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Evaluating wildland fire liability standards – does regulation incentivise good management?

Christopher J. Lauer[A], *Claire A. Montgomery*[B,C] *and Thomas G. Dietterich*[B]

[A]National Oceanic and Atmospheric Administration, National Oceanic and Atmospheric Administration (NOAA), 1315 East-West Hwy, Silver Spring, MD 20910, USA.
[B]Oregon State University, Corvallis, OR 97331, USA.
[C]Corresponding author. Email: claire.montgomery@oregonstate.edu

Abstract. Fire spread on forested landscapes depends on vegetation conditions across the landscape that affect the fire arrival probability and forest stand value. Landowners can control some forest characteristics that facilitate fire spread, and when a single landowner controls the entire landscape, a rational landowner accounts for spatial interactions when making management decisions. With multiple landowners, management activity by one may impact outcomes for the others. Various liability regulations have been proposed, and some enacted, to make landowners account for these impacts by changing the incentives they face. In this paper, the effects of two different types of liability regulations are examined – strict liability and negligence standards. We incorporate spatial information into a model of land manager decision-making about the timing and spatial location of timber harvest and fuel treatment. The problem is formulated as a dynamic game and solved via multi-agent approximate dynamic programming. We found that, in some cases, liability regulation can increase expected land values for individual land ownerships and for the landscape as a whole. But in other cases, it may create perverse incentives that reduce expected land value. We also showed that regulations may increase risk for individual landowners by increasing the variability of potential outcomes.

Additional keywords: approximate dynamic programming, ecological disturbance, fire policy, liability regulation, multi-agent reinforcement learning, risk, spatial, stochastic dynamic games.

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Introduction

Ecological disturbances such as wildfire cross property boundaries, implying that landowners will be affected by the conditions of the surrounding landscape. Many authors have recognised transboundary risks as an important consideration for managing wildfire, including Fischer and Charnley (2012), Zaimes *et al.* (2016), Palaiologou *et al.* (2018) and Ager *et al.* (2018). In a mixed-ownership landscape, individual landowners may not be incentivised to consider the wellbeing of their neighbours in their land-management decisions; at the same time, their ability to effectively manage fire risk on their own land may be compromised without the cooperation of their neighbours. One method for addressing these transboundary issues is to create laws and regulations that hold landowners accountable for fires that spread from their land to damage surrounding areas. In this paper, we examine the effectiveness of liability regulations that can incentivise landowners to account for vegetation conditions that affect the spread of wildland fire. Bourrinet (1992) provides an overview of such regulations that have been implemented around the world. In the USA, rules for private landowners vary by state and can include fines, criminal penalties, liability for damages and negligence standards (Yoder *et al.* 2003). Epstein (2012) provides an overview of the principles of common law as they apply to the problem of damage caused by spreading fire, focusing primarily on liability and negligence. Although the specifics of these regulations can have many forms, Epstein highlights two general categories of regulation that have been applied in the context of wildland fire: *strict liability* where landowners must provide compensation for any damage caused by fire originating on their land, and *negligence standards* that hold landowners responsible for damage only in cases where they do not meet the standard of care required. In recent years, new laws have been proposed and, in some cases, implemented. At the federal level, the Enhanced Safety from Wildfire Act of 2005 (US Congress 2005) would have created stricter negligence standards for fuel conditions on both private and federal land if passed. At the state level, laws have been implemented that limit liability for fire damage to the 'fair market value' of that damage (Oregon State Legislature 2013; Washington State Legislature 2014). These laws, while still falling under the umbrella of strict liability, change the penalties that landowners face and the compensation they can receive. 'Fair market value' is not explicitly defined by these laws, but for timber, this value is often determined using standard economic theory, which says that value should be based on the Faustmann rotation (Faustmann 1849; Samuelson 1976).

These bills have been a response to increasingly dangerous fuel conditions, especially on public land (Schmidt *et al.* 2002; Donovan and Brown 2007), and large damaging wildfires, which have become more frequent (National Interagency Fire Center 2016).

Human management of fire-prone landscapes plays a key role in the outcomes for these systems (Spies *et al.* 2014). Liability regulations change the incentive structure faced by landowners and may cause landowners to change their management actions. This affects the welfare of all landowners on the landscape as well as ecological outcomes. Policy changes have the potential to create positive outcomes, but in complex human–ecological systems, they can also create unintended consequences. In the present paper, we focus on the effect of regulation-based incentives for optimal timber harvest decisions. Although the problem of optimal timber harvest is important, it represents only a small portion of the greater problem of managing fire-prone landscapes. This paper provides a framework for understanding how forest management and the resulting outcomes may change in response to changing landowner incentives. This is an important first step for evaluating proposed regulations or other forest management policies.

Several authors have considered the optimal harvest age of an individual forest stand in the face of stochastic risk. Routledge (1980) and Reed (1984) demonstrated that the optimal response to such risk of loss is to harvest timber at an age earlier than the Faustmann (1849) model suggests. Subsequent papers explored optimal investment in fire protection, such as fuel treatment or fire-fighting infrastructure (Reed 1989, 1993). For example, Amacher *et al.* (2005) and Garcia-Gonzalo *et al.* (2014) looked at how fuel treatment and silvicultural interventions affect optimal rotation age for fire-threatened forest stands. Daigneault *et al.* (2010) examined how carbon sequestration is affected by manager response to fire risk. None of these papers consider the effect of wildfire spread.

As fire risk on an individual stand is a function of the condition of the entire landscape, several authors have developed spatially explicit models of land management with fire spread. For example, Wei *et al.* (2008) and Chung *et al.* (2013) modelled optimal placement of fuel treatments on the landscape to minimise expected loss to fire, and Ager *et al.* (2010) examined the effect on fire risk in the wildland–urban interface of different fuel treatment 'rules'. These models are static because they do not account for how optimal management will adapt to a post-fire landscape, should fire actually occur.

Fire dramatically changes the vegetation on the landscape, and land managers will respond by adapting their management to the new conditions. Therefore, the problem of optimal management of a fire-threatened landscape is inherently dynamic; management decisions will always be made in the context of past wildfire events. Konoshima *et al.* (2008, 2010) developed a dynamic model that examined how optimal management changes when the actions taken on one stand affect the fire risk on adjacent stands.

Liability regulations address the spatial interactions created by fires that spread across property boundaries. Therefore, analysis of liability rules requires a multi-landowner approach. Crowley *et al.* (2009) used the Reed model to determine optimal rotation age for two adjacent landowners with interdependent fire risk. Busby *et al.* (2012) developed a dynamic game-theoretic model to demonstrate how the pattern of public and private ownership might affect fuel management by residential property owners in the wildland–urban interface. Very few studies directly analyse liability rules for wildland fire. Yoder *et al.* (2003) and Yoder (2004) used an analytical model to explore how liability rules affect the use and frequency of controlled burning. Unfortunately, the practical usefulness of these studies for planning and policy analysis is limited by the need to greatly simplify the landscape, fuel models, fire behaviour and weather for the sake of tractability.

The problem of optimal sequential decision-making under uncertainty can be formulated as a Markov decision process or – in the case of multiple landowners – as a stochastic game. These problems can be solved exactly only in very simple cases. Fortunately, recent developments in approximate dynamic programming and multi-agent reinforcement learning allow practical solution of more complex and realistic problems (Sutton and Barto 1998; Powell 2007, 2009). Lauer *et al.* (2017) applied these methods to the problem of optimal forest management by a single landowner on a landscape that allowed for complex spatial interactions. Lauer *et al.* (2019) extended the single-landowner platform to a multi-agent game-theoretic model that demonstrates how dynamic programming methods can be used to analyse the interaction of multiple agents.

In this paper, we apply these methods to analyse potential policy outcomes from liability regulation. Specifically, we predict forest management actions of two landowners with interdependent fire risk under two types of liability regulation – strict liability and negligence standard – and evaluate their potential impacts on landowner wealth and the external effects on neighbouring landowners by comparison with two cases: one in which external effects are fully accounted for and one in which they are not accounted for at all. For each scenario, we estimate value functions that provide a way to compute the expected benefits and costs associated with different management actions. We found that a negligence standard can increase the expected value of individual land ownerships and the landscape as a whole. The strict liability regulation created perverse incentives that could lead to decreased landscape value and did not improve the expected outcomes for individual landowners. We also showed that both of the liability regulations we modelled may increase risk for individual landowners as reflected in the variability of potential outcomes.

Methods

Addressing the effect of liability regulations for wildland fire requires a bio-economic model that integrates landowner objectives, ecological conditions, spatial arrangements and institutional structures. A schematic is presented in Fig. 1 that depicts the relationship between the various components of this model, which will be explained in greater detail in the rest of this section. Models of fire and vegetation must be explicitly spatial because fire spreads across the landscape creating interactions that affect stand value. Forest landowners pursue a variety of values such as protecting structures, preserving habitat, or harvesting timber. Actions taken in pursuit of these values will be affected by incentives created by institutions such as markets for

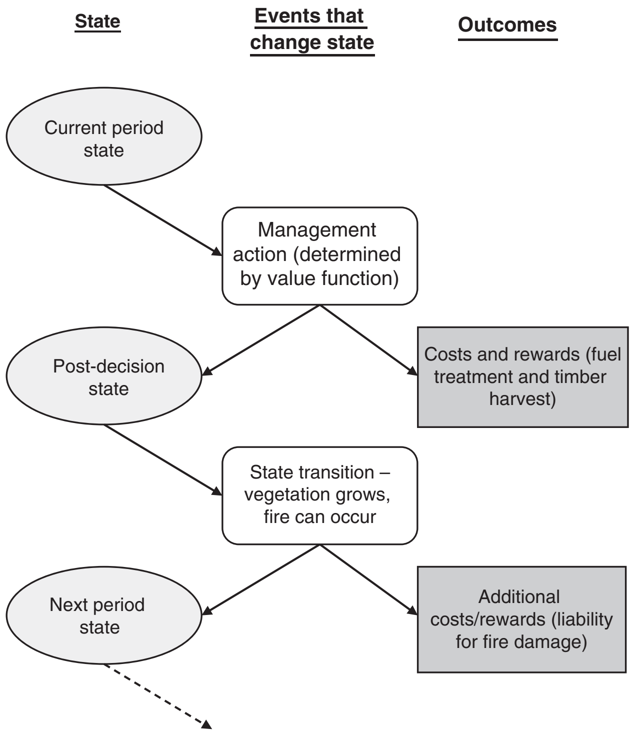

Fig. 1. Schematic of landowner decision making for one time period. In each period, landowners observe the initial landscape, and choose actions (actions are determined using value functions; see Lauer *et al.* (2019) for detailed description of how these value functions are estimated). These actions have costs and rewards, and result in a changed landscape (the post-decision state). Vegetation growth and potentially fire occur (state transition model) on this landscape. The resulting transition creates additional costs and rewards for landowners that depend on the structure of the liability rules. Additionally, the transition results in a new landscape where landowners repeat the process of choosing actions.

forest products or liability laws that govern payments and penalties associated with fire damage.

Economic model

We model the landowners' decision-making by formulating the problem as a Markov decision process (MDP) (Puterman 1994) using Bellman's equation (Bellman 1957), a recursive equation that represents the maximum expected value of the landscape in state S_t at time t, $V(S_t)$. Although we consider only timber value in this analysis, the value function can represent any value that can be quantified. We use the so-called action-value representation, $Q(S_t, x_t)$ also known as the 'Q-value' (Watkins and Dayan 1992) to represent the expected value of taking action x_t in state S_t and behaving optimally thereafter (Eqn 1):

$$V(S_t) = \max_{x_t} Q(S_t, x_t) = \max_{x_t}[C(S_t, x_t) + E[\delta V(S'(S_t, x_t, W_t))]] \quad (1)$$

In choosing management action x_t to maximise $Q(S_t, x_t)$, landowners consider both its immediate cost or benefit, captured by a reward function, $C(S_t, x_t)$, and its implications for the future, captured by the discounted (discount factor δ) expected value of the next period's state, $E[\delta V(S_{t+1})]$. The transition from S_t to S_{t+1} is a function of the current state, S_t, the current actions, x_t, and a vector of stochastic events, W_t, which includes fire arrival and weather, and is represented by a state transition model such that $S_{t+1} = S'(S_t, x_t, W_t)$. We account for spatial interactions by decomposing $Q(S_t, x_t)$ into separate functions, $Q_j(S_t, x_t)$, for each stand, $j = 1,2,\ldots,J$, on the landscape. The specification and solution of the multiple landowner problem are described in Lauer *et al.* (2019).

We further extend the analysis here by imposing liability regulations to hold landowners accountable if fires spread from their land to damage other parts of the landscape. When there are multiple landowners, each can take actions only on the stands they control even though their fire risk is affected by actions on stands they do not control. Regulations change the incentive structure faced by landowners and may force them to account for at least a portion of the external effects of their actions. This is because liability regulations hold landowners accountable if fires spread from their land to damage other parts of the landscape. In this model, we introduce a liability function to represent the payments owed, or compensation received, by landowner n when a fire occurs, $L^n\left(S_t, x_t^n, \boldsymbol{x}_t^{-n}, W_t\right)$. This function depends on the current state of the landscape, S_t, the actions of landowner n, x_t^n the actions of the other landowners, $\boldsymbol{x}_t^{-n}$ and the occurrence of fire, W_t. The value function for each landowner, $n = 1,2,\ldots,N$, includes this liability function and is specified as

$$V^n(S_t) = \max_{x_t^n}\left\{Q^n\left(S_t, x_t^n | \boldsymbol{x}_t^{-n}\right) + E\left[\delta L^n\left(S_t, x_t^n, \boldsymbol{x}_t^{-n}, W_t\right)\right]\right\} \quad (2a)$$

$$Q^n\left(S_t, x_t^n | \boldsymbol{x}_t^{-n}\right) = \sum_{j_n=1}^{J_n} Q_{j_n}^n\left(S_t, x_t^n | \boldsymbol{x}_t^{-n}\right) \quad (2b)$$

$$Q_{j_n}^n\left(S_t, x_t^n | \boldsymbol{x}_t^{-n}\right) = C_{j_n}^n\left(S_t, x_t^n\right) + E\left[\delta V_{j_n}^n\left(S'\left(S_t, x_t^n, \boldsymbol{x}_t^{-n}, W_t\right)\right)\right] \quad (2c)$$

where $j_n = 1,2,\ldots,J_n$ indexes the set of stands owned by landowner n and x_t^n is the vector of actions taken by landowner n on those stands. Note that the value of each stand depends on the state of the entire landscape; therefore, S_t, x_t and W_t are not indexed by j.

Because the value of each landowner's actions is determined in part by the actions of other landowners, we model the interaction between landowners as a game in which each landowner adjusts to account for the actions of other landowners. The optimal set of actions for each landowner, $X^n(S)$, where no landowner can gain by changing their choices as long as other landowners' choices also remain unchanged, is found by solving for the set of actions implied by the value function (Eqn 2*a*–*c*) for all N landowners simultaneously.

Representative landscape

We created a representative landscape using pre-existing models and parameters to characterise the state variables, transition functions and reward functions. These parameters and state-transition rules were selected to approximate forest conditions

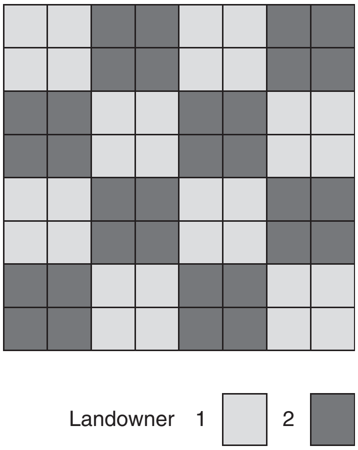

Fig. 2. Case study landscape with ownership pattern. Each of two landowners is assigned alternating blocks of stands, creating a checkerboard pattern with many owner adjacencies.

found in SW Oregon and are described in detail in Lauer *et al.* (2017, 2019); key details about the representative landscape are also available as Supplementary materials to this article (Supplementary material Text S1). We modelled decision-making agents whose objectives were to maximise the net present value of timber harvest. Although this objective was chosen because it is easy to understand and measure, there many other possible objectives for landowners that could be modelled.

The external effects that liability rules are intended to mitigate are greatest where ownership is highly fragmented. Therefore, to highlight the effect of liability rules on landowner behaviour, we modelled an ownership pattern where each of two landowners is assigned alternating blocks of stands, creating a checkerboard pattern with many owner adjacencies (Fig. 2). The Oregon and California Revested Lands, also known as O&C lands, that occupy ~10 000 km^2 of western OR provide an example of this pattern of fragmentation.

For the purpose of policy analysis that relies on inference beyond a particular case, we believe our generalised landscape can provide broadly applicable insights about how landowners might respond to policy-induced changes in incentives; therefore, that is how we applied our modelling framework in this paper. That said, it could be applied to a specific 'real' landscape with more specific landscape features, such as topography and variable stand dimensions, for the purpose of forest management planning.

Liability regulations

We modelled four scenarios. Two scenarios provide alternative bases for comparison that set bounds on the degree to which external effects of management are considered in the decision process by individual landowners, and two represent important general categories of liability regulation – strict liability and negligence standard (Epstein 2012).

(1) Social Planner (Soc) – This scenario represents management that maximises the overall value of the landscape with *full consideration* of the effect of actions on one stand that affect fire spread and, hence, outcomes on other stands. This outcome is equivalent to the optimal management of the landscape under a single owner (i.e. $N = 1$) with no liability regulation.
(2) No Regulation (NoReg) – Each of two landowners ($N = 2$) manages the stands they control with *no consideration* of the impact of their actions on stands they do not own.
(3) Strict Liability (Strict) – In this scenario, landowners are held liable for damage caused by *any* fire originating on their land regardless of the circumstances. We consider two landowners.
(4) Negligence Standard (Neg) – In this scenario, landowners are held liable for damage caused by any fire originating on their land *only* if their land is not maintained in the lowest-risk fuel condition available for the stand's age class. (We note that many other forms of negligence standards exist in statutory law.) Again, we consider two landowners.

Liability payments are calculated as the change in the present land-and-timber value (LTV) resulting from fire based on the Faustmann rotation, which is a common standard for valuing damage to a forest, supported by economic theory (Samuelson 1976). Enforcing liability rules may involve costly litigation, monitoring, or other transaction costs that we do not analyse here.

Solution method

The underlying ecological processes that govern fire spread and damage and vegetation growth are sufficiently complex that it is intractable to enumerate all the states, actions, or stochastic events that could occur on the landscape; this is the curse of dimensionality, which precludes the use of exact dynamic programming methods. The inclusion of multiple landowners compounds this problem because the actions of each landowner affect the outcomes for the others, necessitating solution for the actions of all landowners simultaneously. We address this problem through a combination of two techniques described by Powell (2007): post-decision states and a form of approximate dynamic programming known as value function approximation. We summarise the general solution method here and refer the reader to Lauer *et al.* (2017, 2019) for a detailed description.

The post-decision state simplifies the basic stochastic dynamic programming problem specified in Eqn 2 by formulating the state of the post-decision landscape, $S_t^{x^n} = g(S_t, x_t^n)$ for a particular landowner n in terms of what landowner n can know at the time a decision is made. With multiple landowners, this is the state of the landscape after landowner n has taken an action, but before fire occurs (if it occurs) and before the actions of other landowners are observed. Hence, it is a function of the current state and landowner n's action only, which allows it to be anticipated accurately by landowner n. The problem facing each landowner n in Eqn 2*a*–*c*, when rewritten in terms of the post-decision state, becomes

$$V^n(S_t) = \max_{x_t^n} Q^n(S_t, x_t^n) \quad (3a)$$

$$Q^n(S_t, x_t^n) = \sum_{j_n=1}^{J_n} Q_{j_n}^n(S_t, x_t^n) \quad (3b)$$

$$Q_{j_n}^n(S_t, x_t^n) = C_{j_n}^n(S_t, x_t^n) + V_{j_n}^n(g(S_t, x_t^n)) = C_{j_n}^n(S_t, x_t^n) + V_{j_n}^n(S_t^{x^n}) \quad (3c)$$

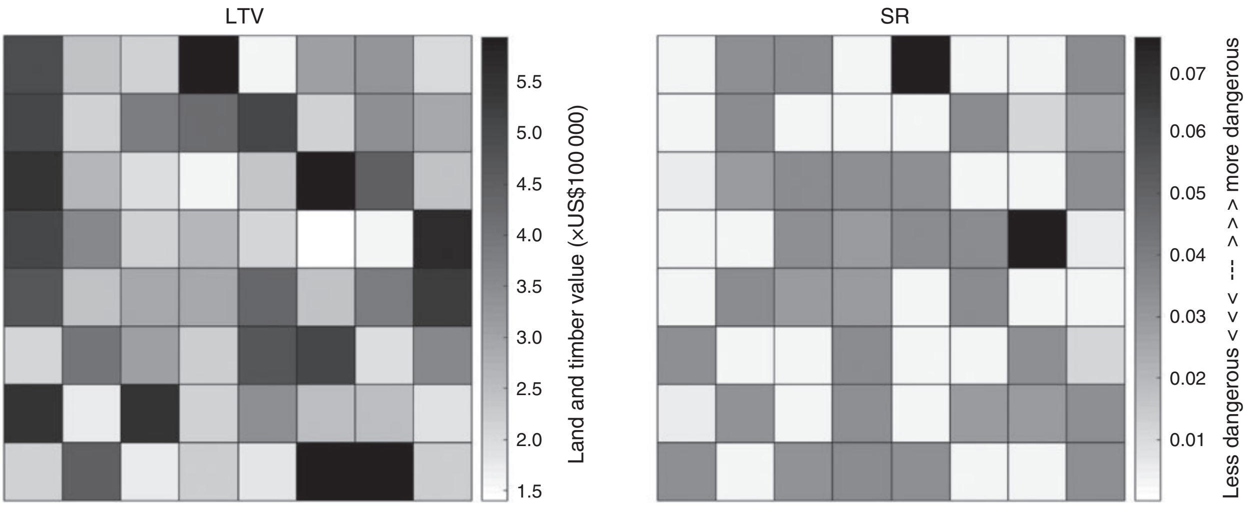

Fig. 3. Case study landscape configuration of land-and-timber value, LTV, and predicted downwind spread rate, SR, by stand.

All of the uncertainty associated with fire (including potential liability payments) and actions of other landowners is absorbed into the value function for the post-decision state:

$$V^n\left(S_t^{x^n}\right) = E_W \delta\left[L^n\left(S_t^{x^n}, \boldsymbol{x}_t^{-n}, W\right)\right] + \max_{x_{t+1}^n}\left\{C^n\left(S_{t+1}, x_{t+1}^n\right) + V^n\left(g\left(S_{t+1}, x_{t+1}^n\right)\right)\right\} \tag{4}$$

where, again, $S_{t+1} = S'(S_t, x_t, W_t)$. Therefore, the landowner chooses the set of actions that generates the highest return in this period plus the expected value of the landscape once those actions have been imposed, given that all other landowners are also trying to act optimally.

Because it is not possible to enumerate all possible outcomes, we approximate the value function as a linear function of landscape attributes, $\bar{V}_{j_n}^n\left(S_t^{x^n}|\boldsymbol{\theta}^n\right)$, that can be observed or predicted by the landowner at the time a decision is to be made and that is a computable function of observable or predictable attributes of the post-decision state. The problem facing the landowner is then solved by replacing the value of the post-decision state in Eqn 3*c*, $V_{j_n}^n\left(S_t^{x^n}\right)$, with its approximation $\bar{V}_{j_n}^n\left(S_t^{x^n}|\boldsymbol{\theta}^n\right)$. To find the values of the coefficients $\boldsymbol{\theta}^n$ of the linear model that provide the best estimate of $V_{j_n}^n\left(S_t^{x^n}\right)$, we implement a value iteration algorithm described in Lauer *et al.* (2017, 2019). After some experimentation, we specified $\bar{V}_{j_n}^n\left(S_t^{x^n}|\boldsymbol{\theta}^n\right)$ as a function of

- land and timber value, LTV_{j_n}, of stand j_n based on the Faustmann rotation, which does not account for fire risk;
- age of stand j_n;
- predicted down-wind spread rate, SR_{j_n}, of stand j_n and its eight adjacent neighbours under extreme weather conditions to indicate fire hazard. Although it is possible for a fire to travel from any stand on the landscape to any other stand if the fuel and weather conditions are right, adjacent stands have a greater impact on fire risk than distant stands. Preliminary experiments showed that including more distant stand attributes did not improve the quality of the value function approximation;
- a dummy variable describing whether an adjacent stand is owned by another landowner;
- a dummy variable describing whether or not the stand was in the lowest-risk fuel condition – included only for the Negligence Standard (Neg).

The attributes LTV_{j_n} and SR_{j_n} are shown for the case study landscape in Fig. 3. Separate value functions were estimated for each liability regulation scenario to reflect the different effects of liability regulation on landscape values.

For each of the four scenarios, once we obtained a value approximation function, $\bar{V}_{j_n}^*\left(S_t^{x^n}|\theta^*\right)$, we estimated the expected value of the case study landscape for each landowner, V_r^n. The resulting values allow us to assess the accuracy of the value function and provide the basis of the discussion of results and policy analysis that follows in the next section. We estimated

$$V_r^n = \sum_{t=0}^{150}\left[\delta^t \sum_{j_n=1}^{J_n} C_{j_n}\left(S_t, x_t^n\right)\right] + \sum_{t=1}^{150}\left[\delta^t \sum_{j_n=1}^{J_n} L_{j_n}\left(S_{t-1}, x_{t-1}^n, x_{t-1}^n, W_{t-1}\right)\right] + \delta^{150}\sum_{j_n}\bar{V}_{j_n}^{n*}\left(S_{150}^{x^n}\right) \tag{5}$$

by performing 500 150-year Monte Carlo simulations in which timber harvest and fuel treatment were chosen in each year to solve $x_t^{n*}(S_t) = \operatorname{argmax}_{x_t^n} \sum_{j_n=1}^{J_n}\left[C_{j_n}\left(S_t, x_t^n\right) + \bar{V}_{j_n}^{n*}\left(S_{j_n}^{x^n}|\theta^{n*}\right)\right]$. The ending value, $\bar{V}_{j_n}^{n*}\left(S_{150}^{x^n}\right)$ in Eqn 5, was computed using the value function approximation and the state of the ending landscape. As an indication of the quality of the value approximation function, we note that the mean landscape value, *mean* V_r, obtained by summing the values for each landowner and averaging over the 500 simulations, differed from the approximated value computed as $\bar{V} = \sum_n\left[\max_{x^n}\sum_{j_n=1}^{J_n} C_{j_n}\left(S_0, x^n\right) + \bar{V}_{j_n}^{n*}\left(S_{j_n}^{x^n}|\theta\right)\right]$ by 0.6, 2.0, 0.8 and 0.4% for NoReg, Strict, Neg and Soc scenarios respectively.

Table 1. Expected net present value of realised landscapes

Mean, *mean* V_r, and variance (in parentheses) over 500 150-year Monte Carlo simulations and approximation function value of the landscape, $\bar{V}$, are shown for each of four scenarios: Social Planner (Soc); No Regulation (NoReg); Strict Liability (Strict); and Negligence Standard (Neg) for the entire landscape and for each of two landowners

	Landscape		Landowner 1		Landowner 2	
	mean V_r	$\bar{V}$	*mean* $V_r^{n=1}$	$\bar{V}^{n=1}$	*mean* $V_r^{n=2}$	$\bar{V}^{n=2}$
Soc	15.08 (7.23)	15.14	7.19 (1.89)	7.25	7.88 (1.93)	7.88
NoReg	14.52 (7.35)	14.61	6.93 (1.82)	6.94	7.59 (1.99)	7.66
Strict	14.30 (8.46)	14.60	6.76 (4.85)	6.99	7.55 (3.73)	7.60
Neg	15.03 (7.00)	14.91	7.16 (3.84)	7.21	7.87 (2.85)	7.70

Results

The Social Planner (Soc) and the No Regulation (NoReg) scenarios set bounds on the extent to which landowners consider the effects of their management on neighbouring properties when making harvest and fuel treatment decisions. In the Soc scenario, all external effects are considered when management actions are determined for each stand whereas in the NoReg scenario, outcomes for neighbouring agents are not considered at all. In this section, we describe the outcomes obtained under the two forms of liability regulation – Strict Liability (Strict) and Negligence Standard (Neg) – and compare them with the Soc and NoReg outcomes.

The mean landscape values and the variance over the 500 Monte Carlo simulations under each scenario are reported in Table 1 for the whole landscape and for the portion assigned to each landowner. We applied Welch's unequal variances *t*-test to assess whether the difference in mean value between each pair of scenarios was statistically significant at the 5% level and confirmed the result using Wilcoxon signed rank and Kolmogorov–Smirnov tests, which do not assume a normal distribution. The Soc scenario generated the highest value for the entire landscape and for the portions assigned to each landowner; it is significantly higher than the NoReg value. The Neg scenario increased landscape value over NoReg almost to the Soc level; it is significantly higher than NoReg and not significantly different from Soc. The Strict scenario did not increase value over NoReg; it is significantly lower than the Soc and not significantly different from NoReg.

Liability regulation appears to increase uncertainty for individual landowners. We applied two-tail *F*-tests to assess whether the difference in variances between each pair of scenarios was statistically significant at the 5% level and confirmed the result using the Kolmogorov–Smirnov test. Although the variances of the simulated outcomes do not differ significantly across the four scenarios for the entire landscape, the variances for the liability regulation scenarios, Strict and Neg, are both significantly greater than the unregulated scenarios, Soc and NoReg, when evaluated for the individual landowners (Table 1). This is because, in the event of a damaging

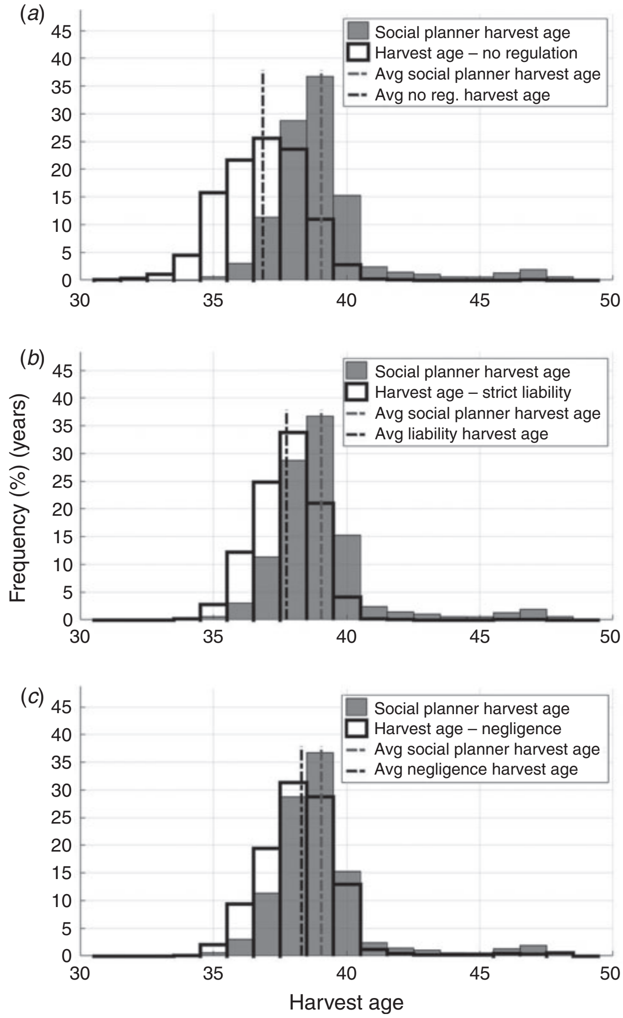

Fig. 4. Harvest age distributions for (*a*) NoReg compared with Soc; (*b*) Strict compared with Soc; and (*c*) Neg compared with Soc.

fire, one landowner compensates the other. Although this compensation does not change the overall value of the landscape, it can represent a significant transfer of wealth depending on where a fire originates.

In this analysis, landowners choose harvest age to maximise LTV. Reed (1984) showed that the presence of fire risk decreases optimal harvest age when effects on adjacent stands are ignored. Konoshima *et al.* (2010) showed that this tendency is offset to some extent when the effect of harvest on adjacent stands is considered; because mature forest stands do not spread fire as well as young stands, timber harvest increases fire risk for adjacent stands. Therefore, the optimal harvest age for any particular stand depends not only on the condition of the stand itself, but also on the surrounding landscape conditions and the extent to which the landowner is affected by damage to adjacent stands when fire occurs. The distributions of harvest ages in our simulations for Soc compared with NoReg, for Soc compared with Strict, and for Soc compared with Neg are shown in Fig. 4*a–c*. On average, trees are held longest in Soc (39.05 years) and harvested earliest in NoReg (36.86 years). Liability regulation affects harvest age in two ways. First, risk is reduced when there is a possibility of compensation for loss to fire originating elsewhere – encouraging later harvest. Second, mature stands have lower-risk fuel models, which reduce the probability that fire will spread to the neighbouring landowner and incur a payment for damage. Therefore, average harvest age for the liability scenarios falls between Soc and NoReg – 37.75 years for Strict and 38.31 years for Neg. The difference between the liability scenarios likely arises from the different fuel treatment behaviour described in the next paragraph.

Fuel treatment protects valuable timber from damage and decreases the ability of fire to spread. In young stands with high spread rates, fuel treatments protect timber value on adjacent stands. In older stands, fuel treatment protects both adjacent stand value and the merchantable timber on the stand. Fuel treatment is performed in all scenarios when the expected benefit for on-site and adjacent stands exceeds the cost of fuel treatment. In the Soc case, the effect of fuel treatment on all stands is considered. In the NoReg case, the marginal value of fuel treatment is decreased because landowners do not capture the increased value for some adjacent stands. When liability regulations are imposed, the incentives are more complicated. In the Strict case, liability is incurred any time a fire spreads to neighbouring stands whereas for Neg, liability for damage to adjacent property can be avoided by maintaining low-risk fuel conditions on one's own stands. In both regulation scenarios, this incentivises fuel treatment in young stands with high-risk fuel conditions to avoid liability payments. Fuel treatment is also incentivised for older stands in the Neg case. But in the Strict case, fuel treatment is less likely in older stands. This is because compensation for damage is based on the no-risk Faustmann LTV, which is higher than the true stand value when fire risk is accounted for; this creates a perverse incentive to avoid fuel treatment when fire spread from a neighbour's property is likely.

The different fuel treatment and harvest choices have implications for the attributes of fire when it occurs. In particular, we found that fires were significantly (by Kolmogorov–Smirnov test) larger on average in the Strict scenario than in the NoReg scenario, owing to lack of fuel treatment. Average fire size was smallest in Soc and Neg, which the Kolmogorov–Smirnov test indicates were not significantly different from one another.

Discussion and conclusions

A fire's ability to spread and cause damage can be amplified or mitigated by human management. Therefore, the potential impacts of fire on a landscape and on the people who own and manage it depend on the pattern of ownership and the incentives for landowners to consider management impacts beyond their own property boundaries. Liability regulations are intended, in part, to change the incentives faced by land managers, thereby changing outcomes. This research is a step towards understanding how proposed and newly implemented liability rules may affect landowner welfare, change forest landscape management, and change outcomes resulting from fire. It provides a framework that can be applied to predict the response to changing land-management regulations.

Our analysis suggests that assigning liability based only on a fire's origin, as is the case in the Strict Liability scenario, can be counterproductive. However, conditioning liability on beneficial risk-reducing management similar to the Negligence Standard scenario can mitigate many of the consequences of failure to consider external effects. We also found that the size of the liability payment matters: payments that do not match the value of the damaged stand can decrease incentives for landowners to take precautionary action. If the payment is too large, the landowner who is likely to suffer damage will not engage in sufficient precautionary effort; however, the landowner likely to cause damage will not take sufficient action if the expected liability payment does not exceed the cost of precautionary effort.

Additionally, we show that introducing liability payments can increase uncertainty faced by individual landowners by imposing the entire cost of a fire on a single landowner rather than spreading the cost over the affected landscape. This is not a concern if landowners are risk-neutral, which may be the case for large-scale corporate landowners for whom risk is spread over time and space. However, even large landowners with access to capital markets can be adversely affected, as shown by the recent bankruptcy filing of Pacific Gas and Electric Co. owing to concerns about wildfire liabilities (PG&E Corporation 2019). Punitive liability regulations may be especially problematic in areas where the landscape is dominated by small woodland owners who tend to be relatively risk-averse, because their forest may represent a large portion of their wealth. The larger variation in outcomes for these landowners in the liability scenarios could represent a decrease in their wellbeing even if expected values of outcomes were greater. Introducing risk preferences into our modelling framework would allow exploration of this idea. For example, risk-averse landowners may pursue a maximum–minimum strategy that maximises the value of the worst possible outcome, rather than the Nash equilibrium we model.

Making insurance available is an alternative policy that could narrow the range of possible outcomes for individuals, and may increase the wellbeing of risk-averse landowners more than liability regulations. However, the availability of insurance may change incentives to engage in risk-reducing behaviour such as fuel treatment, which will have implications for outcomes on the landscape. A careful analysis of the proper design of an insurance program would be another interesting extension of this work.

The effect of liability regulation depends on ecological conditions (for example, how fuel loads affect fire spread over the life of a stand, which may in turn depend on climate). The ecological models used in this study were parameterised to reflect conditions in a particular region and are not perfectly representative. Applying these methods on landscapes parameterised for different conditions could change the conclusions that are drawn. Additionally, this paper did not account for climate change, which may cause the weather that drives fire and the vegetation on the landscape to evolve over time. To account for ecological parameters that include climate change, value functions would need to be indexed by time, leading to a more complex optimisation framework (Powell 2007). Evolving ecological conditions caused by climate change could necessitate regular revisiting of established liability standards to incentivise management.

Ownership configuration on the landscape also plays a crucial role in the effectiveness of liability regulations. As the tracts of land controlled by individual landowners get larger, fires are less likely to cross property boundaries. This could decrease the need for regulations. However, in ecosystems where fires tend to be very large, liability regulations could substantially increase the variance in landowner outcomes, which would reduce the wellbeing of risk-averse landowners. Changes in liability regulations could also affect the ownership configuration on the landscape, as purchasing adjacent land is an alternative means to mitigate the external effects of spreading fire. The effect of fire risk and liability regulations on land ownership patterns is beyond the scope of this paper, but it is a very interesting question in its own right.

Finally, maximising the financial asset value of a forest is just one possible objective for forest management. For example, in the cases of the Moonlight Fire of 2007 (*United States v. Sierra Pacific Industries*, Civ. No. 2: 09–02445 WBS AC (E.D. Cal. Apr. 17, 2015)) and Copper Fire of 2002 (*United States vs CB & I Constructors, Inc.*, No. 10–55371 (9th Cir. June 29, 2012)), costs were paid for environmental damage as well as timber value lost. The optimisation framework demonstrated in the present paper formally links landowner objectives to ecological conditions, spatial arrangements and institutional structures such as markets and regulations to determine optimal actions. Incorporating other important landscape values into the reward and value functions will allow this framework to be adapted for problems that involve non-timber values.

This work demonstrates a method for analysing the impact of changing incentives for landowners. It could be applied to many different policy questions that can affect fire risk on a landscape. In this paper, we analysed how liability regulations affect ecological outcomes and landowner welfare. We are unaware of other studies that model the effect of different approaches to liability on the optimal behaviour of interacting landowners while specifically accounting for spatial interactions generated by fire spread. We demonstrated that liability rules can lead to improved outcomes on the landscape. However, if poorly designed, they can create perverse incentives that reduce values, or increase variability for individuals, thereby decreasing wellbeing.

Conflicts of interest

The authors declare no conflicts of interest.

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