Economic analysis of prescribed burning for wildfire management in Western Australia

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Abstract

Wildfires can cause significant damage to ecosystems, life and property, and wildfire events that do not involve people and property are becoming rare. With the expansion of the rural–urban interface in Western Australia and elsewhere, objectives of life and property protection become more difficult to achieve. We applied the cost plus net value change (C+NVC) model to a synthetic landscape, representative of the northern jarrah forest of the south west of Western Australia. The most economically efficient level of prescribed burning corresponds to a strategy where 5% of the simulated landscape is prescribed-burned per year. Our results are sensitive to changes in the average cost per hectare of prescribed burning, the probabilities of fire occurrence, urban area values (in average dollars per hectare) and suppression costs.

Keywords: wildfire, fire management, economic analysis, cost plus net value change.

JEL Classifications: Q0

Category Fields: Agricultural, Natural Resource, Environmental and Ecological Economics - General

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1. Introduction

Wildfires can cause significant damage to ecosystems, life and property and in many parts of the world the frequency of large, disastrous fires, often referred to as mega–fires, appears to have increased (Morgan, 2009; Williams *et al.*, 2011). Catastrophic wildfires have occurred in Australia, the United States, Canada, Russia, China, South Africa, and Spain, among others. The Black Saturday fires in Victoria, Australia on 7 February 2009 resulted in the highest loss of life and property from a wildfire in Australian history (Teague *et al.*, 2010), causing the death of 173 people and widespread destruction of assets and infrastructure. Since 1998, nine states in the US have suffered their worst wildfires in history (Williams *et al.*, 2011). Although these fires are usually rare, they cause profound and long–lasting social, economic and environmental impacts where they occur (Handmer and Proudley, 2008).

Urban development in fire prone areas has amplified the complexity of the problem. Wildfire events that do not involve people and property are becoming rare (Mutch *et al.*, 2011). The number of houses and infrastructure located within or close to areas of high fire risk continues to increase in Australia (Morgan *et al.*, 2007) and elsewhere (Mell *et al.*, 2010; Mozumder *et al.*, 2009; Mutch *et al.*, 2011; USA, Canada, Europe, among others, see Smalley, 2003; Stockmann *et al.*, 2010), increasing the wildfire risk to life and property.

In light of the increasing wildfire threat, fire agencies have often responded with greater suppression capacity, involving increasing suppression costs. However, this has not solved the problem of catastrophic wildfires (Williams *et al.*, 2011). In Australia suppression expenditures have followed an escalating trend and the country "currently runs the risk of spending ever-greater amounts of money on wildfire suppression, while becoming even less successful in its management of fire in the landscape than is currently the case." (Morgan *et al.*, 2007, p. 1). Other countries with fire–prone landscapes appear to face similar issues. In the US annual suppression expenditures have increased remarkably over the past several years while the western part of the country has been severely affected by large and intense wildfires since the 1980s (Calkin *et al.*, 2005).

Economics can provide improved understanding and comprehensive appraisals of wildfire costs and benefits in order to devise wildfire mitigation and management programs that optimally allocate resources and express informed, evidence-based judgements about trade-offs between available options (Handmer and Proudley, 2008). However, the use of economics in the wildfire literature is still relatively limited. Despite the abundance of theoretical studies on the subject, empirical economic analyses of wildfire management are scarce (Mercer *et al.*, 2007).

In this paper we apply the cost plus net value change (C+NVC) model to a synthetic landscape, representative of the northern jarrah forest of the south west of Western Australia (WA). The purpose of the study is to determine the most economically efficient pre-suppression strategy for the synthetic landscape and evaluate which parameters significantly affect the results. We focus on prescribed burning as the main pre-suppression strategy. The primary objective of this model is to provide preliminary results which may inform the development of a more complete model based on actual areas of WA.

2. Methods

We simulated wildfires in a synthetic landscape under varying climatic conditions and different prescribed burning (pre-suppression) strategies using the AUSTRALIS Wildfire Simulator, which was developed at the School of Computer Science and Software Engineering, The University of Western Australia (see Johnston *et al.*, 2008 for a description of the fire simulator). The synthetic landscape generated for the simulations is a square landscape of 100,000 ha, containing a flat terrain with homogenous northern jarrah forest fuel.

We tested three prescribed burning strategies, each with three patch sizes. The strategies involved prescribed-burning 5, 10 or 20 % of the total area per year, corresponding to rotation cycles of 20, 10 and 5 years respectively. The landscape was partitioned into square-shaped patches of 50, 500 and 4000 ha, and each strategy could be carried out in burning patches of these sizes. The age of the fuel in each patch was a random integer value from $[0,n]$, where $n = 5$, 10 or 20, depending on the burning strategy. In addition to these 9 combinations (3 strategies × 3 patch sizes = 9), we defined a baseline strategy for comparison where the fuel age was uniformly set at 15 years across the entire treatment area and used this baseline as the 0% prescribed burning or no-strategy case. Each strategy-patch size combination was simulated under high, very high, extreme and catastrophic forest fire danger conditions (FFDI), giving $(9+1) \times 4 = 40$ scenarios. Finally, each scenario was tested under 30 random ignitions, making a total of $30 \times 40 = 1200$ simulations.

We used the "McArthur Mk V" forest fire meter (Noble *et al.*, 1980; Sirakoff, 1985) to determine the rate of spread. Fuel load was determined using the fuel accumulation table for Jarrah forest in Sneeuwjagt and Peet (1998), which gives fuel load as a function of fuel age. Fire ignition points were generated according to a random uniform distribution. The weather was constant during simulation. Spotting effects were not modelled. Table 1 summarises the simulator settings. If fire intensity is below a threshold of 2,000 kW/m, then it assumed that the fire is suppressed.

We used the C+NVC model, which is currently the most commonly accepted model for economic evaluations of wildfire management programs (Ganewatta, 2008; Gebert *et al.*, 2008). From Donovan and Rideout (2003), the C+NVC model can be expressed as:

$$\text{Min } C + NVC = W^P P + W^S S(P) + NVC\big(P, S(P)\big) \tag{1}$$

in which W^P is the price of pre–suppression; P is the pre–suppression effort; W^S is the price of suppression; S is the suppression effort, which is dependent on pre–suppression; and NVC is the net fire damage (fire damage less fire benefit).

Table 1. Summary of simulator settings for prescribed burning experiments

	Value				
Scenario parameters					
Patch sizes	50, 500, 4000 ha				
Rotation cycles	5, 10, 20 y				
Weather conditions	High, Very High, Extreme, and Catastrophic				
Ignition points	Uniformly randomly placed across the entire landscape				
Weather conditions	***Temperature (ºCelsius)***	***Relative Humidity (%)***	***Wind direction***	***Wind speed (km/h)***	***Drought factor***
High	30	25	North	30	5
Very High	35	20	North	30	7
Extreme	35	10	North	30	9
Catastrophic	40	10	North	50	10
Fuel					
Rate of spread meter	McArthur Mk V, Forest (Sneeuwjagt and Peet, 1998)				
Fuel accumulation rules	Northern Jarrah Fuel				
Canopy cover	60%				
Topography	Flat				
Cell grid					
Cell spacing	50 m				
Cell neighbourhood	Cells up to 6 links away are considered adjacent				
Simulator configuration					
Lateral rate of spread	Rate of spread at zero wind speed				
Maximum duration of simulated time	36 h				

In our model, we assumed a negative relationship between prescribed burning effort (annual prescribed-burned area as a proportion of the entire landscape) and suppression costs. Prescribed burning is generally expected to improve directly the probability of successful suppression (Fernandes and Botelho, 2003) because prescribed burning decreases the intensity with which wildfires burn. Preliminary results of both empirical and modelling studies suggest that the relationship between the percentage of landscape prescribed–burned and the probability of unplanned high intensity fire at a point may be represented by a complex multiplicative model with a convex shape (Cary *et al.*, 2003). Hence, as the intensity of fires increases, suppression becomes more difficult and more costly (Chatto and Tolhurst, 2004), since more expensive resources such as water bombers are needed when direct attack methods can no longer be used.

The functional relationship between prescribed burning effort and suppression costs is expressed as $s = ke^{-ax}$, where s is suppression expenditure; x is the proportion of area prescribed-burned; k

represents the maximum suppression expenditure and a is a coefficient of prescribed burning effectiveness that affects the marginal benefit of each extra prescribed-burned hectare in the landscape. *Ceteris paribus*, the higher coefficient a is, the lower the expenditure on suppression for a given proportion of prescribed-burned area.

Since we simulated fires under different weather conditions, which have different probabilities of occurrence, we multiplied the outcomes of the fires by their probabilities of occurrence and assumed that under low and moderate weather conditions the fires would be suppressed relatively quickly and have only a minimal effect on the results. Table 2 shows the probabilities that we used for fire occurrence.

Table 2. Probabilities of fire occurrence

Fire category	*Probability of incident occurrence per year*
Catastrophic	0.0001770
Extreme	0.0002360
Very High	0.0007080
High	0.0475789

We assumed in our analysis that a small town of 1,500 ha is located within the synthetic landscape in order to approach our evaluation of a rural-urban interface scenario. Thus, we included values of urban structures and public infrastructure and smoke and fire-related (prescribed or wildfire) health costs. Although the economic literature on human health impacts from exposure to wildfire or prescribed burning smoke is scarce[1] and the differences in estimates between available studies is large, omitting health impacts in economic evaluations of fire management programs could result in underinvestment in pre-suppression activities (Richardson *et al.*, 2012).

In our analysis, we have not accounted for number of days of exposure to the smoke caused by wildfires but linked intensity and area burned to health costs. We assumed an exponential relationship between area burned by wildfire and health costs, which changes with the level of intensity. As intensity and area burned by wildfires increase, fuel combustion and biomass burning emissions (such as particulate matter with an aerodynamic diameter less than 2.5 μm, $PM_{2.5}$) escalate, and ultimately, as they become greater, wildfires may cause serious injuries and casualties. Hence we use an exponential relationship that increases as area burned and wildfire intensity become extreme. The relationship can be expressed as $h = be^{c\omega}$, where h is health costs per person at risk; ω is the size of the simulated fires (area burned); b is a coefficient that integrates the effects of intensity on health costs and a is a coefficient that reflects the impact of area burned on health costs per capita, both

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[1] Some studies that have estimated the adverse health effects from prescribed burning or bushfires smoke exposure include Richardson *et al.* (2012); Butry *et al.* (2001); Martin *et al.* (2007); Rittmaster *et al.* (2006). For a comprehensive review of the literature analysing economic cost of smoke-related health effects see Kochi *et al.* (2010).

coefficients determine the marginal cost of each extra hectare burned by wildfires at a particular level of intensity in the landscape.

Some fires however, can be relatively small and still cause an increase in $PM_{2.5}$ concentration levels in a neighbouring town. We have then to assume that a smoke plume of a rectangular shape is released by the fire and has a probability of reaching the town $P(m, A) = m(\omega)/A$, with m the size of the smoke plume, which is dependent on the size of the fires; and A the size of the whole landscape.

3. Results and Discussion

Our results indicate that the most efficient level of prescribed burning corresponds to a strategy where 5% of the simulated landscape is prescribed-burned per year. With our assumed costs of prescribed burning ($/ha), this is equivalent to an annual investment in prescribed burning of approximately AU$405,000 over an area of 100,000 ha. The minimum of the C+NVC curve equals about AU$785,000. **Figure 1** shows the curves obtained from the C+NVC model.

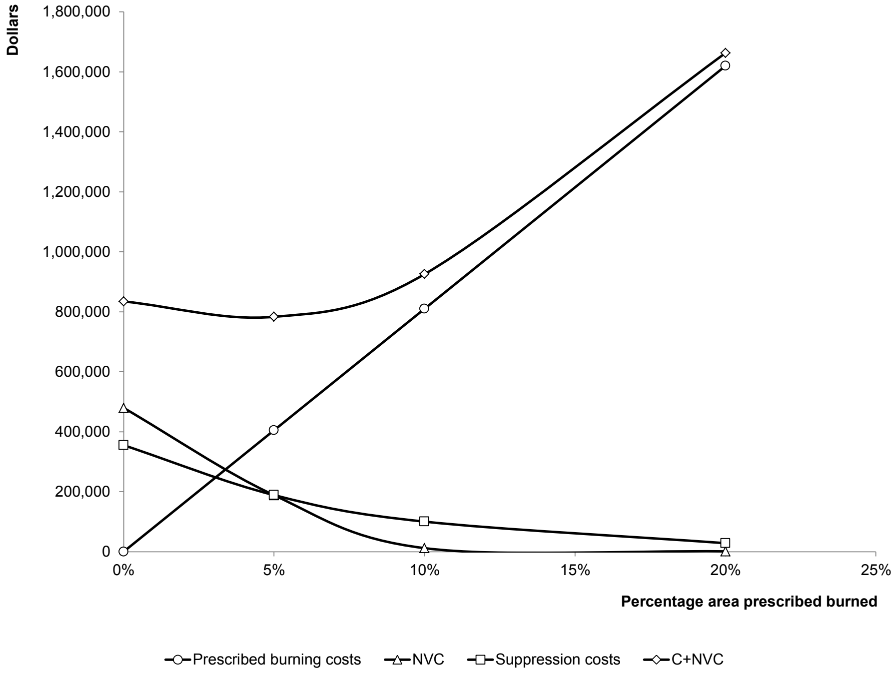

Figure 1. The cost plus net value change (C+NVC) curve

We conducted a sensitivity analysis to evaluate the robustness of the results and determine which parameter values most affect the results. Figure 2 shows the change in the minimum of the costs plus net value change curve in dollars when some parameter values are reduced by 50% or increased by 50%. The parameters shown are those to which the results are most sensitive. As shown in Figure 2, a change in prescribed burning costs (in average dollars per hectare) greatly affects the results.

As prescribed burning costs increase, they quickly become a large proportion of the C+NVC curve. If the slope of prescribed burning costs changes, the point where marginal costs equal marginal benefits shifts accordingly. If the average cost per hectare for prescribed burning is very high, then the minimum of the C+NVC curve corresponds to a strategy of 0% prescribed burned area. This case is illustrated in Figure 2. Change in the minimum of the costs plus net value change curve with an increase and a decrease of 50% in the value of selected parameters

. The minimum value of the C+NVC curve is then the sum of suppression costs and damages for the 0% strategy.

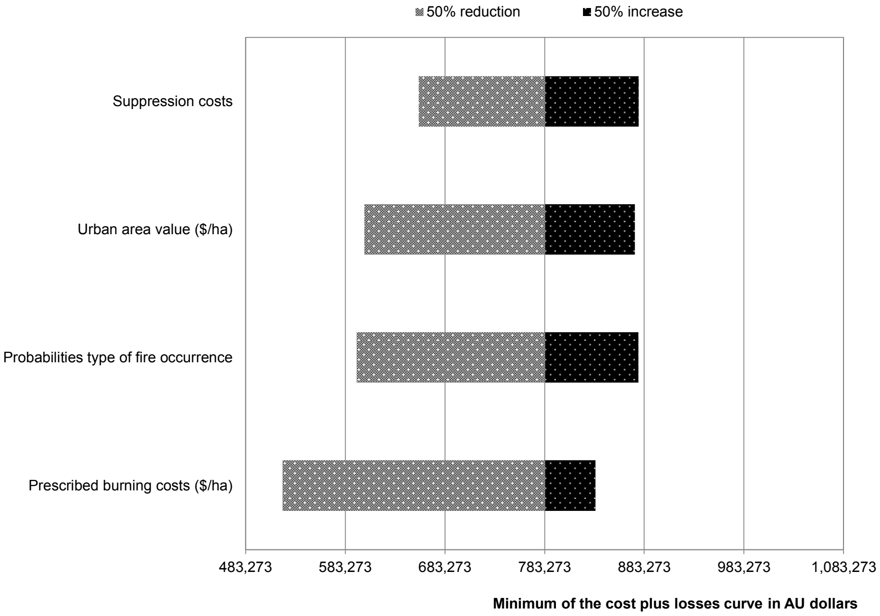

Figure 2. Change in the minimum of the costs plus net value change curve with an increase and a decrease of 50% in the value of selected parameters

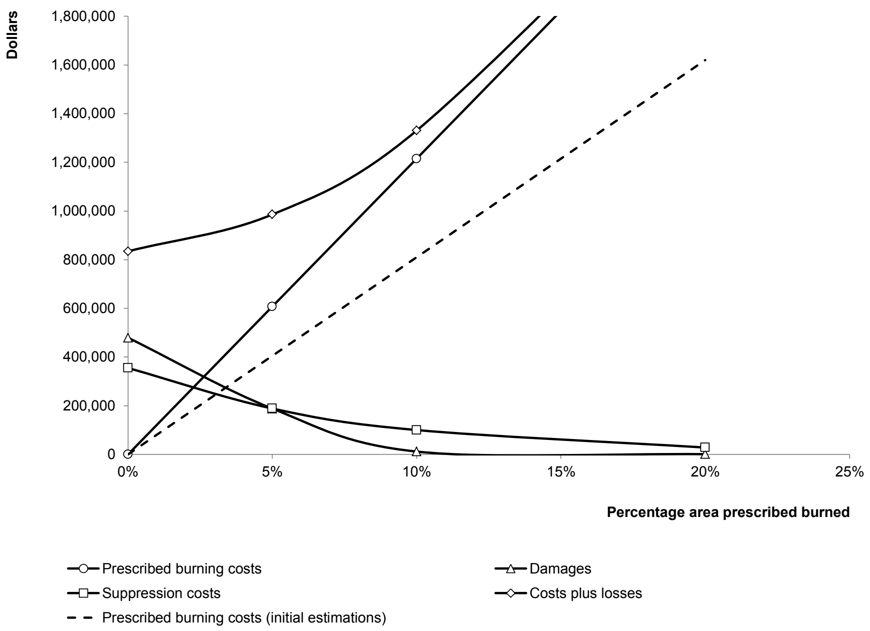

Figure 3. 50% increase in average prescribed burning costs per hectare

When the average prescribed burning cost per hectare is reduced by 50%, the minimum value of the C+NVC curve decreases by 34% (Figure 2) and the most efficient strategy is between 5 and 10% area prescribed burned per year (Figure 4). Comparing the three figures of the C+NVC curve, it can be seen that in our initial estimation (Figure 1) there is a wide range of prescribed burning levels that is near-optimal, but this is not the case when the cost of prescribed burning is modified (Figure 3 and Figure 4).

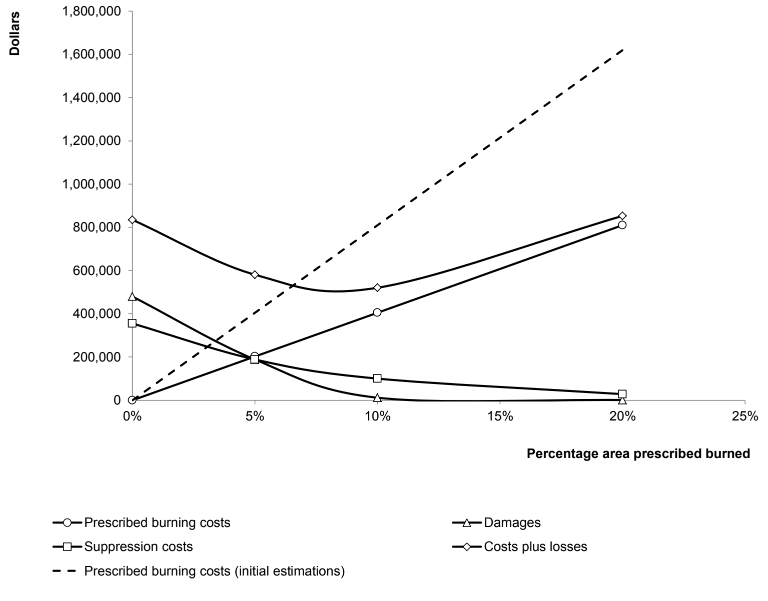

Figure 4. 50% decrease in average prescribed burning costs per hectare

Our results are also sensitive to changes in the probabilities of fire occurrence, urban area values (in average dollars per hectare) and suppression costs. Table 3 shows how the most efficient prescribed burning strategy changes when we increase or reduce the value of the selected parameters described above.

Table 3. Change in the most efficient prescribed burning strategy

	Most efficient prescribed burning strategy (% of landscape prescribed burned)		
	Initial estimation	50% reduction	50% increase
Prescribed burning costs ($/ha)	5%	>5% and <10%	0%
Probabilities type of fire occurrence	5%	0%	>5% and <10%
Urban area value ($/ha)	5%	0%	>5% and <10%
Suppression costs	5%	0%	>5% and <10%

This encapsulates the main challenges faced by fire agencies in developing sustainable fire management practices: climate change, the rural-urban interface and the effectiveness of suppression. Numerous uncertainties still exist regarding the behaviour of wildfires under severe weather conditions and the sustainability of different fire management practices in the context of climate change (Thornton, 2010). With the expansion of the rural-urban interface, objectives of life and property protection become more difficult to achieve. Smalley (2003) identifies the expansion of the rural-urban interface as "one of the three major factors that will propagate the pressures of the interface on communities. The other two are unusually severe weather events (from prolonged drought to severe heating periods and floods that erode soils and vegetation) and inadequate infrastructure due to the rapidity of growth or aging." (p. 5)

The patch size of the prescribed burns had no significant effect on the results of the analysis. The severity measures obtained from the simulated fires were not significantly affected by changes in patch size (which is consistent with previous studies that use simulation to examine the efficacy of prescribed burning, e.g. King *et al.*, 2008; Wiedinmyer *et al.*, 2006) and hence they had no significant impact on the economic analysis.

Although the C+NVC model has been extensively used to assess annual investments in fire prevention and protection, the model has been through some reformulation in the past two decades. Rideout and colleagues (Donovan and Rideout, 2003; Donovan *et al.*, 1999; Hesseln and Rideout, 1999; Rideout and Omi, 1990; Rideout and Ziesler, 2008) identified three inherent errors in the model that have been perpetuated from the earlier least cost plus loss model formulated by Sparhawk (1925). First, suppression expenditure is determined solely as a function of fire occurrence. Donovan and Rideout (2003) argued that both pre–suppression and suppression should be modelled as endogenous decision variables, with the benefits of suppression depending on the level of pre-suppression. As commonly applied, the C+NVC minimum may differ from the one obtained when pre–suppression and suppression are modelled correctly.

Second, suppression and pre–suppression expenditures are incorrectly modelled as negatively correlated (Donovan and Rideout, 2003; Rideout and Ziesler, 2008). And third, by analysing a single fire season, the long term effects of natural fuel accumulation processes, unplanned fires, fuel treatments and land management strategies on wildfire risk are overlooked (Hesseln and Rideout, 1999). Fire scars, whether caused by fuel reduction treatments or unplanned fires, affect fire behaviour and intensity for longer than one year. Likewise, natural fuels accumulate over time and if left undisturbed, they gradually increase the risk of catastrophic fires year by year. Despite the limitations mentioned above, the application of the C+NVC model in its current formulation can help fire managers identify potential benefits and costs of different fire management options for a given year, even if a global minimum is not obtained (Rodriguez y Silva and Gonzalez-Caban, 2010). We recognise the limitations of the model and their implications, and hope to address them in future work. The C+NVC framework has been used here as a first step towards a more comprehensive analysis.

4. Summary

We applied the cost plus net value change (C+NVC) model to a synthetic landscape of 100,000 ha, representative of the northern jarrah forest of the south west of Western Australia. We used the AUSTRALIS Wildfire Simulator to simulate wildfires in this landscape under varying climatic conditions. We tested three different prescribed burning (pre-suppression) strategies and a no-strategy option. We found that the most economically efficient level of prescribed burning corresponds to a strategy where 5% of the simulated landscape is prescribed-burned per year over an area of 100,000 ha. Our results are sensitive to changes in the average cost per hectare of prescribed burning, the probabilities of fire occurrence, urban area values (in average dollars per hectare) and suppression costs.

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