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DISSERTATION  
AN ECONOMIC ANALYSIS AND OPERATIONS RESEARCH OF WILDFIRE  
MANAGEMENT

Submitted by  
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Department of Forest Sciences

In partial fulfillment of the requirements  
For the Degree of Doctor of Philosophy  
Colorado State University  
Fort Collins, Colorado  
Spring 2001

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COLORADO STATE UNIVERSITY

November 17, 2000

WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED  
UNDER OUR SUPERVISION BY GEOFFREY H. DONOVAN ENTITLED AN  
ECONOMIC ANALYSIS AND OPERATIONS RESEARCH OF WILDFIRE  
MANAGEMENT BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS  
FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

Committee on Graduate Work.

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Adviser

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Department Head

ABSTRACT OF DISSERTATION  
AN ECONOMIC ANALYSIS AND OPERATIONS RESEARCH OF WILDFIRE  
MANAGEMENT

PART ONE: The Cost plus Net Value Change (C+NVC) model provides the theoretical foundation for wildland fire economics, and provides the basis for the National Fire Management Analysis System (NFMAS). The C+NVC model is based upon the earlier least Cost plus Loss model (LC+L) expressed by Sparhawk (1925). Mathematical and graphical analysis of the LC+L model illustrates three errors in model formulation. First, suppression is incorrectly modeled as a model output. Second, suppression and loss are incorrectly illustrated as positively correlated. Third, suppression and primary protection are incorrectly modeled as negatively correlated. These errors are shown to be perpetuated by the contemporary C+NVC model, and to have serious implications for the model's capacity to correctly identify the most efficient level of fire management expenditure. A corrected graphical representation of the C+NVC model is presented, which allows the most efficient level of fire management expenditure to be correctly identified.

PART TWO: The economic efficiency of the National Fire Management Analysis System (NFMAS) and FIREPRO is examined. A brief history of the two programs is provided, as well as recent improvements to the contemporary theory of C+NVC. The NFMAS process is reviewed in relation to the theory of C+NVC with particular focus on its ability to reliably locate the Most Efficient Level of preparedness/presuppression

(MEL). FIREPRO is reviewed with regard to its ability to ensure cost effective resource allocations. Improvements and alternative approaches for both systems are suggested.

PART THREE: Determining the specific mix of fire-fighting resources for a given fire, is a necessary condition for identifying the minimum of the C+NVC function. Current wildland fire management models do not reliably do so. The optimal mix problem is characterized mathematically using integer-programming techniques. This mathematical exposition is then solved using the LINGO optimization language. Sensitivity analysis is conducted on model inputs to demonstrate the flexibility of the model architecture. Further, the model is used to accommodate budget constraints commonly faced by fire managers.

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PART ONE

A REFORMULATION OF THE COST PLUS NET VALUE CHANGE (C+NVC)  
MODEL OF WILDFIRE ECONOMICS

## INTRODUCTION

Economic theory has long played an important role in establishing federal wildfire management budgets. This role has increased in significance over the last 30 years in response to consistently rising wildfire management budget requests. For example, between the periods 1970-74 and 1991-95 the Forest Service's average annual expenditure on fire management rose five-fold from \$106,574,520 to \$537,161,067 (Schuster 1997). The U. S. Senate Appropriations Committee in its review of the 1979 Forest Service fire management budget request noted this trend of increasing expenditures, and mandated the Forest Service to conduct cost-benefit analysis on all future budget requests (NFMAS reference material 1997).

The Forest Service responded by developing the National Fire Management Analysis System (NFMAS), a computerized fire budgeting and planning tool (NFMAS reference material 1997). NFMAS is designed to calculate the most efficient annual fire management budget<sup>1</sup> (MEL) for a given geographical area, by minimizing the sum of all wildfire related costs. The sum of all wildfire related costs is known as "Cost plus Net Value Change" or C+NVC, where C denotes all costs associated with fire suppression, and NVC denotes net fire related damages. Increasing expenditures on fire suppression (C) are intended to reduce net fire related damages (NVC), and the optimal level of suppression and damage is that which minimizes total cost (Simard 1976). The C+NVC model is closely related to the earlier Least Cost Plus Loss model (LC+L) illustrated by Sparhawk (1925). Since Sparhawk's original work there have been significant

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<sup>1</sup> The level of fire management expenditure that minimizes the sum of all fire related costs and damages.

improvements in micro-economic theory, including the introduction of comparative statics by Samuelson (1947), with subsequent applications by Silberberg (1978), Varian (1978), and others. Further, the importance of the C+NVC model has increased with time, reflecting its evolution from the theoretical basis for wildfire economics to additionally providing the conceptual foundation for NFMAS.

The increasing magnitude of fire management budgets and significant improvements in micro-economic theory warrant a thorough review of the C+NVC and LC+L models. This paper employs graphical and comparative static techniques to analyze the C+NVC and LC+L models, and suggests potentially significant improvements. The analysis focuses on the implications of the theoretical structure of the C+NVC model, and how improvements to this structure can be incorporated into the model to ensure the correct identification of the most efficient level of fire management expenditure.

## **SPARHAWK'S LC+L MODEL**

The objective of Sparhawk's LC+L model (Sparhawk 1925) was to, "determine how much money can justifiably be spent for fire protection on national forests." Using an illustration (fig. 1.1), he showed that expenditures on a fire protection organization (presuppression *and* suppression in contemporary models) could be justified so long as the sum of these expenditures and loss (cost plus net value change in contemporary models) was declining:

## Figure 1.1

I show that Fig. 1.1 reflects three interrelated misconceptions found in Sparhawk (1925) regarding the relationships between the three model variables (primary protection [presuppression in contemporary models], suppression, and loss). Each misconception has important implications for the integrity of the LC+L and C+NVC models. Hence, each is developed below.

The first misconception in fig. 1.1 is that suppression is expressed as a model output, solely dependent on fire occurrence. This misconception is reflected in his statement that, “These costs [suppression], like losses, can not be determined in advance, but together with the losses depend upon the occurrence of fires.” This assertion led Sparhawk to treat suppression as a model output rather than a decision variable. Observing a correlation between suppression and fire occurrence, he mistakenly inferred a causal relationship. Although fire managers often respond to severe fire seasons with a heavier utilization of suppression resources, this response remains a management decision variable. It is therefore incorrect to model suppression as a model output. Simard (1976) recognized suppression as a model input in creating a total cost function linking costs to fire management effort.

Second, fig. 1.1 mistakenly illustrates suppression and loss as being positively correlated within a given time period. In fig. 1.1 suppression and loss decrease in response to increasing levels of primary protection, and are combined into one function

(suppression plus loss). Modeling suppression and loss as a single function likely stemmed from his observation that suppression expenditures are positively correlated with losses across time. For example, severe fire seasons are associated with both high levels of suppression and high levels of loss. However, Sparhawk's LC+L model is a static model whose scope is typically a single fire season. During a particular season, suppression is applied to reduce losses. Therefore, the relationship between suppression and loss is negative, not positive as illustrated in fig. 1.1.

Third, fig. 1.1 illustrates suppression and primary protection as negatively correlated; i.e. primary protection increases as suppression declines<sup>2</sup>. It seems probable that Sparhawk modeled primary protection and suppression in this manner on a consideration of the different combinations of primary protection and suppression that could result in a given amount of loss. For a fixed amount of loss, a decrease in primary protection (suppression) expenditures could be offset by an increase in suppression (primary protection) expenditures. However, since loss is not held constant in Sparhawk's LC+L model, modeling primary protection and suppression as negatively correlated cannot be justified.

The implications of these three errors in model formulation can be more precisely specified when the model is expressed by a mathematical objective function. Although Sparhawk did not present an objective function for the minimization of all fire-related costs and losses, one is implied by fig. 1. Examination of the implied objective function

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<sup>2</sup> If loss were to decline sufficiently in response to increasing levels of primary protection, then suppression and primary protection need not be negatively correlated. However, historically this is how the relationship between primary protection and suppression has been interpreted (see fig. 1.2).

in [1.1] helps to identify the consequences of Sparhawk's errors in model formulation, which are obscured by graphical representations:

$$[1.1] \quad MIN(C + L) = P(P) + [S + L](P)$$

The terms S, P, L, and C denote suppression, primary protection, loss, and total loss respectively. Equation 1.1 cannot identify the optimal levels of primary protection, suppression and loss for two reasons. First, to correctly identify the optimal level of suppression it must be multiplied by its factor price. This cannot be done within the framework of equation 1.1 because suppression and loss are summed. Changing the factor price of suppression would change the optimal level of suppression employed in the optimal solution. Therefore, as equation 1.1 cannot correctly accommodate the factor price of suppression it cannot correctly identify optimal levels of suppression, primary protection, and loss. Second, combining suppression and loss into one function means that optimal levels of both variables cannot be identified, since an infinite number of combinations of the two could sum to a particular value of suppression plus loss.

## **CONTEMPORARY C+NVC MODEL**

Sparhawk's errors in model formulation have implications for the contemporary C+NVC model. As with Sparhawk's LC+L model, examination of the implied objective function of the C+NVC model helps to identify the implications of Sparhawk's original errors. In addition, a comparison is made between the comparative statics of the C+NVC objective function and the comparative statics of an alternative objective function in

which presuppression and suppression are treated as independent model inputs. This comparison aids in determining the capacity of the contemporary C+NVC model to identify optimal levels of presuppression, suppression, and NVC.

The contemporary C+NVC model contains two important revisions to the LC+L model. First, Sparhawk's suppression plus loss function is separated into two functions: a suppression function and an NVC function (fig. 1.2). Second, the NVC function denotes the net effects of wildfire, to allow for the inclusion of beneficial impacts (Simard 1976). In addition, primary protection is referred to as presuppression:

Figure 1.2

Although these revisions are important to contemporary expressions of wildfire economics and planning, they do not correct the three errors in Sparhawk's 1925 formulation. However, the revisions result in Sparhawk's errors having different implications in the context of the C+NVC model and its implied objective function:

$$[1.2] \quad MIN(C + NVC) = W^p P + W^s S(P) + NVC(P, S(P))$$

The dependent relationship between suppression and presuppression in [1.2] has become accepted as a legitimate approach to the fire management problem. For example, Pyne (1996) in describing the theory of LC+L states, "It assumes, in essence, [a] relationship between the investment in fire protection (variously measured) and its

returns in the form of suppression costs and resource damages (again variously measured).” To illustrate the implications of such dependence [1.2] is contrasted with an objective function [1.3] where S and P are treated as independent inputs related through the NVC function (Rideout and Omi 1990):

$$[1.3] \quad MIN : C + NVC = W^P P + W^S S + NVC(P, S)$$

Differentiating [1.3] with respect to P and then S gives the first order conditions [1.4] and [1.5]:

$$[1.4] \quad \frac{\partial(C + NVC)}{\partial P} = W^P + \frac{\partial NVC}{\partial P} = 0$$

$$[1.5] \quad \frac{\partial(C + NVC)}{\partial S} = W^S + \frac{\partial NVC}{\partial S} = 0$$

The second order conditions are expressed in [1.6] and [1.7]:

$$[1.6] \quad \frac{\partial^2(C + NVC)}{\partial P^2} = \frac{\partial^2 NVC}{\partial P^2} > 0$$

$$[1.7] \quad \frac{\partial^2(C + NVC)}{\partial S^2} = \frac{\partial^2 NVC}{\partial S^2} > 0$$

If the NVC function is convex with respect to P and S, then the C+NVC function will have a minimum.

Identification of the minimum of the C+NVC function in the restricted case (suppression is dependent on presuppression, a condition common to the LC+L and

C+NVC models) is represented by [1.2]. Equation [1.2] can only be differentiated with respect to P:

$$[1.8] \quad \frac{\partial(C + NVC)}{\partial P} = W^p + W^s \frac{dS}{dP} + \frac{\partial NVC}{\partial P} + \frac{\partial NVC}{\partial S} \frac{dS}{dP} = 0$$

Differentiating again with respect to P yields the following second order condition:

$$[1.9] \quad \frac{\partial^2(C + NVC)}{\partial P^2} = \frac{d^2S}{dP^2} (W^s + \frac{\partial NVC}{\partial S}) + \frac{\partial^2 NVC}{\partial P^2} > 0$$

Convexity of the NVC function with respect to P and S is sufficient to ensure that [1.6] and [1.7] are positive. However, convexity of the NVC function will not ensure that [1.9] is positive. The presence of the first derivative of the NVC function with respect to suppression ( $\frac{\partial NVC}{\partial S}$  which is assumed negative) means that the relative magnitudes of

the elements of the second order condition will determine its sign. Should

$(W^s + \frac{\partial NVC}{\partial S}) = 0$  then there would be no ambiguity concerning the sign of [1.9].

However, fulfillment of the first order condition [1.8] ensures that this will not be the case. Therefore, the dependent relationship between presuppression and suppression (expressed in [1.2]) may result in a C+NVC function without a global minimum.

Further, even if the restricted C+NVC function has a minimum, it may not coincide with the minimum of the unrestricted C+NVC function. To illustrate this point, fig. 1.3 charts an unrestricted and a restricted C+NVC function. Both are drawn using the

same NVC function [ $NVC = 50 - (4P^{0.4}S^{0.4})$ ], but the restricted C+NVC function includes a dependent relationship between suppression and presuppression [ $S = 23 - 7LN(P)$ ](points for both graphs were generated using a linear program. Parameters for the NVC and S functions were chosen to provide a clear illustrative example.):

Figure 1.3

Fig. 1.3 shows that the restricted function lies on or above the unrestricted function for all values of P, and that the minima of the two functions occur at significantly different values of P (8 restricted, 10.5 unrestricted).

Therefore, the dependent relationship between presuppression and suppression, stemming from Sparhawk's original errors in specifying the LC+L model, has two implications for the C+NVC model. First, the restricted C+NVC function may not have a minimum. Second, even if the restricted C+NVC function does have a minimum, it should not be expected to coincide with the minimum of the unrestricted C+NVC function.

## **C+NVC CORRECTED**

To correctly illustrate the C+NVC model presuppression and suppression should be modeled as independent inputs (Rideout and Omi 1990). That is, both should be

allowed to vary independently, while remaining related through the NVC function. The envelope approach shown in fig. 1.4 allows the relationship between the three variables to be correctly illustrated in two dimensions:

Figure 1.4.

Fig. 1. 4 shows three C+NVC curves, each drawn with progressively higher, fixed levels of presuppression. The lower envelope of the C+NVC curves drawn in this manner will trace out the unrestricted C+NVC function (P and S independent). This envelope approach illustrates the relationship between P, S and NVC in two dimensions. The relationship between the C+NVC functions with fixed levels of presuppression and the unrestricted C+NVC function they trace out may be expressed mathematically using the envelope theorem (see appendix).

Fig. 1.4 does not illustrate individual P, S, and NVC functions. To illustrate these functions in two dimensions one of the variables must be held constant. Fig. 1.5 shows the relationship between S and NVC with P fixed at its optimal level.

Figure 1.5

Comparison of figs. 1.5 (unrestricted C+NVC function) and 1.2 (contemporary C+NVC graphical representation) reveals important differences related to Sparhawk's original errors. Fig. 1.2 treats suppression as a model output, while in fig. 1.5 suppression is treated as a model input. Fig. 1.2 treats NVC and suppression as positively

correlated, while in fig. 1.5 they are negatively correlated. Fig. 1.2 models suppression and presuppression as negatively correlated, while fig. 1.5 allows only suppression to vary. Consequently fig. 1.5 identifies the global minimum of the C+NVC function, while fig. 1.2 does not.

## **DISCUSSION**

Sparhawk's LC+L model is shown to have three fundamental errors in model formulation. These errors result from misconceptions about the relationships between the variables in the model, and the model's scope. The use of a graphical representation as opposed to a mathematical formulation masked the inability of the LC+L model to identify the optimal levels of suppression, primary protection and loss. Failure to identify Sparhawk's original errors has led to their perpetuation by contemporary C+NVC expositions.

The C+NVC model separates Sparhawk's suppression plus loss function into an NVC and a suppression function. As a result, Sparhawk's errors in model formulation have different consequences for the C+NVC model. First, the objective function may not have a minimum value, preventing the identification of the optimal levels of presuppression, suppression, and NVC. Second, the objective function may have a minimum value, but this may occur at an inefficient level of presuppression, thus misidentifying the optimal levels of presuppression, suppression, and NVC.

The C+NVC model provides the theoretical foundation for NFMAS, and thus any errors in model formulation could have significant implications for the integrity of the

NFMAS process. The modifications presented in this paper correcting current errors in the C+NVC model could improve the NFAMS process, and any future applications of the C+NVC model.

The C+NVC model is a strategic level model that solves for optimal levels of presuppression, suppression, and NVC. The model does not provide information on how these optimal budgets should be allocated (Gonzalez-Caban 1986). Future work could valuably focus on extending the scope of the C+NVC model so that it could address this problem. Such a broadening of the model's scope would be helpful in designing operational optimization models for use in wildfire budgeting and planning.

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# FIGURES

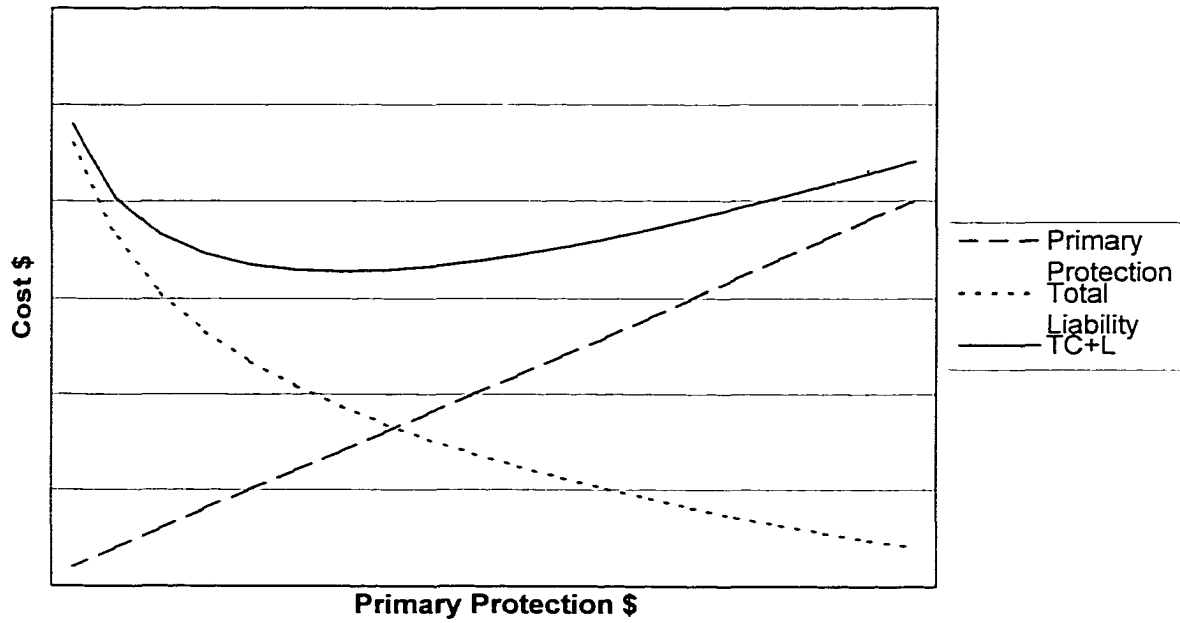


Figure 1.1: Sparhawk's Least Cost Plus Loss Model.

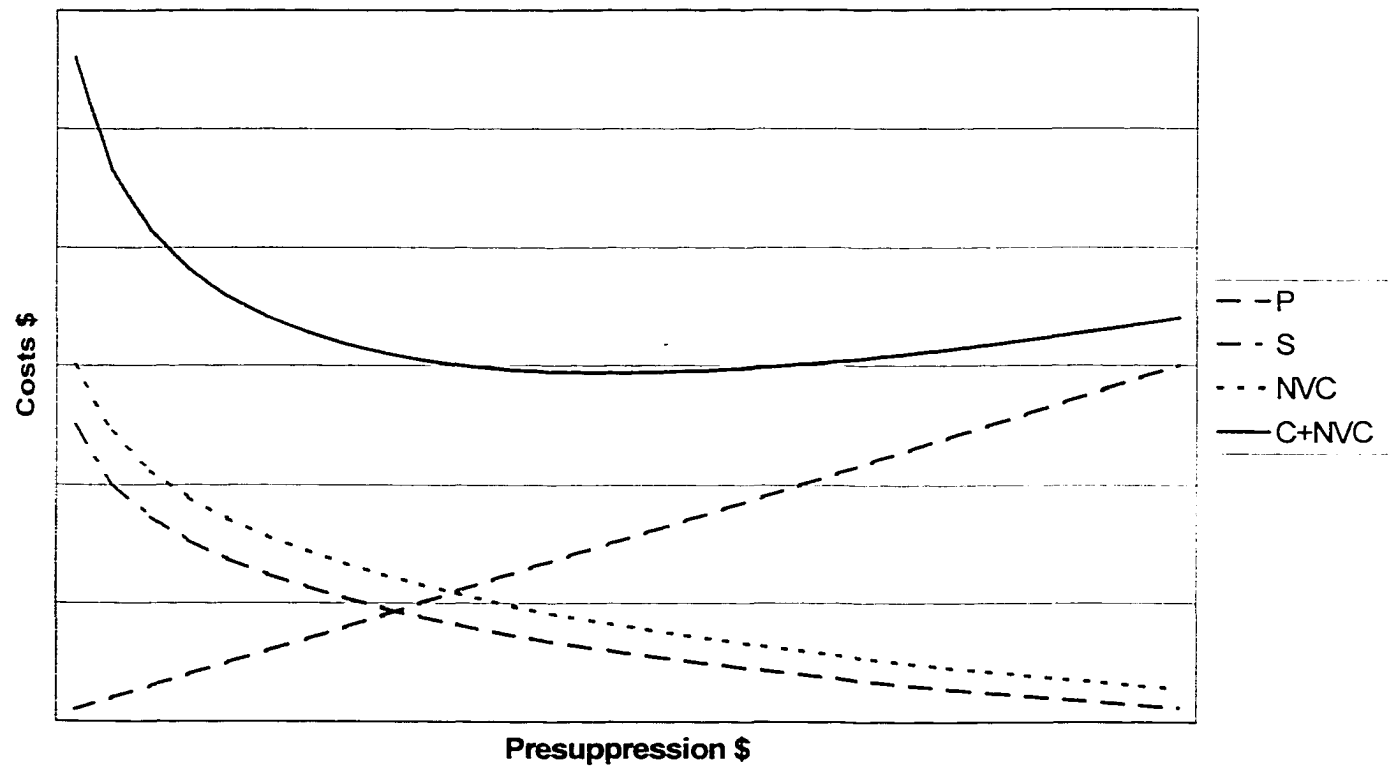


Figure 1.2: Contemporary C+NVC Illustration.

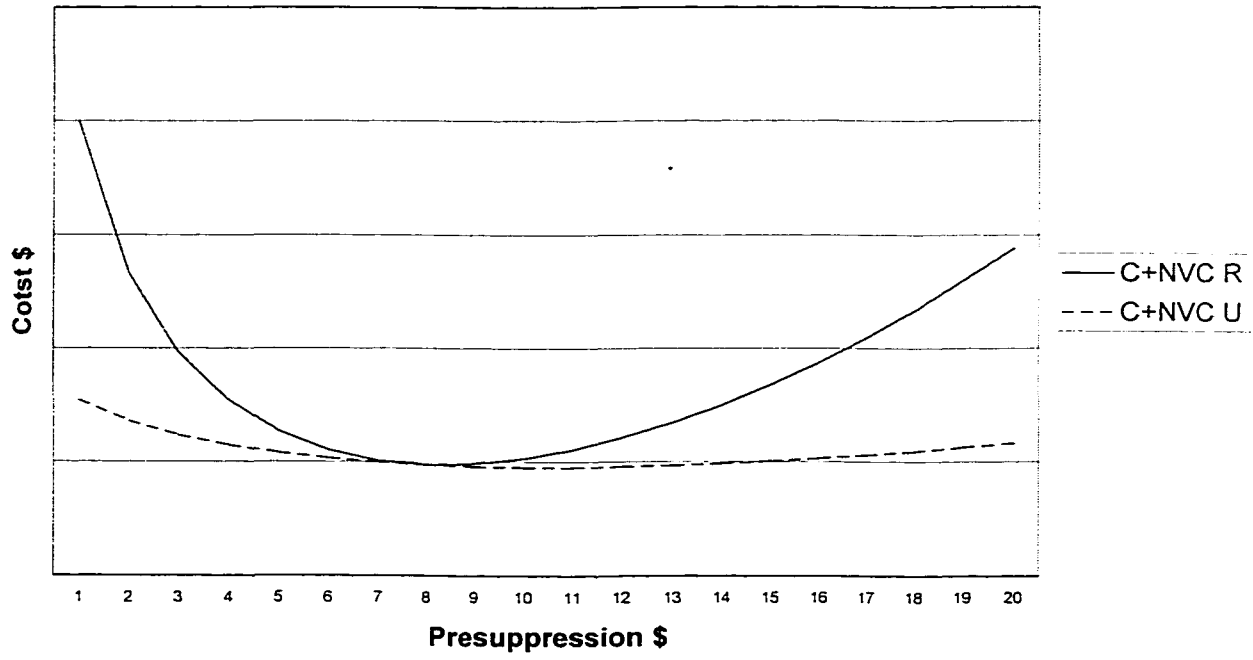


Figure 1.3: Comparison of Restricted and Unrestricted C+NVC Functions.

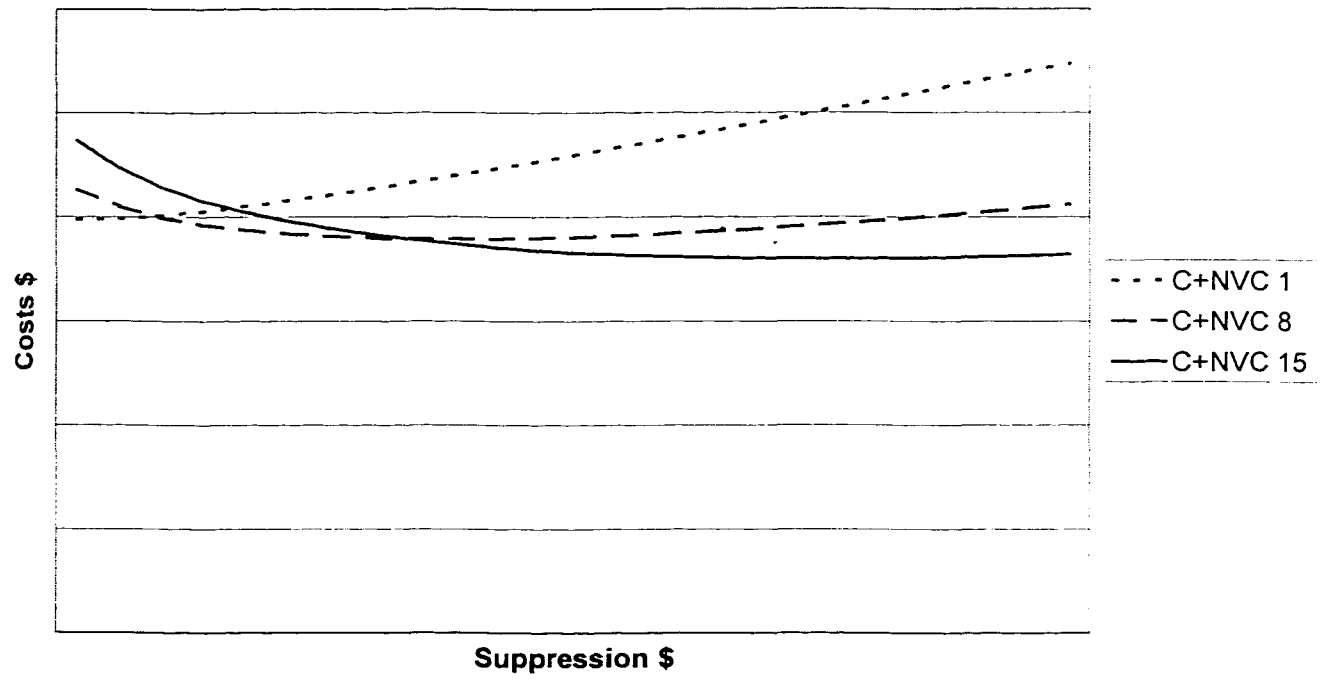


Figure 1.4: Envelope of C+NVC Curves With Fixed Levels of Presuppression.

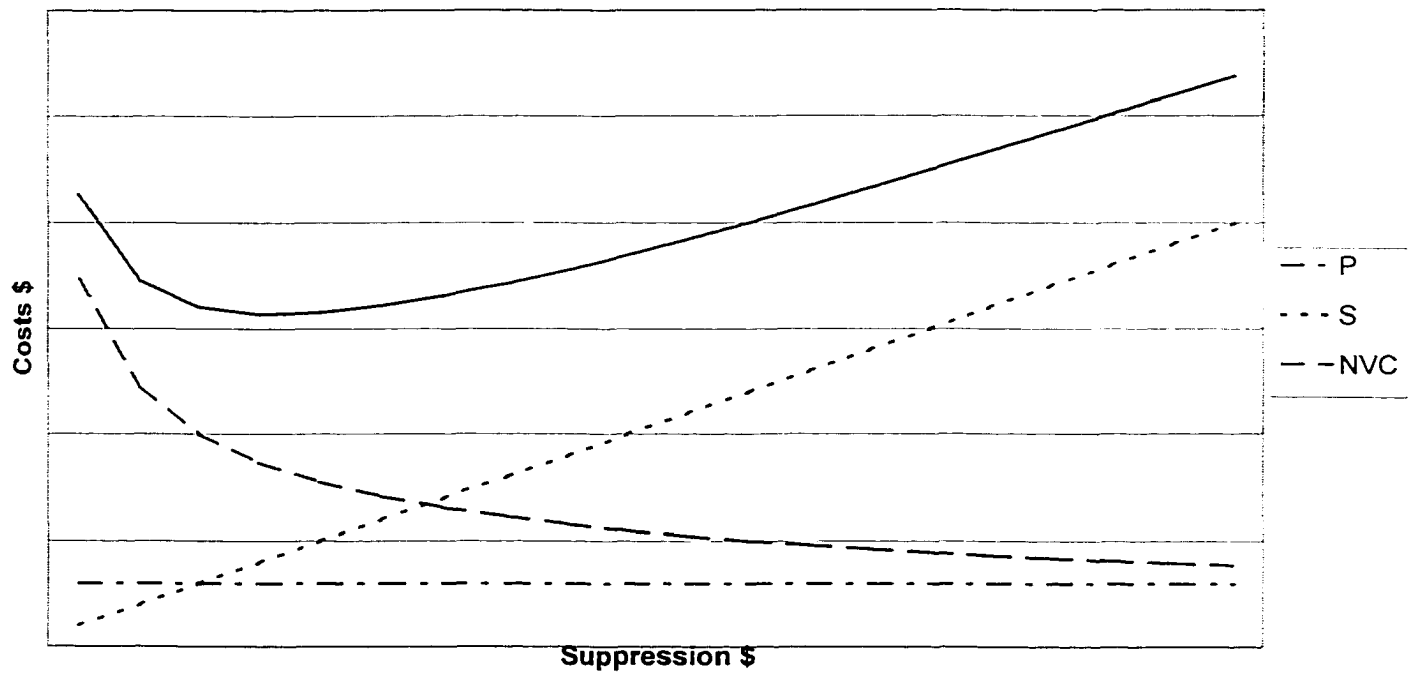


Figure 1.5 Corrected Illustration of C+NVC Model

## APPENDIX: Mathematical Relationship Between Restricted and Unrestricted C+NVC Functions

The functions in fig. 1.4, plotted with fixed levels of presuppression may be expressed by:

$$[1.10] \quad C + NVC^f(S, \bar{P})$$

The lower envelope of these functions, that traces out the unrestricted C+NVC function, may be expressed by:

$$[1.11] \quad C + NVC(P, S)$$

The envelope theorem indicates the following relationship between functions 1.10 and 1.11 (assuming the level of S employed is optimal):

$$[1.12] \quad \frac{\partial(C + NVC)}{\partial P} = \frac{\partial(C + NVC^f)}{\partial P}$$

PART TWO

THE ECONOMIC EFFICIENCY OF THE NATIONAL FIRE MANAGEMENT

ANALYSIS SYSTEM AND FIREPRO.

## INTRODUCTION.

This paper examines the economic efficiency of the two most widely used wildfire management computer programs in the United States: NFMAS and FIREPRO. The USDA Forest Service and the Bureau of Land Management use NFMAS, while FIREPRO is used by the National Park Service, and its related program FIREBASE is used by the Fish and Wildlife Service. These programs provide key guidance in allocating significant wildfire management budgets. For example, in 1994 the Forest Service spent nearly 1 billion dollars on fire management (Bell et al 1995). Thus, even small improvements in economic efficiency would have a significant effect on the costs of fire management on public lands administered by these three agencies. This paper does not provide a comprehensive review of all parts of the two programs. Instead, it examines how these programs conform to the theory of Cost plus Net Value Change (C+NVC).

Since the pioneering work of Sparhawk (1925), Hornby (1936) and Headley (1943), there has been a realization that at least in theory there is an optimal level of fire management effort. Implicit in this realization is that not all fires should be fought as aggressively as possible. Despite this ground breaking work the Forest Service in 1935 adopted the “10:00 a.m. policy” (Gorte and Gorte 1979) after two severe fire seasons in the Pacific Northwest:

“The approved protection policy on the National Forests calls for fast, energetic, and thorough suppression of all fires in all locations, during possible dangerous fire weather.

When immediate control is not thus obtained, the policy then calls for the prompt calculating of the problems of the existing situation and probabilities of spread, and organizing to control every such fire within the first work period. Failing in this effort, the attack each succeeding day will be planned and executed with the aim, without reservation, of obtaining control before ten o'clock of the next morning.”

Interestingly, this policy was viewed at the time as being consistent with the idea of economic efficiency (Hornby 1936). The policy continued into the 1970's, when Congressional budget requests by the Forest Service for fire fighting increased significantly, without a concomitant decrease in suppression costs or damages. This resulted in Congress including a mandate for cost-benefit analysis in the 1979 appropriation (NFMAS Reference Material 1997). As a result, the Forest Service developed NFMAS in 1979. The theoretical foundation of NFMAS is the C+NVC model, which is based upon the Least Cost plus Loss model developed by Sparhawk (1925) some 55 years previously.

In the mid-1980's the National Park Service (NPS) developed the first version of its own wildfire management program called FIREPRO. FIREPRO has gone through several incarnations since, with the current version designed to implement performance

targets established in 1989 (NPS 1997). FIREPRO is a very different program than NFMAS, which is partly due to the different philosophies of the two agencies. The NPS is charged with land stewardship and public enjoyment of resources rather than resource utilization (NPS 1997). This is reflected in the architecture of FIREPRO, which does not consider resource values lost to fire. While resource values are not considered directly in formulating performance targets, FIREPRO is charged with finding the least cost way of achieving them. Although these two models have differing objectives, they are both philosophically based on economic theory.

The mechanics of FIREPRO and NFMAS are examined to illuminate their principles of operation. Data for NFMAS illustrative examples were drawn from the sample administrative unit data set that accompanies NFMAS. Although a specific data set is used, the conclusions drawn are generally applicable.

## **RECENT IMPROVEMENTS TO THE THEORY OF C+NVC**

Donovan and Rideout (1999) showed that the Sparhawk model, and those derived from it, are inappropriate representations of the fire management problem. In two-dimensional graphical representations of the model, too many inputs (both presuppression and suppression) are allowed to vary. If the x-axis is labeled presuppression (as is conventionally done.) then suppression becomes a function of presuppression and a model output. Treating suppression as a model output may lead to misidentification of the minimum of the C+NVC function. Two changes to the current

C+NVC model must be made for the true minimum of the C+NVC function to be identified:

1. Allow inputs (presuppression and suppression) to be independent and simultaneously modeled, but related through the production function, unless a formal dependence is established.
2. Two-dimensional illustrations including presuppression, suppression, and net value change must hold one of the variables constant while viewing the relationship between the other two. Such a requirement is fundamental to properly carrying out partial sensitivity analysis, which is central to the way NFMAS identifies the most efficient level of presuppression expenditure. (MEL)

## **NFMAS**

NFMAS is a computerized fire management and budgeting system. The Interagency Initial Attack Assessment (IIAA) component is its key computational element used to test different fire organizations and dispatch philosophies against specific wildfire conditions and resource values. The analysis is carried out at the smallest organizational level that is responsible for planning, budgeting, and administering its own fire management plan (NFMAS Reference Material 1992). For the Forest Service this is most often a National Forest. Budget data so generated can be aggregated into a national budget request.

## NFMAS AND SENSITIVITY ANALYSIS

Partial sensitivity analysis is central to the running of IIAA. To correctly carry out partial sensitivity analysis only one input/assumption may be varied at once, while holding the others constant. In other words (Boardman et al 1996 page 197)):

**“Partial sensitivity analysis:** How do benefits change as we vary a single assumption while holding all others constant? Partial sensitivity analysis is most appropriately applied to what the analyst believes to be the most important and uncertain assumptions.”

Violation of this condition can produce an identification problem. When two variables simultaneously change, it may be impossible to track changes in an output to specific changes in an input. In the context of NFMAS there are three types of inputs: presuppression expenditure (preparedness), suppression expenditure, and mix of presuppression activities. Conventionally when considering the C+NVC model the specific resource mix of the presuppression organization is not considered. This is appropriate when examining the fire management problem at a strategic level, but not when trying to apply it at an operational level. Consider the graphical representation of isoquants when examining the theory of the firm. The specific mix of capital goods is not considered, but implicit in this generalization is that the mix of capital goods is at all times technically efficient. Therefore, no increases in output can be achieved by reallocating a fixed amount of capital. The importance of optimizing the mix of

presuppression resources has been recognized by both Mills (1979) and Gonzales-Caban (1986). The principle of technical efficiency presents particular problems when conducting partial sensitivity analysis. In principle partial sensitivity analysis could be carried out on either presuppression or suppression when the mix of presuppression activities is not optimized, as long as organizations of equal technical inefficiency are examined. In practice it would be problematic to ensure that two organizations were of equal inefficiency, so the only meaningful comparison is between technically efficient organizations.

Presuppression expenditure is determined in NFMAS via the included items list (Fig. 2.1).

Fig 2.1: NFMAS Included Items List.

Included Items List				
<b>Options</b>				
GD1	HWBLM1	BLM Helicopter	0	X
GD2	PV51	Silver Spr Prev Tech	39775	X
GD3	PV52	Dayton Prev Tech	32935	X
GD4	PVREC1	Rec. Patrolman	70	
GD5	SJ071	Smokejumpers, stk 1	70179	X
GD6	SJ072	Smokejumpers, stk 2	38156	X
GD7	SJ073	Smokejumpers, stk 3	17242	X
GD8	SJ074	Smokejumpers, stk 4	17242	X
GD9	SJ075	Smokejumpers, stk 5	17242	X
GDA	SJG4	Geof's Jumpers	70179	
HIS	WL1702	Reserve Engine,	85613	
	WL5102	Crest Engine, Type 4	85613	X
	WL5201	Foothill Engine,	83450	X
	WL5204	Highland Engine,	82650	X
<b>Run Group</b>				
	HIS	\$0.00	\$1,712,686.00	(\$1,712,686.00)
<b>Select</b>				
<b>Exit</b>				
				Note: "M" allows you to view MRT. "S" allows entry of special costing.
				Print

The included items list indicates which items from the menu of available resources are funded, and allows presuppression expenditure to be fixed while other variables are changed (a cross next to an item indicates that it has been funded at a given budget level).

NFMAS treats suppression expenditure differently. For each fire fighting resource, in each geographical location a fire intensity level at which this resource is to be dispatched is established (Fig. 2.2).

Fig 2.2: Default FIL Dispatch Levels.

The screenshot shows a software window titled "IIAA Interagency Initial Attack Assessment (SAUI)". The menu bar includes "File", "Unit", "FMZ", "Item", "MRT", "QST", "Options", "Results", "Utilities", and "Help". The main window is titled "Line Items" and displays the following information:

- ID: AT0701
- Description: Air Tanker 01
- Budget: \$3,000
- Navigation tabs: 1:General, 2:Personnel, 3:Budget, 4:MRT Defaults, 5:Comments
- Title: Water-Dropping Air Tanker or Helicopter
- UMC: 1600 (Basic UMC (supplies))
- UMC: 3 (Plus. Per Mile)
- UMC: 1900 (UMC Per Reload)
- Get Away: 10
- Speed (MPH): 215
- Default FIL: 4
- Total Number of Water Drops: 4
- Use Auto-MRT For This Line Item:
- Wait for Arrival of ENG or WT:
- EDIT 46
- Buttons: Clear, Save, Search, Delete, First, Prev, Next, Last, Exit, Print

An important consequence of treating suppression in this way is that suppression expenditure cannot be fixed independently of presuppression expenditure, as the number of resources on the included items list will have a direct effect on suppression. Therefore, partial sensitivity analysis cannot be correctly performed on presuppression levels, as suppression expenditure cannot be kept constant.

The final element of an optimal fire budget is the specific mix of fire-fighting resources employed. The importance of optimizing the mix is recognized in the NFMAS literature, "...[the objective of NFMAS is] identifying the most efficient (lowest C+NVC) program budget, and the mix of program components that goes with that budget." (NFMAS Material 1997) The problem of suppression not staying constant as

presuppression varies, also applies when varying the presuppression mix. This leads to an identification problem that prevents the efficient mix from being found. The inability of NFMAS to assure technical efficiency in presuppression organizations means further identification problems in trying to find optimal levels of presuppression and suppression. For example, if an increase in presuppression expenditure results in a decline in  $C+NVC$ , there is no way of knowing whether this is a result of the increment of presuppression expenditure, changes in technical efficiency, or changes in suppression activities.

An extreme example of technical inefficiency is given by the removal of the NVC function from NFMAS runs. Because this often leaves optimal presuppression little changed, it is offered as evidence of NFMAS's insensitivity to resource values (Bell and others 1995). This observation illustrates both the issue of technical efficiency and misunderstandings about its importance to the NFMAS process. If the NVC function is removed from the analysis the optimal levels of presuppression and suppression are zero, since expenditures on either presuppression or suppression cannot reduce wildfire damage. Any solution that has positive values of presuppression and suppression is technically inefficient, as  $C+NVC$  can be reduced (in this case to zero) without any increase in NVC. This misconception indicates that although NFMAS users are instructed to consider presuppression mix, it is perhaps not being given the weight it should.

Thus, NFMAS is not able to correctly perform partial sensitivity analysis. Because sensitivity analysis is central to identifying efficient solutions, any  $C+NVC$

curve generated will be on, or more likely above, the true C+NVC curve. There is also reason to believe that the levels of MEL generated by NFMAS will be systematically too high. This is due to the deterministic nature of NFMAS. Previously, it was shown that suppression levels depended both on dispatch philosophy and presuppression level. While an aggressive dispatch philosophy is not the sole determinant of suppression level, it will tend, all other things being equal, to increase suppression expenditure. Under certain production conditions this will increase the marginal productivity of presuppression resources, therefore increasing the optimal level of presuppression. The required production conditions are that the cross partial of the NVC function with respect to presuppression and suppression is positive:

$$[2.1] \quad \frac{\partial^2 NVC}{\partial P \partial S} > 0$$

Nicholson (1995) says that while this is the most prevalent case, it is not always true. Truet (1984) goes further and gives examples of when production functions might not have a positive cross partial. He states that a negative cross partial is nearly always found between two inputs that are very close substitutes. The example of male and female waiters in the production of meals at a restaurant is given. This close substitutability would not seem to be the case in the wildfire problem. Consider the case of an air tanker. If presuppression resources are not used to buy the air tanker, then it can't be used as a suppression resource. The requirement of some expenditure on one of the inputs in order for the other one to contribute to the production process implies a degree of complementarity, and therefore a positive cross partial, over the range of output

examined. Consequently, a NFMAS user who uses an aggressive dispatch philosophy will likely generate higher levels of MEL. Therefore, NFMAS generated C+NVC curves will likely be above the true C+NVC curve, and their minimum will occur at higher levels of presuppression expenditure (budget).

## **IMPROVEMENTS TO THE NFMAS PROCESS**

If the current NFMAS architecture is to be retained, then the most important improvements that could be made are those that would allow partial sensitivity analysis to be correctly carried out. Of these, the most fundamental is that NFMAS has the capacity to vary one input while holding all others constant. The included items list allows presuppression to be held constant, so no changes are required in the way that NFMAS fixes presuppression. However, the manner in which the dispatch philosophy is currently used does not allow suppression to be fixed. The use of a dispatch philosophy does have some operational realism, so there may be some benefit to retaining elements of it. One solution would be to use the dispatch philosophy to rank resources in order of importance, and use this ranking in conjunction with a suppression budget cap to determine what resources should be used given a particular budget.

Ensuring technical efficiency for each presuppression organization is problematic. For example, each change in presuppression expenditure may result in significant changes to the efficient mix of resources. Consider the example of two presuppression organizations with a modest increment in budget between them. The organization with

the smaller budget may have been just unable to afford an air tanker, and so would have to rely more heavily on less productive and less expensive ground resources. The organization with the higher budget would be able to afford the air tanker and would therefore use less ground resources. If changes were made in the way that NFMAS deals with suppression, then the main problem NFMAS would have in ensuring technical efficiency would be a practical as opposed to a theoretical one. The number of runs that would have to be made in order to ensure the technical efficiency of just one presuppression organization is daunting. Considering the numerous runs that are required to identify MEL, the number becomes prohibitive. Thus, even if the flaws in NFMAS's sensitivity analysis are addressed, practical problems remain that would prevent MEL from being reliably identified.

Considering the problems with the current NFMAS process, as well as vastly improved computer and programming technology, an optimization as opposed to a simulation approach should be considered. An optimization approach could address the problems that NFMAS has with sensitivity analysis, and with identification of the most efficient mix of fire-fighting resources.

## **FIREPRO.**

FIREPRO is a computerized fire management programming system developed and used by the National Park Service (NPS 1997). FIREPRO has very different goals and approaches to the fire management problem. This is partly because of the different objectives of the NPS. Rather than having a goal of optimizing an objective function,

such as NFMAS, FIREPRO was designed to implement nine program performance targets at least cost. These targets address such issues as initial attack success rate; hazard fuels reduction projects, and fire effects monitoring.

FIREPRO focuses on generating staffing levels, and does not address all components of a presuppression organization, such as capital equipment. It is impossible to calculate the efficient level of staffing for a fire organization without considering all elements of that organization. This is because the utilization of one resource may have an affect on the productivity of another, and thus its efficient level. Similarly, FIREPRO does not generate a complete suppression budget, which needs to be done even if the user is not directly concerned with suppression levels.

Unlike NFMAS, FIREPRO does not have a simulation component but applies a rules base approach to analyze a park's workload and program complexity to assign a fire management budget. Ninety-six matrices are used to perform the actual analysis.

Another major difference between the two programs is the role of the user. Unlike NFMAS, FIREPRO is operated centrally with the parks providing data, but not conducting the analysis. The FIREPRO analysis falls into four phases, with the user making changes to the raw output (output generated by the matrices.) in the last three phases. These changes are made in response to unique local conditions, or because the user feels that the unmodified output will not allow parks to reach their performance

targets. An advantage of having fixed performance targets is that they provide verifiable grounds for budget changes. However, this is predicated on the performance targets themselves being appropriate.

FIREPRO could generate a complete fire organization but because it lacks a simulation component, it could not compare alternative organizations. For the sake of illustration, the FIREPRO process can be considered to have two parts. The first part is the attainment of the program performance targets. The success of this part of the FIREPRO process is verifiable at the end of a given fire season. The second part of the FIREPRO process is ensuring that these targets are achieved at least cost, which FIREPRO cannot do. The problems with the FIREPRO process stem from the scope of the analysis being too narrow and that alternative organizations cannot be compared. Thus changes to the current FIREPRO framework should concentrate on expanding the elements of a fire organization considered, and including a capability to compare different organizations.

## **DISCUSSION**

NFMAS and FIREPRO embody different approaches to the fire management problem, reflecting contrasting agency missions. Both programs were developed from the ground up and represent real progress in applying economic principles to the fire management problem. If some of the areas for improvement in this paper were addressed, the two processes might be more similar. For example, one of the main problems with the FIREPRO process is that its scope is too narrow. If FIREPRO were to consider all

elements of presuppression and suppression, along with a simulation component then its architecture might more closely match that of NFMAS. Further, the optimization approach suggested for NFMAS would be particularly useful to the NPS with its many ecological constraints. It would be a more productive approach to design a program around a generic principle such as constrained optimization, rather than allow the specific agency requirements to drive the establishment of the core process. With this central principle in place, its application could be agency specific.

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PART THREE

AN INTEGER PROGRAMMING APPROACH TO SOLVING FOR THE MOST  
EFFICIENT WILDFIRE ORGANIZATION

## INTRODUCTION

Economic theory has played a central role in wildland fire management since the work of Headley (1916) and Sparhawk (1925) (Pyne et al 1996). The theoretical framework used to identify the most economically efficient level of fire management expenditure has been the Cost plus Net Value Change model (C+NVC) (Gorte and Gorte 1979). This model minimizes the cost of wildfire by minimizing the sum of presuppression (expenditure on wildfire management prior to a fire season), suppression (direct wildfire suppression expenditures during a fire season), and NVC (net wildfire damages). While the C+NVC model, as typically illustrated (Pyne et al), provides a theoretical framework for wildfire management, it does not specify which fire-fighting resources should be used to achieve the minimum value of C+NVC. A solution that is to have operational value must also indicate the specific mix of fire-fighting resources to be employed for a given wildfire (Gonzalez-Caban 1986).

In response to a 1978 congressional mandate (Gorte and Gorte 1979) requiring cost-benefit analysis of future budget requests, the U. S. Forest Service developed the National Fire Management Analysis System (NFMAS). NFMAS was the first operational model based on the C+NVC theoretical framework designed to solve for the most efficient mix of fire fighting resources. NFMAS requires extensive use of sensitivity analysis to identify the minimum C+NVC value. The user selects specific fire

fighting resources, presuppression budgets, and dispatch rules<sup>3</sup>, and tracks the resulting costs and damages for a given geographical area and set of fire behavior conditions.

This reliance upon sensitivity analysis has presented both practical and theoretical difficulties (Donovan and Rideout 1999). For most problems of interest, the number of combinations of fire-fighting resources that could be employed is practically infinite, making it unlikely that the most efficient organization can be reliably identified. In addition, to correctly apply partial sensitivity analysis all inputs should remain constant while one is varied. The NFMAS architecture precludes this, leading to potential identification problems (Donovan and Rideout 1999).

While NFMAS is the most widely used economic fire management model for public lands in the United States, others, not so closely tied to economic theory have been developed. For example, the CFES-IAM model (Fried and Gilless 1988) was developed for the California Division of Forestry. It does not directly consider the economic costs of wildfire damages, but rather implements a California legislative mandate, to provide equal protection for lands of equal value. The National Park Service (NPS) uses a fire management model called FIREPRO (NPS 1997), which does not directly consider resource values, nor was it designed to solve for the optimal mix of fire-fighting resources.

To identify the minimum of the C+NVC function I characterize the optimal fire organization mathematically, using integer-programming techniques. LINGO, a linear

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<sup>3</sup> The fire intensities at which fire fighting resources are dispatched in different geographical areas.

and integer programming software package, is then used to solve the mathematical exposition. The integer program selects those fire-fighting resources that minimize the sum of all fire related costs and damages. By identifying the optimal mix of fire-fighting resources, the model applies the theory of C+NVC to a meaningful fire management scenario. Sensitivity analysis is conducted on fire behavior and fire-fighting resource inputs, which demonstrates the ability of the model to respond to differing model inputs (In contrast to NFMAS the model does not require the use of sensitivity analysis to identify the optimal fire organization). Further, the model is used to solve for the optimal mix of fire-fighting resources while facing different types of budget constraints. This type of constrained optimization illustrates the model's capacity to accommodate fire management constraints often faced by fire managers.

## **METHODS**

### **Problem Characterization**

Defining the economically most efficient fire organization for a particular fire requires determining which resources should be dispatched in which time periods, to contain (construct a line around) the fire at minimum cost (C+NVC). This constitutes an optimization problem that lends itself to Integer Programming (IP) because fire-fighting resources are indivisible units and are dispatched accordingly.

Determining the optimal fire organization has characteristics in common with the well-characterized knapsack problem (Winston 1994). The knapsack involves maximizing the benefit from the contents of a knapsack, given a range of possible items

that can be selected. Each item has a defined benefit and weight, while the knapsack itself has a total weight limit. To aid in solving the problem, a binary decision variable is defined, which takes on a value of 1 if the item is selected, 0 otherwise:

The variable  $x_i = 1$  if the  $i$ th item is selected, and 0 otherwise.

As with the knapsack problem, the optimal fire organization problem involves optimizing an objective function by selecting from a menu of possible items, while subject to a constraint. The objective to be optimized is the sum of fire related costs and damages, and the selection is made from a menu of discrete fire-fighting resources, while the constraint is fire containment. The fire organization problem has an additional temporal dimension not present in the knapsack problem. In the knapsack problem a resource is selected only once. However, in the fire organization problem a resource may be selected for use during more than one time period. Therefore, the fire organization decision variable is represented by a binary decision variable with two subscripts, and refers to a given fire-fighting resource in a given time period:

the variable  $x_{i,j} = 1$  if the  $i$ th resource is dispatched in the  $j$ th time period, 0 otherwise.

The temporal dimension of the fire problem complicates the containment constraint. If the fire is contained in a given time period, then its final perimeter will be smaller than if the fire is contained in a later time period. Further, the containment constraint need only be fulfilled in one time period, as fire containment is assumed to result in fire control.

Each fire-fighting resource is defined as having four attributes: fixed rental cost, variable cost, arrival time, and rate of line production. The fixed rental charge represents the cost of renting a resource, and is paid once if a resource is used in one or more time periods. In addition to a fixed rental charge, a variable cost must be paid for every time period in which a resource is used. This variable cost represents the hourly cost of operating a given resource. Arrival time is the period of time it takes a fire-fighting resource to travel to the fire; during this period it cannot produce line.

The following formulation mathematically characterizes the objective function and constraints that are required to identify the fire organization that minimizes the sum of all fire related damages and costs. The model has  $m$  time periods and  $n$  fire fighting resources.

$$[3.1] \quad MIN = \sum_{j=1}^m \sum_{i=1}^n C_i D_{i,j} H_j + \sum_{i=1}^n P_i Z_i + \sum_{j=1}^m NVC_j N_j$$

subject to

$$[3.2] \quad \sum_{i=1}^n \sum_{j=1}^m (H_j - A_i) PR_i D_{i,j} \geq \sum_{j=1}^m N_j PER_j$$

$$[3.3] \quad \forall_i \sum_{j=1}^m D_{i,j} \leq mn(Z_i)$$

$$[3.4] \quad \forall_j (SP_j N_j - L_j) \leq mn(Y_j)$$

$$[3.5] \quad \forall_j \sum_{i=1}^n (H_j - A_i) PR_i D_{i,j} = L_j$$

$$[3.6] \quad \forall_j \sum_{i=1}^n D_{i,j} \leq mnN_j$$

$$[3.7] \quad \forall_i \sum_{j=1}^m D_{i,j} \leq 1$$

$$[3.8] \quad \forall_j N_j = Y_{j+1}$$

where

$C_i$  Hourly cost of operating the  $i$ th resource.

$P_i$  Rental cost of the  $i$ th resource.

$PR_i$  Line production rate of the  $i$ th resource.

$A_i$  Arrival time to the fire of the  $i$ th resource.

$K_i$  and  $Z_i$  Binary solution variables defining whether the  $i$ th resource has been dispatched.

$PER_j$  Increment in fire perimeter growth for the  $j$ th time period.

$H_j$  Time period counter.

$NVC_j$  Increment in net value change for the  $j$ th time period.

$SP_j$  Total fire perimeter up to and including the  $j$ th time period.

$Y_j$  and  $W_j$  Binary solution variables defining whether the fire is uncontained in the  $j$ th time period.

$L_j$  Total line construction up to and including a given time period.

$N_j$  A one time period lagged variable on  $Y_j$ .

$D_{i,j}$  Binary solution variable that takes on a value of 1 for the time period during which containment is achieved, for resources employed.

The objective function specifies that resources are dispatched to ensure that the sum of all costs and damages is minimized. The  $N$  variable ensures that increments of NVC are only included for time periods during which the fire is not contained, or in the process of being contained ( $N$  is constrained to be zero for time periods during which the fire is fully contained.). Once the fire has been contained it is assumed to cause no further damage.

Constraint (3.2) requires that during one of the  $m$  time periods, total line construction must exceed total fire perimeter. If quickly dispatched resources are used, then the fire can be contained when its perimeter is smaller. If resources with longer arrival times are used, then the fire perimeter will be larger at containment. The  $N$  variable is used to model the changing fire perimeter over time.

Inequality (3.3) constitutes a conditional if/then constraint for  $Z$ . If a resource  $i$  is used during any time period, then  $Z_i$  is constrained to be 1. If a resource  $i$  is not used during any time periods, then  $Z_i$  can be either 1 or 0. However, the presence of  $Z$  in the objective function ensures that if  $Z$  is not constrained to be 1 then it will take on a value of 0 to minimize costs. The constant  $mn$  appears in the constraint to ensure that

$$\forall_i \sum_{j=1}^m D_{i,j} \leq mn \text{ holds for all possible values of } \sum_{j=1}^m D_{i,j} .$$

Line (3.4) establishes a similar if/then constraint for  $Y$ , which takes on a value of 1 for time periods during which the fire is uncontained, and 0 otherwise.

Line (3.5) defines  $L_j$  as total line construction up to and including time period  $j$ . Constraint (3.6) prevents resources from being dispatched after the fire is contained. Constraint (3.7) prevents resources from being dispatched more than once. Constraint (3.8) defines  $N$  as a one time period lagged variable on  $Y$ . The lagged  $N$  variable is used in the place of  $Y$  in [3.1], [3.2], and [3.10] to ensure that increments of fire perimeter growth and damage are included for the time period during which fire containment is achieved, and not just time periods during which the fire is uncontained.

### Example Applications

The results in this section were generated using the LINGO optimization language to encode lines [3.1] through [3.8] (Appendix I). For illustration six time periods and seven fire fighting resources are used. The necessary fire behavior inputs in Table 1 (fire perimeter and area growth per hour) were generated using the FARSITE fire simulation program.

Table 3.1: Fire Growth Characteristics.

HOURS	PERIMETER meters	AREA hectares
1	300	0.7
2	1,000	5.6
3	1,300	9.6
4	1,800	15.9
5	2,000	20.3
6	2,200	24.3

The damage caused by the fire is assumed to be \$100 per hectare. Fire-fighting resource production rates, in table 2 are within ranges given in the National Wildfire Coordinating Group fireline handbook (1998). Values of: arrival time (ARR), suppression (COST), and fixed rental cost (PRE) will vary between fires, and so were chosen to provide illustrative examples.

Table 3.2: Fire-fighting resource characteristics.

RESOURCE	DESCRIPTION	ARR (hr)	COST(\$/hr)	PRE (\$)	PROD (m/hr)
1	Dozer	2	175	300	360
2	Tractor Plow	2.5	150	500	450
3	Type I Crew	0.5	125	500	200
4	Type II Crew	1	175	600	250
5	Engine #1	1.5	75	400	90
6	Engine #2	1.5	100	900	100
7	Engine #3	1	125	600	150

Given these data, the objective function [3.1], and constraints [3.2]-[3.8], the optimal solution dictates that the fire is contained in time period three, when the fire has a total perimeter of 1,300 meters. This is accomplished by dispatching resources one, three, and four. Applying these resources incurs total fixed rental charges of \$1,400, and total suppression costs of \$1,425. The optimal resource damage (NVC) incurred is \$960, resulting in a total C+NVC of \$3,785.

An important advantage of using integer programming to solve the optimal fire organization problem is that sensitivity analysis can be readily performed on model

parameters. Sensitivity analysis can be used to isolate those parameters that have a significant effect on the optimal solution. Table 3.3 contains the results from two such sensitivity analyses on model parameters. Run two simulates the affect of a less damaging wildfire, by reducing per acre fire damages to \$20 from \$100 (All other model inputs are left unchanged). Run three demonstrates the impact of changes in fire-fighting resource characteristics by doubling the arrival time of all fire-fighting resources (All other model inputs are left unchanged).

Table 3.3: Model run comparisons.

MODEL RUN	COST	PRE	NVC	C+NVC	Fire-fighting resources used	Hour in which containment is achieved.
1. Original model inputs (Damage per hectare \$100.).	\$1,425	\$1,400	\$960	\$3,785	1,3,4	3
2. Fire related damages \$20 per hectare.	\$1,375	\$1,000	\$406	\$2,781	2,3	5
3. Arrival times doubled (Damages per hectare \$100).	\$1,500	\$1,100	\$3,355	\$5,855	2,3	5

In addition to being well suited to conducting sensitivity analysis, integer programs can readily accommodate additional constraints. This is a particularly useful characteristic when modeling fire containment, as fire managers often face such constraints. For example, a fire manager may have a finite fire management budget. The following run illustrates this by including a constraint that places a cap of \$2,500 on total

costs (presuppression plus suppression): (Unconstrained optimal costs for this run are \$2,825):

$$[3.9] \quad \sum_{i=1}^n \sum_{j=1}^m D_{i,j} C_i H_j + \sum_{i=1}^n Z_i PRE_i \leq 2,500 \quad (\text{LINGO code Appendix I})$$

The model can also accommodate constraints on just presuppression expenditure, a type of constraint fire managers commonly face. For example, Bell (1997) states that the USDA Forest Service receives only 85% of the funds it requests for presuppression expenditures. However, in the event of a severe fire season, additional funding has been available for suppression expenditures. This type of management scenario may be modeled by including the following constraint on presuppression expenditure. Presuppression expenditure is constrained not to exceed \$900, while suppression expenditure is unconstrained (Unconstrained presuppression costs are \$1,400):

$$[3.10] \quad \sum_{i=1}^n Z_i PRE_i \leq 900 \quad (\text{LINGO code Appendix I})$$

Table 3.4: Comparison of constrained and unconstrained costs.

MODEL RUN	COST	PRE	NVC	C+NVC	Fire-fighting resources used (See table 2).	Hour in which containment is achieved.
Costs unconstrained.	\$1,425	\$1,400	\$960	\$3,785	1,3,4	3
Costs constrained not to exceed \$2500.	\$1,375	\$1,000	\$2,030	\$4,405	2,3	5
Presuppression constrained not to exceed \$900	\$1,625	\$800	\$2,030	\$4,455	1,2	5

## DISCUSSION

The C+NVC model provides the theoretical foundation for wildfire economics. The integer program presented successfully applies this theoretical framework to a meaningful wildfire management scenario, by identifying the specific fire-fighting resources that must be deployed to attain the minimum value of C+NVC.

Given this optimal solution the model architecture is well suited to conducting partial sensitivity analysis on model inputs. This allows the user to identify those inputs that may have a significant impact on the optimal solution. For example, table three compares two runs (one and three), whose model inputs are identical except that the arrival times for run three are double those of run one. This difference in arrival times has a significant impact on optimal C+NVC, but no impact on the optimal mix of fire-fighting resources employed. This result would indicate to the user that for this particular a delay in dispatching fire-fighting resources (equivalent to a doubling of arrival times) would not alter the optimal mix of fire fighting resources employed.

The model architecture is also well suited to modeling additional constraints on the fire containment process. Table four illustrates the results of runs made with a total budget constraint and a constraint on just presuppression expenditure. Both constraints have only a small affect on C+NVC, but the reduction in costs is achieved at the expense of a large increase in fire size and associated damage. The user could use this result to demonstrate the implications of constraints on fire management expenditure.

The example applications illustrate the general applicability and versatility of the model architecture and its capacity to model realistic fire management constraints. However, the model's scope could be expanded so that it could be applied to a broader range of wildfire management scenarios. For example, multiple fire events are often expensive and difficult to manage, and the model could be expanded to address the problem of spatially and temporally determining the optimal mix of fire-fighting resources for such situations.

## **APPENDIX: LINGO Code Lines 1-10**

MODEL:

SETS:

FIGHT/X1,X2,X3,X4,X5,X6,X7/:PROD,ARR,PRE,Z,K,COST;

TIME/T1,T2,T3,T4,T5,T6/:PER,HOUR,NVC,Y,W,SP,L,N;

LINKS(FIGHT,TIME):DISP;

ENDSETS

MIN=@SUM(LINKS(I,J):COST(I)\*DISP(I,J)\*HOUR(J))+@SUM(FIGHT(I):PRE(I)\*Z(I))+@SUM(TIME(J):NVC(J)\*N(J));

@SUM(LINKS(I,J):(HOUR(J)-

ARR(I))\*PROD(I)\*DISP(I,J))>@SUM(TIME(J):N(J)\*PER(J));

@FOR(FIGHT(I):@SUM(LINKS(I,J):DISP(I,J))<10\*(1-K(I)));

@FOR(FIGHT(I):(-Z+1)<10\*K(I));

@FOR(TIME(J):(-Y+1)<10000\*W(J));

@FOR(TIME(J):SP(J)\*N(J)-L(J)<10000\*(1-W(J)));

```

@FOR(TIME(J):@SUM(LINKS(I,J):((HOUR(J)-ARR(I))*PROD(I)*DISP(I,J))=L(J));
@FOR(TIME(J):@SUM(LINKS(I,J):DISP(I,J)<100*N(J));
@FOR(FIGHT(I):@SUM(LINKS(I,J):DISP(I,J)<1);
N(T1)=1;
N(T2)=Y(T1);
N(T3)=Y(T2);
N(T4)=Y(T3);
N(T5)=Y(T4);
N(T6)=Y(T5);
@FOR(FIGHT(I):@BIN(Z));
@FOR(FIGHT(I):@BIN(K));
@FOR(TIME(J):@BIN(Y));
@FOR(TIME(J):@BIN(W));
@FOR(TIME(J):@BIN(Q));
@FOR(LINKS(I,J):@BIN(DISP));
DATA:
PROD=250,190,200,250,90,100,150;
ARR=2,2.5,0.5,1,1.5,1.5,1;
PRE=300,500,1000,1200,400,900,600;
COST=90,440,135,170,60,175,150;
PER=300,700,300,500,200,200;
NVC=70,490,400,630,440,410;
HOUR=1,2,3,4,5,6;

```

SP=300,1000,1300,1800,2000,2200;

ENDDATA

END

**LINGO Code Line 11:**

@SUM(LINKS(I,J):DISP(I,J)\*COST(I)\*HOUR(J))+@SUM(FIGHT(I):Z(I)\*PRE(I))<2500;

**LINGO Code Line 12:**

@SUM(FIGHT(I):Z(I)\*PRE(I))<900;

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