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Economic optimisation 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 minimise 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 although 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), whereas 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 minimised.

Additional keywords: fire economics, hazard mitigation, wildland–urban interface, wildland fire.

Introduction

Wildfires are produced on a landscape from a combination of purchased and free inputs. Free (i.e. non-market) inputs to wildfire include natural fuels (vegetation), weather conditions, and lightning ignitions and those caused by humans. 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, minimising 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 minimising the sum of long-run management costs and expected societal losses. We describe a long-run model that accounts for: (1) the dynamics of wildfire, which provides fuel reduction as a free input in subsequent fire seasons; (2) the short- and long-run effects of fuels management on fire extent and occurrence; and (3) the short- and long-run effects of wildfire prevention education on the occurrence and extent of targeted unintentional wildfires (i.e. human-caused, unintentional ignitions targeted by prevention education activities).

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 the trade-off between wildfire prevention and prescribed fire in the pursuit of an optimal policy. Prescribed fire operates over whole landscapes and therefore affects the losses associated with all fire types, whereas fire prevention only operates directly on a subset of potential fire starts. Previous research has focussed on individually optimising either fuels management activities (e.g. Yoder

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2004; Mercer *et al.* 2007; Wei *et al.* 2008; Kim *et al.* 2009) or suppression resources (MacLellan and Martell 1996; Donovan and Rideout 2003; Donovan 2006; Haight and Fried 2007), so as to minimise the expected losses of wildfire. Joint optimisations have been explored, but these have focussed on optimising between a preoperational and an operational phase (Minciardi *et al.* 2009), such as optimising effort between fuels management (preoperational phase) and suppression (operational phase) (e.g. Drucker *et al.* 2008; Mercer *et al.* 2008). We, instead, optimise over two preoperational wildfire management strategies while holding suppression effort constant. Third, we show that the quantities of free inputs (that is, inputs provided by nature or society that are not intended to manage wildfire) 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 organisation of the rest of the manuscript is as follows: the second section presents our theoretical model of wildfire management economics; the third section describes the study site and the two wildfire management variables of interest (wildfire prevention education and prescribed fire treatments); the fourth section introduces the empirical model of wildfire ignition risk and the fifth section describes the optimisation methodology; the sixth and seventh sections present the empirical and optimisation results; and the eighth section provides the conclusion.

Theoretical model

The expected cost-plus-loss of wildfire is the sum of expected ignitions multiplied by the expected fire size and the loss value per hectare, and the sum of all the intervention costs. Let $I_{i,t}^p$ be the count of ignitions of targeted unintentional fire types 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 non-targeted unintentional, intentional, and 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 directly influence fire size,[A] and can be represented by:

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

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

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

The fire management problem is:

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

where M is the expected cost-plus-loss of wildfire, $S_{i,t}^p$ and $S_{i,t}^n$ are the loss per hectare of targeted unintentional and non-targeted wildfire, E is the expectations operator, and r is the discount rate. As written, fire prevention efforts directly affect only $I_{i,t}^p$ whereas the other inputs to the fire production process (prescribed fire and free inputs) 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 (minimising cost-plus-loss) at M^*. At the optimum, the partial derivative of M^* with respect to $x_{i,t}^{p*}$ should equal the unit price of those efforts, or $\partial M^*/\partial x_{i,t}^{p*} = w^p$; similarly, $\partial M^*/\partial x_{i,t}^{R*} = w^R$. 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.

Wildfire interventions

Wildfire prevention education (WPE), defined here as the avoidance of targeted unintentional human-caused wildfires through education,[B] includes activities such as radio, television and newspaper public service announcements (PSAs); home visitations (Visits); presentations (Presentations); flyers and brochures distributed (Brochures); and community wildland hazard assessments (a systematic, community-wide wildfire risk analysis) (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 minimise the impact of future wildfire.

We explored the effect of these two interventions across the four wildfire management regions in Florida (see Fig. 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

[A] Prevention success may affect fuels, and thereby, indirectly affect wildfire size. We address this negative feedback below.

[B] 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).

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, in its 18 counties includes Lake Okeechobee, the Everglades, the city of Miami and the Keys.

Over the study period (2002 to 2007), Florida experienced 6338 targeted unintentional ignitions accounting for 39 186 ha burned. The number of targeted unintentional wildfire ignitions varied between 20 per month in Region 3 to 37 per month in Region 2 (see Table 1). The number of hectares burned varied between 103 ha month^{-1} in Region 1 to 335 ha month^{-1} in Region 2. Region 2 experienced more than twice the amount of burned hectares than the next fire-prone region (Region 4). Although targeted unintentional ignitions made up 37% of all wildfire ignitions reported over this period, targeted unintentional wildfires remained small. They comprised only 7% of the total burned hectares. In the past (i.e. before the study period), targeted unintentional wildfires have accounted for larger areas burned (natural fires may burn larger areas owing 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).

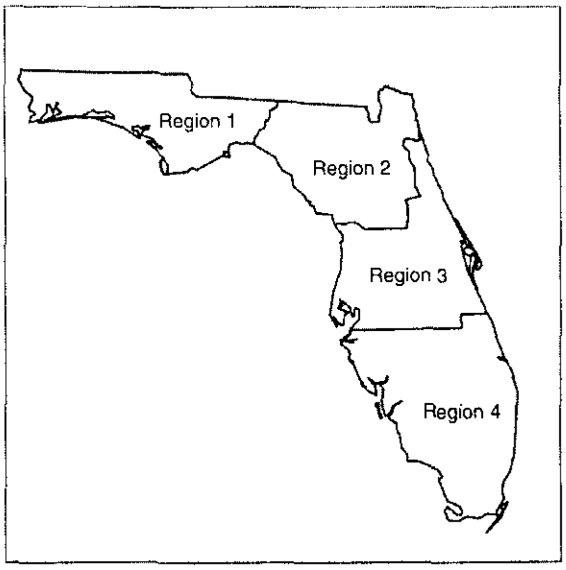

Fig. 1. Fire management regions in Florida.

Over the study period, more than 0.6 million hectares burned from wildfire. Another 1.5 million hectares were authorised for burning by silvicultural-based prescribed fire treatments targeting hazardous fuels. The number of prescribed fire permits issued varied from as low as 28 per month in Region 4 to as high as 149 per month in Region 1, on average (see Table 1). Region 1 also averaged the most requested number hectares for treatment, at 9314 ha month^{-1}, compared with Region 2 with 2625 ha month^{-1}. On average, monthly prescribed fire fuel treatments involve 8 to 90 times more hectares than do wildfires.

The intensity and mix of WPE activities varied by wildfire management region (see Table 2). Distributing Brochures was the most common activity across regions (176 452 were distributed in all). 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 Visits, 890 Presentations, and 156 Assessments.

Timing is important when developing mitigation strategies. Fig. 2 presents the average seasonality of targeted unintentional and non-targeted wildfire ignitions (e.g. arson and lightning), authorised prescribed fire hectares and WPE activities over the

Table 1. Monthly number of targeted unintentionally ignited wildfires and hectares burned, and prescribed fire (for hazard reduction) permits issued and hectares 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 hectares	103	0	1008	58
Prescribed fire permits	149	2	836	58
Prescribed fire hectares	9314	1.2	51 750	58
Region 2				
Targeted unintentional wildfire ignitions	37	2	139	57
Targeted unintentional wildfire hectares	335	0.2	14 423	57
Prescribed fire permits	85	1	420	57
Prescribed fire hectares	2625	1.2	13 156	57
Region 3				
Targeted unintentional wildfire ignitions	20	1	78	60
Targeted unintentional wildfire hectares	105	0	1614	60
Prescribed fire permits	41	0	160	60
Prescribed fire hectares	3662	0	14 398	60
Region 4				
Targeted unintentional wildfire ignitions	26	0	97	57
Targeted unintentional wildfire hectares	136	0	1277	57
Prescribed fire permits	28	0	98	57
Prescribed fire hectares	3696	0	15 240	57

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

	Monthly			
	Average	Minimum	Maximum	Observations
Region 1				
Radio PSAs	44	2	143	58
TV PSAs	5	0	48	58
Newspaper PSAs	5	0	39	58
Visits	96	0	1923	58
Presentations	0.3	0	1	58
Brochures	162	0	1935	58
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
Visits	9	0	210	57
Presentations	2	0	23	57
Brochures	904	0	3400	57
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
Visits	4	0	115	60
Presentations	6	0	37	60
Brochures	275	0	1897	60
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
Visits	16	0	500	57
Presentations	6	0	109	57
Brochures	1737	0	24 500	57
Assessments	1	0	9	57

2002 to 2007 study period. Shown is the monthly count of each data series compared with its 12-month average value. Targeted unintentional wildfire ignitions peaked in the late winter and early spring (i.e. the dry season), as did authorised prescribed fire treatments, Brochures (including flyers and CDs) distributed, and Presentations. Media PSAs and Homes Visits peaked prominently in late spring and early summer. Assessments did not show any strong seasonal trend. Interestingly, Media PSAs and Homes Visits peaked after the peak of targeted unintentional ignitions. Non-targeted 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 authorisations 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 there is likely to be some simultaneous determination occurring. Our statistical model, presented in the next section, untangles 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).

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:

$$I^{p}_{i,t} = e^{\alpha' \mathbf{z}_{i,t} + \beta' \mathbf{x}_{i,t-k} + \varepsilon_{i,t}} \tag{2}$$

where $I^{p}_{i,t}$ is the number of targeted unintentional wildfires for location i in time t, $\mathbf{z}$ are the free inputs to wildfire production, $\mathbf{x}$ are the M interventions occurring over the current and k previous months, α and β are the parameters associated with the inputs and

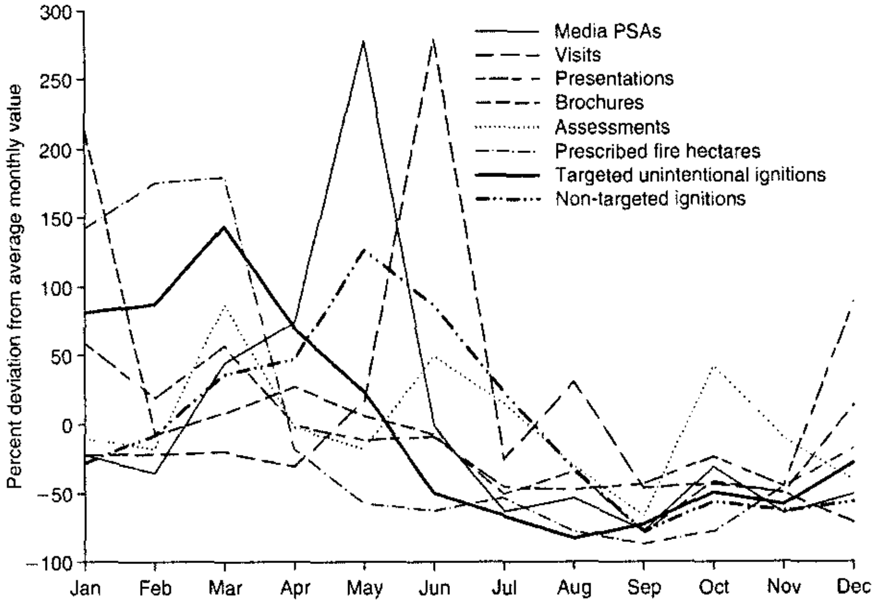

Fig. 2. Trends of percentage deviation from average monthly count of media public service announcements (PSAs); visits; presentations; brochures; assessments given, prescribed fire fuel treatments (for hazard reduction); targeted unintentional ignitions, and non-targeted ignitions.

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, $E[\varepsilon_{m,i,t}|x_{m,i,t}] \neq 0$. Thus, we augment Eqn 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 Eqn 2 (see Hausman 1978):

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

where $\mathbf{h}$ is a set of instruments and $\mathbf{c}$ 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:

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

Eqn 2 is augmented to become:

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

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

$$\begin{aligned}\ln L = \sum_{i=1}^{I} \sum_{t=1}^{T} & -e^{\alpha'\mathbf{z}_{i,t} + \beta'\mathbf{x}_{i,t-k} + \delta'\hat{c}_{i,t} + \xi_{i,t}} \\ & + (\alpha'\mathbf{z}_{i,t} + \beta'\mathbf{x}_{i,t-k} + \delta'\mathbf{c}_{i,t}) I^p_{i,t} - \ln(I^p_{i,t}!)\end{aligned} \tag{6}$$

The intervention variables, $\mathbf{x}_{i,t-k}$, 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 1, 2, and 3 years (e.g. Mercer *et al.* 2007). The WPE variables include the number of media public service announcements (TV, radio, and print ads) (PSAs), homes visited (Visits), presentations given (Presentations), brochures and flyers distributed (Brochures), and community wildfire hazard assessments (Assessments) provided in current month t and over the last 6 months (Florida Division of Forestry, fire prevention activities by wildfire mitigation specialist by month, paper and electronic records, 1999–2007, pers. comm., 23 April 2008). Although several other WPE measures (fairs, billboards, movie-theatre public service announcements) were undertaken by wildfire prevention specialists, the occurrence of such measures was too infrequent to allow for identification. All included WPE variables were normalised 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 authorised for hazard removal (as opposed to for ecological or wildlife reasons) by prescribed burning (Florida Division of Forestry, prescribed fire permits issued, electronic records, 1989–2007, pers. comm., 22 August 2008) lagged up to 3 years to account for treatment longevity (Outcalt and Wade 2004).

The vector of free inputs, $\mathbf{z}_{i,t}$, 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, precipitation) (Goodrick 2002, S. L. Goodrick, pers. comm., 3 July 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 hectares) by wildfire lagged up to 6 years (Florida Division of Forestry, wildfire activity, electronic records, 1980–2007, pers. comm., 13 June 2008), county population estimates (US Bureau of the Census 2008), the number of sworn full-time equivalent police officers per capita (Florida Department of Law Enforcement, sworn police officer data, 1989–2007, pers. comm., 14 February 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 to 5 years) and the 1-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 behaviour, except through their effect on WPE. For instance, prior wildfire behaviour could influence future WPE strategies, and sales tax revenues could influence future WPE by affecting WPE budgets. Descriptive statistics of the variables used in estimation of the empirical models are shown in Table 3.

Optimal mitigation

We assumed that a prevented fire reduced the number of targeted unintentional fires in the same location and the same month and year of the average size as the targeted unintentional fires that occurred in that month and location, and this is independent of intervention type (i.e. WPE or prescribed fire). Interventions affect wildfire hectares 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}):

$$\Delta A^* = \Delta A^{*n} + \Delta A^{*p} \tag{7}$$

This has been found to be equal to a proportion of the short-run change in area of targeted unintentional wildfire due to prevention change (A_t^p) (Mercer *et al.* 2007):

$$\Delta A^* = (1 - 0.633) \times \Delta A_t^p \tag{8}$$

Mercer *et al.* (2007) demonstrated that for each hectare prevented from wildfire, 0.633 additional wildfire hectares (of all wildfire types) occur in the future owing to a fuel accumulation effect. (Thus, only 36.7% of the total prevented wildfire hectares are eliminated in the long run, on average.) The short-run change in area of targeted unintentional wildfire due to a prevention change ($\Delta A_{i,t}^p$) is:

$$\Delta A_{i,t}^p = \frac{\partial I_{i,t}^p}{\partial X_{i,t}} \times \overline{A}_{i,t} \tag{9}$$

where $\partial I_{i,t}^p / \partial X_{i,t}$ is determined via estimation of Eqn 5 ($\partial I_{i,t}^p / \partial X_{i,t} = \beta$) and $A_{i,t}$ 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) minimise cost-plus-loss by altering WPE, holding prescribed fire constant; (2) minimise cost-plus-loss by altering prescribed fires, holding WPE constant; and (3) minimise cost-plus-loss by altering both WPE and prescribed fires. Losses from wildfire were set at US\$3131 ha^{-1} burned (per Mercer *et al.* 2007; adjusted to 2005 US dollars, US Department of Commerce 2008).[C]

Florida's annual wildfire prevention education budget over the estimation period was US\$0.47 million. The annual budget allocation across wildfire management regions is not known with precision; however, it is believed the allocation is roughly the same for each of the four regions (equal allocation) (R. Rhea, Florida Division of Forestry, pers. comm., 24 October 2008). We explored the sensitivity of this assumption by examining the change when the spending was allocated proportionally based on historical targeted unintentional wildfire hectares burned (proportional allocation). The allocation to regions under the equal and proportional allocations is shown in Table 4.

The annual cost of prescribed fire fuel treatments is ~US\$3.2 million per year and these costs are largely borne by both private landowners and government. We assume a unit price of US\$62 ha^{-1} (based on an approximation from Cleaves *et al.* 2000) for evaluating changes in WPE alone, but allow the unit price to vary with increases in demand for evaluating changes in prescribed fire and for evaluating changes in both interventions. Mercer *et al.* (2007) found that the 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.

Statistical results

The empirical control function models (Eqn 5) are significant and the covariates explain as much as 25 to 52% of the variation in the WPE variables (see Table 5). 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

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

Table 3. Descriptive statistics of variables used in the empirical models

PSAs, public service announcements; Rx Fire, prescribed fire

Variable	Mean	s.d.	Minimum	Maximum
Dependent				
Targeted unintentional ignitions	27.32	26.93	0.000	139.0
Intervention				
PSAs: current month	4.1×10^{-5}	1.0×10^{-4}	0.000	0.001
Visits: current month	2.0×10^{-5}	9.5×10^{-5}	0.000	0.001
Presentations: current month	7.8×10^{-7}	1.4×10^{-6}	0.000	1.3×10^{-5}
Brochures: current month	2.1×10^{-4}	4.0×10^{-4}	0.000	0.003
Assessments: current month	1.9×10^{-7}	5.5×10^{-7}	0.000	6.3×10^{-6}
PSAs: 1–6 months prior	1.9×10^{-4}	2.1×10^{-4}	3.3×10^{-6}	0.002
Visits: 1–6 months prior	8.1×10^{-5}	1.4×10^{-4}	0.000	5.3×10^{-4}
Presentations: 1–6 months prior	4.5×10^{-6}	4.4×10^{-6}	0.000	2.3×10^{-5}
Brochures: 1–6 months prior	0.001	0.001	8.3×10^{-6}	0.006
Assessments: 1–6 months prior	1.1×10^{-6}	1.5×10^{-6}	0.000	9.8×10^{-6}
Rx Fire: 1-year lag	5.2×10^4	3.2×10^4	1.1×10^4	1.7×10^5
Rx Fire: 2-year lag	4.3×10^4	2.6×10^4	5172	1.3×10^5
Rx Fire: 3-year lag	3.8×10^4	2.4×10^4	3375	1.2×10^5
Free inputs				
FWI	7.276	2.164	3.181	13.98
RH	51.29	6.098	35.96	63.16
KBDI	246.0	140.5	4.707	559.7
MFWI	6.090	2.524	1.916	16.43
Niño3: March	−0.168	−0.645	0.844	1.000
Niño3: October	0.462	0.665	−0.454	1.342
Precipitation	4.536	3.193	0.070	16.55
Fire: 1-year lag	1.9×10^4	2.8×10^4	858.3	2.3×10^5
Fire: 2-year lag	2.0×10^4	3.0×10^4	858.3	1.7×10^5
Fire: 3-year lag	2.7×10^4	3.6×10^4	1083	1.7×10^5
Fire: 4-year lag	3.1×10^4	4.3×10^4	1083	1.7×10^5
Fire: 5-year lag	4.5×10^4	5.2×10^4	1732	1.7×10^5
Fire: 6-year lag	4.5×10^4	5.1×10^4	1900	1.7×10^5
Region 2	0.246	0.431	0.000	1.000
Region 3	0.259	0.439	0.000	1.000
Region 4	0.246	0.431	0.000	1.000
Spring	0.259	0.439	0.000	1.000
Summer	0.233	0.424	0.000	1.000
Winter	0.259	0.439	0.000	1.000
Population	4.4×10^6	2.8×10^6	1.3×10^6	8.3×10^6
Police per capita	0.003	0.001	0.002	0.005
2003	0.207	0.406	0.000	1.000
2004	0.207	0.406	0.000	1.000
2005	0.207	0.406	0.000	1.000
2006	0.207	0.406	0.000	1.000
2007	0.103	0.305	0.000	1.000
Trend	29.51	16.80	1.000	60.00
Instruments				
Ignitions: 2-year lag	813.3	297.7	273.0	1765
Ignitions: 3-year lag	1033	456.4	273.0	2074
Ignitions: 4-year lag	1156	486.8	273.0	2074
Ignitions: 5-year lag	1339	418.6	450.0	2185
MFWI: 12-month lag	6.005	2.308	1.916	15.02
FWI: 12-month lag	7.289	2.047	3.181	13.90
RH: 12-month lag	52.11	5.916	37.66	63.16
KBDI: 12-month lag	237.7	133.2	4.707	578.4
Sales tax: 1-year lag	4.1×10^9	2.9×10^9	8.9×10^8	9.1×10^9
Controls				
Control variable: PSAs	-2.1×10^{-13}	-7.1×10^{-5}	3.1×10^{-4}	7.7×10^{-4}
Control variable: Visits	6.1×10^{-15}	-7.5×10^{-5}	1.9×10^{-4}	9.3×10^{-4}
Control variable: Presentations	1.8×10^{-15}	-1.2×10^{-6}	2.7×10^{-6}	1.1×10^{-5}
Control variable: Brochures	-3.8×10^{-13}	3.0×10^{-4}	-5.7×10^{-4}	0.002
Control variable: Assessments	-2.1×10^{-13}	-7.1×10^{-5}	3.1×10^{-4}	7.7×10^{-4}

Table 4. Initial allocation of spending under equal or proportional assumptions

Region	Equal (%)	Proportion (%)
1	25	15
2	25	49
3	25	16
4	25	20

unintentional ignitions, meaning endogeneity exists between WPE and targeted unintentional ignition rates (see Table 6). The positive correlations imply that a standard Poisson regression estimation would produce a downward bias of the treatment effects on the WPE variables. The empirical ignition model (Eqn 6) is significant and, based on the calculated pseudo R^2, explains 72% of the variation in targeted unintentional ignition counts.

PSAs, Presentations, Brochures, and Assessments are significant (at the 10% level) and negatively related to targeted unintentional wildfire ignition occurring in the same month, after accounting for endogeneity. Visits are only weakly correlated (13% level). Lagged levels (activity within the last 6 months) of PSAs, Presentations, and Brochures are also significant (10% level) and negatively related to ignitions. The implication is that PSAs, Presentations, and Brochures have both immediate and short-term mitigation effects, whereas Assessments have an immediate effect, but no lasting impact. Authorised prescribed fire hectares have longer-term effects, compared with WPE. Prescribed fire had a beneficial statistical effect (10% level) on targeted unintentional ignitions 2 and 3 years after 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 elasticity associated with PSAs (normalised by population) over the last 6 months (-0.26) is the same as the elasticity associated with prescribed fire treatments performed 2 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 ha treated by prescribed fire. The non-linearity 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).

Optimal mitigation results

Optimal change in WPE spending (only)

The optimal change in state-wide WPE spending, holding prescribed fire constant, is a 225% increase (Fig. 3). This figure shows that large increases in WPE would be needed in all four regions to minimise cost-plus-loss under the two assumptions of initial equal or initial proportional spending allocation.

Regions 1 and 3 have larger percentage increases in spending under the proportional allocation than the equal allocation in part owing to the low initial allocation under proportional compared with equal allocation. Thus, these regions produce the greatest return on WPE investment when the initial allocation is proportional, and hence the substantial need for increased funding. The return on WPE also looks more favourable for Region 4 under the proportional allocation. Expansion of WPE in Regions 1, 3 and 4 comes at the expense of Region 2, which begins with a high initial allocation level under the proportional allocation, and quickly experiences larger diminishing returns.

Optimal change in prescribed fire (only)

The optimal change in prescribed fire area, holding WPE spending constant, is a 79% increase, state-wide (Fig. 4). Results are similar 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 (9314 ha month^{-1}) 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). Whereas on average Region 4 treated the second most hectares (3696) and performed the highest 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 61.3 ha; Region 2 was second with an average size of 10.9 ha, followed by Region 3 (average of 7.4 ha) and Region 1 (average of 6.0 ha). Looking at the historical annual number of hectares burned, this ordering is preserved: Region 4 – 51 873 ha year^{-1}; Region 2 – 23 148 ha year^{-1}; Region 3 – 9255 ha year^{-1}; and Region 1 – 5259 ha year^{-1}. 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 constant. Those solutions are useful when one strategy can be varied (i.e. additional funding) whereas the other faces the status quo. The optimal solution will result when both strategies (prescribed fire and WPE) can adjust. As we show below, however, the optimal solution 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 spending and prescribed fire area, assuming equal allocation of initial WPE spending and price-responsive prescribed fire services, is a 168% increase in WPE and 74% increase in prescribed fire, state-wide (Fig. 5). Region 1 faces the most extreme changes: a 304% increase in WPE and a 29% decrease in prescribed fire. Region 3 faces a 251% increase in WPE and a 22% increase in prescribed fire. Regions 2 and 4 fall in between, both requiring roughly a doubling of WPE and prescribed fire effort.

Table 5. Control function equation estimates for five prevention education variables

MFWI, modified fire weather index; FWI, fire weather index; RH, relative humidity; KBDI, Keetch–Byram Drought Index; Rx Fire, prescribed fire; PSAs, public service announcements. ***, **, * denote significances at the 0.01, 0.05, 0.10 levels respectively

	PSAs coefficient	Visits coefficient	Presentation coefficient	Brochures coefficient	Assessments coefficient
Ignitions: 2-year lag	1.3×10^{-7}	1.6×10^{-7}*	-9.2×10^{-10}	-8.8×10^{-8}	-9.0×10^{-11}
Ignitions: 3-year lag	1.2×10^{-7}	7.4×10^{-8}	-3.0×10^{-10}	-3.4×10^{-8}	-4.7×10^{-10}
Ignitions: 4-year lag	1.7×10^{-7}**	9.7×10^{-9}	1.2×10^{-9}	-2.7×10^{-7}	-6.4×10^{-10}
Ignitions: 5-year lag	1.1×10^{-7}*	-6.4×10^{-8}	9.2×10^{-10}	-3.1×10^{-7}	-4.3×10^{-10}
MFWI: 12-month lag	-5.4×10^{-6}	-2.7×10^{-6}	-1.3×10^{-7}	-1.2×10^{-5}	-5.0×10^{-8}
FWI: 12-month lag	8.8×10^{-7}	6.6×10^{-7}	1.2×10^{-7}	-2.1×10^{-5}	3.6×10^{-8}
RH: 12-month lag	1.7×10^{-6}	-3.3×10^{-6}*	-5.4×10^{-9}	-5.3×10^{-6}	-1.4×10^{-8}
KBDI: 12-month lag	1.0×10^{-7}	1.1×10^{-7}	8.4×10^{-10}	2.3×10^{-7}	1.8×10^{-10}
Sales tax: 1-year lag	2.9×10^{-14}	-5.1×10^{-15}	5.6×10^{-16}	-6.9×10^{-14}	-3.6×10^{-16}
FWI: current	-2.2×10^{-5}*	2.0×10^{-5}	3.3×10^{-7}	2.4×10^{-5}	1.4×10^{-7}
RH: current	2.1×10^{-6}	8.5×10^{-7}	5.1×10^{-8}	3.2×10^{-6}	8.7×10^{-9}
KBDI: current	1.6×10^{-7}	2.8×10^{-7}**	2.4×10^{-9}	7.2×10^{-7}	1.0×10^{-9}
MFWI: current	3.1×10^{-5}**	1.5×10^{-5}	3.0×10^{-7}	-4.5×10^{-6}	1.5×10^{-7}
Niño 3: March–September	1.8×10^{-6}	1.4×10^{-5}	1.7×10^{-7}	-3.5×10^{-5}	-1.3×10^{-8}
Niño 3: October–February	-7.8×10^{-6}	5.2×10^{-6}	2.1×10^{-7}	4.4×10^{-5}	3.0×10^{-8}
Precipitation	-1.6×10^{-6}	-2.1×10^{-7}	-6.1×10^{-8}	-7.8×10^{-6}	-1.0×10^{-8}
Rx Fire: 1-year lag	1.6×10^{-10}	9.0×10^{-10}	-2.2×10^{-11}	4.9×10^{-9}	-7.3×10^{-12}
Rx Fire: 2-year lag	-3.3×10^{-10}	2.0×10^{-9}***	-8.7×10^{-12}	5.4×10^{-10}	-6.7×10^{-12}
Rx Fire: 3-year lag	3.9×10^{-10}	-3.7×10^{-10}	-1.1×10^{-11}	-3.9×10^{-9}	-2.7×10^{-12}
Fire: 1-year lag	2.6×10^{-10}	-2.6×10^{-10}	7.2×10^{-12}	2.2×10^{-10}	2.2×10^{-12}
Fire: 2-year lag	-1.8×10^{-9}*	-2.5×10^{-9}**	1.7×10^{-11}	-7.1×10^{-9}*	-3.6×10^{-12}
Fire: 3-year lag	-1.1×10^{-9}*	-8.7×10^{-10}	9.2×10^{-12}	-7.3×10^{-11}	9.6×10^{-13}
Fire: 4-year lag	-8.0×10^{-10}*	-3.4×10^{-10}	3.0×10^{-12}	3.7×10^{-9}*	-1.7×10^{-13}
Fire: 5-year lag	-8.0×10^{-10}	-1.1×10^{-9}*	7.7×10^{-12}	-3.0×10^{-10}	-3.7×10^{-13}
Fire: 6-year lag	-5.4×10^{-10}	-9.1×10^{-10}**	5.0×10^{-12}	-7.1×10^{-10}	1.1×10^{-13}
Region 2	0.006**	−0.002	-1.3×10^{-5}	0.002	6.2×10^{-6}
Region 3	0.008***	3.1×10^{-4}	-1.3×10^{-5}	0.003	1.1×10^{-5}
Region 4	0.008***	0.001	-1.5×10^{-5}	0.004	1.3×10^{-5}
Spring	5.6×10^{-5}**	-3.2×10^{-5}	7.0×10^{-7}	7.8×10^{-5}	1.0×10^{-7}
Summer	2.4×10^{-5}	4.6×10^{-5}	4.7×10^{-7}	5.4×10^{-5}	2.1×10^{-7}
Winter	-2.1×10^{-6}	-1.0×10^{-5}	4.0×10^{-7}	1.2×10^{-4}	-1.6×10^{-7}
Population	-5.7×10^{-10}**	-3.9×10^{-10}	-5.9×10^{-13}	-3.4×10^{-10}	-9.1×10^{-13}
Police per capita	1.752**	−0.656	−0.004	0.076	0.002
2003	-3.2×10^{-6}	3.1×10^{-5}	-9.4×10^{-7}	-4.1×10^{-6}	-1.5×10^{-7}
2004	3.7×10^{-5}	5.5×10^{-5}	-1.5×10^{-6}	3.2×10^{-4}	-5.5×10^{-8}
2005	4.0×10^{-5}	7.8×10^{-5}	-1.7×10^{-6}	0.001***	-3.1×10^{-7}
2006	6.8×10^{-5}	8.7×10^{-5}	-6.1×10^{-7}	0.001**	-1.6×10^{-7}
2007	7.6×10^{-5}	1.7×10^{-4}	-3.1×10^{-7}	0.001**	3.7×10^{-7}
Trend	1.3×10^{-5}**	-1.8×10^{-6}	7.1×10^{-8}	-3.4×10^{-5}	6.6×10^{-9}
PSA: 1–6 months prior	−0.255***	−0.009	-6.6×10^{-4}	0.513**	-7.6×10^{-4}*
Home visits: 1–6 months prior	−0.206	0.452***	6.2×10^{-4}	1.089*	4.7×10^{-4}
Presentations: 1–6 months prior	−4.145*	−3.607	−0.042	2.589	-5.8×10^{-4}
Brochures: 1–6 months prior	0.002	0.002	3.4×10^{-5}	−0.139***	9.8×10^{-5}*
Assessments: 1–6 months prior	41.35***	10.46	−0.044	25.48	−0.054
Intercept	−0.009**	0.003	1.6×10^{-5}	6.2×10^{-4}	-3.4×10^{-6}
$P > F$	0.0000	0.0000	0.0671	0.0000	0.0000
R^2	0.5155	0.3742	0.2471	0.4367	0.3973

The optimal overall state-wide change in WPE spending and prescribed fire area, assuming proportional allocation of initial WPE spending and price-responsive prescribed fire services, is also a 168% increase in WPE and a 74% increase in prescribed fire area. The initial allocation assumption does not affect the optimal level of prescribed fire state-wide or for individual regions. Assuming proportional allocation, 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%.

Trade-off analysis

Comparing the optimal change in wildfire interventions in both strategies (Figs 5, 6) with the optimal change in a single strategy

Table 6. Poisson model estimate of the count of targeted unintentional wildfires, 2002 to 2007, and associated elasticities, calculated at the mean of the data

FWI, fire weather index; RH, relative humidity; KBDI, Keetch–Byram Drought Index; MFWI, modified fire weather index; Rx Fire, prescribed fire; PSAs, public service announcements

	Coefficient	s.e.	*z*-score	$P > \|z\|$	Elasticity
FWI	0.146	0.061	2.390	0.017	1.060
RH	−0.033	0.009	−3.800	0.000	−1.700
KBDI	0.002	5.7×10^{-4}	2.900	0.004	0.410
MFWI	−0.052	0.060	−0.880	0.379	−0.320
Niño 3: March	0.030	0.058	0.510	0.609	−0.010
Niño 3: October	0.044	0.055	0.800	0.422	0.020
Precipitation	−0.121	0.013	−9.130	0.000	−0.550
Rx Fire: 1-year lag	-3.5×10^{-6}	3.5×10^{-6}	−1.010	0.311	−0.180
Rx Fire: 2-year lag	-6.0×10^{-6}	3.6×10^{-6}	−1.700	0.089	−0.260
Rx Fire: 3-year lag	-9.0×10^{-6}	2.5×10^{-6}	−3.670	0.000	−0.340
Fire: 1-year lag	6.4×10^{-6}	1.9×10^{-6}	3.300	0.001	0.120
Fire: 2-year lag	-1.7×10^{-5}	3.4×10^{-6}	−5.150	0.000	−0.350
Fire: 3-year lag	-5.4×10^{-6}	2.1×10^{-6}	−2.590	0.010	−0.140
Fire: 4-year lag	3.5×10^{-7}	2.2×10^{-6}	0.160	0.875	0.010
Fire: 5-year lag	4.7×10^{-6}	1.7×10^{-6}	2.800	0.005	0.210
Fire: 6-year lag	-4.0×10^{-6}	1.1×10^{-6}	−3.690	0.000	−0.180
Region 2	28.54	10.29	2.770	0.006	7.010
Region 3	46.18	14.23	3.250	0.001	11.94
Region 4	53.36	15.84	3.370	0.001	13.11
Spring	0.924	0.137	6.760	0.000	0.240
Summer	0.659	0.118	5.600	0.000	0.150
Winter	0.509	0.110	4.610	0.000	0.130
Population	-4.5×10^{-6}	1.2×10^{-6}	−3.780	0.000	−19.95
Police per capita	8118	3209	2.530	0.011	22.17
2003	0.671	0.156	4.290	0.000	0.140
2004	2.179	0.194	11.25	0.000	0.450
2005	3.307	0.337	9.810	0.000	0.680
2006	4.807	0.373	12.87	0.000	0.990
2007	6.264	0.453	13.84	0.000	0.650
Trend	0.043	0.019	2.280	0.023	1.260
PSAs: 1–6 months prior	−1344	587.0	−2.290	0.022	−0.260
Visits: 1–6 months prior	449.9	701.7	0.640	0.521	0.040
Presentations: 1–6 months prior	-4.9×10^{4}	8690	−5.630	0.000	−0.220
Brochures: 1–6 months prior	−215.0	46.58	−4.620	0.000	−0.240
Assessments: 1–6 months prior	6.5×10^{4}	5.0×10^{4}	1.300	0.194	0.070
Control variable: PSAs	3589	1350	2.660	0.008	0.000
Control variable: Visits	1434	845.4	1.700	0.090	0.000
Control variable: Presentations	3.1×10^{5}	1.1×10^{5}	2.960	0.003	0.000
Control variable: Brochures	526.4	307.5	1.710	0.087	0.000
Control variable: Assessments	6.6×10^{5}	3.0×10^{5}	2.200	0.028	0.000
PSAs: current month	−4123	1339	−3.080	0.002	−0.170
Visits: current month	−1290	841.4	−1.530	0.125	−0.030
Presentations: current month	-3.0×10^{5}	1.1×10^{5}	−2.820	0.005	−0.230
Brochures: current month	661.8	303.1	−2.180	0.029	−0.140
Assessments: current month	-6.3×10^{5}	3.0×10^{5}	−2.110	0.035	−0.120
Intercept	−29.66	14.61	−2.030	0.042	
Log-likelihood	−890.5587				
$P > \chi^2$	0.0000				
Pseudo R^2	0.7193				

(holding the other input fixed) (Figs 3, 4) shows that the optimal increases in state-wide WPE and prescribed fire are less than that required when one of the inputs is held fixed. Also, we find that a trade-off between WPE and prescribed fire exists. Although WPE is effective, it targets only a subset of unintentional ignitions, whereas prescribed fire targets all wildfire types, regardless of the ignition source. This indiscriminate targeting of prescribed fire mitigates the loss of the 'fuel treatment effect' of wildfire caused by ignition prevention because prescribed fire still impacts the burn area of those

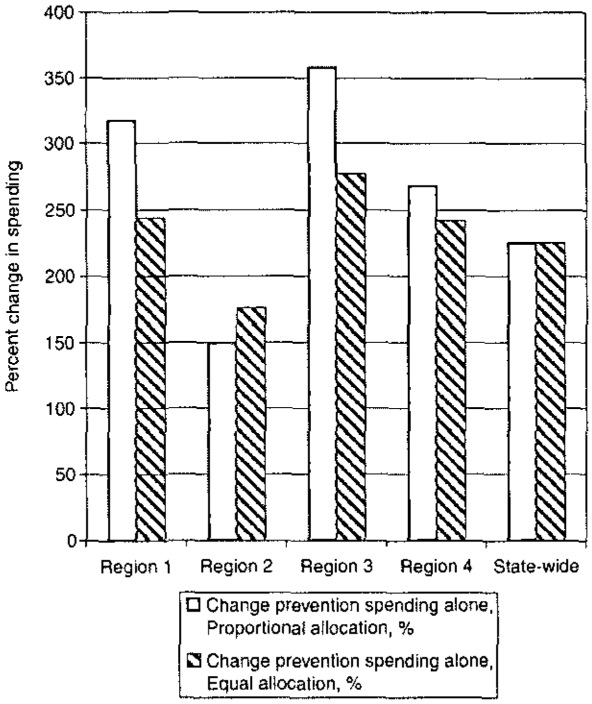

Fig. 3. Optimal change in spending: wildfire prevention education only.

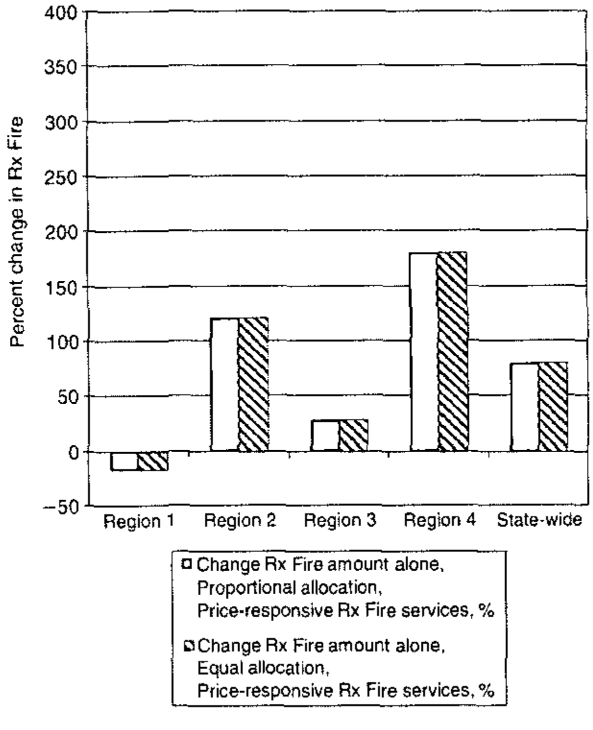

Fig. 4. Optimal change in area treated: prescribed (Rx) fire fuel treatments only.

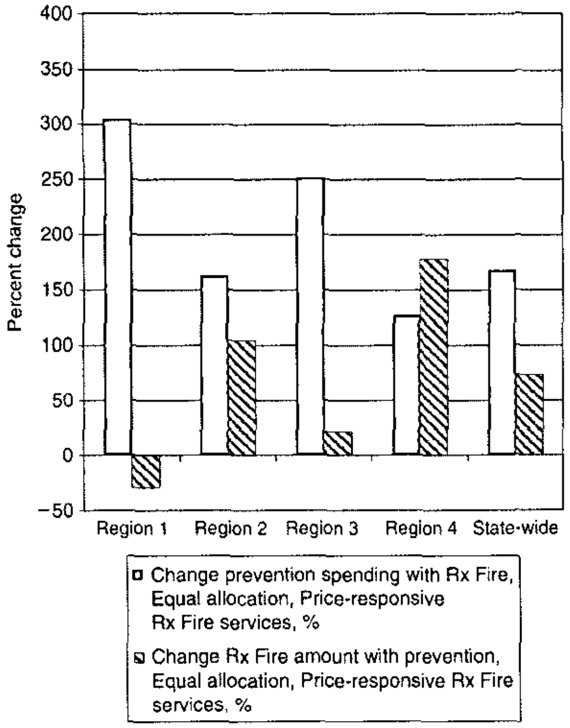

Fig. 5. Optimal change in wildfire mitigation effort: wildfire prevention education (assuming equal allocation across regions) and prescribed fire (Rx) fuel treatments.

wildfires that do occur. Joint optimisation is preferred to single optimisation as it produces an expected cost-plus-loss lower than any produced through single estimation (Table 7).

Based on a state-wide allocation strategy (i.e. increasing WPE and prescribed fire equally across regions), the expected cost-plus-loss is US\$301 million, a savings of US\$24 million (Table 7). This scale of increase results in a non-marginal benefit–cost ratio of 1.61. Whereas the optimal *state-wide* expansion of WPE and prescribed fire is independent of the assumed allocation strategy, the optimal *regional* distribution of WPE is not. This allocation assumption affects the estimated cost-plus-loss of mitigation, although the results are similar. 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 US\$287 million, a savings of US\$38 million (Table 7). These savings are net saving and already account for (or offset) increased program costs. This regional allocation strategy produces a non-marginal benefit–cost ratio of 1.63.

Conclusion

We examined the effect of WPE and prescribed fire, two alternative prefire intervention strategies, on targeted unintentional ignitions in Florida from 2002 to 2007. These targeted unintentional ignitions included those occurring from escaped debris fires, escaped campfires, and 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 hectares 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 minimised with an increase in WPE of 168% and prescribed fire hectares treated of 74%.

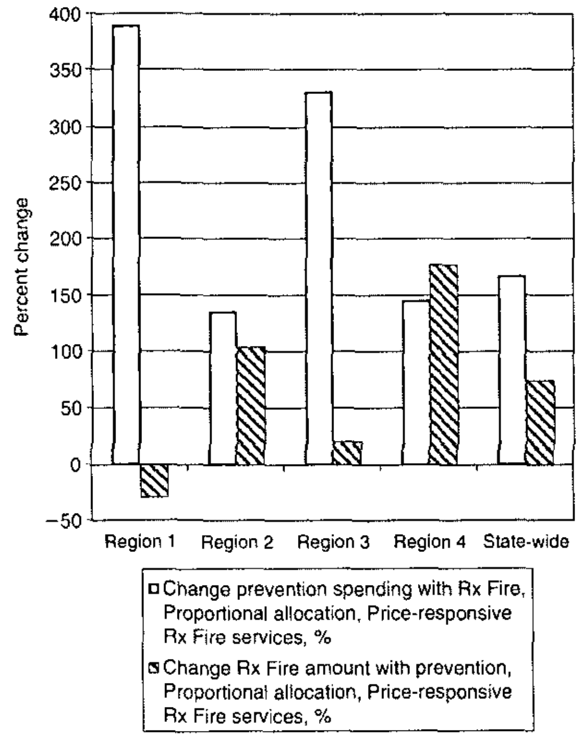

Fig. 6. Optimal change in wildfire mitigation effort: wildfire prevention education (assuming proportional allocation across regions) and prescribed fire (Rx) fuel treatments.

Although 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 owing to land ownership limitations. Only a portion of at-risk forests are under State (or other governmental) control, and these were where prescribed fire could most easily be expanded by government policy.[D] Constraints on prescribed fire, related to weather or smoke, may also limit its expansion to levels less than 74%. Related, prescribed fires usually occur early in the calendar year, and although 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.

In contrast, the State of Florida may find it easier to expand WPE efforts, as these are conducted by the government. Although the effect of WPE that we found in our modelling is shorter-lived than prescribed fire (we only found a 6-month maximum lagged effect), there is evidence that WPE could be used successfully to respond to outbreaks of targeted unintentional ignitions. PSAs, Presentations, Brochures, and 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 unintentional ignitions of the same month. Longer-term (up to 6 months) effects were shown to occur for PSAs, Presentations, and Brochures. 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 6 months. A 10% increase in PSAs, for example, is expected to result in a 4.9% reduction in targeted unintentional ignitions over a 7-month period. This marginal effect is on the order of magnitude of prescribed fire. In sum, prescribed fire offers a longer-term solution at the expense of short-term

Table 7. Cost-plus-loss totals under alternative assumptions and state variables
Rx Fire, prescribed fire

	Regional allocations cost + loss (US$ million)	State-wide allocations cost + loss (US$ million)
Current (base case)	325	325
Change prevention spending alone, Proportional allocation	318	318
Change Rx Fire amount alone, Proportional allocation, Price-responsive Rx Fire	292	306
Change prevention spending alone, Equal allocation	318	318
Change Rx Fire amount alone, Equal allocation, Price-responsive Rx Fire	292	306
Change prevention spending with Rx Fire, Proportional allocation, Price-responsive Rx Fire	287	301
Change prevention spending with Rx Fire, Equal allocation, Price-responsive Rx Fire	287	301
Change prevention spending alone, Equal allocation, No budget change	323	
Change prevention spending alone, Proportional allocation, No budget change	324	

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

flexibility, whereas 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 minimised.

Previous research suggests that ignition prevention leads to larger average wildfires in the future (Mercer *et al.* 2007), although the ignition effect dominates the size effect, and society is economically better off because (i) the total number of hectares burned are fewer (all else equal), and (ii) the future increases in wildfire resulting from today's fire reduction successes are discounted to the present when evaluating economic success. However, the negative feedback underscores the rationale for coordinating fuels management with WPE – to offset the fuels accumulation from ignition prevention – thereby reducing both frequency and size of wildfire.

Refinements of our analyses could be pursued. We chose a simple analysis that asked how much more or less effort should be expended to minimise the sum of costs and expected losses from wildfire in Florida. But a time-varying optimisation analysis could also have been explored: how much should WPE or prescribed fire efforts be changed over each of the units of time of our analysis to minimise cost-plus-loss? 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, a land manager may prefer to allocate efforts across types to achieve optimal fire management outcomes. In addition, 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.

Care should be given in applying the results to other locations, either across the USA or abroad. The statistical models demonstrated that targeted unintentional wildfire ignitions are sensitive to variations in weather, climate, recent wildfire activity, fuels management and community factors, including population size and law enforcement. These factors may not be present in other areas, or their relationship with ignitions may or may not hold. Further, the size of prevented wildfires, and the negative (fuel accumulation) feedback caused by preventing wildfires are likely influenced by suppression effort and success, as well forest composition. Finally, the ways in which populations respond to prevention messages may vary across locations and time. For instance, prevention messages may be influenced by recent wildfire activity (e.g. populations may better receive prevention messages after recent large wildfire incidents). Taken together, this suggests prevention messages may be more or less economical in other places; however, this research does make clear that in some forested ecosystems, wildfire prevention education can be coordinated with other wildfire management techniques to more effectively, and economically, limit the damages from wildfire.

References

Bradshaw WG (1988) Fire protection in the wildland/urban interface: who plays what role? *Fire Technology* **24**(3), 195–203. doi:10.1007/BF01038177

Butry DT, Pye JM, Prestemon JP (2002) Prescribed fire in the interface: separating the people from the trees. In 'Proceedings of the Eleventh Biennial Southern Silvicultural Research Conference'. (Ed. KW Outcalt) pp. 132–136. USDA Forest Service, Southern Research Station, General Technical Report SRS-48. (Asheville, NC)

Cleaves DA, Martinez J, Haines TK (2000) Influences on prescribed burning activity and costs in the national forest system. USDA Forest Service, Southern Research Station, General Technical Report SRS-37. (Asheville, NC)

Donovan GH (2006) Determining the optimal mix of federal and contract fire crews: a case study from the Pacific North-west. *Ecological Modelling* **194**(4), 372–378. doi:10.1016/J.ECOLMODEL.2005.10.043

Donovan GH, Rideout DB (2003) An integer programming model to optimize resource allocation for wildfire containment. *Forest Science* **49**(2), 331–335.

Drucker AG, Garnett ST, Luckert MK, Crowley GM, Gobius N (2008) Manager-based valuation of alternative fire management regimes on Cape York Peninsula, Australia. *International Journal of Wildland Fire* **17**(5), 660–673. doi:10.1071/WF07102

Florida Department of Revenue (2008) Tax collections from July 2003. Available at http://dor.myflorida.com/dor/taxes/colls_from_7_2003.html [Verified 5 December 2008]

Fosberg MA (1978) Weather in wildland fire management: the Fire Weather Index. In 'Proceedings of the Conference on Sierra Nevada Meteorology', 19–21 June 1978, Lake Tahoe, CA. pp. 1–4. (American Meteorological Society: Boston, MA)

Goodrick SL (2002) Modification of the Fosberg fire weather index to include drought. *International Journal of Wildland Fire* **11**, 205–221. doi:10.1071/WF02005

Haight RG, Fried JS (2007) Deploying wildland fire suppression resources with a scenario-based standard response model. *INFOR: Informational Systems and Operational Research* **45**(1), 31–39. doi:10.3138/INFOR.45.1.31

Hausman JA (1978) Specification tests in econometrics. *Econometrica* **46**(6), 1251–1271. doi:10.2307/1913827

Keetch JJ, Byram GM (1968) A drought index for forest fire control. USDA Forest Service, Southeastern Forest Experiment Station, Research Paper SE-38. (Asheville, NC)

Kim YH, Bettinger P, Finney M (2009) Spatial optimization of the pattern of fuel management activities and subsequent effects on simulated wildfires. *European Journal of Operational Research* **197**(1), 253–265. doi:10.1016/J.EJOR.2008.05.025

MacLellan JI, Martell DL (1996) Basing airtankers for forest fire control in Ontario. *Operations Research* **44**(5), 677–686. doi:10.1287/OPRE.44.5.677

Mercer DE, Prestemon JP, Butry DT, Pye JM (2007) Evaluating alternative prescribed burning policies to reduce net economic damages from wildfire. *American Journal of Agricultural Economics* **89**(1), 63–77. doi:10.1111/J.1467-8276.2007.00963.X

Mercer DE, Haight RG, Prestemon JP (2008) Analyzing trade-offs between fuels management, suppression, and damages from wildfire. In 'The Economics of Forest Disturbances: Wildfires, Storms, and Invasive Species'. (Eds TP Holmes, JP Prestemon, KL Abt) pp. 247–272. (Springer: Dordrecht, the Netherlands)

Minciardi R, Sacile R, Trasforini E (2009) Resource allocation in integrated preoperational and operational management of natural hazards. *Risk Analysis* **29**(1), 62–75. doi:10.1111/J.1539-6924.2008.01154.X

National Oceanic and Atmospheric Administration (2008) El Niño–Southern Oscillation sea surface temperatures. Available at ftp.cpc.ncep.noaa.gov/wd52dg/data/indices/sstoi.indices [Verified 8 December 2008]

Outcalt KW, Wade DD (2004) Fuels management reduces tree mortality from wildfires in south-eastern United States. *Southern Journal of Applied Forestry* **28**, 28–34.

Prestemon JP, Butry DT (2005) Time to burn: modeling wildland arson as an autoregressive crime function. *American Journal of Agricultural Economics* **87**(3), 756–770. doi:10.1111/J.1467-8276.2005.00760.X

Rideout DB, Omi PN (1990) Alternate expressions for the economic theory of forest fire management. *Forest Science* **36**(3), 614–624.

US Bureau of the Census (2008) Population estimates. Available at http://www.census.gov/popest/counties/ [Verified 2 June 2008]

US Department of Commerce (2008) Consumer price index for all urban consumers, not seasonally adjusted, monthly. Available at http://146.142.4.24/ [Verified 5 February 2008]

Wei Y, Rideout D, Kirsch A (2008) An optimization model for locating fuel treatments across a landscape to reduce expected fire losses. *Canadian Journal of Forest Research* **38**(4), 868–877. doi:10.1139/X07-162

Yoder J (2004) Playing with fire: endogenous risk in resource management. *American Journal of Agricultural Economics* **86**(4), 933–948. doi:10.1111/J.0002-9092.2004.00644.X

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