Economic optimization of wildfire intervention activities

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Abstract

We describe how two important tools of wildfire management, wildfire prevention education and prescribed fire for fuels management, can be coordinated to minimize the combination of management costs and expected societal losses resulting from wildland fire. We present a long-run model that accounts for the dynamics of wildfire, the effects of fuels management on wildfire ignition risk and area burned, and the effects of wildfire prevention education on the ignition risk of human-caused, unintentional wildfires. Based on wildfire management activities in Florida from 2002 to 2007, we find that while wildfire prevention education and prescribed fire have different effects on timing and types of fires, the optimal solution is to increase both interventions. Prescribed fire affects whole landscapes and therefore reduces losses from all wildfire types (including lightning), while wildfire prevention education reduces only human-caused ignitions. However, prescribed fire offers a longer-term solution with little short-term flexibility. Wildfire prevention education programs, by comparison, are more flexible, both in time and space, and can respond to unexpected outbreaks, but with limited mitigation longevity. Only when used together in a coordinated effort do we find the costs and losses from unintentional wildfires are minimized.

I. Introduction

Wildfires are produced on a landscape from a combination of purchased and free inputs. Free (i.e., non-market) inputs to wildfire include lightning ignitions and those caused by humans, natural fuels (vegetation), and weather conditions. Purchased inputs include anything employed by fire managers to affect fire occurrence, extent, and intensity. Wildfire managers operate in a world of constraints to their actions to affect wildfire processes, so the decisions made are typically choices among competing means of intervening in wildfire processes.

Economic theory (e.g., Rideout and Omi 1990) provides a framework for understanding the effects of decisions and quantifying the trade-offs among alternative actions: under risk neutrality, minimizing the sum of management costs incurred and the expected losses experienced by society from wildfires that occur. In economics, at the optimum, the cost of the last unit of each purchased input reduces the expected losses by the identical amount. Because inputs and wildfires themselves have both short- and long-run impacts on costs and losses, this economic expression of optimality—and hence purchased input trade-offs—is inherently long-run (e.g., Mercer et al. 2007).

A challenge in empirical wildfire economics is obtaining the information needed to quantify the marginal contributions among alternative fire management actions, enabling better decision-making. This article describes how two important purchased inputs of wildfire management, wildfire prevention education and prescribed fire, can be used in combination to achieve the economic objective of minimizing long-run management costs and expected societal losses. We describe a long-run model that accounts for the dynamics of wildfire, which provides fuel reduction as a free input in subsequent fire seasons; the short- and long-run effects of fuels management on fire extent and occurrence; and the short- and long-run effects of wildfire prevention education on the occurrence on targeted unintentional wildfires.

This paper makes the following contributions to the literature. First, we outline a model that incorporates both fire ignitions and prescribed fire in an economic model of wildfire management. Second, we describe how wildfire prevention and prescribed fire trade off in the pursuit of an optimal policy. Prescribed fire operates over whole landscapes and therefore affects the losses associated with all fire types, while fire prevention only operates directly on part of potential fire starts. Previous research has focused on individually optimizing either fuels management activities (e.g., Kim et al. 2009; Wei et al. 2008; Mercer et al. 2007; Yoder 2004) or suppression resources (Haight et al. 2007; Donovan 2006; Donovan and Rideout 2003; MacLellan and Martell 1996), so to minimize the expected losses of wildfire. Joint optimizations have been explored, but these have focused on optimizing between a preoperational and an operational phase (Minciardi et al. 2009). An example would be to jointly optimize fuels management and suppression effort (e.g., Drucker et al. 2008, Mercer et al. 2008). We, instead, optimize over two preoperational wildfire management strategies while holding suppression effort constant. Third, we show that the quantities of free inputs affect trade-offs and optimal amounts of purchased inputs in wildfire management, implying that the optimal combinations of purchased inputs should vary, along with the variation in free inputs, both over time and across space.

The organization of the rest of the manuscript is as follows: Section II presents our theoretical model of wildfire management economics; Section III describes the study site and the two wildfire management variables of interest (wildfire prevention education and prescribed fire treatments); Section IV introduces the empirical model of wildfire ignition risk and Section V describes the optimization methodology; Sections VI and VII present the empirical and optimization results; and Section VIII provides the conclusion.

II. A Theoretical Model

The expected cost plus loss of wildfire is the sum of expected ignitions times expected fire size times the loss value per acre, and the sum of all the intervention costs. Let $I_{i,t}^{p}$ be the count of ignitions of targeted unintentional fire types (i.e., human-caused, unintentional ignitions targeted by prevention education activities) in location *i* (*i* = 1 to *J*) in period *t* (*t*= 1 to *T*); $I_{i,t}^{n}$ be the count of other ignitions (i.e., other unintentional, intentional, naturally-occurring wildfire ignitions) in *i* and *t;* $\mathbf{x}_i^p$ be a vector of an unspecified number of lags of wildfire prevention actions in period *t*; $\mathbf{x}_i^R$ be a vector of an unspecified number of lags of other actions (e.g., prescribed fire); $\mathbf{z}_i$ be an unspecified number of lags of free inputs to wildfire production in period *t*. Thus, targeted unintentional and other ignitions can be represented as

$$I_{i,t}^{p} = f(\mathbf{x}_i^{p}, \mathbf{x}_i^{R}, \mathbf{z}_i)$$

And

$$I_{i,t}^{n} = f(\mathbf{x}_i^{R}, \mathbf{z}_i)$$

The size of wildfires, $A_{i,t}$, is a function of lagged values of prescribed fire and free inputs, as prevention inputs do not influence fire size, and can be represented by

$$A_{i,t} = A(\mathbf{x}_i^{R}, \mathbf{z}_i)$$

Let w^p be an index of the cost of wildfire prevention actions, $x_{i,t}^{p}$ the quantity of those actions in period *t*, w^R be an index of the price of other actions, $x_{i,t}^{R}$ the quantity of those other actions in period *t*, so that the costs of intervention are

$$C_{i,t} = w^p x_{i,t}^{p} + w^R x_{i,t}^{R}$$

$Y_{i,t}^{p}$ and $Y_{i,t}^{n}$ are the loss per acre of targeted unintentional and non-targeted wildfire. In addition, *E* is the expectations operator and *r* is the discount rate. Thus, the fire management problem is:

$$\min_{x_i^p, x_i^r} M = \sum_{i}^{J} \sum_{t}^{T} (1+r)^{-t} \{C_{i,t} + Y_{i,t}^{p} E[I_{i,t}^{p} A_{i,t}^{p}] + Y_{i,t}^{n} E[I_{i,t}^{n} A_{i,t}^{n}]\} \qquad (1)$$

where *M* is the expected cost plus loss of wildfire. As written, fire prevention efforts affect only $I_{i,t}^{p}$ while the other inputs to the fire production process (prescribed fire and free) affect all ignitions as well as the expected fire sizes of both types of fires.

The optimal allocation of wildfire prevention education, ($x_{i,t}^{p*}$) across space and time and the analogous allocation of prescribed fire ($x_{i,t}^{R*}$) would yield a long-run minimum of the objective function (minimizing cost plus loss) at Z^*. At the optimum, the partial derivative of Z^* with respect to $x_{i,t}^{p*}$ should equal the unit price of those efforts, or $\partial Z^* / \partial x_{i,t}^{p*} = w^p$; similarly, $\partial Z^* / \partial x_{i,t}^{R*} = w^p$. Depending on the specification of the ignition process, free inputs may affect optimal levels of purchased inputs (i.e., a non-linear in parameters functional form). For example, a Poisson specification of the ignition process implies that inputs are non-separable and thus optimal input quantities are jointly determined.

III. Wildfire Interventions

Wildfire prevention education (WPE), defined here as the avoidance of targeted unintentional human caused wildfires through education,[2] includes activities such as radio, television, and newspaper public service announcements (PSAs); homes visitations; presentations; fliers and brochures distributed; and community wildland-urban interface hazard assessments. We also explored the effect of prescribed fire fuel treatments, those specifically targeted towards reducing wildfire hazards, on targeted unintentional ignitions. WPE and prescribed fire offer land managers different mechanisms to minimize the impact of future wildfire.

We explored the effect of these two interventions across the four wildfire management regions in Florida (Figure 1). Region 1 includes 16 counties in the panhandle of Florida, as well as the cities of Tallahassee and Pensacola and, along with Region 2, represents the primary timber growing region of the state. The 18 counties in Region 2 are home to both the city of Jacksonville and the extreme southern part of the Okefenokee Swamp. Region 3 includes 15 counties in central Florida, including the cities of Orlando, Daytona, and Tampa. The southernmost region, Region 4, includes Lake Okeechobee, the Everglades, the city of Miami and the Keys in its 18 counties.

[2] These include debris fire escapes, campfire escapes, and fires caused by discarded cigarettes and by children. We ignore other kinds of unintentional fire starts (such as equipment and railroad fires) because they are not the focus of wildfire prevention education, and we ignore arson because its occurrence is affected by a different combination of managerial (and law enforcement) actions (e.g., Prestemon and Butry 2005).

Over the study period (2002 to 2007), Florida experienced 6338 targeted unintentional ignitions accounting for 96 830 acres burned. The number of targeted unintentional wildfire ignitions varied between 20/month in Region 3 to 37/month in Region 2. The number of acres burned varied between 255 acres/month in Region 1 to 828 acres/month in Region 2. Region 2 experienced more than twice the amount of burned acres than the next fire-prone region (Region 4). While targeted unintentional ignitions made up 37 % of all wildfire ignition reported over this period, targeted unintentional wildfires remained small. They comprised only 7 % of the total burned acres. Historically, targeted unintentional wildfires have accounted for more acres burned (natural fires may burn larger areas due to changes in climate and weather). However, because targeted unintentional ignitions are caused by humans, these wildfires tend to occur in places close to values at risk (e.g., Bradshaw 1988, Butry et al. 2002).

Over the study period more than 1.4 million acres burned from wildfire. Another 2.8 million acres were authorized for burning by silvicultural-based prescribed fire treatments targeting hazardous fuels. The number of prescribed fire permits issued varied from as low as 28/month in Region 4 to as high as 149/month in Region 1, on average. Region 1 also averaged the most requested number acres for treatment, at 23 016 acres/month, compared to Region 2 with 6487 acres/month. On average, monthly prescribed fire fuel treatments involve 8 to 90 times more acres than do wildfires.

The intensity and mix of WPE activities vary by wildfire management region (see Table 2). Distributing wildfire prevention fliers, brochures, and CDs appeared to be the most common activity across regions (176 452 were distributed in all). Public service announcements (PSAs) were also very common (30 931). Overall, television PSAs (12 504) were most widely used followed by newspaper (11 020) and radio (7407) spots. Also used were 7314 homes visitations, 890 presentations, and 156 community WUI hazard assessments.

Timing is important when developing (pre-fire) mitigation strategies. Figure 2 presents the average seasonality of targeted unintentional and non-targeted unintentional (e.g., arson and lightning) wildfire ignitions, authorized prescribed fire acres and WPE activities over the 2002 to

2007 study period. Shown is the monthly count of each data series compared to its 12-month average value. Targeted unintentional wildfire ignitions peaked in the late winter and early spring, as did authorized prescribed fire treatments, fire prevention brochure distribution, and wildfire education presentations. Media PSAs and home visitations peaked prominently in late spring and early summer. Hazard assessments did not follow any strong seasonal trend. Interestingly, media PSAs and home visitations peaked after the peak of targeted unintentional ignitions. In fact, the relatively large peaks exhibited by media PSAs and home visitations were followed with declines in targeted unintentional ignitions, perhaps indicative of their effectiveness at reducing wildfire risks. Non-targeted unintentional ignitions peaked during this period, providing an indication that climatological and fuel conditions in the summer improve wildfire ignition success. Likely this explains why prescribed fire authorizations also were fewer during this fire-prone period (i.e., higher likelihood of escaped prescribed fires).

Casually, it appears wildfire mitigation effort reduced targeted unintentional ignitions, as periods of high effort were followed by periods of lower targeted unintentional ignitions. Of course, it also looks as if high periods of effort were accompanied by high periods of ignitions, so likely there is some simultaneous determination occurring. Our statistical model, presented in the next section, untangled the complicated relationships between wildfire and prevention by accounting for endogeneity and other factors related to the ignition generation process (e.g., weather, fire history, and socioeconomic characteristics of the spatial units of inference).

IV. Empirical Model

The statistical model estimates the effect of free inputs (including the weather, vegetation and climate) and purchased inputs (WPE and prescribed fire) on the monthly occurrence of targeted unintentional wildfires across the four fire management regions. We assume the occurrence of reported targeted unintentional wildfire follows a Poisson distribution:

$$I_{i,t}^{p} = e^{\boldsymbol{\alpha}_i'\mathbf{z}_{i,t} + \boldsymbol{\beta}_i'\mathbf{x}_{i,t-k} + \varepsilon_{i,t}} \qquad (2)$$

where $I_{i,t}^{p}$ is the number of targeted unintentional wildfires for location *i* in time *t*, **z** are the free inputs to wildfire production, **x** are the *M* interventions occurring over the current and *k* previous months, $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$ are the parameters associated with the inputs and interventions, respectively, and ε is an error term. Because of simultaneity between the number of targeted unintentional wildfires and interventions, the inputs to wildfire production are correlated with the error term, $E[\varepsilon_{m,i,t} \mid x_{m,i,t}] \neq 0$. Thus, we augment equation (2) with a set of auxiliary equations, called "control functions" to construct a set of variables to control for the unobserved heterogeneity creating bias in (2) (see Hausman 1978):

$$x_{m,i,t} = \boldsymbol{\gamma}'_{m,i,t}\mathbf{h}_{m,i,t} + c_{m,i,t} \tag{3}$$

where **h** is a set of instruments and **c** is a normally-distributed error term. Procedurally, the controls are obtained by regressing intervention effort on the set of instruments and estimating the residuals, so that,

$$\hat{c}_{m,i,t} = x_{m,i,t} - \hat{\boldsymbol{\gamma}}'_{m,i,t}\mathbf{h}_{m,i,t} \tag{4}$$

Equation (2) is augmented to become:

$$I_{i,t}^{p} = e^{\boldsymbol{\alpha}'_i\mathbf{z}_{i,t} + \boldsymbol{\beta}'_i\mathbf{x}_{i,t-k} + \boldsymbol{\delta}'_i\hat{\mathbf{c}}_{i,t} + \xi_{i,t}} \tag{5}$$

where ξ is a normally-distributed error term and by construction it is not correlated with the inputs to wildfire production (i.e., $E[\xi_{m,i,t} \mid x_{m,i,t}, \hat{c}_{m,i,t}] = 0$). We used maximum likelihood estimation to maximize the log-likelihood function based on (5) :

$$\ln L = \sum_{i=1}^{I}\sum_{t=1}^{T} -e^{\boldsymbol{\alpha}'_i\mathbf{z}_{i,t} + \boldsymbol{\beta}'_i\mathbf{x}_{i,t-k} + \boldsymbol{\delta}'_i\hat{\mathbf{c}}_{i,t} + \xi_{i,t}} + \left(\boldsymbol{\alpha}'_i\mathbf{z}_{i,t} + \boldsymbol{\beta}'_i\mathbf{x}_{i,t-k} + \boldsymbol{\delta}'_i\mathbf{c}_{i,t}\right)I_{i,t}^{p} - \ln(I_{i,t}^{p}!) \tag{6}$$

The intervention variables, $\mathbf{x}_{i,m,j,t-k}$, include WPE variables for current and k=6 lagged months (a vector that includes the individual sums of the WPE variables over the previous 6 months) and the area of prescribed fire permits issued in the previous one, two, and three years. The WPE variables include the number of media public service announcements (TV, radio, and print ads) (Media), homes visited (Homes), presentations given (Presentations), brochures and flyers distributed (Brochures), and community wildfire hazard assessments (Hazard) provided in current month *t* and over the last six months (Florida Division of Forestry 2008a). Although several other WPE measures (fairs, billboards, movie theater public service announcements) were undertaken by wildfire prevention specialists, the occurrence of such measures was too sparse to allow for identification. All included WPE variables were normalized by population, but population was included as an additional explanatory variable in the statistical models to account for the changes in the levels of the integer Poisson process. The other intervention variables include the annual area authorized for hazard removal (as opposed to for ecological or wildlife reasons) by prescribed burning lagged up to three years (Florida Division of Forestry 2008b).

The vector of free inputs, $\mathbf{z}_{i,j,t}$, includes measures of fire weather (relative humidity (RH, current month and 12 month lag), Keetch-Byram Drought Index (KBDI, current month and 12 month lag; Keetch and Byram [1968]), Fire Weather Index (FWI, current month and 12 month lag; Fosberg [1978]), Modified Fire Weather Index (MFWI, current month and 12 month lag; Goodrick [2002]), precipitation) (Goodrick 2008), climate (the March to September monthly average and the October to February monthly average of the Niño-3 sea surface temperature anomaly in degrees centigrade, [National Oceanic and Atmospheric Administration 2008]), the annual area burned (in acres) by wildfire lagged up to six years (Florida Division of Forestry 2008c), county population estimates (U.S. Bureau of the Census 2008), the number of sworn full-time equivalent police officers per capita (Florida Department of Law Enforcement 2008), and dummy variables for region (Region 1 is included in the intercept), season (fall is included in the intercept), and year (2002 is included in the intercept). Finally, we include a trend variable to account for the net effects of unspecified steady changes not captured by other variables.

The vector of instruments included all of the variables used in the prevention models except current WPE activities (in this model the dependent variable), and also included wildfire ignitions of targeted unintentional causes (lagged 2 years to 5 years) and the one-year lagged value of sales tax revenues (Sales Tax) (Florida Department of Revenue 2008). These variables were chosen as instruments based on our assumption that they are correlated with WPEs but not with current wildfire behavior, except through their effect on WPE. For instance, prior wildfire behavior could influence future WPE strategies, and sales tax revenues could influence future WPE by affecting WPE budgets.

V. Optimal Mitigation

We assumed that a prevented fire reduced the number of fires in the same location and the same month and year of the average size as the fires that occurred in that month and location. Interventions affect wildfire acres burned through two methods: (1) the effect of prevention on targeted unintentional ignitions (current model); and (2) the effect of prescribed fire on area burned for fires that occur (Mercer et al. 2007 model).

We simulated the effects of changes in prevention efforts and prescribed fire (*X*) on targeted unintentional ignitions (I^p) and area burned (*A*). In the long-run the change in area burned (A^*) equals the sum of the change in the long-run area burned ignited by non-targeted sources (A^{*n}) and the change in the long-run area burned ignited by targeted unintentional sources (A^{*p}):

$$\Delta A^* = \Delta A^{*n} + \Delta A^{*p} \quad (7)$$

This is ultimately a function of the short-run change in area of targeted unintentional wildfire due to prevention change (A_t^p):

$$\Delta A^* = -0.633 * \Delta A_t^p + (1 - 0.633) * \Delta A_t^p + \sum_k \frac{\Delta A_t^p}{\Delta A_{t-k}} \quad (8)$$

where we accounted for the fuel treatment effect of wildfire. An average acre in period *t* increases wildfire in the long-run by about 0.633 (Mercer et al. 2007). The short-run change in area of targeted unintentional wildfire due to a prevention change (ΔA_t^p) is:

$$\Delta A_t^p = \frac{\partial I_t^p}{\partial X} * \overline{A}_{i,t} \qquad (9)$$

where $\partial I_t^p / \partial X$ is determined via estimation of (5) $(\partial I_t^p / \partial X = \beta)$ and $\overline{A}_{i,t}$ is the average size of the targeted unintentional fires that occurred in the same month, year, and fire management region.

We explored three scenarios: (1) minimize cost plus loss by altering WPE, holding prescribed fire constant; (2) minimize cost plus loss by altering prescribed fires, holding WPE constant; and (3) minimize cost plus loss by altering both WPE and prescribed fires. Losses from wildfire were set at $1267/acre burned (per Mercer et al. [2007] adjusted to 2005 dollars).[3]

Florida's annual wildfire prevention education budget is $0.47 million. The annual budget allocation across wildfire management regions is not known with precision; however, it is believed the allocation is roughly equivalent across regions (R. Rhea, Florida Division of Forestry, pers. comm., October 24, 2008). We explored the sensitivity of this assumption by examining the change when the spending was allocated proportionally based on historical targeted unintentional wildfire acres burned.

The annual cost of prescribed fire fuel treatments is about $3.2 million/year and they are largely borne by both private landowners and government. We assume a unit price of $25/acre (based on an approximation from Cleaves et al. [2000]), but also explore the effect a price sensitive unit cost has on the results (i.e., prices rises with demand). Mercer et al. (2007) found that the

[3] This figure assumes a constant cost plus loss per acre of wildfire. An alternative assumption, allowing costs plus losses to have a fixed cost per fire and a variable cost per acre burned, was not testable with the available data.

elasticity of the prescribed fire service supply with respect to price was 0.54 in Florida, and that the short-run wildfire area elasticity with respect to prescribed fire area was -0.73.

VI. Statistical Results

The control function models are significant and the covariates explain as much as 25 % to 52 % of the variation in the WPE variables (see Table 3). The constructed control function variables were used as additional model regressors in the targeted unintentional wildfire ignition model. They have significant positive correlations (at the 10 % level) with targeted unintentional ignitions, meaning endogeneity exists between WPE and targeted unintentional ignition rates (see Table 4). The positive correlations imply that a standard Poisson regression estimation would produce biased downward treatment effects on the WPE variables. The ignition model is significant and based on the calculated pseudo-R^2, explains 72 % of the variation in targeted unintentional ignition counts.

Media PSAs, presentations, brochures, and community hazard assessments are significant at the (10 % level) and negatively related to targeted unintentional wildfire ignition occurring in the same month, after accounting for endogeneity. Home visitations are only weakly correlated (13 % level). Lagged levels (activity within the last six months) of media PSAs, presentations, and brochures are also significant (10 % level) and negatively related to ignitions. The implication is that media PSAs, presentations, and brochures have both immediate and short-term mitigation effects, whereas community hazard assessments have an immediate effect, but no lasting impact. Authorized prescribed fire acres have longer term effects, as compared to WPE. Prescribed fire had a beneficial statistical effect (10 % level) two and three years post-treatment; however, prescribed fire performed within the last year did not have an impact on targeted unintentional ignitions. (This does not rule out treatment effects on other types of ignitions; this was not explored.) Other estimated relationships produced expected signs and significance. Weather, climate, seasonality, historical fire patterns, and socioeconomic variables are correlated with targeted unintentional ignitions, as are differences across regions and years.

The elasticities associated with prescribed fire fuel treatments (two and three year lagged) are larger, in absolute terms, than most of the WPE variables, although in many cases the difference is small. The elasticity associated with media PSAs (normalized by population) ran over the last six months (-0.26) is the same as the elasticity associated with prescribed fire treatments performed two years prior (-0.26). Thus, a 20 % increase in PSAs and prescribed fire would have each decreased ignitions by 5.2 %, or on average 1.5 ignitions. This 20 % increase would have required either an additional 118 PSAs or 2140 acres treated. The nonlinearity of the Poisson model also assumes that WPE and fuel treatments are interdependent, thus the amount of fuel treatment applied impacts the effect WPE had on ignition success (and vice-versa).

VII. Optimal Mitigation Results

Optimal Change in WPE Spending (Only)

The optimal change in WPE spending, holding prescribed fire constant, is a 225 % increase, statewide (Figure 3). This figure shows that large increases in WPE would be needed in all four regions to minimize costs plus losses under the two assumptions of initial equal or initial proportional spending allocation.

The relative large increases when moving from the assumption of equal allocation to proportional, in Regions 1 (+ 74 %) and 3 (+ 81 %), is likely due to the assumed initial small spending level with a proportional allocation compared to the equal allocation. Under the proportionality assumption Regions 1 and 3 initially receive 15 % and 16 %, respectively. Region 2 receives 49 %, Region 3 receives 16 %, and Region 4 receives 20 % of the initial spending allocation. Thus, Regions 1 and 3 appear to produce the greatest return on WPE investment, and hence the substantial need for increased funding. The return on WPE also looks more favorable for Region 4 under the proportionality assumption. Expansion of WPE in Regions 1, 3, and 4 come at the expense of Region 2, which begins with a high initial allocation level under the proportionality assumption, and quickly experiences larger diminishing returns.

Optimal Change in Prescribed Fire (Only)

The optimal change in prescribed fire, holding WPE spending constant, is a 79 % increase, statewide (Figure 4). Results are nearly identical regardless of the prescribed fire unit cost price assumption. Optimality results in a 17 % decrease for Region 1, a 28 % increase for Region 3, a 122 % increase for Region 2, and a 180 % increase for Region 4. On average, Region 1 performed substantially more prescribed fire treatments (23 016 acres/month) over the observed study period than any of the other regions—nearly 2.5 times the amount of the next largest region (see Table 1). While on average Region 4 treated the second most acres (9134) and performed the most number of WPE activities (individually and as a whole) per month, it also experienced far more wildfire (by any cause). Prescribed fire affects wildfire regardless of ignition. So, this explains the substantial increase in prescribed fire in the region. Over the study period Region 4 experienced an average fire size of 151.5 acres; Region 2 was second with an average size of 26.9 acres, followed by Region 3 (average equal to 18.2 acres) and Region 1 (average equal to 14.9 acres). Looking at the historical annual number of acres burned, this ordering is preserved: Region 4—152 891 acres/year; Region 2—57 201 acres/year; Region 3—22 870 acres/year; and Region 1—13 984 acres/year. With less wildfire, from all causes, Regions 1 and 3 have less need to increase prescribed fire.

Optimal Change in Wildfire Interventions (Both)

Previously we explored the optimal change in one prevention strategy while holding the other fixed. Those solutions are useful when one strategy can be varied (i.e., additional funding) while the other faces the status quo. The optimal solution will result when both strategies (prescribed fire and WPE) can adjust. As we show below, it does not always lead to an expansion of both strategies. Given the functional form of ignition processes and the feedbacks that wildfires have on aggregate fuels levels, the optimal levels of both sets of inputs (WPE and prescribed fire) are determined jointly.

The optimal change in WPE and prescribed fire, assuming equal allocation of initial WPE spending and price responsive prescribed fire service, is a 168 % increase in WPE and 74 % increase in prescribed fire, statewide (Figure 5.) Region 1 faces the most extreme changes: a 304 % increase in WPE and a 29 % decrease in prescribed fire. Region 3 faces a similar pattern: a 251 % increase in WPE and a 22 % increase in prescribed fire. Regions 2 and 4 fall in between. Both require roughly a doubling of WPE and prescribed fire effort.

The optimal overall statewide change in WPE and prescribed fire, assuming proportional allocation of initial WPE spending and price responsive prescribed fire service, is identical to the solution for an equal allocation (Figure 6). The relative increases are similar to that with the equal allocation assumption. In fact, the initial allocation assumption does not affect the optimal level of prescribed fire. When the proportionality assumption is maintained, WPE expenditures are expanded over the case with an equal allocation assumption for Regions 1, 2 and 4. These expansions come at the expense of Region 2 where the optimal increase is reduced from 162 % to 136 %.

Tradeoff Analysis

Comparing the joint optimization strategy to the single strategy (holding the other input fixed) shows that the optimal increases in statewide WPE and prescribed fire are less than that required when one of the inputs is held fixed. In the joint optimization, the optimal increase in WPE is 168 % and 74 % for prescribed fire. Compare this to the case when prescribed fire is held fixed, the optimal increase in WPE is 225 %, or when WPE is held fixed, the optimal increase in prescribed fire is 79 %. In all regions, except Region 2, joint optimization results in a smaller relative increase in WPE and prescribed fire. Joint optimization results in a larger relative increase in WPE for Region 2, however. (Region 2 experienced the most unintentional wildfires in terms of ignitions and acres burned; see Table 1).

In the joint optimization, there is a tradeoff between WPE and prescribed fire. While WPE is effective, it targets only targeted unintentional ignitions; whereas prescribed fire targets all wildfire types, regardless of the ignition source. This indiscriminate targeting mitigates the loss of the "fuel treatment effect" of wildfire caused by ignition prevention because prescribed fire still impacts the burn area of those wildfires that do occur. The optimal level of pre-fire mitigation occurs through joint optimization of WPE and prescribed fire, requiring an increase of WPE by 168 % and 74 % for prescribed fire. Joint optimization is preferred to single optimization as it produces an expected cost plus loss lower than any produced through single estimation (Table 5). Based on a statewide allocation strategy (i.e., increasing WPE and prescribed fire equally across regions), the expected cost plus loss is $301 million, a savings of $24 million (Table 5; Figure 7). Based on a regional allocation strategy (i.e., varying the increase of WPE and prescribed fire across regions), the expected cost plus loss is further reduced to $287 million, a savings of $38 million (Table 5). These savings are net saving and already account for (offset) increased program costs.

VIII. Conclusion

We examined the effect of WPE and prescribed fire, two alternative pre-fire intervention strategies, on targeted unintentional ignitions in Florida from 2002 to 2007. These targeted unintentional ignitions included those occurring from escaped debris fires, escaped campfire, fires caused by discarded cigarettes, and by children. During the study period, targeted unintentional ignitions accounted for 37 % of all wildfire ignitions, but only 7 % of acres burned. Leveraging the measured effect of WPE and prescribed fire on targeted unintentional ignitions and on the observed sizes of wildfires based on previous studies, we simulated changes in the intervention levels to identify their optimal levels and the corresponding expected cost plus loss due to wildfire damage. Expected cost plus loss was minimized with an increase in WPE of 168 % and prescribed fire acres treated of 74 %.

While these levels may be optimal, they may not be feasible. In fact, the State may not have the ability to dramatically alter the scale of prescribed fire programs, unlike WPE, in Florida due to land ownership limitations. Only a portion of at-risk forests are under State (or other governmental) control, and these would where prescribed fire could most easily expanded by government policy.[4] Constraints on prescribed fire, related to weather or smoke, may also limit its expansion to levels less than 74 %. Relatedly, prescribed fires usually occur early in the calendar year, and while our results suggest benefits last for several years, they also require a year to take effect (at least statistically). At-risk areas must be identified well ahead of the threat. The effect of WPE that we found in our modeling is shorter lived than prescribed fire, as we only found a six-month maximum effect; however, there is evidence that WPE could be used successfully to respond to outbreaks of targeted unintentional ignitions. Media PSAs, presentations, brochures and fliers, and WUI community hazard assessments were found to reduce the number of targeted unintentional ignitions in the same month that they were performed. A 10 % increase in WPE was shown to have a 1.2 % to 2.3 % decrease in targeted

[4] A program focusing on private lands would require a prescribed fire incentive program, which we did not evaluate in this study.

unintentional ignitions of the same month. Longer-term (up to six months) effects were shown to occur for media PSAs, presentations, and brochures and fliers. In addition to the 1.4 % to 2.3 % real-time decrease in targeted unintentional ignitions from a 10 % increase in these education strategies, another 2.2 % to 2.6 % decrease in targeted unintentional ignitions would be expected over the next six months. A 10 % increase in media PSAs, for example, is expected to have 4.9 % reduction in targeted unintentional ignitions over a seven month period. This marginal effect is on the order of magnitude of prescribed fire. Prescribed fire offers a longer-term solution at the expense of short-term flexibility. On the other hand, wildfire prevention education programs offer the flexibility, both in time and space, to respond to outbreaks. When used together in a coordinated effort, the program costs and wildfire damages from targeted unintentionally set fires are minimized.

Refinements of our analyses could be pursued. We chose a simple analysis that asked how much greater or lesser effort should be expended to minimize the sum of costs and expected losses from wildfire in Florida. But a time-varying optimization analysis could also have been explored: how much should WPE or prescribed fire efforts been changed over each of the units of time of our analysis to achieve a minimum of costs plus losses? Further, we chose to change all WPE activities simultaneously, assuming that absolute levels of each may vary only together, not independently. However, given that each WPE type has a different observed effect on targeted unintentional ignitions, it makes sense that the fire manager would prefer to allocate efforts across types to achieve optimal fire management outcomes. Finally, our analysis was backward-looking. A forward-looking analysis might simulate future quantities of free inputs and identify optimal stationary quantities of WPE and prescribed fire that would achieve minimum long-run discounted costs plus losses, along the lines of Mercer et al. (2007). Given that absolute amounts of free inputs vary across space in Florida, that analysis would identify differential amounts and paths of future expected fire across fire regions in the state.

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Tables and Figures

Table 1. Monthly number of targeted unintentionally-ignited wildfires and acres burned, and prescribed fire (for hazard reduction) permits issued and acres treated in Florida from 2002 to 2007, by regions.

	Average	Minimum	Maximum	Observations
Region 1				
Targeted Unintentional Wildfire Ignitions	27	1	128	58
Targeted Unintentional Wildfire Acres	255	0.1	2490	58
Prescribed Fire Permits	149	2	836	58
Prescribed Fire Acres	23,016	3	127,878	58
Region 2				
Targeted Unintentional Wildfire Ignitions	37	2	139	57
Targeted Unintentional Wildfire Acres	828	0.4	35,639	57
Prescribed Fire Permits	85	1	420	57
Prescribed Fire Acres	6487	3	32,508	57
Region 3				
Targeted Unintentional Wildfire Ignitions	20	1	78	60
Targeted Unintentional Wildfire Acres	260	0.1	3989	60
Prescribed Fire Permits	41	0	160	60
Prescribed Fire Acres	9050	0	35,578	60
Region 4				
Targeted Unintentional Wildfire Ignitions	26	0	97	57
Targeted Unintentional Wildfire Acres	337	0	3156	57
Prescribed Fire Permits	28	0	98	57
Prescribed Fire Acres	9134	0	37,660	57

Table 2. Monthly wildfire prevention education activities recorded by wildfire mitigation specialists in Florida 2002 to 2007, by regions.

	Average	Minimum	Maximum	Observations
Region 1				
Radio PSAs	44	2	143	58
TV PSAs	5	0	48	58
Newspaper PSAs	5	0	39	58
Homes visited	96	0	1923	58
Presentations offered	0.3	0	1	58
Fliers, brochures, or CDs	162	0	1935	58
WUI hazard assessments	0.2	0	1	58
Region 2				
Radio PSAs	38	0	704	57
TV PSAs	59	0	911	57
Newspaper PSAs	75	0	1181	57
Homes visited	9	0	210	57
Presentations offered	2	0	23	57
Fliers, brochures, or CDs	904	0	3400	57
WUI hazard assessments	0.8	0	13	57
Region 3				
Radio PSAs	7	0	42	60
TV PSAs	23	0	147	60
Newspaper PSAs	14	0	83	60
Homes visited	4	0	115	60
Presentations offered	6	0	37	60
Fliers, brochures, or CDs	275	0	1897	60
WUI hazard assessments	0.6	0	6	60
Region 4				
Radio PSAs	41	0	283	57
TV PSAs	131	10	1630	57
Newspaper PSAs	99	0	2031	57
Homes visited	16	0	500	57
Presentations offered	6	0	109	57
Fliers, brochures, or CDs	1737	0	24500	57
WUI hazard assessments	1	0	9	57

Table 3. Control function equation estimates for five prevention education variables.

	MEDIA		HOMES		PRESENT	BROCHURES		HAZARD
	Coeff.		*Coeff.*		*Coeff.*	*Coeff.*		*Coeff.*
Ignitions: 2 year lag	1.32E-07		1.61E-07	*	-9.21E-10	-8.83E-08		-8.97E-11
Ignitions: 3 year lag	1.17E-07		7.37E-08		-2.96E-10	-3.44E-08		-4.72E-10
Ignitions: 4 year lag	1.66E-07	**	9.74E-09		1.17E-09	-2.68E-07		-6.44E-10
Ignitions: 5 year lag	1.11E-07	*	-6.41E-08		9.17E-10	-3.10E-07		-4.26E-10
MFWI: 12 month lag	-5.44E-06		-2.73E-06		-1.31E-07	-1.24E-05		-4.98E-08
FWI: 12 month lag	8.84E-07		6.62E-07		1.22E-07	-2.14E-05		3.61E-08
RH: 12 month lag	1.66E-06		-3.26E-06	*	-5.38E-09	-5.32E-06		-1.40E-08
KBDI: 12 month lag	1.03E-07		1.05E-07		8.37E-10	2.32E-07		1.81E-10
Sales Tax: 1 year lag	2.88E-14		-5.09E-15		5.64E-16	-6.91E-14		-3.56E-16
FWI :current?	-2.24E-05	*	2.03E-05		3.34E-07	2.42E-05		1.35E-07
RH	2.07E-06		8.47E-07		5.11E-08	3.23E-06		8.66E-09
KBDI	-1.57E-07		2.81E-07	**	2.36E-09	7.18E-07		1.04E-09
MFWI	3.11E-05	**	-1.51E-05		-2.99E-07	-4.54E-06		-1.52E-07
Niño 3: March-September	1.82E-06		-1.39E-05		1.69E-07	-3.52E-05		-1.30E-08
Niño 3: October-February	-7.80E-06		-5.20E-06		2.05E-07	4.43E-05		3.02E-08
Precipitation	-1.64E-06		-2.05E-07		-6.06E-08	-7.84E-06		-1.00E-08
Rx Fire: 1 year lag	6.37E-11		3.65E-10		-9.02E-12	2.00E-09		-2.94E-12
Rx Fire: 2 year lag	-1.34E-10		8.17E-10	***	-3.50E-12	2.18E-10		-2.72E-12
Rx Fire: 3 year lag	1.57E-10		-1.50E-10		-4.47E-12	-1.56E-09		-1.10E-12
Fire: 1 year lag	1.04E-10		-1.07E-10		2.92E-12	8.76E-11		9.05E-13
Fire: 2 year lag	-7.23E-10	*	-1.01E-09	**	6.83E-12	-2.86E-09	*	-1.44E-12
Fire: 3 year lag	-4.43E-10	*	-3.52E-10		3.73E-12	-2.95E-11		3.90E-13
Fire: 4 year lag	-3.24E-10	*	-1.39E-10		1.22E-12	1.51E-09	*	-6.89E-14
Fire: 5 year lag	-3.25E-10		-4.37E-10	*	3.12E-12	-1.20E-10		-1.49E-13
Fire: 6 year lag	-2.20E-10		-3.69E-10	**	2.03E-12	-2.87E-10		4.25E-14
Region 2	5.50E-03	**	-1.52E-03		-1.34E-05	1.69E-03		6.15E-06
Region 3	7.70E-03	***	3.13E-04		-1.31E-05	2.98E-03		1.09E-05
Region 4	8.45E-03	***	1.26E-03		-1.53E-05	3.97E-03		1.29E-05
Spring	5.57E-05	**	-3.24E-05		6.99E-07	7.77E-05		1.02E-07
Summer	2.40E-05		4.60E-05		4.73E-07	5.40E-05		2.11E-07
Winter	-2.10E-06		-1.04E-05		4.00E-07	1.19E-04		-1.61E-07

Population	-5.69E-10	**	-3.90E-10		-5.92E-13	-3.42E-10		-9.10E-13	
Police per capita	1.75E+00	**	-6.56E-01		-3.84E-03	7.56E-02		1.59E-03	
2003	-3.19E-06		3.08E-05		-9.35E-07	-4.11E-06		-1.53E-07	
2004	3.65E-05		5.48E-05		-1.49E-06	3.19E-04		-5.47E-08	
2005	3.99E-05		7.80E-05		-1.72E-06	1.01E-03	***	-3.13E-07	
2006	6.75E-05		8.69E-05		-6.14E-07	1.02E-03	**	-1.55E-07	
2007	7.56E-05		1.70E-04		-3.12E-07	1.30E-03	**	3.72E-07	
Trend	1.25E-05	**	-1.79E-06		7.08E-08	-3.39E-05		6.58E-09	
Media: 1-6 months prior	-2.55E-01	***	-8.91E-03		-6.60E-04	5.13E-01	**	-7.61E-04	*
Homes: 1-6 months prior	-2.06E-01		4.52E-01	***	6.18E-04	1.09E+00	*	4.75E-04	
Presentations: 1-6 months prior	-4.15E+00	*	-3.61E+00		-4.21E-02	2.59E+00		-5.77E-04	
Brochures: 1-6 months prior	-1.74E-03		2.02E-03		3.42E-05	-1.39E-01	***	-9.76E-05	*
Hazard: 1-6 months prior	4.13E+01	***	-1.05E+01		-4.44E-02	2.55E+01		-5.42E-02	
Intercept	-8.76E-03	**	3.43E-03		1.62E-05	6.19E-04		-3.35E-06	
Prob > F	0.0000		0.0000		0.0671	0.0000		0.0000	
R^2	0.5155		0.3742		0.2471	0.4367		0.3973	

***, **, * Denotes significances at the 0.01, 0.05, 0.10 levels, respectively.

Table 4. Poisson model estimate of the count of targeted unintentional wildfires, 2002 to 2007, and associated elasticities, calculated at the mean of the data.

	Coeff.	Std. Error	z	P>|z|	Elasticity
FWI	1.46E-01	6.11E-02	2.39	0.017	1.06
RH	-3.32E-02	8.72E-03	-3.8	0	-1.70
KBDI	1.66E-03	5.72E-04	2.9	0.004	0.41
MFWI	-5.25E-02	5.96E-02	-0.88	0.379	-0.32
Nino 3: March	2.98E-02	0.058193	0.51	0.609	-0.01
Nino 3: October	4.41E-02	0.0548857	0.8	0.422	0.02
Precipitation	-1.21E-01	1.33E-02	-9.13	0	-0.55
Rx Fire: 1 year lag	-1.41E-06	1.40E-06	-1.01	0.311	-0.18
Rx Fire: 2 year lag	-2.44E-06	1.44E-06	-1.7	0.089	-0.26
Rx Fire: 3 year lag	-3.66E-06	9.96E-07	-3.67	0	-0.34
Fire: 1 year lag	2.57E-06	7.79E-07	3.3	0.001	0.12
Fire: 2 year lag	-7.03E-06	1.36E-06	-5.15	0	-0.35
Fire: 3 year lag	-2.17E-06	8.37E-07	-2.59	0.01	-0.14
Fire: 4 year lag	1.42E-07	8.99E-07	0.16	0.875	0.01
Fire: 5 year lag	-1.88E-06	6.72E-07	-2.8	0.005	-0.21
Fire: 6 year lag	-1.60E-06	4.34E-07	-3.69	0	-0.18
Region 2	2.85E+01	1.03E+01	2.77	0.006	7.01
Region 3	4.62E+01	1.42E+01	3.25	0.001	11.94
Region 4	5.34E+01	1.58E+01	3.37	0.001	13.11
Spring	9.24E-01	1.37E-01	6.76	0	0.24
Summer	6.59E-01	1.18E-01	5.6	0	0.15
Winter	5.09E-01	1.10E-01	4.61	0	0.13
Population	-4.53E-06	1.20E-06	-3.78	0	-19.95
Police per capita	8.12E+03	3.21E+03	2.53	0.011	22.17
2003	6.71E-01	1.56E-01	4.29	0	0.14
2004	2.18E+00	1.94E-01	11.25	0	0.45
2005	3.31E+00	3.37E-01	9.81	0	0.68
2006	4.81E+00	3.73E-01	12.87	0	0.99
2007	6.26E+00	4.53E-01	13.84	0	0.65
Trend	-4.28E-02	1.88E-02	-2.28	0.023	-1.26
Media: 1-6 months prior	-1.34E+03	5.87E+02	-2.29	0.022	-0.26

Homes: 1-6 months prior	4.50E+02	7.02E+02	0.64	0.521	0.04
Presentations: 1-6 months prior	-4.89E+04	8.69E+03	-5.63	0	-0.22
Brochures: 1-6 months prior	-2.15E+02	4.66E+01	-4.62	0	-0.24
Hazard: 1-6 months prior	6.54E+04	5.03E+04	1.3	0.194	0.07
Control variable: Media	3.59E+03	1.35E+03	2.66	0.008	0.00
Control variable: Homes	1.43E+03	8.45E+02	1.7	0.09	0.00
Control variable: Presentations	3.14E+05	1.06E+05	2.96	0.003	0.00
Control variable: Brochures	5.26E+02	3.08E+02	1.71	0.087	0.00
Control variable: Hazard	6.64E+05	3.02E+05	2.2	0.028	0.00
Media: current month	-4.12E+03	1.34E+03	-3.08	0.002	-0.17
Homes: current month	-1.29E+03	8.41E+02	-1.53	0.125	-0.03
Presentations: current month	-2.97E+05	1.06E+05	-2.82	0.005	-0.23
Brochures: current month	-6.62E+02	3.03E+02	-2.18	0.029	-0.14
Hazard: current month	-6.35E+05	3.00E+05	-2.11	0.035	-0.12
Intercept	-2.97E+01	1.46E+01	-2.03	0.042	
Log Likelihood	-890.5587				
Prob > chi^2	0.0000				
Psuedo-R^2	0.7193				

Table 5. Cost plus loss totals under alternative assumptions and state variables.

	Regional Allocations Cost + Loss ($ Million)	Statewide Allocations Cost + Loss ($ Million)
Current (Base Case)	325	325
Change Prevention Spending Alone, Proportional Allocation	318	318
Change RxFire Amount Alone, Proportional Allocation, Price Responsive RxFire	292	306
Change Prevention Spending Alone, Equal Allocation	318	318
Change RxFire Amount Alone, Equal Allocation, Price Responsive RxFire	292	306
Change Prevention Spending with Rx Fire, Proportional Allocation, Price Responsive RxFire	287	301
Change Prevention Spending with Rx Fire, Equal Allocation, Price Responsive RxFire	287	301
Change Prevention Spending Alone, Equal Allocation, No Budget Change	323	
Change Prevention Spending Alone, Proportional Allocation, No Budget Change	324	

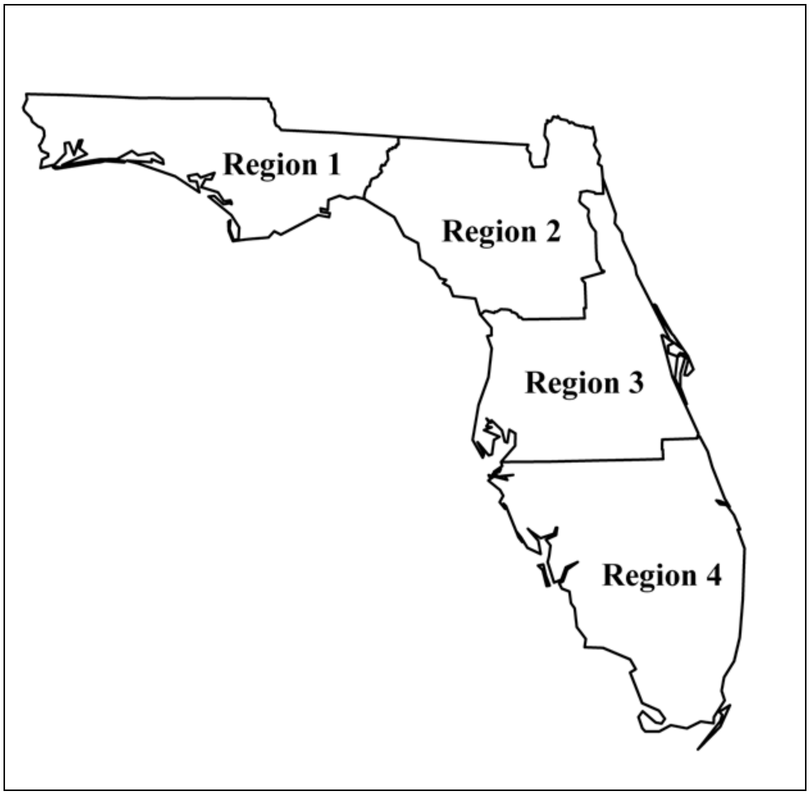

Figure 1. Fire management regions in Florida.

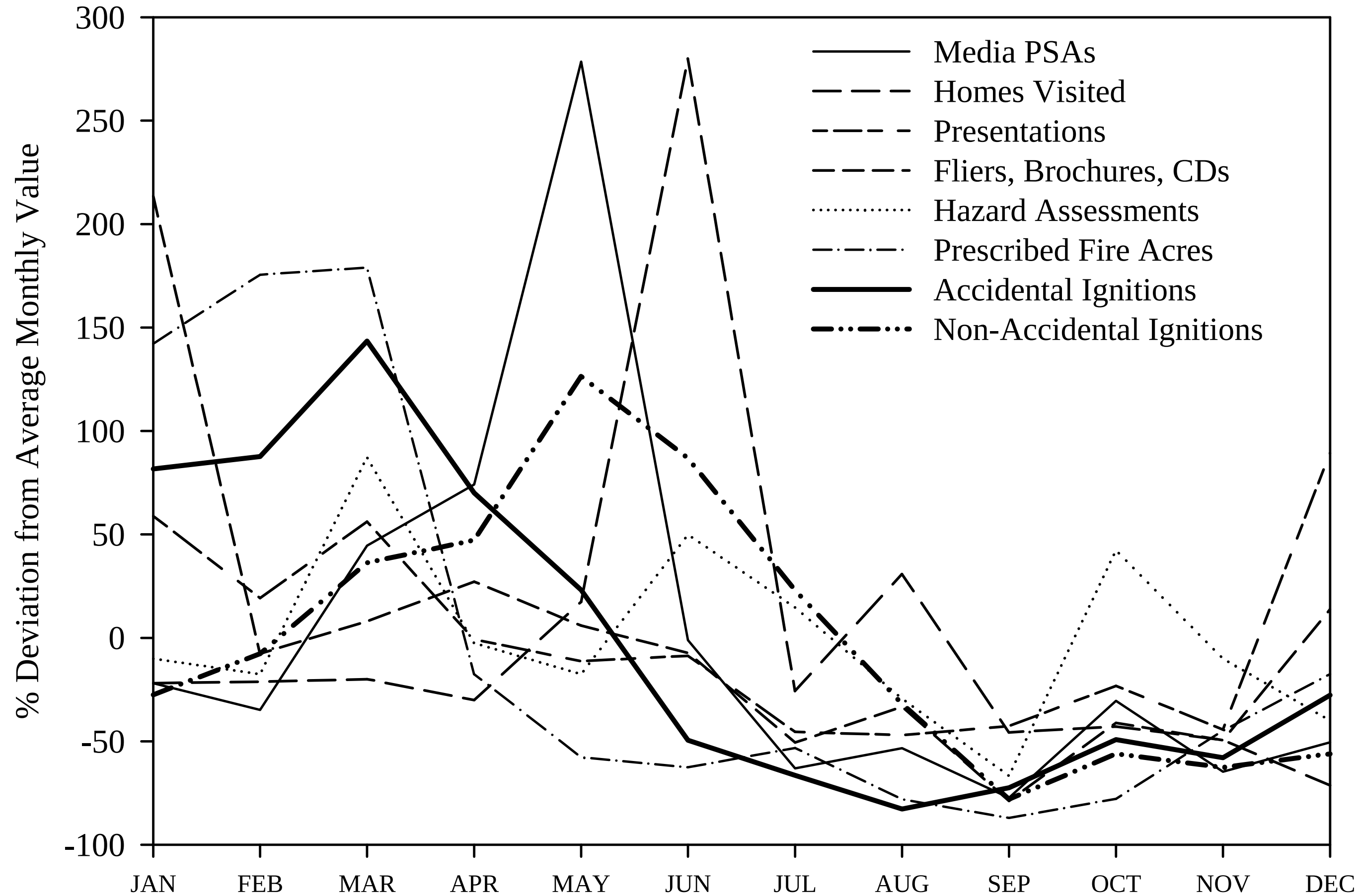

Figure 2. Trends of percent deviation from average monthly count of media pubic service announcements (PSAs); homes visited; presentations offered; fliers, brochures, and CDs distributed; WUI hazard assessments given, prescribed fire fuel treatments (for hazard reduction); and targeted unintentional ignitions.

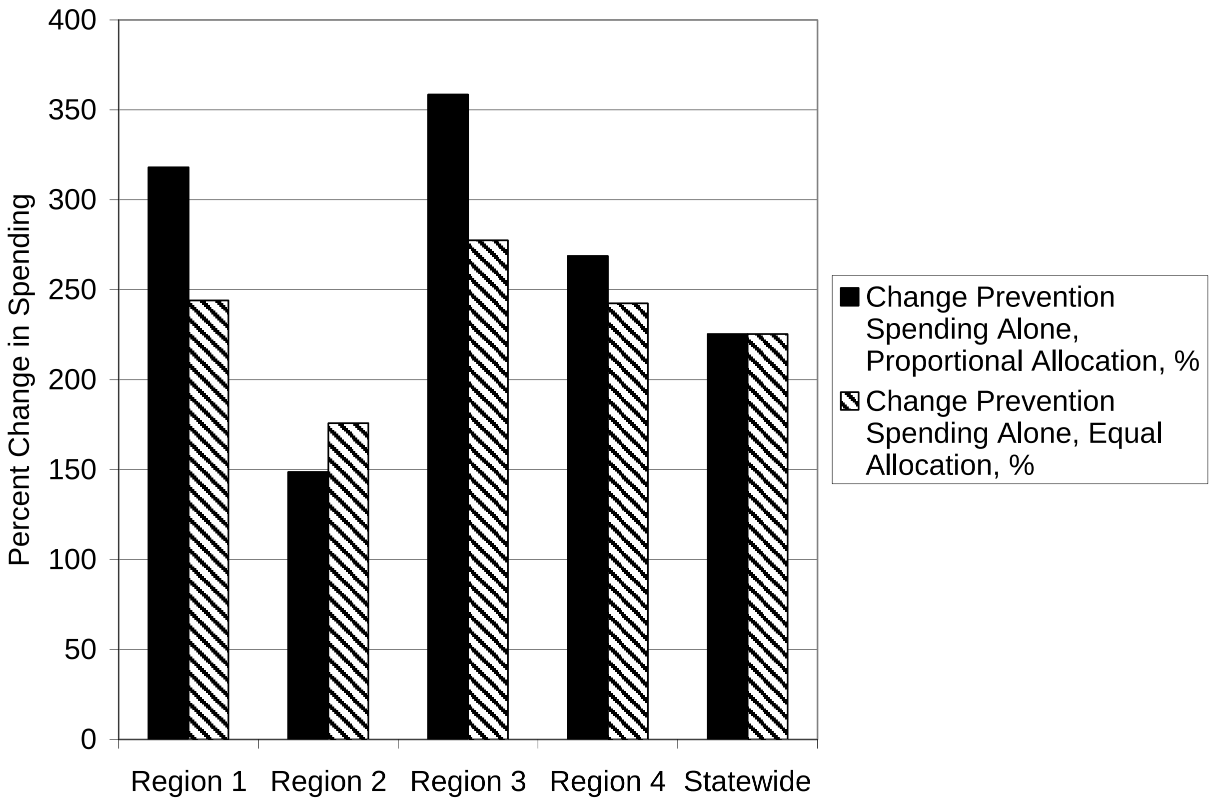

Figure 3. Optimal change in spending: wildfire prevention education only.

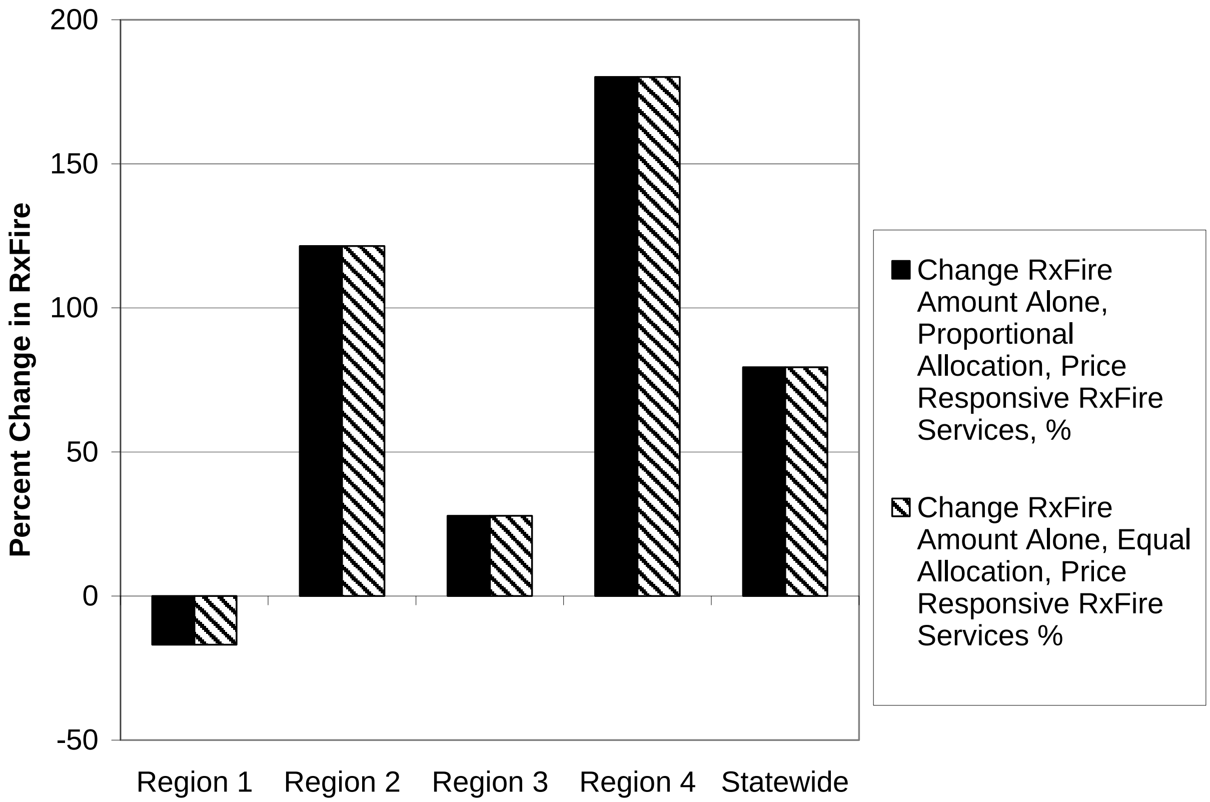

Figure 4. Optimal change in area treated: prescribed fire fuel treatments only.

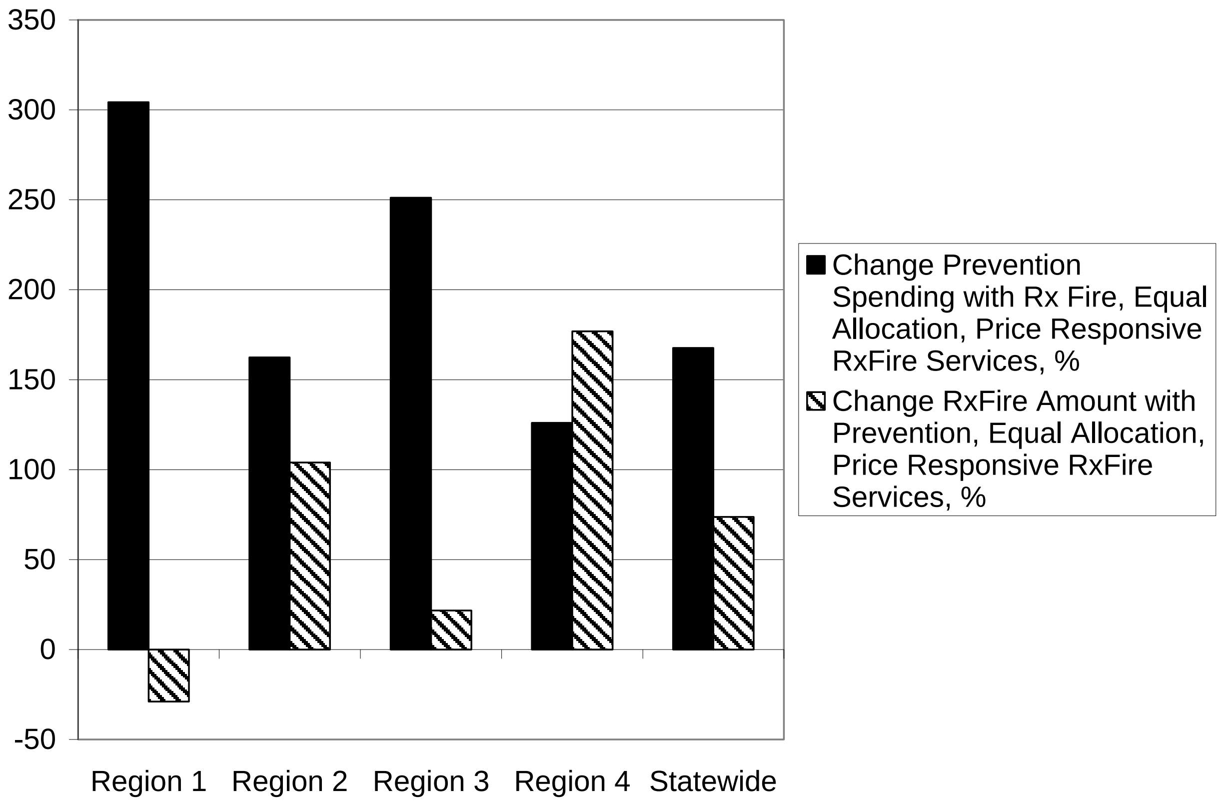

Figure 5. Optimal change in wildfire mitigation effort: wildfire prevention education (assuming equal allocation across regions) and prescribed fire fuel treatments.

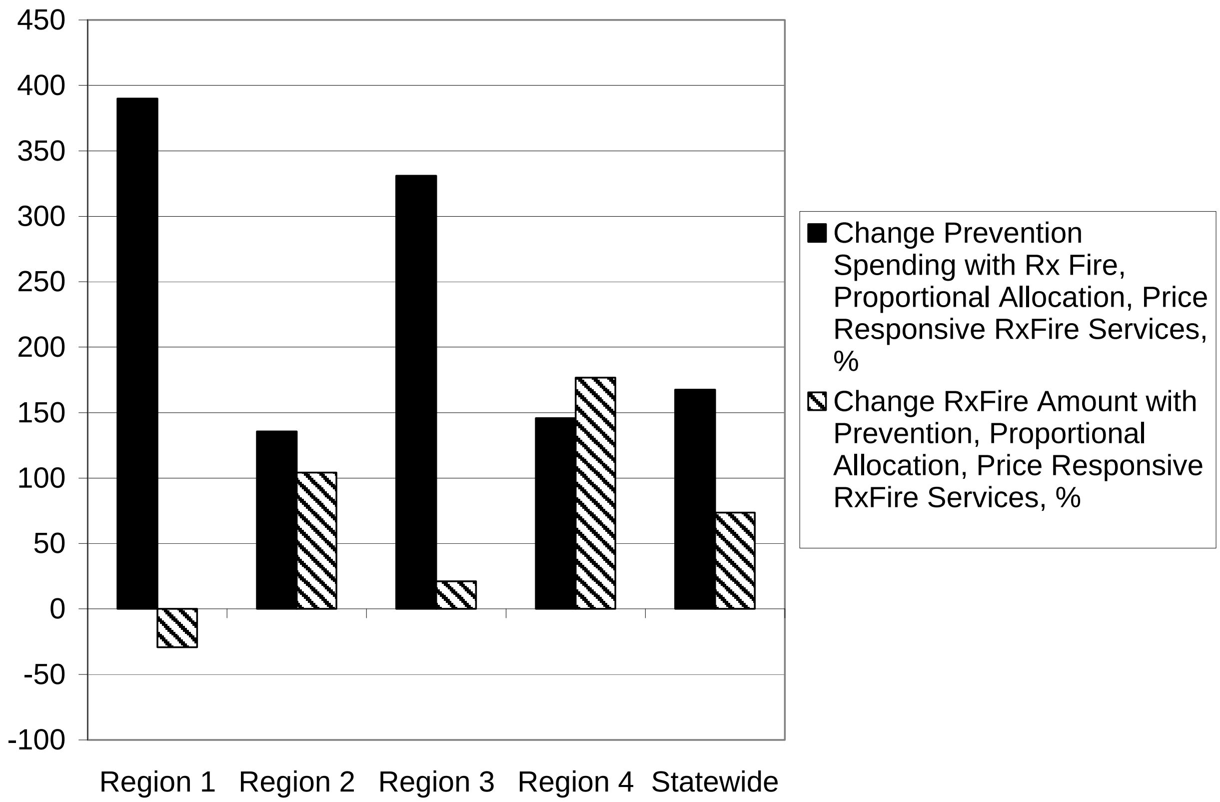

Figure 6. Optimal change in wildfire mitigation effort: wildfire prevention education (assuming proportional allocation across regions) and prescribed fire fuel treatments.

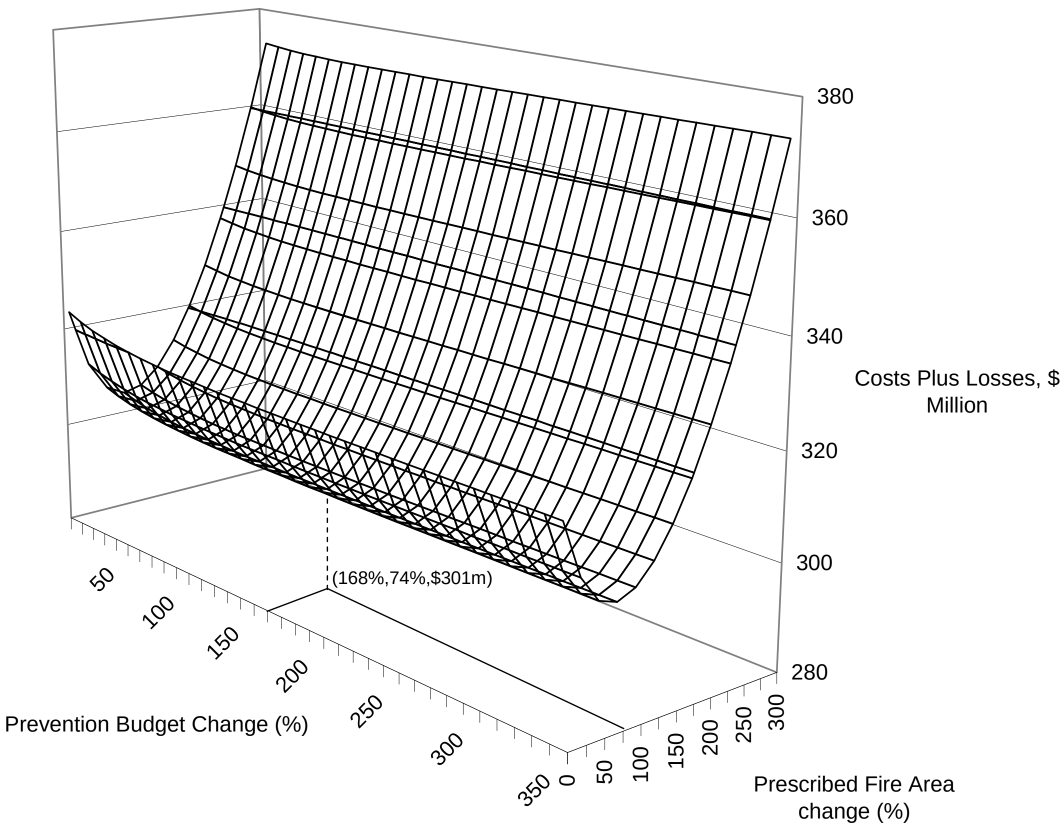

Figure 7. Fire mitigation tradeoff: wildfire prevention education versus prescribed fire fuel treatments.