CHAPTER 13.

# Economic Analysis of Fuel Treatments

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## Introduction

The economics of wildfire is complicated because wildfire behavior depends on the spatial and temporal scale at which management decisions made, and because of uncertainties surrounding the results of management actions. Like the wildfire processes they seek to manage, interventions through fire prevention programs, suppression, and fuels management are scale dependent and temporally and spatially dynamic. The objective of this chapter is to describe the status of research into the economics of fuels management. We review studies describing the economic question of fuel treatment choices in wildfire management. We discuss the importance of framing the questions and issues surrounding wildfire management to include influences of space and time on wildfire processes. Finally, we offer a case study that provides one example of evaluating the economics of fuel treatments.

### *Approaches to Economics of Wildfire Management*

#### Defining the issues

Initial studies into the economics of wildfire management expressed the problem simply, but research in more recent years has begun to examine the full complexity of the issues involved. For example, Headly (1916) and Sparhawk (1925) described the situation of a fire boss or agency seeking to minimize the sum of wildfire losses (damages) and the costs of fire suppression for a single fire. Forty years later, Davis and Cooper (1963) and Davis (1965) recognized that fire managers could alter the distribution and quantity of fuels on a managed landscape—not just suppress fires—thereby describing a multiple-input problem with much greater spatial complexity. The task of the manager had evolved to include finding the level of fuels management that would alter the likelihood that fires reach a particular size. The economic problem, then, was to minimize the sum of fuels management costs, which included the costs of suppressing fires that do occur and the losses created by the wildfires on the landscape in a fire season. Note that in this chapter, wildfire damages or wildfire-related degradation of ecosystem goods and services are defined as "losses," the expenses incurred to manage wildfire on the landscape (prevention, fuels management, suppression, and rehabilitation after a fire) are defined as "costs," and the economic goal is described as minimizing the sum of costs plus losses (also known as net value change).

Subsequent to these pioneering analyses, researchers have begun to describe the issue even more broadly. Donovan and Rideout (2003), Mercer and others (2007), Prestemon and others (2002), and Rideout and Omi (1995) identified the problem of wildfire management as one in which a manager can take any number of actions to alter the fire regime in support of an overall wildfire program or societal benefit objectives. These actions include preventing fire ignitions, managing fuels, building firebreaks, positioning firefighting resources before fire seasons begin, suppressing fires, evacuating local residents, and reducing the impact of wildfire through timber salvage and site rehabilitation. The issue can be specified either as maximizing values protected minus the costs of protection, or as minimizing the sum of losses and costs of actions taken to affect those losses. Further, many researchers have properly described wildfire management as a long-term dynamic optimization problem in which management actions and wildfire in previous periods affect wildfire in the current period. For example, fuel treatments—including fuel breaks, prescribed fire, and mechanical removals—may have long-term or multiple-season effects on many measures of fire activity and therefore affect the levels of expected damages over many years (Mercer and others 2007).

### Determining tradeoffs

Given any of the available objectives of wildland management, the extent of wildfire managers interventions into wildfire processes depends on the costs of those interventions and on the degree, duration, and spatial extent of the intervention's effectiveness. For example, if the per-acre cost of prescribed fire on a given landscape is greater than the value of the expected wildfire damages, then prescribed fire would not, from the perspective of wildfire alone, be an economical option for management. A key objective for fuels management is maximization of effectiveness, reduction of cost, or a combination of the two. Maximizing effectiveness can mean applying fuels management in the places likely to do the most "good," and reducing cost means applying fuels management in places where it is inexpensive compared to the values at risk and in ways that require fewer or cheaper inputs.

The question of fuel treatment efficiency and the role of treatments in wildland management become more complicated when considering other costs and benefits derived from the treatment itself. For example, fuel treatments can provide many benefits that extend beyond wildfire management—prescribed fire may reduce vegetative competition and therefore enhance the growth of desired tree species (Crow and Shilling 1980), enhance production of nutritious forage for livestock, and provide habitat for fire-dependent species (González-Cabán and McKetta 1986). Mechanical fuel treatments offer benefits similar to prescribed fire, and they also produce wood that can be sold (Abt and Prestemon 2006, Rummer and others 2005). Fuel treatments applied in one location, or to one property, can offer benefits in other locations or properties by breaking up fuel contiguity, slowing the spread of wildfires, or enhancing the efficiency of fire suppression activities. Consideration of these benefits can lower the overall per-acre (or other unit) net costs of implementation, viewed from the broader perspective of the landscape or society as a whole.

At the same time, treatments may carry costs that go beyond their explicit implementation costs. For example, treatments can degrade environmental attributes and other environmental values important to society and may produce risks for neighboring landowners. Prescribed fire can affect water quality by altering vegetative cover (González-Cabán and others 2004), and it produces smoke that reduces air quality (Martin and others 1977). Mechanical treatments can increase siltation and compact the soil, reducing productivity and damaging residual trees and other plants. Chemical methods for reducing fuels also may have negative environmental impacts that need to be considered when evaluating treatment costs.

## Results of Past Fuel Treatment Studies

Economic studies of fuel treatments can be divided into three broad classes: (1) those focused on the factors that affect the costs of fuel treatments, (2) those concerned with how fuel treatments can lead to changes in wildfire processes, and (3) those evaluating how fuel treatments can be applied to achieve societal or landowner goals. Some studies straddle all classes, recognizing that choices about the best locations, timing, and extent of fuel treatments depend on their costs and on whether, where, and when fuel treatments are effective. Other studies quantify how the location and characteristics of fuels management affect their costs and hence their net contributions to the achievement of desired goals.

## Factors Affecting Fuel Treatment Costs

Although current knowledge on the costs of fuel treatments cannot be summarized in a few paragraphs, for the sake of brevity, this chapter focuses on some of the more influential studies. For more detailed reviews see Hesseln (2000) and Kline (2004).

Perhaps the first refereed journal article on prescribed fire costs in the Southern United States was by Vasievich (1980), who emphasized the importance of vegetation characteristics and scale of activity in influencing costs. Vasievich found that the thicker the vegetation, the higher the cost, because of denser undergrowth and ladder fuels that require higher labor, capital, and materials requirements. Recognizing the importance of fixed and variable costs in fuels management, the study showed that prescribed burns greater than 2,000 acres cost nine times less per acre than 50-acre burns. Because all treatment actions must contend with fixed costs such as burn management and larger fires require less perimeter management relative to area contained within the perimeter, greater efficiencies in the use of labor, capital, and other inputs can be achieved. This effect is termed in economics as an “economy of scale.” Jackson and others (1982) examined the costs of fuel treatments in the Western United States focusing on how prescribed fire could enhance wildlife habitat rather than change wildfire risk. Their analysis of fuels treatments on national forests in Montana and northern Idaho was one of the first modern studies to document economies of scale for prescribed fire in the West—larger treatments are less costly per acre treated, a central focus of their analysis.

González-Cabán and McKetta (1986) focused on prescribed fire with and without mechanical treatment on two national forests in Montana and Oregon. Linear regression quantified the average effects of the fuel treatment method used and site factors on the per-acre cost. To identify fuel treatment effects beyond reducing fire probabilities and damages, they conducted surveys that asked fire managers to allocate the costs of treatments to benefits; managers allocated 45 of the treatment cost to reduction of wildfire damage risks on the Lolo National Forest, compared to 36 percent on the Willamette National Forest. Fuel treatment costs were found to be influenced slightly by the size of the treatment (indicating economies of scale) but more significantly by the type of treatment, the type of stand, the initial fuel conditions in the stand, the primary objective for the treatment (fuel reduction versus silviculture), and the seasonal variables that contribute to weather conditions at the time of the burn. González-Cabán and McKetta concluded that an important factor influencing costs is the objective of the treatment. Treatments that are focused on reducing wildfire risk appear to be significantly more costly than those focused on silvicultural objectives. Presumably, this is because risk-reduction treatments are designed to decrease fuel contiguities and reduce crowning and torching potentials, which require significantly more handling and fire treatment of downed woody debris.

A subsequent study by González-Cabán (1997) focused on the role that managerial and institutional factors play in the cost of prescribed burning. Based on a survey of U.S. Department of Agriculture Forest Service managers in the West, González-Cabán found that efforts to reduce the negative impacts of prescribed fire—such as risk of escape and smoke emissions—led to higher per-acre costs, indicating an important tradeoff between the two. The size of the burn was a significant explainer of costs, with larger burns lowering per-unit costs. Slope and other site factors also mattered, but management objectives did not. Thus, efforts to minimize the externalities from risk reduction appear to increase costs, but these costs can be reduced by treating large areas simultaneously.

Cleaves and others (2000) conducted a nationwide survey of national forests that sought to quantify the variability of prescribed fire costs. The study, based on a survey of managers, illustrates the combined importance of interforest variations in the availability of prescribed fire services, management objectives, site factors, prescribed-fire escape risks, and other constraints. Nationwide, from 1985 to 1994, the costs of prescribed fire were found to vary by tenfold or more, with some of the most expensive prescribed fire occurring in the western mountains (more than \$300 per acre) and the cheapest in the South (\$20 per acre). Mercer and others (2007) used the same dataset to further identify the factors that influence costs of prescribed fire on national forests. Their analysis showed that part of the differential is explained by differences in labor costs, with the average cost per acre in each national forest mirroring statewide labor costs. However, significant cost differences also existed from one region to another and according to the amount of forest available for treatment, indicating the importance of other influences.

Rideout and Omi (1995) concentrated their analysis on understanding how the scale of operations affects the cost of fuels treatments on national parks. They found strong economy-of-scale effects on costs, with lower per-acre costs associated with larger burn areas. They also found that costs are higher when managers take additional steps to reduce prescribed-fire escape risks or protect key resource values, when treatments are accompanied with mechanical, chemical, or biological pretreatments, and when significant effects of ecosystem structure or other factors related to location are present. In short, efforts to protect valuable resources, property, and people from the dangers of prescribed fire tend to drive up costs. This implies that ecosystem restoration and fire risk reduction activities may be more frequent in areas where there are fewer values at risk—a practical reality that complicates actions and economic analyses of where best to place treatments.

The importance of management constraints is also highlighted in a study of the role of private property protection by Berry and Hesseln (2004). This analysis found that per-acre mechanical and prescribed fire treatment costs in the Pacific Northwest were higher in the wildland-urban interface than in other areas. Size of treatment was negatively related to cost, confirming once again the effect of economies of scale. As stands became denser, they required more fuels management, increasing the cost of treatment, as would be expected. Validating previous research, treatments on sites with high fuels levels that were closer to values at risk tended to carry a higher cost. Because treatment costs and risk reduction benefits appear to be positively related, careful economic and statistical analyses are required to identify where best to place treatments on landscapes.

Research into the economics of fuel treatments has also been advanced by recent studies into the costs of mechanical fuel treatments and the factors affecting them. Rummer and others (2005) quantified the costs of fire- and ecosystem-enhancing mechanical fuel treatments for all forest lands in the western United States, and found that fuel treatment costs varied greatly according to the location of treatment and stand type. Costs per acre were high, ranging from a few hundred to thousands of dollars, suggesting that restoring ecosystems to fire-adapted conditions may be very costly. Working with data from Rummer and others (2005), Abt and Prestemon (2006) evaluated the timber market consequences of selling the products from fuel treatments in western timber markets. Focused on Federal lands, Abt and Prestemon showed that significant revenues were possible, thereby reducing their overall costs, but unintended consequences in the market may also occur. Concentrating treatments on higher risk sites could mean less outlay and possibly greater overall benefit than spending money on all at-risk sites without regard to degree.

Prestemon and others (2008) evaluated the costs of fuel treatments using the same framework as Abt and Prestemon (2006) but expanding the scope to all Federal lands in the South and the effects of treatments on fire risk and having to return to stands to apply additional treatments when risky conditions return. Prestemon and others (2008) also controlled for the effects of slope and stand conditions when conducting treatments based on a modified stand-density index or a thin-from-below type treatment in fire prone stands. They concluded that fuel treatments of these types could be less costly if marketable materials are removed and sold, but that the net cost of conducting treatments was still well over $600 per acre.

Much of the historical analyses of the factors influencing treatment costs have focused on U.S. public land management. Only rarely have studies focused on private lands. The important influence of legal and institutional constraints in driving up fuel treatment costs on private lands is clarified in a study by Yoder and others (2003). Liability issues affect the amount of effort a land manager puts into reducing the risk of fire escape from a prescribed burn. Strict liability laws that penalize managers for escapes tend to increase treatment costs compared to laws that only penalize managerial negligence. Liability laws vary across the United States, implying that the use of prescribed fire will be less frequent in places with strict liability compared to those with more relaxed rules. Enforcement of liability laws may therefore conflict with societal and managerial goals of ecosystem restoration and wildfire risk reduction, but the practical effect of the laws has not been fully evaluated. In locations where escapes are important, strict laws would not necessarily be as much in conflict with achievement of societal objectives as they would be in places where escape risk is low. Yoder and others (2003) showed that liability laws inflict costs on society in two ways: through increased treatment costs or through increased losses and suppression costs from wildfires that result after landowners begin reducing fuel treatments. However, the total of these costs must be weighed against the potential losses and costs associated with escaped prescribed fires.

## *Effects on Fire Processes*

Since the groundbreaking work by Davis (1965) and Davis and Cooper (1963), many wildland managers have recognized that the economical use of fuel treatments depends on how effective they are at changing wildfire activity across broad landscapes. More recently, Prestemon and others (2002)—bolstered by subsequent analyses by Butry (2006, 2009), Mercer and others (2007), and Mercer and Prestemon (2005)—described the importance of understanding the spatial and temporal dynamics of fuel treatments in managing fire activity. The effects of fuel treatments can span large areas and long time spans—accounting for them must not be limited to short-term responses to actions taken in one confined location.

Davis (1965) described wildfire activity as a conditional probability distribution across a range of wildfire sizes and frequencies, with the level of wildfire activity conditional on actions taken to affect fire activity. Davis (1965) and Davis and Cooper (1963) offered evidence of shifts in the expected amount of area burned in a management unit during a fire season in California and Florida. More broadly, Butry (2006, 2009), Mercer and others (2007), Prestemon and Butry (2005), and Prestemon and others (2002) provided evidence that prescribed fire and other treatments have long-term impacts, and that their effects are felt across space and time. Generally, prescribed fire was found to reduce wildfire area burned, with or weighting for intensity, in the long term with an elasticity ranging from about -0.05 to -0.30. In other words, each percentage increase in prescribed fire is expected to yield a long-term decrease in wildfire activity by 0.05 to 0.30 percent.

Many of the above studies used statistical techniques—actual data on wildfire and fuel treatment amounts—to quantify fuel treatment effects on wildfire. In the absence of historical data or when new types of treatments are being considered, statistical analyses are difficult. In these cases, simulation approaches are often used. For example, Finney and Cohen (2003) focused on how fuel treatments may affect wildfire area burned and the number of structures damaged. Emphasizing the scale of analysis for evaluating fuel treatment effects and the desired outcome measures, their simulations focused especially on how the placement of treatments may affect overall wildfire risk on the landscape and how fuel treatments can reduce fire intensity. Random location of fuel treatments produced fewer beneficial fire-control outcomes than a more systematic pattern of treatment.

Mercer and others (2007) confirmed the dual effects of fuel treatments on wildfire intensity (the rate at which a fire produces thermal energy) and area burned. They combined intensity and area burned data from Florida to identify the effectiveness of prescribed fire on the landscape to show that prescribed fire reduces wildfire in both the season following treatment and up to two subsequent seasons afterwards. The long-term impact of prescribed fire, however, was about 60 percent less than the short-term impact because of the dynamic impacts on wildfire. Fuel treatments were found to be less effective than wildfires in reducing the size and intensity of future wildfires, suggesting that short-term reductions are partially offset by subsequent wildfire activity. Mercer and others (2007) and Prestemon and others (2002) found that roundwood removals have various impacts on wildfire activity, serving to increase or decrease wildfires and intensities. This result, they speculate, is due to temporary increases in fine fuels in the aftermath of thinning.

Fernandes and Botelho (2003) reviewed the effectiveness of prescribed fire in achieving societal objectives—largely from studies of Mediterranean forest types—reporting that prescribed fire is quite effective at reducing fine fuels and therefore fire intensities and possibly the amount of area burned. They found empirical data suggesting that prescribed fire is most effective at reducing fire intensities and areas burned only when weather conditions during fires are not extreme. They also showed that strategic application of fuel treatments may be the most effective approach to reducing fire activity (Keeley 2002).

Piñol and others (2005) developed a simulation model that documents the importance of fire weather in modifying the effectiveness of fuel treatments. An interesting finding from their analysis is that the amount of fire area burned is about constant, regardless of whether the fire burns as a fuel treatment (prescribed fire) or as a wildfire. Nevertheless, prescribed fire must be done in places with high fuels levels if its purpose is to be a sufficient surrogate to wildfire; this can be operationally challenging.

The importance of targeting fuel treatment locations is confirmed by Hof and others (2000). In a simulation model of wildfire and fuel treatments, they found that effectiveness of treatments at protecting valued resources or property depends on the spatial distribution of the treatments, with layout and segmentation of the landscape important determinants. Implied here, given other research on prescribed fire and mechanical treatments (González-Cabán 1997, González-Cabán and McKetta 1986), is a tradeoff between costs and protection offered. Given that specific and effective treatment spatial orientations may be more costly than typical layout designs, the finding on the importance of layout, with support by Finney and Cohen (2003), also implies tradeoffs between treatment design and implementation costs.

## *Achieving Landowner and Societal Objectives*

To our knowledge, the first published (in a refereed journal) assessment of the role of fuels management in achieving improved desired outcomeswas by Saveland (1987). But even this analysis was based on simulation and was highly theoretical. Based on untested assumptions about the costs of prescribed fire and the damages from wildfire, Saveland estimated the level of prescribed fire efficacy that would result in positive net societal benefits (reducing total fire program costs and losses). The analysis, however, advanced consideration of the long-term effects of a fuel treatment program, a major contribution.

Although researchers such as Bellinger and others (1983) and Rideout and Omi (1995) recognized the importance of the potential role of making "presuppression" interventions in a wildfire program, prescribed fire was not considered part of the toolkit. Omi and others (2000) revisited the overall question of cost effectiveness, using a simulation approach to assess how fuel treatments might affect area burned. The analysis was purely theoretical, although it was based on simulations from national parks.

It was not until Prestemon and others (2002) broached the issue of the long-term, broadscale scope of the fuels management problem that actual historical data were used to evaluate the economics of fuel treatments. In their statistical analysis of wildfire in Florida, Prestemon and others (2002) showed that prescribed fire has long-term and short-term impacts and that its effects can be identified at broad spatial scales. Butry (2006) also showed how the economics of fuels management depend on the recognition of the tradeoffs among fuel treatments, suppression expenditures, and wildfire damages. Mercer and others (2007) extended these analyses to show how prescribed fire can lead to aggregate net benefits for reducing damages to timber, housing, and the broader economy.

Other research addressed fuel treatments at a stand rather than a landscape level, still recognizing the inherent spatial and long-term complexities. Using a Faustmann model of optimal timber rotation, Amacher and others (2006) described how landowners may choose a level of fuel treatment given the random nature of wildfire, the changed intensities of wildfires after treatments, the changed value of salvage timber resulting from treatments that followed wildfires, and the long-term nature of the effects. This study was the first to mathematically describe the spatial and temporal complexities of fuels management within the context of a multi-ownership landscape.

## Prescribed Fire and Sediment Production: Costs and Benefits

Soil erosion from wildfires is an important contributor to accelerated sedimentation which can result in lost storage capacity and increased treatment costs for municipal watersheds (González-Cabán and others 2004). A study by Wohlgemuth and others (1999) studied areas affected by recent wildfires and found that sediment production was about 90 to 95 percent lower in areas previously burned compared to nontreated areas. Gonzáles-Cabán and others (2004) present a methodology for estimating the costs and benefits of using prescribed fire to reduce sedimentation following wildfires; and then apply it in a case study of the watersheds in the Los Angeles foothills (encompassing the Angeles National Forest and adjacent private lands). They found that a wildfire interval of 22 years produced $2.5 million in sediment management and watershed rehabilitation costs for local, State, and Federal agencies. A multiple regression analysis of the impact of fire interval on sediment yield indicated that using prescribe fire to reduce the fire interval to 5 years would decrease sediment yield by 2.6 million cubic yards in the 33.3 square-mile watershed adjacent to the Angeles National Forest. A 1 percent decrease in the fire interval was found to reduce annual sediment yield by 0.58 percent. Implementing a prescribed burning program on a 5-year interval would save the County of Los Angles Department of Public Works $24 million per year in debris basin cleanout costs (Gonzáles-Cabán and others 2004).

### *Case Study: Defining Socially Optimal Fuel Reduction Programs*

Defining the “best” level of fuel treatment to apply to a forested landscape remains one of the most important and difficult issues for wildfire management because: (1) treatment effectiveness is difficult to measure and varies over time, (2) treatment costs are variable and are influenced by the scale of operations, (3) wildfire damages are complex and vary regionally, and (4) future fire occurrences are inherently uncertain. Over the past 5 years, Forest Service scientists have completed a series of studies to address this large question (Butry 2006, Butry and others 2001, Butry and Prestemon 2005, Mercer and Prestemon 2005, Mercer and others 2007, Prestemon and Butry 2005, Prestemon and others 2002, Prestemon and others 2008, Pye and others 2003). Using data on forest resources, meteorology, fire occurrence, and economic impacts within a probabilistic modeling framework, they built a state-of-the-science assessment of prescribed burning efficacy in Florida. Unlike previous studies, this work goes well beyond natural resource impacts to address how prescribed fire programs affect total societal benefits at a broad scale (for the purposes of these studies, societal benefits and costs are defined as the diversion of resources to vegetation management and away from other economically productive activities in the economy; in other words, the opportunity cost of foregone uses of these resources in the economy).

Mercer and others (2007) applied the approach to evaluate the optimal prescribed burning regime for a broad range of potential fire scenarios in Volusia County, Florida. Their results indicate that the current prescribed burning regime generated expected net gains in societal benefits, and in addition these gains would exceed the increased cost of a considerably expanded prescribed burning program. Although landowners currently burn about 4 or 5 percent of their forests each year, the optimal treatment to achieve societal benefits is approximately 13 percent.

These results provide information for forest managers in Florida but also suggest broader policy and program implications: (1) the available supply of fuel treatment providers plays a key role on the ability to accomplish goals; (2) understanding and predicting the potential fire severity and burned areas under different management regimes are crucial to identifying optimal policies; and, (3) the use of private sector prescribed burning services by public land agencies may drive up fuels treatments costs for private forest landowners—an unintended consequence of public programs can be a reduction in beneficial activities on private land.

## Model Construction

Next is a brief description of the methods used for the analysis conducted by Mercer and others (2007). In general, determining the optimal level of prescribed burning to achieve societal benefits requires solving a stochastic dynamic optimization problem. Therefore, to find the optimal levels of prescribed fire (or other vegetation management) inputs for wildfire risk reduction, we maximize the sum of expected current and future net present value of societal benefits:

$$\max_{x_t} A = E\left\{VW_t - v(x)' x_t + \sum_{i=t+1}^{T} e^{-ri}\left(VW_i - v(x)' x_i\right)\right\},$$
$$\text{and } W_t = W\left(Z_t, W_{t-j}, x_{t-k}\right) + \varepsilon_t, x_t \geq 0 (\forall t) \quad (1)$$

where

*A* is the maximization criterion (a measure of societal benefits)

*V* is the net value change per acre of wildfire (a negative value per unit, measuring damages per unit of wildfire realized)

$W_t$ is current area (acres) burned by wildfire (if expressed as a quantity measure of resources “saved” by applying resource inputs, *V* would be a positive number, reflecting positive values) for the spatial unit of observation in year *t*

**v** is a vector of the prices per acre of suppression, presuppression, and vegetation management inputs

$\mathbf{x} = (\mathbf{x_t}, \mathbf{x_{t+1}}, \ldots, \mathbf{x_T})$ is a vector of the amount of suppression, presuppression, and vegetation management inputs for year *t* through *T* (the planning horizon)

$\mathbf{Z}_t$ are exogenous inputs to wildfire production including stochastic climate variables

$\mathbf{W}_{t-j}$ is a vector of *j* lags of wildfire area

*r* is the discount rate

Solving this optimization problem produces a *T*×1 vector of optimal input quantities and a *T*×1 vector of wildfire quantities over time. The uncertainty associated with random events (errors in prediction of weather, for example) means that the area burned by wildfire is known only with error, complicating the solution process. In the presence of such error, simulation techniques may be used to identify, for example, the amounts of prescribed burning most likely to maximize the societal benefits criterion. Hadar and Russell (1969) describe how to evaluate these types of uncertain prospects.

Identifying the long-term expected impact of prescribed fire requires accounting for variable weather and the uncertainties associated with the "true" form of equation (1). Although equation (1) was estimated using historical data on fire output and wildfire production inputs, observed wildfire output always differs from that predicted by empirical models because of the random nature of the phenomenon and the imprecision of statistics. To identify the "best" level of prescribed fire to apply in a fire-prone landscapetwo versions of equation (1) were estimated—one expressing wildfire output in area burned without including fire intensity and one expressing wildfire output in area burned weighted by the intensity of the wildfire. Research has shown that wildfire intensity is closely related to the resulting damages to forests. So, measuring how prescribed fire affects the intensity of wildfire output should provide a more accurate prediction of the impacts of prescribed fire on wildfire damages.

## Methods

Next, the results from the empirical estimates of equation (1) were used to forecast the expected damages from wildfire under different prescribed fire scenarios for Volusia County, which was representative of the fire-prone landscape of Florida. Forecasts of each year's wildfire activity were made for 100 years into the future using the following procedure:

1. Select a fixed level of prescribed fire to apply every year,
2. Randomly select the values of two climate variables found to influence wildfire in Florida (an ocean temperature measure of the El Niño-Southern Oscillation and an index of sea level air pressure quantifying the North Atlantic Oscillation),
3. Randomly select a forecast error for wildfire area burned—with and without weighting for intensity—from the historical distribution of weather factors and from prediction errors,
4. Calculate the total annual expected wildfire damages and suppression costs and the annual cost of applying the fixed amount of prescribed fire to the county,
5. Vary the amount of prescribed fire chosen in step one and then repeat steps 2 through 4.

This process was continued, starting from 5,000 acres prescribed burned per year, up to about 100,000 acres per year (out of 313,000 acres of forest in the county). After all of the simulations were completed, the total, long-term discounted cost plus losses associated with wildfire and prescribed fire were compared across all levels of prescribed fire to identify the acreage of annual prescribed fire where the sum of costs and losses was smallest.

Data were obtained from many State and Federal agencies. Florida Division of Forestry fire data on State and private lands from 1981 to 2001 provided daily records of the location and the features of each wildfire, sufficient information to construct a damage measure that incorporated fire intensity into each county's metrics of acres burned per year. Data on wildfires on Federal lands were obtained from the Forest Service, U.S. Fish and Wildlife Service, and the National Park Service. The prescribed fire data from 1994 to 2001 were obtained from permits granted by the State for prescribed fire. The U.S. Department of Commerce National Oceanic and Atmospheric Administration provided data on the Niño-3 sea-surface temperature anomaly from 1994 to 2001 (U.S. Department of Commerce National Oceanic and Atmospheric Administration 2003a)—necessary because fires burn more in Florida when the Niño-3 anomaly is negative; and also provided the values of the North Atlantic Oscillation from 1994 to 2001, another ocean temperature measure linked to wildfire in Florida (U.S. Department of Commerce National Oceanic and Atmospheric Administration (2003b). The Forest Service provided count-level survey data on the forest extent. Data on annual housing counts in each county—the instrument for measuring the impact of available wildfire suppression resources—were provided by the Florida Bureau of Economics and Business Research (2002). Weighting for wildfire intensity was calculated by categorizing all wildfires into intensity classes using actual observations of the average flame length for each fire, based on research by Byram (1959). Annual intensity-weighted risk was derived by summing for each county the product of the annual number of acres burned in each intensity class times the average intensity for that class divided by the county's total forest area.

Models were estimated for fire at the county level. County fixed-effects time series models estimated of area burned with and without weighting for wildfire intensity. The dependent variables for the two models were: (1) intensity-weighted acres per acre of forest area in the county in the year and (2) the area of wildfire area burned in the county per acre of forest area in the county.

Losses associated with wildfire were calculated based on the 1998 wildfires (Butry and others 2001). Two versions of losses were generated: one version assembled losses in terms of societal benefits—consumer plus producer surplus. Another version assembled losses in terms of market values—prices multiplied by quantities. Losses accounted for timber losses from wildfire, housing losses, and suppression expenditures.

### *Results*

The original statistical models, relating fire area burned with and without weighting for intensity, show that prescribed burning at the county level has a large, statistically significant effect in the county. The elasticity of the area burned with weighting for intensity with respect to prescribed fire permitted area was –0.9 in the short term and –0.31 in the long term, –0.72 in the short term and –0.28 without weighting for intensity.

We also estimated a model for the supply of prescribed fire service providers, which showed a long-term supply elasticity of about 0.54. This indicates that the cost of prescribed fire per acre would increase twice as fast as the increase in the areal increase in prescribed fire. This extra cost associated with higher levels of prescribed fire was included in the cost plus loss simulations.

The simulation results in Figure 1 show that the optimal levels of prescribed fire depend on whether wildfire is measured purely by area burned or if intensity is also included. Based on the losses and costs associated with wildfire and prescribed fire applied to achieve these levels of losses and costs, the expected value of losses plus costs is minimized when prescribed fire is set at about 19,000 acres per year for simulations that take wildfire intensity into account, compared 14,000 acres per year for simulations that rely solely on area burned. From 1994 to 2001, actual wildfires in the area averaged about 13,000 acres per year, which is 30 percent less than the prediction that incorporated intensity data, but very close to the prediction that was based on the amount of area consumed without considering intensity data.

## Conclusions

The most striking finding from our survey of the economics of fuel treatments is mainly how little work has been done to evaluate net economic benefits. Most economic studies of wildfire management have focused on assessing wildfire economic impacts, understanding the economic questions surrounding wildfire suppression and prepositioning of suppression resources (an area that we did not thoroughly review), and evaluating the costs of fuel treatments and the variables affecting those costs. Many of the economic analyses of fire suppression have been theoretical, which limits their usefulness to managers; almost no experimental applications have been reported in the refereed literature.

Still less work has been published that quantifies how treatments may affect wildfire processes. Without models that can quantify the impacts of treatments on

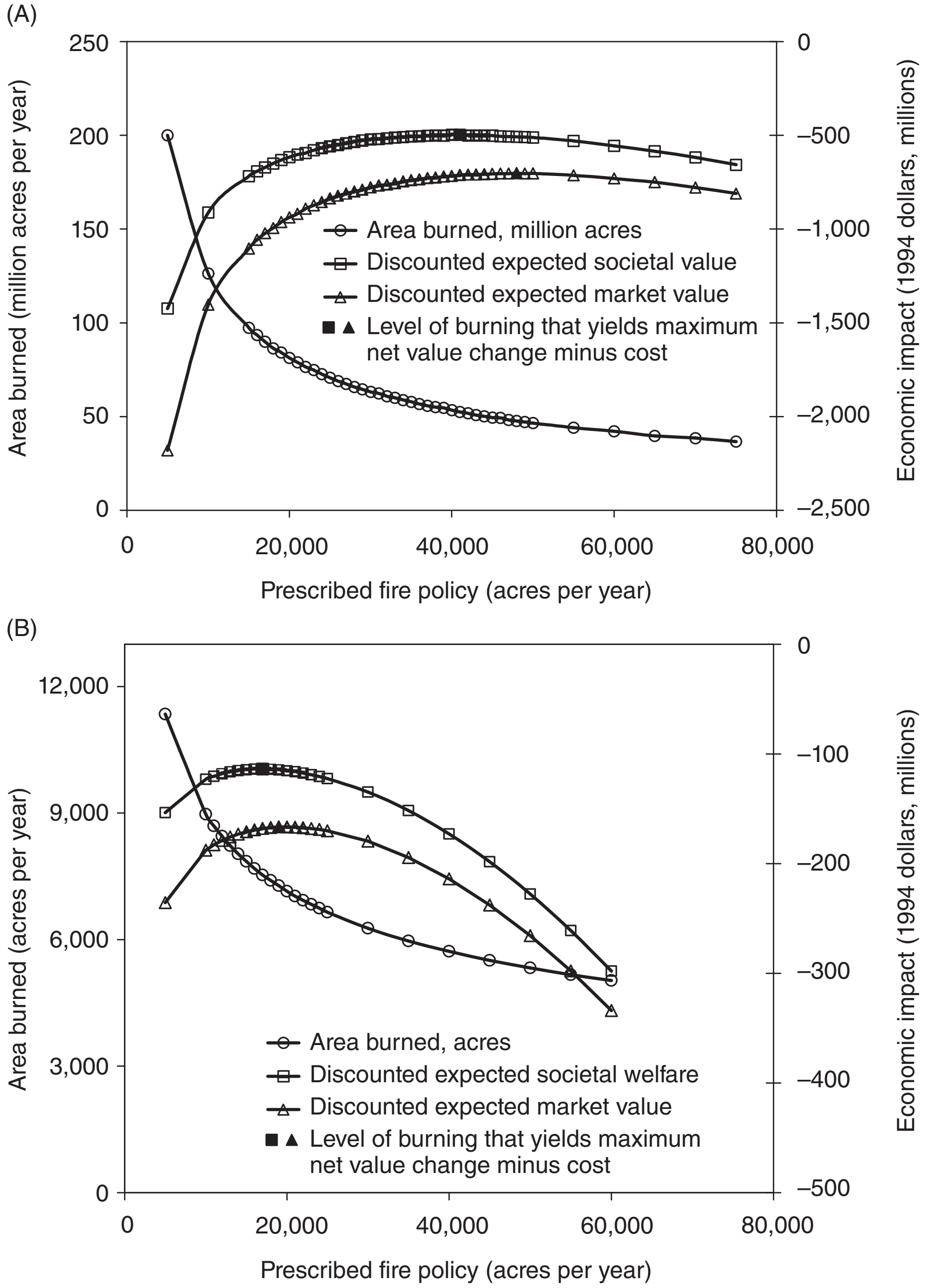


**Figure 1.** The economic value (avoided losses minus costs) of applying prescribed fire to reduce wildfire impacts, derived from (A) simulations that take wildfire intensity into account and (B) simulations that rely solely on area burned by wildfire (Mercer and others 2007).

wildfire activity, answering questions about the economics of treatments is not possible. Simulation models of wildfire, such as FARSITE, that can account for the effects of fuel treatments are available (Finney 1998, Finney and Andrews 1999), but they are in early development stages. The only known data-driven assessments in the refereed literature that we could find are analyses for Florida (Mercer and Prestemon 2005, Prestemon and others 2002). Only Davis and Cooper (1963), Davis (1965), and Mercer and others (2007) have done actual empirical analyses that place fuel treatments into the question of wildfire management economics.

Even the received literature has many information gaps that need to be addressed. For example, all of the literature ignores many of the externalities and nonmarket effects of fuel treatments. No study has integrated into an economic analysis of fuel treatments the possible damages associated with treatments, including the risks from escaped prescribed fires, the negative site impacts from mechanical thinnings, or the smoke from prescribed fires. Similarly, no study has integrated the benefits of fuel treatments on processes other than wildfire. These benefits include ecosystem restoration and improvement of timber growing conditions.

Additionally, we found only one study that examined impacts on watersheds (González-Cabán and others 2004), and it was not published in the refereed literature. These gaps in knowledge about the connections among wildfire, fuel treatments, and watersheds do not necessarily indicate lack of interest. We believe that the most recent advances in the science have occurred due to the availability of new historical data on wildfire and fuel treatments in the same landscapes, enhanced computational power (which allows fine-scale simulations), and the emergence and application of new statistical methods. We anticipate that future research in the area of fuel treatment economics will advance rapidly. In terms of water, the most significant research need that we see is for experimental and field experiments that measure water and watershed responses to wildfires and fuels management.

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