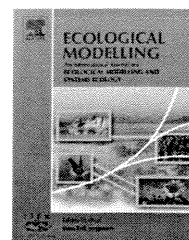


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Determining the optimal mix of federal and contract fire crews: A case study from the Pacific Northwest

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ABSTRACT

Federal land management agencies in the United States are increasingly relying on contract crews as opposed to agency fire crews. Despite this increasing reliance on contractors, there have been no studies to determine what the optimal mix of contract and agency fire crews should be. A mathematical model is presented to address this question and is applied to a case study from the Pacific Northwest. Results show that the optimal number of agency crews is sensitive to assumptions about fire season severity and the availability of alternative work for agency crews on nonsuppression days.

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1. Introduction

The number of contract fire crews used by federal land managers in the United States has increased significantly in recent years. For example, in the Pacific Northwest between 2000 and 2003, the number of private fire crews under contract rose from 126 to 300 (ODF, 2004). This increasing reliance on contract fire crews is partly due to the severity of recent fire seasons. However, contract fire crews are also replacing agency fire crews. Suppression expenditures have also reached record levels in the last 5 years (both total and per acre suppression costs), raising concerns that an increased reliance on contract fire crews may be contributing to higher suppression costs (USDA, 2003). However, determining if this is the case is not a simple matter, because it is difficult to determine the true cost of an agency fire crew. It is straightforward to calculate the direct wage costs of an agency crew and relatively straightforward to determine the costs of benefits such as retirement and health

insurance. However, estimating the cost of workers compensation claims and the cost of support staff, for example, is more problematic. A recent study (Donovan, 2005) compared the cost of Forest Service and contract fire crews in the Pacific Northwest. Results showed that Forest Service crews¹ working continually, or nearly so, have a lower daily cost than contract fire crews. However, as the number of idle² days for a Forest Service crew increases, it quickly loses its cost advantage over a contract crew. This is because the hiring of contract crews is more flexible; managers only call upon – and pay – contract crews when needed. At times of low demand contract crews are laid off. In contrast, agency fire crews are hired – and

¹ This study compared the cost of 20-person type II crews. There are two main categories of fire crews used for wildland firefighting. Type I crews can be used for all aspects of fire suppression, and typically have more training and experience. Type II crews are more restricted and are less likely to be used for hotline work and more likely to be used for holding operations and mop-up. Federal fire managers do not use type I contract crews.

² I consider all days that a crew is not actively engaged in fire suppression to be idle days.

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paid – for an entire season.³ Therefore, one cannot say definitively whether contract crews are more or less expensive than agency crews, as the relative cost of agency crews depends on the availability of work. The more meaningful question is, for a particular fire season, or set of fire seasons, what is the most efficient mix of agency and contract crews? This paper presents an optimization model to answer this question, and provides an example of its application to a case study from the Pacific Northwest.

Although the question of determining the optimal mix of agency and contract crews has not been addressed in the literature, optimization techniques have been used to solve a number of other wildfire-related problems. The area that has seen the most work is optimizing the dispatch of suppression resources (fire crews, airtankers, engines, etc.), either for initial attack or for large fire suppression. The pioneering work in this field was done by Parks (1964), who used a deterministic model to identify the optimal level of initial attack resources for a given wildfire. He applied the model to a case study on the Plumas National Forest in California, concluding that most of the time fire managers used inefficiently low levels of fire crews. Parlar and Vickson (1982) used control theory to more rigorously formulate and extend Park's original model, allowing the model to better accommodate the uncertainty inherent in wildfire containment. Martin-Fernandez et al. (2002) developed a real-time optimization model designed to help fire managers make tactical dispatch decisions. The authors applied the model to a case study in northwestern Spain, demonstrating the model's capacity to accommodate chaotic fire behavior and real-time weather changes. Donovan and Rideout (2003) used a mixed-integer programming approach to optimize the dispatch of initial attack resources. An illustrative example is used to model the effect of different budget constraints. Kourtz (1988) used dynamic programming techniques to optimize the dispatch of airtankers and fire crews. A case study from Thunder Bay in Ontario demonstrates that the model can match or exceed the efficiency of experienced dispatchers. Wiitala (1999) also used dynamic programming to design an optimization model for the dispatch of initial attack resources. Unlike other models, Wiitala explicitly considered the cost of fire mop-up. Greulich (2003) used a spreadsheet-based approach to model the initial attack performance of airtankers. The author emphasized the importance of arrival time to initial attack success and uses the model to, among other things, optimize the location of airbases. In a series of articles (Mees and Strauss, 1992; Mees et al., 1993, 1994) Mees and others incorporated uncertainty into models of wildfire containment, demonstrating that deterministic models may misidentify optimal wildfire suppression strategies.

Optimization techniques have been used to address other wildfire-related problems. Boychuk and Martell (1996) looked at the effect of considering wildfire on forest management

planning models. They conclude that the uncertainty introduced by wildfire is best addressed by establishing a buffer stock of timber, which would both reduce uncertainty and increase long-term timber supply. Hof et al. (2000) developed a model to schedule the timing of fire management effort to protect developed areas. A case study is presented that suggests that concentrating fire management efforts around developed areas may not be the optimal strategy. The possible use of the model to schedule fuels management treatments is also discussed.

Ecological Modeling regularly publishes articles dealing with wildfire modeling. These articles have covered a broad range of topics, but the modeling of fire occurrence (Li, 2002; Podur et al., 2003) and fire effects (Boychuk et al., 1997; Franklin et al., 2001) have received particular attention. This journal has not, however, published any papers dealing with strategic fire-fighting issues. This paper, therefore, extends the range of fire-related questions addressed by this journal as well as adding to the broader fire modeling literature.

2. Methods

I assume that the goal of federal fire managers is to select the mix of agency and contract fire crews that will minimize the expected cost of wildfire suppression for a particular fire season. I model a fire season as a series of discrete periods, with each period having a demand for fire crews determined by fire occurrence. The fire manager's choice variable is the number of agency crews to hire for a fire season.⁴ The principal constraint is that during each period the number of agency crews plus the number of contract crews must meet or exceed demand. Therefore, if the demand for crews in a given period exceeds the number of agency crews, the excess demand will be met by hiring contract crews. If the demand for fire crews in a given period is less than the number of agency crews then some of the agency crews will be idle. Although these idle crews must still be paid, they are paid less than crews actively engaged in suppression, as they do not receive hazard or overtime pay. Contract crews are laid off if there is insufficient work for them, and therefore, do not incur idle-day costs. However, the cost of contract crews is not constant, for a given period, the cost of contract crews rises as more crews are hired. The pricing of contract crews will be discussed in more detail in the following case study, but briefly, providers of private fire crews sign a contract at the beginning of a fire season agreeing to provide a number of crews at a specified price. During the

³ Agency crews are sometimes formed by temporarily taking employees from other jobs within the agency. However, these ad hoc crews are more expensive than dedicated crews hired for an entire season (because the regular agency employees generally have higher wage costs), and they are sometimes more expensive than contract crews. For this reason, I only consider dedicated agency fire crews in this paper.

⁴ In practice, the hiring of agency crews is sometimes staggered. Nonetheless, crews are guaranteed a certain length of employment, and managers cannot dismiss agency crews if a fire season is less severe than anticipated. Conversely, the hiring and training process for agency crews is sufficiently long that it is impractical to hire additional agency crews mid-season, if a fire season is more severe than anticipated. One exception are emergency administratively determined hires. Employees hired in this manner are not entitled to the benefits of regular federal employees and may be hired and fired with more flexibility. For the purpose of this paper, I consider administratively determined hires to be contract rather than agency employees.

fire season, the cheapest crews are dispatched first;⁵ therefore, as more contract crews are dispatched their unit price increases.

I first formulate the above problem as a deterministic n -period balanced transportation problem (I later address the problem of uncertain demand for fire crews). Models of this type typically identify the optimal transportation strategy from a set of m supply points to a set of n demand points. There is an upper limit on the amount that can be shipped from each supply point and a lower limit on the amount that must be received at each demand point: if the problem can be formulated so that total supply equals total demand, then the problem is considered balanced. There are two related advantages to such a model formulation. First, the computational complexity of the problem is reduced. Second, if model inputs are integer, then the model will provide integer solutions without the need for integer-forcing procedures (Winston, 1994).

I define two types of agency crews: crews actively engaged in suppression and idle crews. In addition, I define low-, medium-, and high-priced contract crews. The division of contract crews into three categories is an arbitrary simplification intended to maintain a linear, tractable model. In addition, I define surplus variables for low-, medium-, and high-priced contract crews. None of these variables enter into the objective function: they are solely accounting variables used to balance supply and demand for each period.

2.1. Objective function

$$\text{Min : } Z_1 = \sum_{i=1}^n (A1_i PA1 + A2_i PA2 + C1_i PC1 + C2_i PC2 + C3_i PC3)$$

2.2. Constraints

- (1) $A1_i + A2_i = X \quad \forall_i$
- (2) $A1_i + C1_i + C2_i + C3_i = D_i \quad \forall_i$
- (3) $C1_i + C1S_i = a \quad \forall_i$
- (4) $C2_i + C2S_i = b \quad \forall_i$
- (5) $C3_i + C3S_i = c \quad \forall_i$
- (6) $A2_i + C1S_i + C2S_i + C3S_i = (X + a + b + c) - D_i \quad \forall_i$

2.3. Decision variables

X , the number of agency crews employed for a season
 $A1_i$, the number of agency crews employed and actively engaged in suppression during the i th period
 $A2_i$, the number of idle agency crews employed during the i th period
 $C1_i$, the number of low-priced contract crews employed during the i th period
 $C1S_i$, the number of surplus low-priced contract crews in the i th period

$C2_i$, the number of medium-priced contract crews employed during the i th period
 $C2S_i$, the number of surplus medium-priced contract crews in the i th period
 $C3_i$, the number of high-priced contract crews employed during the i th period
 $C3S_i$, the number of surplus high-priced contract crews in the i th period

2.4. Parameters

D_i , demand for crews during the i th period
 $PA1$, the cost per period of an agency crew actively engaged in suppression
 $PA2$, the cost per period of an idle agency crew
 $PC1$, the cost per period of a low-priced contract crew
 $PC2$, the cost per period of a medium-priced contract crew
 $PC3$, the cost per period of a high-priced contract crew
 a , maximum number of low-priced contract crews
 b , maximum number of medium-priced contract crews
 c , maximum number of high-priced contract crews

The objective of minimizing the total cost of low-, medium-, and high-priced contract crews in addition to the cost of agency crews on both suppression and idle days is subject to six constraints. The first constrains the total number of agency crews to be constant across all periods. The second constraint requires that for each period the total number of crews (agency and contract) actively engaged in suppression equals the demand for crews. Constraints three through five define surplus low-, medium-, and high-priced contract crews to be the difference between the number of crews dispatched and the maximum number of crews of each type available. Constraint six ensures that the total number of crews demanded in each period equal the total number supplied.

I chose the Pacific Northwest for the following case study for the pragmatic reason that it was the only region of the country for which an estimate of the cost of agency fire crews was available. Furthermore, I restricted the analysis to the period 1993–2002, because until the early 1990s total acres burned and per-acre suppression costs in the Northwest were relatively stable. However, since that time both total acres burned and per-acre suppression costs have risen significantly. Therefore, data from before the early 1990s would not be representative of current conditions.

2.5. Agency and contract crew costs

Cost estimates are drawn from Donovan (2005), which estimated the cost of 33 Forest Service⁶ crews dispatched from the Pacific Northwest (Oregon and Washington) during the

⁵ Dispatching crews in this manner implicitly assumes that all crews are equally productive. Conversations with fire managers suggest that there are significant productivity differences between crews, but that these differences are not systematic. Therefore, I also assume that crews are equally productive.

⁶ This study focused on the cost of USDA Forest Service crews only; whereas this paper considers all five federal land management agencies with wildfire management responsibilities (The USDA Forest Service has the largest fire management organization). I have no a priori reason to believe that the costs of non-Forest Service agency crews are systematically different from Forest Service crews. Nonetheless, the cost estimate used likely differs somewhat from the true mean cost of an agency crew.

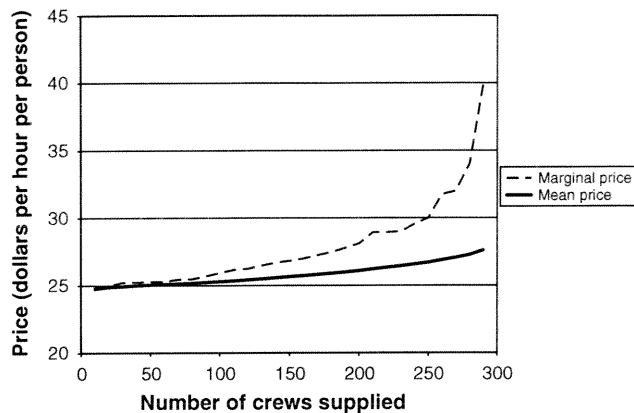


Fig. 1 – The mean and marginal price of private crews under contract during the 2002 fire season in Oregon and Washington.

2002 fire season. The author estimated the daily cost (12-h day) of an agency type II fire crew to be US\$4753. I used the same method to estimate the cost of an 8-h idle day (no hazard or overtime pay) for an agency crew to be US\$2819. These estimates include the cost of wages, retirement, health-care, social security, workers compensation claims, human resource support, training, vacation, unemployment, equipment, and transportation.

In the Pacific Northwest, the dispatch of fire crews, both agency and contract, is coordinated by the Oregon Department of Forestry (ODF). Before the start of a fire season, providers of private fire crews sign a contract with 1 of 13 dispatch centers in the Pacific Northwest agreeing on the price and number of crews to be provided. When a fire breaks out, ODF assigns dispatch responsibility to the closest dispatch center, which first dispatches agency (federal and state) crews to the fire. If there are insufficient agency crews available, then the dispatch center calls on contract fire crews, dispatching the cheapest crews first. Therefore, the mean cost of contract crews increase as more crews are dispatched. Fig. 1 shows the marginal and mean cost of 288 crews under contract with ODF during the 2002 fire season.⁷ At first glance, the marginal cost curve may appear to represent a supply curve for contract crews; however, this is not the case. For a regular supply curve, the same price applies to all units supplied, and therefore, the total cost of supplying these units is the product of price and quantity. However, in the case of the marginal cost curve in Fig. 1, a different price applies to each crew provided; therefore, the total cost of supplying these units is the area underneath the marginal cost curve. The mean cost curve provides an easier way of calculating the total cost of providing a particular number of crews, as in this case total cost is the product of price and quantity.

Dividing the contract crews into three cost categories yields a mean price for the first 100 crews dispatched of US\$6087 (for

a 12-h day), a mean price of US\$6482 for the second 100 crews dispatched, and a mean price of US\$7579 for the final 88 crews dispatched.

Note the wide range in contract crew prices. It appears that contractors employ different pricing strategies. A low price will provide more consistent work, whereas a higher price will probably result in more intermittent but more profitable work. The choice of strategy likely depends on the nature of the costs a contractor faces, concerns about employee retention, and a contractor's expectations about the severity of the upcoming fire season.

2.6. Demand for fire crews

Before the start of fire season fire managers do not know what the demand for fire crews will be, and they certainly do not know what the demand for fire crews will be in a given period. However, fire managers often have forecasts of the overall severity of an upcoming season. Given such a severity forecast, a manager may be able to estimate fire-crew demand for an upcoming fire season in reference to previous fire seasons. For example, a manager may estimate that an upcoming fire season is going to be more severe than normal, and that the most severe⁸ 4 seasons out of the last 10 approximate the range of variability of that estimate. In this case, running the model using the demand profile of the most severe four fire seasons would be reasonably representative of the manager's decision process. The model would then identify the number of agency crews that would minimize suppression costs across all four seasons. This is equivalent to treating crew demand as uncertain in each period. Historical fire seasons provide the different possible values for crew demand, with each value having an equal probability of occurring.

For past fire seasons demand for fire crews was estimated by using the CHEETAH 2 program,⁹ which contains data on all fires that have burned on federal land in the United States from 1980 to 2002. The user is required to input data on the number of fire-fighting resources (fire crews, engines, air tankers, etc.) sent to fires of different sizes, and the number of days the resources stay on the fire. Dispatch records from the Northwest Interagency Coordination Center for 2001 through 2003 were used to calculate these values for type II crews (Table 1). Given these data, the program can then calculate fire-fighting resource needs for a specified geographic area and period.

Fire crews are typically dispatched for 2 weeks at a time. Therefore, I calculated the number of fire crews required, in 2-week increments, for the 1993 through 2002 fire seasons. I assumed a 14-week fire season starting on June 16th (Table 2).

3. Results

Model runs using 1993–2002 fire data show the optimal number of agency crews to be 28 for the four most severe fire

⁷ For simplicity, I consider all 288 crews jointly, irrespective of which dispatch center a crew is assigned to. For a particular dispatch center, the marginal cost of a crew will rise more steeply.

⁸ Severity was measured by the total number of crews demanded in a fire season.

⁹ National Interagency Fire Center, Boise, ID. The version of this model, and the data used to run it, were obtained in 2004.

Table 1 – Mean number of type II fire crews, and their length of stay, sent to forested and grass/brush fires in Oregon and Washington, 2001–2003

Fire size class	Forested		Grass/brush	
	Number of crews	Number of days	Number of crews	Number of days
D	6.2	5.1	2.0	2.0
E	10.7	6.0	2.4	2.9
F	12.6	10.4	3.0	2.8
G	24.7	25.8	2.7	5.9

seasons, 29 for the four middle seasons, and 16 for the four least severe fire seasons. It is interesting that the optimal number of agency crews is lower for the most severe four fire seasons than for the middle four seasons. This suggests that it is not the peaks in demand that determine the optimal number of agency crews, as these peaks will largely be met by contract crews. Rather, it is low demand periods, during which some agency crews are idle, that have a greater influence on the optimal number of agency crews. To further illustrate this point, I repeated the analysis using median crew demand – reducing the influence of periods with very high demand – to determine the severity of a fire season. In this case the optimal number of agency crews was 46 for the four most severe fire seasons, 27 for the four middle seasons, and 18 for the four least severe fire seasons. The sensitivity of results to how fire season severity is determined shows that managers should choose the fire seasons to use as model inputs with care.

3.1. Idle-day costs and the availability of alternative work

An implicit assumption of the above analyses is that agency fire crews do not do any productive work on their idle days. Conversations with fire managers suggest that this is rarely the case. If productive alternative work is available (for example, fuels management or trail maintenance) on idle days, then all or some of the crew's idle day wage costs need not be considered in the analysis. Therefore, the results reported for low, moderate, and severe fire seasons may be interpreted as lower bounds on the optimal number of agency crews because the effect of considering the value of work done on idle days will always decrease the cost of an agency crew relative to a contract crew (assuming the agency crew has at least one idle day during the fire season). The proportion of idle day wage costs that must be considered depends on the continuity of available work and its prevailing wage. I assume that the availability and/or prevailing wage of alternative work declines as

the number of idle agency crews increases. For example, finding work for 2 idle crews is probably easy, but finding work for 20 idle crews would be more challenging. To model the effect of alternative work on idle days, I reformulate the model to accommodate low-, medium-, and high-cost idle days for agency crews.

3.1.1. Objective function

$$\text{Min : } Z_2 = \sum_{i=1}^n (A1_i PA1 + A2_i^L PA2^L + A2_i^M PA2^M + A2_i^H PA2^H + C1_i PC1 + C2_i PC2 + C3_i PC3)$$

3.1.2. Constraints

- (1) $A1_i + A2_i^L + A2_i^M + A2_i^H = X \quad \forall_i$
- (2) $A1_i + C1_i + C2_i + C3_i = D_i \quad \forall_i$
- (3) $C1_i + C1S_i = a \quad \forall_i$
- (4) $C2_i + C2S_i = b \quad \forall_i$
- (5) $C3_i + C3S_i = c \quad \forall_i$
- (6) $A2_i^L + A2S_i^L = d \quad \forall_i$
- (7) $A2_i^M + A2S_i^M = e \quad \forall_i$
- (8) $A2_i^H + A2S_i^H = f \quad \forall_i$
- (9) $A2_i^L + A2_i^M + A2_i^H + C1S_i + C2S_i + C3S_i = (X + a + b + c) - D_i \quad \forall_i$

where

$A2_i^L$, the number of low-priced idle agency crews employed during the i th period

$A2S_i^L$, the number of surplus low-priced idle agency crews during the i th period

$A2_i^M$, the number of medium-priced idle agency crews employed during the i th period

$A2S_i^M$, the number of surplus medium-priced idle agency crews during the i th period

Table 2 – Demand for type II fire crews in Oregon and Washington, 1993–2002

Period starting	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
16 June	13	37	5	18	17	32	7	76	28	17
30 June	24	47	16	58	9	57	24	46	125	212
14 July	4	425	28	92	89	59	37	85	27	237
28 July	36	135	43	146	61	156	150	129	112	23
11 August	6	9	18	284	56	73	78	124	263	50
25 August	15	101	59	83	22	72	64	2	25	29
8 September	18	14	47	20	28	9	22	13	26	12

Table 3 – Optimal number of agency type II fire crews under different assumptions about the availability of alternative work and determination of fire season severity

Fire season severity	Scenario A		Scenario B	
	Mean	Median	Mean	Median
Low	27	28	37	38
Medium	42	37	52	49
High	43	57	57	60

$A2_i^H$, the number of high-priced idle agency crews employed during the i th period

$A2S_i^H$, the number of surplus high-priced idle agency crews during the i th period

$PA2^L$, the cost per period of a low-priced idle agency crew

$PA2^M$, the cost per period of a medium-priced idle agency crew

$PA2^H$, the cost per period of a high-priced idle agency crew

d , maximum number of low-priced idle agency crews

e , maximum number of medium-priced idle agency crews

f , maximum number of high-priced idle agency crews

The basic structure of the model remains the same, but is expanded to accommodate different categories of costs for agency crews on idle days. Idle-day costs are modeled in a similar way to contract crew costs, with three cost categories and constraints on the number of low-, medium-, and high-priced crews.

To model the effect of alternative work on idle days, I repeat the previous analysis under one of two sets of assumptions. In scenario A, I assume that for a particular period alternative work with an equivalent wage is available for the first 10 idle agency crews, and therefore, the cost per period of these crews ($PA2^L$) is zero. I further assume that, for the same period, less alternative work is available for the next 10 idle crews, and therefore, the cost per period of these crews ($PA2^M$) is US\$ 1410 per day (half the full idle-day cost of an agency crew). Finally, I assume that, for the same period, no alternative work is available for additional idle agency crews, and therefore, the cost per period of these crews ($PA2^H$) is US\$ 2819 (the full idle-day cost of an agency crew). In scenario B, I assume that the cost per period of the first 20 crews is zero, and that the cost of the next 20 crews is half the full idle-day cost of an agency crew (the analysis is repeated using median and mean number of fire crews demanded to determine fire season severity).

The results in Table 3 show that the availability of alternative work increases the optimal number of agency crews for both methods of determining fire season severity.

4. Discussion

A model is presented to determine the optimal number of agency type II fire crews prior to the start of a fire season and is applied to a case study from the Pacific Northwest. Results indicate that the optimal solution is sensitive to assumptions about the severity of the upcoming fire sea-

son and the availability and prevailing wage of alternative work. The model allows the user to address uncertainty about the severity of a fire season by running the model across a series of past fire seasons that the user believes approximate the likely range of variability of the upcoming season. In contrast, determining the availability and prevailing wage of alternative work is more difficult. One approach would be to ask managers of individual units (for example, USDA Forest Service or Bureau of Land Management ranger districts) to compile a list of available work that would be suitable for idle fire crews, and what the cost would be to complete the work by using other employees or contractors. In addition to helping make strategic staffing-level decisions prior to the start of a fire season, such a list could be used to make tactical decisions during a fire season. For example, suppose fire crews from around the Pacific Northwest were sent to fight a large fire. As the fire is gradually contained, the incident commander on the fire must make decisions about which crews to send home first. If the incident commander knew which land management units had the most available work, then crews from these units could be released first.

The availability of alternative work increases the optimal number of agency crews irrespective of assumptions about the severity of an upcoming fire season. It would seem intuitively obvious that when deciding how many crews to hire, managers should invest in, and pay attention to, forecasts of the severity of an upcoming fire season. However, results from this study support two less intuitive conclusions. First, periods of low demand, not periods of high demand, determine the optimal number of agency crews. Second, the availability of alternative work appears to be at least as important as fire season severity in determining of the optimal number of agency crews. It would, therefore, be useful for managers to estimate the availability of alternative work, and to take steps to ensure that alternative work is available when possible for idle agency crews.

The uncertainty inherent in estimates of fire season severity and the availability of alternative work, and the sensitivity of the optimal solution to these estimates, means that any solution should not be regarded as definitive. Rather the model provides a framework for considering the trade-offs between agency and contract crews and should be used in conjunction with other tools and expert judgment to decide how many agency crews to hire for a particular fire season.

The model presented need not be restricted to determining the optimal mix of crews, but could also be applied to other fire-fighting resources such as engines. In addition, the modeling approach could be used more generally to analyze contracting arrangements. For example, in the United States all aerial resources (airtankers and helicopters) used by federal agencies are operated by private contractors. However, agencies use a mix of contracting arrangements. Some resources are under contract for fixed periods and are paid a base amount irrespective of workload. Other resources are under “call when needed” contracts and are only called upon, and paid, when work is available. The model could be used to help determine the optimal type and mix of contracting arrangements.

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