus is on the theory and its related principles. In the same way that the well established "theory of the firm" provides a theoretic framework that reveals principles and structure, as opposed to operational detail, we formulate a static economic model to capture the key underlying structure of the wildfire problem across program components. We note that firms face important intertemporal choices, including long-term investments. While this limits the applicability of the static theory, the static theory continues to provide a rich foundation for intertemporal analysis including the development of capital theory (for example, see the classic by Hirshleifer 1970).

We begin with the most general structure in (18.1a) to minimize a budget constrained expected loss (Z) from wildfire where program components, fuels (F) and suppression (S) are modeled as decision variables.

$$MinZ = \Lambda[P(F,S)] + \lambda(B - C(F,S)) \qquad (18.1a)$$

Where:

Λ (capital lambda) denotes a general loss function of burn probability P across the program.

P(F,S) denotes the probabilistic production function for the program.

C denotes the cost function of the fire program

B denotes the fire program budget

λ (Lambda) denotes the Lagrange multiplier for the program budget constraint.

First, we note that if performance is measured in the same units as cost, such as dollars, then the budget constraint could be omitted assuming the objective would be to solve for *the* optimal levels of program components to minimize the total cost. However, we include the budget constraint as a central feature for two important reasons. First, regardless of analysis aimed at identifying economically efficient levels of program components, public budgets are appropriated at levels that are dependent upon the appropriations process and there is no evidence to suggest that appropriations are economically optimal. That is, even if we solved for the optimal level of the program, we should not expect it to be appropriated. Instead, it is more realistic and useful to incorporate the budget as a "hard" constraint to illuminate the economic principles required for efficient allocation of a fixed, but unknown budget. Modeling a budget constraint

[2] Static formulations of the theory are customary in fire management (Rideout and Omi 1990)

better demonstrates how alternative appropriations affect decisions and performance. Secondly, since the Government Performance and Results Act (1993), federal agencies, including the agencies entrusted with wildfire management, are required to engage in performance based planning and have increasingly relied upon physical measures of performance[3] that are problematic to measure in dollars.

The general function Λ(P) translates the physical impact of fire into a present value of expected loss. Therefore, Λ(P) depends upon the resources affected, the fire intensity, seasonality, and potentially on the extent of risk aversion. The function Λ(P) allows for risk aversion where increasing probabilities by intensity level may be non-linearly related to the value of loss from fire. We typically expect increases in fire probability to cause increases in expected fire loss. For more on the economic impacts of wildfire see related chapters in section III. In a risk-neutral program, increases in probability would increase the expected value of loss at a constant rate, or price (L), such that $\frac{\partial \Lambda}{\partial P} = L$ and $\frac{\partial^2 \Lambda}{\partial P^2} = 0$. In a risk neutral program, L denotes a constant "price" of fire risk. For risk-averse management, the second derivative of Λ with respect to P is positive, $\frac{\partial^2 \Lambda}{\partial P^2} > 0$, indicating that the importance of loss (or loss mitigation) increases with increasing loss probability. Risk aversion suggests that fire program managers would be willing to disproportionately allocate fire resources in an effort to avoid higher expected losses resulting from higher fire probabilities. Risk aversion may be especially prevalent with respect to the probability of high intensity fires and for fires threatening highly valued resources such as fires in the wildland urban interface.

While fire managers may be risk averse, and this topic deserves further investigation, we continue with the customary simplification of risk neutrality in public management so that the expected loss can be expressed linearly as:

$$MinZ = L \bullet P(F,S) + \lambda(B - C(S,F)) \qquad (18.1b)$$

Here we substitute *L* for Λ to denote the customary but special case of risk neutrality. The cost function in (18.1a) and (18.1b) is generalized to support appropriate specification as needed. An important consideration in program component analysis is the economic problem of joint costs discussed earlier.

[3] Our development reflects a single program appropriation that we assume is observable. In the event that the program components are separately appropriated, we would introduce a separate budget constraint for each component. Independent program appropriation is problematic to the extent that costs are joint between the program components.

When program components share fire management resources, jointness in cost will inevitably occur. We therefore add structure to (18.1b) to accommodate the joint and separable costs of the program components. Equation (18.2) includes terms for the separable costs for each program component (SCS only for suppression and SCF only for fuels) and for the program joint cost (JC).

$$C(F,S) = SCS(S) + SCF(F) + JC(F,S) \tag{18.2}$$

By substituting the cost function from (18.2) into (18.1b) we arrive at (18.3) that includes our probabilistic production function, the assertion of risk neutrality, the recognition of jointness between the program components and a fixed budget or appropriation that would be fully allocated to the components to minimize overall program loss.

$$MinZ = L \bullet P(F,S) + \lambda(B - SCS(S) - SCF(F) - JC(F,S)) \tag{18.3}$$

Also note that L denotes a constant price of fire loss and P denotes the probability function of burns under the fuel treatment level F and suppression level S. Using subscripts to denote partial derivatives, the first order conditions for minimization of (18.3) are expressed as:

$$Z_S = L \bullet P_S - \lambda\ (SCS_S + JC_S) = 0 \tag{18.4a}$$

$$Z_F = L \bullet P_F - \lambda\ (SCF_F + JC_F) = 0 \tag{18.4b}$$

$$Z_\lambda = B - (SCS + SCF + JC) = 0 \tag{18.4c}$$

The first-order conditions reflect the usual marginal benefit-cost condition that the change in expected loss ($L \bullet P_S$ or $L \bullet P_F$) is equal to the marginal cost of the program component ($SCS_S + JC_S$ or $SCF_F + JC_F$) adjusted for the shadow price of the budget restriction (λ). For example, suppression would be applied (18.4a) until the increase in cost (joint plus separable), adjusted for the shadow price of budget restriction (λ), equals the decrease in expected loss. A parallel interpretation is made for (18.4b).

It might be tempting to interpret the fuel and suppression first-order condition as stating that allocations are made to each component until the components marginal cost (adjusted by λ) equals the reduction in loss, but this would be incorrect. The terms JC_S and JC_F denote the increase in joint cost from an increase in suppression (fuels) effort; not from an increase in suppression (fuels) cost or appropriation. The implications of this are important in today's inclination to budget by program component. Where joint costs matter, budgeting for fuels is budgeting for suppression and visa-versa. As discussed above, there is no logical way to divide the joint portion of cost by component. Instead, recognizing that costs cannot be fully divided by component, at least logically, implies that appropriating the system instead of the component deserves consideration.

Dividing (18.4a) by (18.4b) yields (18.5) revealing the familiar equi-marginal principle.

$$\frac{P_S}{P_F} = \frac{(SCS_S + JC_S)}{(SCF_F + JC_F)} \tag{18.5}$$

In this context, the principle is interpreted as stating that for a constant loss rate, L, and budget, B, the ratio of the reduction in fire probabilities of the two programs must equal the ratio of their respective marginal costs. Setting the marginal costs equal to one dollar directly produces the usual interpretation of the principle. Here, minimization requires the addition of a dollar to each program component to yield equal reductions in wildfire probabilities. While directly observing such a ratio is unlikely, this interpretation provides a powerful conceptual tool for understanding a fundamental condition required for cost minimization under multiple program components.

The marginal cost of each program is assumed to be positive, requiring that the sum of costs in parentheses is positive. The "strong" case for this is that the marginal joint and separable costs are each positive for each component. Condition (18.4c) requires the budget to be fully allocated to the program component separable costs plus the program joint cost. Because increases in program components reduce the expected loss ($L \bullet P_S$), the marginal value of the program component $L \bullet P_S$ is negative because P_S is negative. This relationship is illustrated in figure 18.1 where the reduction in expected loss is shown to diminish with increasing suppression holding all else constant.

While (18.5) focuses on comparisons between the program components, λ addresses the value of another dollar to the program as defined in (18.6).

$$\lambda = \frac{\partial Z}{\partial B} = \frac{P_F}{C_F} = \frac{P_S}{C_S} < 0 \tag{18.6}$$

We can think of λ as having two equivalent interpretations: the first defines the value of another dollar to the fire program while the second defines the equilibrium condition for expenditures between program components. From left to right, the second term $\frac{\partial Z}{\partial B}$ denotes the marginal value of an increase in budget in reducing program loss. Because increases in program budget are fully expended on program components to reduce loss, λ is negative[4]. This is consistent with the signs of the ratio of partials P_F/C_F and P_S/C_S. The equality of the ratios explains that a minimum is achieved when the probability reduction per unit cost increase

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[4] Further, to the extent that Z is strictly concave, as in fig. 18.1, the rate of change of λ* with respect to the budget would also be negative denoting declining marginal benefit of increasing budgets.

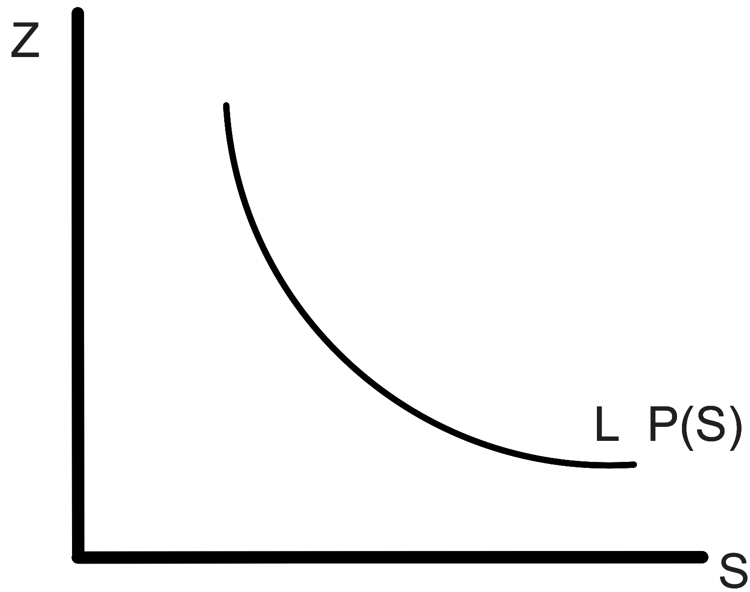

Figure 18.1. Loss as a function of suppression.

is equilibrated across the program components. Note that these ratios are negative as the reduction in probability from a program increase is negative while the marginal cost of each program component is positive.

Prevention is often considered as another important program component that is managed under the overall system. Consider that a key role of any prevention and education program is to reduce the probability of human-caused ignitions. Because prevention can be conveniently expressed as affecting probability, it fits well into the probabilistic framework. Specifically, the probabilistic production function (18.1a and 18.1b) is directly modified to include the prevention component "V" such that P = P(F,S,V). All of the conditions developed above, and below, for the relationship between fuels and suppression can be directly expanded to consider the prevention program component and its interactions.

The second order conditions are of particular interest because they reveal the conditions for program component complementarity and ultimately reveal the program supply condition. These conditions are often assumed to hold, and then swept away to simplify the development. However, they capture the interactions that are the theme of this chapter so we encourage an extra dose of caution and persistence on the part of the reader. It will enhance the marginal product to economic knowledge. Conditions (18.7) list the second order conditions while ignoring the redundant cross partials[5].

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[5] For a minimum we assume the sign of the bordered Hessian is negative.

$$Z_{SS} = L \bullet P_{SS} - \lambda\,(SCS_{SS} + JC_{SS}) \quad (18.7a)$$

$$Z_{FF} = L \bullet P_{FF} - \lambda\,(SCF_{FF} + JC_{FF}) \quad (18.7b)$$

$$Z_{SF} = L \bullet P_{SF} - \lambda\, JC_{SF} \quad (18.7c)$$

$$Z_{\lambda\lambda} = 0 \quad (18.7d)$$

$$Z_{\lambda F} = -SCF_F - JC_F \quad (18.7e)$$

$$Z_{\lambda S} = -SCS_S - JC_S \quad (18.7f)$$

First we note that Z_{SS}, Z_{FF}, P_{SS} and P_{FF} are each positive reflecting diminishing returns (convexity consistent with fig. 18.1) and that the sum of cost terms would be positive so long as marginal cost increases with increases in the level of each program component. Therefore, to the extent that the budget constraint is binding, $L \bullet P_{SS}$ exceeds $\lambda\,(SCS_{SS} + JC_{SS})$, indicating that the marginal value product function will be increasing faster than the budget adjusted (λ) marginal cost function with respect to increases in each program component.

For complementary program components Z_{SF} is negative defining component "synergism." This is the fundamental rationale for managing program components within a unified program. The "strong" case for Z_{SF} being negative is that program components are known to be complementary (see discussion above) in production (indicating that P_{SF} is negative) and in cost making JC_{SF} also negative. Complementarity in the production function is represented by a negative P_{SF} indicating that the marginal product of suppression (fuels) is enhanced by increases in fuels (suppression). Because the positive function Z is being minimized, improvement is denoted by reducing Z such that complementarity is represented by the negative cross-partial. A weaker argument for component complementarity is achieved through complementary production (cost) so long as it is not overwhelmed by a substitution effect in the budget constrained cost (production) function[6]. For example, if the programs are complementary overall ($Z_{S,F} < 0$) and complementary in reducing wildfire probabilities $P_{S,F} < 0$, but if the cost of one component adversely affects the marginal cost of another component the cost function ($JC_{S,F} > 0$, which we suspect is unlikely) then $P_{S,F}$ would need to exceed $JC_{S,F}$ to preserve complementarity.

Synergism in the components with respect to productivity (the probabilistic loss function) addresses the interaction between suppression and fuels and is illustrated in figure 18.2.

In figure 18.2 the effect of suppression on reducing expected loss before a fuel treatment is denoted by F_O. Following the fuels treatment, the marginal productivity of suppression is improved by reducing expected loss at all levels

[6] While program component substitution (Z_{SF}) is unlikely, substitution is also best managed through combining components into a common system. Only $Z_{SF} = 0$ suggests separating the components into independent management.

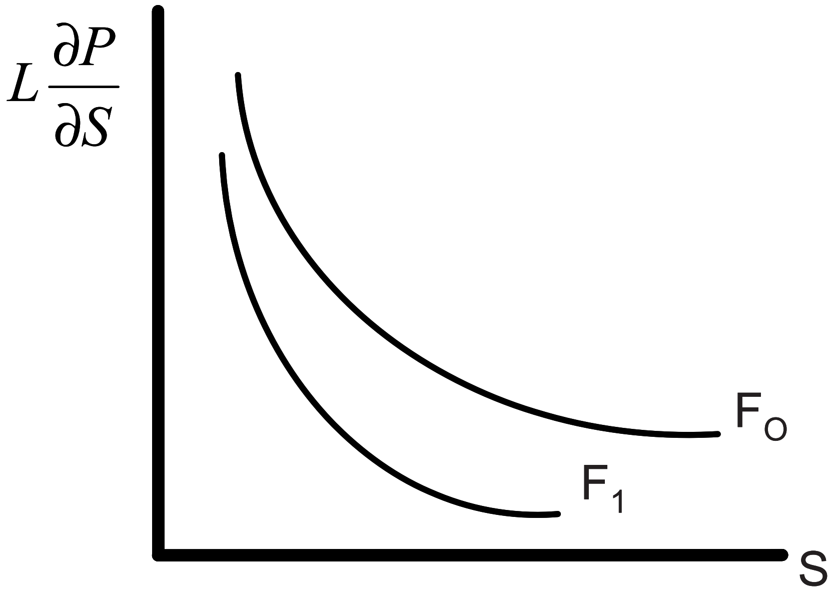

Figure 18.2. Marginal value product of suppression at two levels of fuel treatments.

of suppression and, importantly, by increasing productivity of suppression forces as denoted by the steeper slope of the F_1 function. This illustrates the normal complementary relationship between inputs fuels and suppression.

Increasing fuels treatments (suppression) may enhance the marginal product of the suppression (fuels) program. This can be seen in the example of a fuels treatment that both reduces hazardous fuels, but also increases the marginal productivity of the suppression activities by improving the physical environment for suppression as in figure 18.2. Fuel treatments may make suppression forces more able to move through the forest, improving line production and they may make fire lines hold better. Consider a fuel treatment designed to reduce the intensity of wildfire with the assumption that suppression forces are best designed to contain low intensity fires. This crucial interaction between the productivity of the program components remains largely unquantified. However, management of the components in common federal programs provides evidence of a complementary interaction at the program level and there are many landscape level examples where fuel treatments have stopped or diverted the progression of intense wildfires, e.g., the 2002 Rodeo/Chediski Fire in the Apache-Sitgreaves National Forests in Arizona (Schoennagel et al. 2004). Additional evidence is provided by fireline production rates that are adjusted by fuel type. For example, fuel treatments are often intended to change fuel types in ways that reduce fireline intensity while improving fireline production rates (Haven et. al. 1982, Hirsch et. al. 2004).

How often have you heard that increases in fuels treaments will reduce suppression expenditures? The statement is difficult to evaluate without considering the implied level of damage. Perhaps implicit in such statements is the notion of a constant level of damage. By holding the expected value of loss constant (Z°), we can envision the tradeoff between the two components using the construct of the iso-loss function shown in figure 18.3.

For a constant level of expected loss (Z°), consider alternative mixes of S and F. The slope of the Z° function is known as a "marginal rate of substitution" and it does not imply that the program components are properly considered substitutes. Program component substitution is shown in figure 18.2. For additional material on the tradeoff between program components, see chapter 16.

Understanding why we can substitute fuels for suppression for a given level of expected loss (fig. 18.3), while the program components themselves can be defined as complements (18.7c and fig. 18.2) is crucial to understanding the economic structure of a wildfire program. Planning documents often promote increasing fuels treatments as a means of reducing suppression costs. While this may apply for a constant level of expected loss (fig 18.3), if the fuels treatment improves the productivity of suppression (fig 18.2), then the optimal level of suppression may actually increase. Therefore, to the extent that the fuels and suppression components exhibit normal complementarity, the promise of reduced

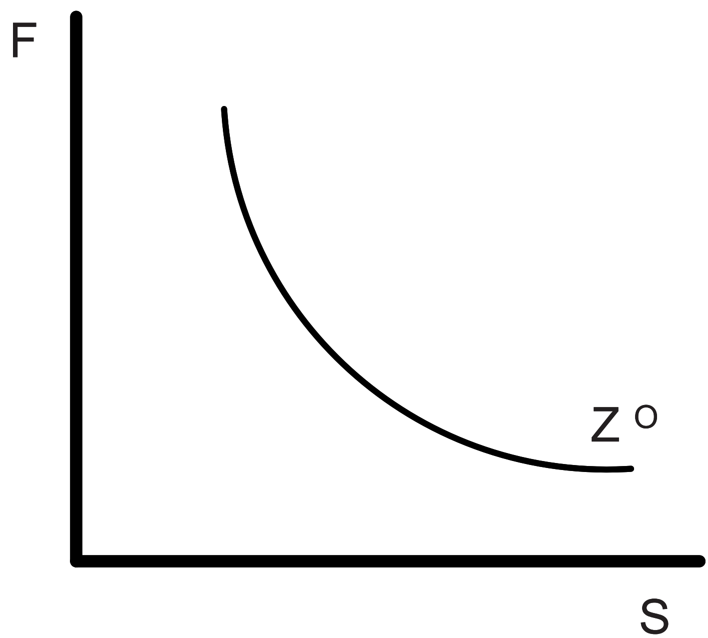

Figure 18.3. Varying fuels and suppression levels to produce a constant expected loss.

suppression expenditures resulting from fuels treatments should be made with copious caution and qualification. For example, behavior that is inconsistent with cost minimization, such as maximization of initial attack success rate, might not reflect such complementarity.

Finally, the cross partials with respect to the budget constraint, $Z_{\lambda F}$ and $Z_{\lambda S}$ in (18.7e) and (18.7f), each reveal that the marginal value of the budget is affected by its marginal cost of each program component. For example, (18.7e) denotes that an increase in the fuels component affects the marginal value of the budget (λ). The implication of this is that λ* changes with changes in the program component marginal cost. When a program component level is altered, minimization requires re-equilibrating between program components (when changing the component involves changing the marginal cost). The marginal value of a dollar added to the program changes with changes in the component's marginal cost.

Further application of the second-order conditions reveals the interesting comparative static result when the slope of the minimized loss function Z*(L,B) in figure 18.4 is analyzed.

Consider the cost minimizing indirect loss function (Z*) where optimal levels of program components F* and S* have been applied.

$$Z^*(L,B) = L \bullet P(F^*,S^*) + \lambda^*(B - C(S^*,F^*)) \tag{18.8}$$

Differentiating Z* with respect to L once and twice yields the envelope result denoted in (18.9a) and (18.9b) respectively.

$$\frac{\partial Z^*}{\partial L} = P^* > 0 \tag{18.9a}$$

$$\frac{\partial^2 Z^*}{\partial L^2} = \frac{\partial P^*}{\partial L} < 0 \tag{18.9b}$$

Figure 18.4 illustrates the indirect loss function Z* that forms a strictly concave envelope. Setting Z equal to Z* we see that slope of the Z and Z* functions each equal P*, but that the <u>slope</u> of the Z* function is declining while the <u>slope</u> of the Z function is constant at P*. Because this change in slope is equal to the change in probability with respect to the change in the unit value of loss (18.9b), our model reveals that cost minimizing behavior will reduce the probability of loss (P*) in response to an increasing the price of wildfire damage (L). This would reflect an upward sloping supply function for damage reduction. This comparative static result is of some importance because it provides a testable and potentially refutable proposition, regarding fire management that has not been investigated. Accepting or rejecting (18.9b) as a hypothesis provides evidence for accepting or rejecting the unobservable assertion of cost minimization in fire program management. Equation (18.9b) is the only comparative-static result available because the other model parameter, B, enters the constraint[7] and not the loss function.

Movement toward a unified economic theory of wildfire analysis provides many economic principles that enhance our ability to understand and model fire systems. The theory reveals many new and important principles in the context of fire program analysis. The theory also provides guidelines to develop specific fuel treatment and suppression resource allocation models. Compared with previous approaches focused on individual program components, the unified approach emphasizes the importance of integrating multiple program components by utilizing their joint productivity and joint costs in order to improve the overall fire management efficiencies. However, integrating multiple components in a fire management project remains a challenge from both theoretical and practical aspects. To address this challenge, we next discuss related empirical modeling strategies. Through the discussion, we hope to gain better understanding about how different integration strategies can be used to fully or partially capture the joint production and cost that are often ignored by previous modeling strategies focused on separate program component.

4. EMPIRICAL STRATEGIES FOR INTEGRATING PROGRAM COMPONENTS

While development of the theory provides a framework for analysis and for understanding the principles at work in program management, it does not show how such principles could be implemented. Consequently, this section will explain the basic approaches that could be considered in formulating applications of the unified theory. In defining empirical strategies, we will assume the landscape can be spatially represented as a raster map.

4.1 Individual Components

We review the fire program components individually and then address approaches for formulating models for an integrated system.

4.1.1 Suppression component

We assume fire suppression resources reduce the fire probability in a given cell. This represents an important departure from the traditional method of modeling specific fires or fire events. Consider a landscape where the existence of suppression resources at particular dispatch points could be used to decrease the expected fire loss (L•P) within a certain distance from that point. If we call the area under

[7] Envelope results with respect to B would require analyzing changes in B while program component levels changed. This would violate the constraint.

the influence (control) of suppression resources at a certain dispatch point an influence zone, an operations research based fire suppression model could be used to allocate suppression resources to reduce the expected fire losses. As suppression resources are allocated to particular dispatch locations, they would reduce the fire probability inside the influence zone and mitigate the accumulated fire losses across the landscape.

4.1.2 Fuel treatment component

Fuel reduction programs such as prescribed burning or mechanical treatments are frequently used to reduce hazardous fuels under the consideration of spatial aspects of fire spread (Loehle 2004). Fuel treatments decrease the expected fire loss by changing the fire behavior, including fire intensity and spread rate. An approach consistent with the unified economic model would be reflected in a probability based allocation under the assumption that fuel treatments are not aimed at specific fire events, but focus on the likelihood of ignition locations and spread patterns. Effective fuel treatments need to be located in places that can efficiently decrease the overall expected fire losses in a landscape.

4.1.3 Prevention component

Much like the suppression component, consider a landscape where the probability of human caused ignitions can be potentially reduced through prevention activities. By spatially locating prevention activities, such as signage and law enforcement efforts, the spatial area can be mapped as an influence zone. Considering the effects of prevention activities on the probability surface, prevention activities can be coordinated with fuels and suppression programs.

4.2 Integrating the Components

Under the framework of a unified economic model, fuel treatments and suppression combine to mitigate the fire probability while sharing a common budget. The difference between the approaches discussed below depends on how the interactions are addressed. We focus on five broad strategies that might apply to a variety of specific model formulations: 1) non-linear, 2) total enumeration, 3) serial, 4) joint impact and 5) additive. They are presented in an order of decreasing complexity.

4.2.1 Non-linear approach

The nonlinear approach recognizes the inherent dependencies of the interactions between the fire program components. To the extent that fuel treatments and suppression are complementary, a "synergism" between them is denoted by the negative cross partial ($P_{SF} < 0$). The negative cross partial indicates that either the fuel program or suppression program could potentially increase the marginal productivity (more effective at decreasing the probability of fire) of the other. This negative cross partial supports the development of a unified economic system for efficient fire management. Theoretically, the non-linear approach fully accounts for the joint cost and joint production of all fire program components. The difficulties associated with the non-linear approach are in the generation of practical formulations and solutions. Non-linear formulations are notoriously difficult to solve and often require linear approximations.

4.2.2 Total enumeration

Total enumeration accounts for the non-linear dependencies and avoids the complex non-linear formulation. Here, all of the possible combinations of management actions on a given cell are identified as a possible solution. The model would then choose the "best" combination of management components. The exhaustive list of possible combinations for each cell accounts for all of the synergies and interactions between the components but is often impractical because of the large number of possibilities. Subsets of this approach are the serial and the order indifferent approaches explained below. Solution techniques such as Bayesian Belief Networks and Influence Diagrams might also be considered here.

4.2.3 Serial

To reduce the number of possible combinations, the serial approach can limit the interactions to just one dependency. For example, for practical purposes, we might assume that fuels treatments have a large impact on optimal positioning of suppression resources. Initial attack models that use a given fuel model as an input provide an example of this. We might assume that locating suppression resources has negligible impact on our fuels planning. This assumption reduces the number of combinations that need to be considered for modeling purposes while accounting for the increased marginal productivity of one component.

4.2.4 Joint impact with no interaction

This simplifying approach assumes that a cell can receive treatment from either or both components but that treatments do affect each other. Suppression or fuels treatment impact cell probability individually. However both may be applied to capture the full effect of the combination. The strength of this approach is that it keeps the application linear while enabling the model to capture any joint (synergistic or detracting) effect on the reduction of probability. The number of possible solution combinations is reduced while accounting for the individual or total impact of treatment application by component.

4.2.5 Additive approach

The additive approach assumes that the reduction in the probability of loss from both fuel treatments and suppression actions can be added linearly. Diminishing returns in each component (P_{SS} and P_{FF}> 0) and potential nonlinear interrelationship between components ($P_{SF} = P_{FS} \neq 0$) are both ignored by assuming $P_{SS} = P_{FF} = 0$ and $P_{SF} = P_{FS} = 0$. Because this approach only considers the additive relationship between components, it addresses the joint impact on the probabilistic production function as a simple linear approximation. The difference between this approach and the joint impact approach is that there is no opportunity here for jointness, e.g., synergism, if impacts are strictly linear.

5. CONCLUSIONS

The unified economic theory represents a potentially important advancement in the economic modeling of wildland fire. The principles of program component interaction illuminate the advantages of managing suppression, fuels and prevention under a single program. To develop the unified theory we focused on three key interactions among the program components: cost, productivity (substitutes and complements) and a common budget/appropriation. Each requires careful consideration in any implementation effort. While these interactions can be modeled in the comparative-statics framework used above, developing operationally meaningful strategies and model formulations constitutes an enormous challenge across uncharted territory.

Modeling these interactions in the context of a unified economic theory will likely prove to be a key challenge in this new era of strategic fire management and planning. We outlined five modeling strategies to illustrate key considerations of the implementation problem. By assessing these strategies, we conclude each has strengths and weaknesses and none, except the non-linear strategy, fully capture the interactions analyzed in our unified economic theory. The choice of modeling strategy may ultimately depend upon the scale of application, the information needs of managers and upon the need to demonstrate cost effectiveness in the program at the federal level. Regarding scale, it is likely that cost and product interactions would be less prevalent at coarse scales. While coarse scale modeling moves beyond meaningful interactions at the landscape level, there are still strategic or national wildland fire management resources, such as smoke jumpers and air tankers to consider that will involve joint costs and product interactions. Smaller scale analysis, such as provided by the landscape level analysis, will involve extensive consideration of joint costs and product interactions such that approaches resembling the non-linear strategy may have more appeal. Consequently, we reach two additional and potentially important conclusions. First, the unified theory provides a powerful tool for addressing and evaluating the design of integrated program components. Secondly, because there currently is no empirically based modeling approach that will fully capture the problem, difficult choices are required regarding modeling strategies.

While the pragmatics of implementation often require sacrifices in the theory, the theory represents an important advancement beyond the basis used for current planning and budgeting systems. Even with the more robust theoretical foundation of the unified theory, much enhancement will be required by enriching the spatial integration and inter-temporal choice analysis.

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