Effects of Spatial Externality on Efficient Spatial Allocation of Forest Fuel Management

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Abstract: We investigate the effects of spatial interactions across plots during forest fire - in particular a spatial externality - on efficient allocation of fuel management efforts, which are intended to mitigate the risk of wildfire damage. These spatial externalities are captured in a spatial, endogenous risk framework. Our framework integrates a fire behavior model and a spatially explicit stochastic dynamic optimization model. By solving computationally from a number of hypothetical and bio-economically heterogeneous landscapes, general insights into implementing spatial allocation of fuel management are derived.

1. Introduction

In recent years, fire has caused significant economic and environmental damage to drier ecosystems in the United States. In Oregon and Washington alone, there are nearly 5 million ha of dry forestland currently at high risk of fire (Agee, 2002). This situation appears to be the result of aggressive and effective fire suppression efforts during the last century that have allowed fuel - small trees, bushes, debris, and other undergrowth - to accumulate (Sampson and Sampson, 2005) and past harvesting practices that selectively removed fire-tolerant large trees and left small trees with low fire tolerance. When these tinderbox forests do ignite, the resulting high intensity fires can be catastrophic for the ecosystem, in addition to claiming large forest areas and threatening non-forest areas.

The National Fire Plan of 2000 and the Healthy Forest Restoration Act of 2003 recommend active management in the form of mechanical thinning and prescribed fires on federal lands to reduce hazardous fuel accumulation in order to control wildfire within the historical range in terms of size, intensity, and severity (O'Laughlin, 2005). Prior to these acts, resources to implement fuel management on public land were limited and little headway had been made. Even with this recent legislation, annual budgets for fuel management on public land are low, making cost-effective allocation of fire prevention efforts a particularly timely issue.

Mathematicians and economists have modeled fire risk in forests using non-spatial stand-level models that implicitly assume actions conducted in one stand do not affect fire risk in adjacent stands. For example, Reed (1984) found that, at the stand level, fire risk acts as a risk premium on the discount rate and shortens the optimal rotation age of a stand. Yoder (2004) extended the Reed models to incorporate prescribed fire as a tool for reducing fire risk. Amacher *et al.* (2005) modeled planting density, in addition to rotation age and timing of fuel treatments. The volume of salvageable timber was assumed to increase with an increase in fuel treatment efforts and to decrease with planting density. They found that the optimal rotation age can be higher than the Faustmann rotation age for two reasons: (1) fuel treatment cost acts as a planting cost so that increasing rotation age reduces the present value of the infinite series of fuel treatment cost and (2) fuel treatment cost reduce the potentially large expected losses associated with higher rotation ages, which is beneficial because salvage is a decreasing function of planting density so that less timber volume due to low densities can be offset by a longer rotation age. Although these models have endogenous risk on one stand, they ignore spatial relations between management activities in one stand and fire risk in other stands. Fires commonly move across management unit boundaries, which limit the value of single-stand level analyses. In the forest planning literature, analysts incorporate the spatial movement of fire but omit uncertainty. For example, Sessions *et al*. (1999) and Hof *et al*. (2000) model the optimal spatial pattern of fuel management and timber harvest for a particular realization of fire events. These studies do not model the relations between management decisions and the risk of fire damage.

In this paper, we integrate a fire simulation model into a 2-period stochastic dynamic program to search for and analyze optimal spatial allocations of timber harvest and fuel management in the face of spatial endogenous fire risk. By spatial endogenous fire risk, we mean that the spatial allocation of management activities partially determines fire risk. Because fuel management is needed before the fire season, locating that activity requires consideration of both stochastic events - fire ignition and weather - and spatial interactions - fire spread. Here, ignition occurs randomly over the forest but the spatial pattern of forest attributes paired with the spatial pattern of fuel management determine how fire spreads from a particular ignition point. Using a fire simulation model to create all possible fire patterns for all possible decisions, a land manager in our model considers trade-offs between fire risk, timber harvest value, and fuel treatment cost in a spatially explicit manner.

From the solutions, we draw insights regarding profit-maximizing behavior under the risk of fire. The results inform the spatial focus of fuel treatments, often ensuring that no fast fire spread corridors develop, even if some high fire spread rate areas are left untreated. The spatial, multi-plot results depict different relations between the optimal harvest age and risk than most single stand analyses and describe situations in which diverse management actions occur on stands that are identical except for their location.

2. The Model

A risk-neutral land manager solves a stochastic dynamic program that condenses the problem into a series of recursive equations. There are $s = 1,....,M$ possible states of the initial landscape, S_s^t ,that are described by a spatial configuration of stand age and fuel condition at time t . These transition to $n = 1,....,N$ possible future states, S_n^{t+1} , at the beginning of period $t+1$ depending on the decision vector, D_k^t (a spatial allocation of actions: fuel treatment and harvesting, see Figure 1), and stochastic fire events that occur after the decisions are applied in period t . In each recursive equation, a land manager must choose a set of actions, D_k^t, applied during period t to maximize $V(S_s^t)$, the net present value of the current period plus the expected maximum net present value of future periods, $V(S_r^{t+1})$:

[1] $$V(S_s^t) = \max_{D_k^t} \ \{v(S_s^t, D_k^t) \ + \ \beta \ \sum_{r=1}^{N} P(S_r^{t+1}; S_s^t, D_k^t) \ \ V(S_r^{t+1})\}$$

In our two-period problem, we consider M possible initial states at the beginning of the first period. A land manager chooses the spatial configuration of forest management activities in each of two 10-year planning periods to maximize net revenue in the current period and the expected maximum net present value of future periods. There are N possible states at the beginning of the second period arising from decisions and fire events in the first period and R possible ending states at the end of the time horizon arising from decisions and fire events in the second period. The decision vector represents $k = 1,....,K$ possible combinations of actions taken in each management unit (MU).

The problem is solved in two stages using backwards induction. The algorithm uses complete enumeration in the first stage to identify the decision in the second period, D_k^2, that maximizes net revenue plus expected net present value of the ending forest for each beginning state, S_s^2, $s = 1,....,N$:

[2] $$V(S_s^2) = \max_{D_k^2}\{v(S_s^2, D_k^2) \ + \ \beta \ \sum_{r=1}^{R} P(S_r^T; S_s^2, D_k^2) \ \ L(S_r^T)\}$$

and then, in the second stage, to identify the decision in the current period, D_k^1, that maximizes net revenue plus the expected maximum net present value of the second period for a given initial state, S_s^1, $s = 1,....,M$:

[3] $$V(S_s^1) = \max_{D_k^1}\{v(S_s^1, D_k^1) \ + \ \beta \ \sum_{r=1}^{N} P(S_r^2; S_s^1, D_k^1) \ \ V(S_r^2)\}$$

where all variables are defined as follows:

$v(S_s^t, D_k^t)$ The net revenue (income from timber harvest less planting and fuel treatment costs) in period $t = 1,2$ as a function of state s at the beginning of decision period t and decision vector k.

β The discount factor.

$P(S_r^{t+1}; S_s^t, D_k^t)$ The probability that state *r* occurs at the beginning of period $t+1$

for a given initial state s and decision vector k in period t.

$L(S_r^T)$ The discounted value of the land and standing timber at the end of the time horizon, assuming there is no fire, timber standing at the end of the time horizon is harvested at financial maturity, the stand is replanted, and, again, harvested at financial maturity, and so-on in perpetuity.

In this model, the probability of a particular fire pattern (e.g. a particular landscape representing a particular spatial arrangement of fuel and vegetation conditions) is computed by:

$$P(S_r^{t+1}; S_s^t, D_k^t) = \sum_{w_i=1}^{W} P_w \sum_{i=1}^{I} \prod_{j=1}^{I} \{\delta_{ij} \cdot \lambda_j + (1-\delta_{ij})(1-\lambda_j)\}\{z_{rj} \cdot \gamma_{ij}(S_s^t, D_k^t, w_i) + (1 - z_{rj})(1 - \gamma_{ij}(S_s^t, D_k^t, w_i))\} \quad [4]$$

where all variables are defined as follows:

P_w The probability of a weather condition w occurring.

δ_{ij} The Kronecker delta, i.e., $\delta_{ii} = 1$ and $\delta_{ij} = 0$ for $i \neq j$.

λ_i The probability of fire ignition occurring in stand i.

$\gamma_{ij}(S_s^t, D_k^t, w_i)$ The binary variable representing stand j burning when ignition occurs in stand i as a function the state S_s^t at the beginning of decision period t, and decisions D_k^t applied during decision period t and weather condition w during the fire. The fire model that was used to generate these variables is described below.

Z_r A vector describing the burn pattern that corresponds with state S_r^{t+1} with $z_{rj} = 1$ if stand j burns, and $z_{rj} = 0$ if stand j does not burn.

To parameterize the model, we used a hypothetical landscape consisting of seven hexagonal management units (MUs) in which one MU is surrounded by six MUs from all directions. This landscape is owned by a risk neutral individual who faces an inter-temporal decision over two 10-year periods. The size of each MU was set so that, given the parameters in a fire simulation model (described below), (1) the whole landscape can be burned only if each MU has fuel conditions that lead to very high or high spread rates and the weather condition is severe and (2) most other combinations of fuel and weather conditions result in fires that spread from the ignition point to at least one other MU. These conditions allow us to illustrate spatial strategies for selectively applying fuel treatments and to avoid extreme outcomes in which all MUs are harvested or no MUs are treated[i].

We constructed a set of initial landscapes to demonstrate the effect of spatial fire movement on efficient forest fire fuel management. We assumed that no prior fuel treatment had been applied. This assumption reflects the current situation in many areas because little area has been treated due to limited budgets - especially on public land. This assumption restricts fuel conditions to two initial states: (1) untreated young stands with a very high fire spread rate and (2) untreated mature stands with a medium fire spread rate. To limit the number of initial landscapes while allowing spatial interactions between MUs with different fuel conditions, we set young stands to age class 1 (10–19 years old) and mature stands to age class 3 (30-to-39 years old). In this forest type, financial maturity in the absence of fire occurs in age class 4 (40-to-49 years old). With two states and no wind or slope (so that mirror images are identical), there are 26 unique initial landscapes, as depicted in Figure 2 (descriptions of the state variables used in Figure 2 can be found below the graphic).

A decision in each 10-year decision period is a vector indicating which action should be taken in each MU. In the current period, a land manager chooses from four possible actions:

1. harvest (residues are not removed, denoted as “cut”),
2. harvest and fuel treatment (prescribed burning and mechanical thinning, denoted as “cut & fuel”),
3. fuel treatment only (denoted as “fuel”), and
4. grow only (denoted as “grow”).

In our problem, we only consider forest fire fuel management in the current period, so that in the second period only two actions, “cut” and “grow,” are available. Decisions made in the first and second periods reflect a terminal condition where the management unit’s future value is calculated as the present discounted value of harvesting at financial maturity forever - that is, fire beyond the second period is not considered in earlier decisions. Fire events can occur in the current and in the second period after decisions are applied to the landscape.

The state of each MU's forest is defined by two attributes - age class and fuel condition. Age class determines timber harvest volume and affects fire spread rate. To ensure the empirical relevance of our results, we use timber and fire models that reflect conditions in Oregon's dry, "eastside" forests.[ii] Timber harvest volume was projected using the East Cascade Variant of the Forest Vegetation Simulator (Smith-Mateja, 2004). The initial tree list for the simulation was constructed to represent the eastern Oregon dry forest type. We employed ponderosa pine forest type stand data from Malheur National Forest. Age class is incremented by one in each period unless the MU is harvested or burned, in which case age class is set to zero. Because tree growth in each MU is deterministic here, the only stochastic factor in this model is fire disturbance.

Fuel condition, along with stand age class, determines fire spread rate. We used fuel conditions and fire spread rates for untreated stands that were developed by Anderson (1982) and fuel conditions and fire spread rates for treated stands that were developed by Stephens (1998). These fuel models (Table 1) represent typical field situations for Oregon's eastside forests.

In the framework developed here, spatial endogenous risk arises because a management action in an MU changes the fuel condition and, hence, the fire spread rate in the MU, depending on the initial fuel condition and age class. Fire spreads faster in young stands than in old stands. Fuel treatment slows the spread rate of fire. As a result, management actions in one MU affect fire risk in adjacent MUs. Computation of the probability of transitioning from state S_m^t to state S_n^{t+1} for a given decision vector D_k^t, as defined by equation [4], requires:

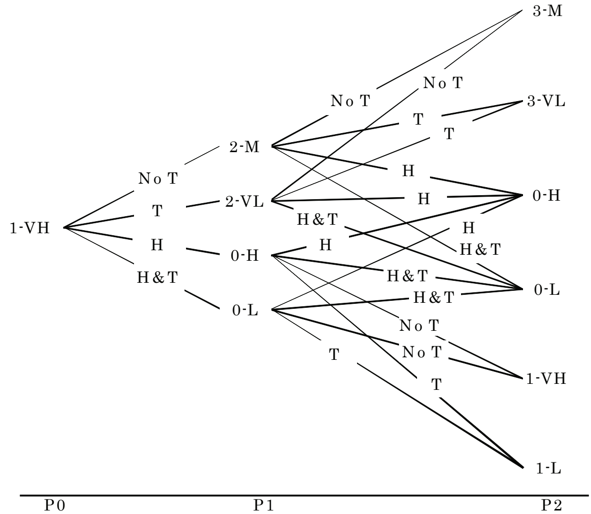
γ_{ij} The binary variable of the j^{th} MU burning when ignition occurs in the i^{th} MU. We used a fire simulation model to project fire growth for a given weather condition, ignition point, and spatial pattern of fuel conditions. Fire growth and behavior are modeled using Huygens' principle of wave propagation (Anderson, 1982), which is commonly used in fire behavior models such as FARSITE (Finney, 2004) and BEHAVE (Andrews, 1986).

This technique simulates the growth of a fire front as a two-dimensional ellipse wave (Richards, 1990). The dimensions of an elliptical wave are calculated using a spread rate that depends on fuel conditions. Fire duration is determined by weather[iii]; we assumed that fire duration is 48 hours for moderate weather and 96 hours for severe weather (Graetz, 2000)[iv]. We define an MU as burned if at least half of the area of the MU is burned[v]. For a given landscape, weather condition, and ignition point, the simulation model is deterministic, making the probability of spread from MU_i to MU_j, γ_{ij} a binary variable equal to 1 if unit j burns and 0 if unit j does not burn. Simulations for each combination of ignition point, weather condition, and unique initial spatial pattern of fuel conditions that can arise from the 26 initial landscapes after all possible decision vectors are applied define the probability of spread from MU_i to MU_j.

λ_i The probability of ignition occurring in MU i. The fire may ignite in any MU after the current period's decision is made. In this study, each MU has a fixed ignition probability of 0.2 to represent the probability of fire ignition over a decade[vi].

P_w The probability of weather condition w occurring. The frequency of different weather conditions during fire events is exogenous. In this study, moderate and severe weather are assumed to occur with probability of 0.6 and 0.4 respectively[vii].

Stochasticity of the fire event is captured by a combination of ignition probabilities in each MU and probabilities of different weather condition occurrence. Because there are seven possible ignition locations and two different weather conditions, a set of possible spatial fire patterns is derived from each spatial pattern of fuel conditions. The specific economic parameters used in this study are within a recent historical range of values. For example, fuel treatment costs range from \$125/ha to \$2,500/ha depending on fuel conditions (USDA, 2006); we used a value of \$500/ha. The other values in the model are a real discount rate of 4%, which represents the real long-



P0: period 0, P1: period 1, P2: period 2
No T: grow only (no fuel treatment), T: fuel treatment only, H: harvest, H&T: harvest and fuel treatment

Figure 1. Dynamic programming network for an initial condition

Table 1. Fuel conditions and fire spread rates used in the fire simulation model.

Fuel Condition	Age Class	Fuel Treatment	Source	Fire Spread Rate (m /min)
Very High (VH)	1	No	Anderson (1982)	0.82
High (H)	0	No	Anderson (1982)	0.66
Medium (M)	2 or higher	No	Anderson (1982)	0.35
Low (L)	0 or 1	Yes	Stephens (1998)	0.28
Very Low (VL)	2 or higher	Yes	Stephens (1998)	0.18

term productivity of capital as suggested by USDA Forest Service guidelines (Row *et al.*,1981), a stumpage price of \$1,250/ha[viii], and a regeneration cost of \$500/ha[ix]. We assume the landowner is a price-taker so that stumpage price is independent of harvest volume and timber inventory, implying that changes in timber supply from this landscape are too small to affect stumpage price.

3. Optimization Results

In discussing the results, we focus on the impact of two types of spatial externalities on the spatial allocation of fuel management efforts. First, if fire ignites in an MU with a very high spread rate, it is highly likely to spread into adjacent MUs. Hence, the management decision on one MU alters the fire risk facing other MUs - a “spread rate externality.” Second, harvesting an MU without fuel treatment increases the spread rate of fire and, therefore, increases fire risk on neighboring MUs - a “harvest externality.” As a result of these spatial externalities, land managers face spatial trade-offs that affect the optimal spatial pattern of fuel treatment and the optimal timing of harvest.

To examine the pure “spread rate externality,” the model was solved for each of the initial landscapes shown in Figure 2. The optimal decisions for each landscape are shown in Figure 3 and the landscapes resulting from application of the decisions are shown in Figure 4. The landscapes depicted in Figure 4 are subjected to fire events in the current period. Only two of the four management options were selected “grow” and “fuel.” Because no stands reach financial maturity until the second period and there is no constraint on the number of MUs which can be treated, there is no harvest in the current period. If MUs with young stands and very high fire spread rates “1-VH” are treated, their fuel condition changes to a low fire spread rate “1-L.” If MUs with stands in age class 3 and medium fire spread rates “3-M” are treated, their fuel conditions change to a very low fire spread rate “3-VL.”

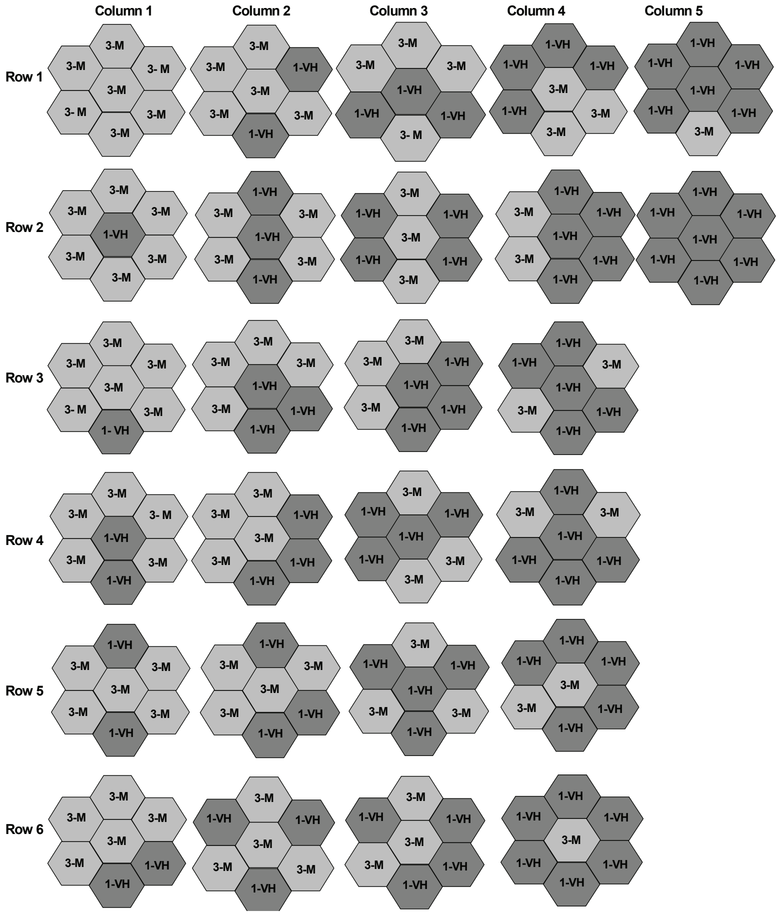
Some general tendencies can be observed in Figures 2, 3, and 4 with respect to: (1) the treatment of MUs with very high spread rates (“1-VH”), (2) the treatment of the center MU, and (3) the allocation of treatment between MUs with very high spread rates but young trees with little timber value in the current period and MUs with medium spread rates but mature stands (“3-M”) that will likely be harvested in the second period.

First, optimal fuel treatment strategies for “1-VH” MUs fall into two categories - either treat all “1-VH” MUs or selectively apply fuel treatment to insure that treated MUs (“1-L” or “3-VL”) surround all “1-VH” MUs after applying the optimal decision. These treatments result in either eliminating "1-VH" MUs or separating them from each other. Separating MUs with high spread rates reduces the risk of a significant loss of value in multiple MUs because this strategy slows down the spread of fire when fire fronts move into treated MUs. It also reduces the chance that fire will threaten high value timber (age class 3) from more than one side.

Second, the center MU is always treated if it is "1-VH." If the "1-VH" center MU were not treated, fire ignition from this MU could spread all over the landscape and cause a significant loss of value. When the center MU is "3-M," deciding whether or not to treat it depends on spatial configurations. For example, in the landscape shown in Figure 3, row 5, column 1, all "3-M" MUs are treated, including the center MU. The "1-VH" MUs are not treated because they are separated on the initial landscape. However, in the landscape shown in Figure 3, row 6, column 4, the "3-M" center MU is not treated, while all of the surrounding "1-VH" MUs are. If the "1-VH" MUs were not treated, an ignition in any one of them would spread through adjacent "1-VH" MUs and fire would attack the valuable "3-M" timber in the center MU from multiple sides, increasing the chance that MU burns.

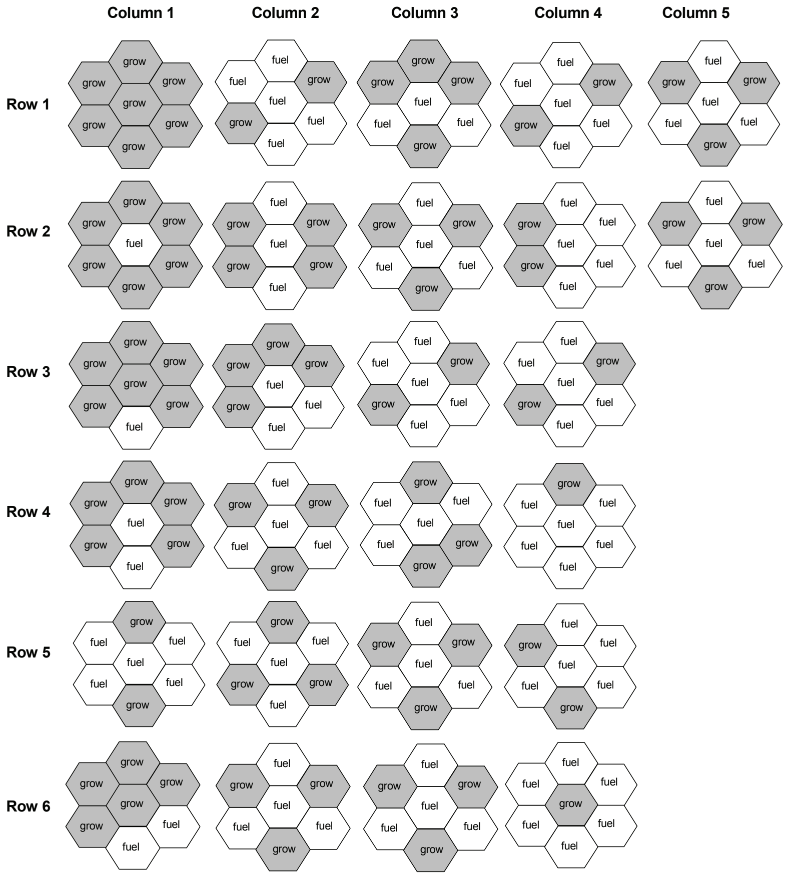
The example of not treating the "3-M" center MU also illustrates our third point. There is a trade-off between protection of on-site values by treating "3-M" MUs and prevention of the spread of fire by treating "1-VH" MUs. In a non-spatial model, the incentive to protect nearly mature stands is higher than it is to protect young stands. But in a spatial model, the spread of fire through "1-VH" units can threaten multiple MUs, or threaten valuable MUs from multiple sides, so that the overall loss due to fire on the landscape may be greater if the "1-VH" MUs are left untreated.

To examine the second externality - the harvest externality - and its impact on harvest age, we compared the effect of fire risk on harvest age in a non-spatial model to the effect of fire risk on harvest age in our spatial model. In this forest type and economy, when no fire risk exists or is considered, it is financially optimal to harvest at age class 4. In a non-spatial model, fire risk lowers harvest age because, as Reed (1984) demonstrated, the probability that a stand will burn acts as a risk premium on the discount rate. However, in a spatial model, because newly harvested and young stands have high fire spread rates (Anderson, 1982; Huff *et al*., 1995), harvesting a stand increases fire risk in adjacent stands. This spatial externality causes land managers to postpone harvest in order to reduce risk in adjacent stands.



Fuel Conditions – Fire Spread Rate (Table 1)				
VL=Very Low	L=Low	M=Medium	H=High	VH=Very High

Figure 2. Spatial configuration of age class and fuel condition for each of 26 initial landscapes at the beginning of the current period. Each MU is labeled "age class—fuel condition."



Decisions – Management Activities Applied			
Fuel	Cut & Fuel	Grow	Cut

Figure 3. Spatial configuration of optimal decisions for each of 26 initial landscapes in the current period. Each MU is labeled "action."

Fuel Conditions – Fire Spread Rate (Table 1)				
VL=Very Low	L=Low	M=Medium	H=High	VH=Very High

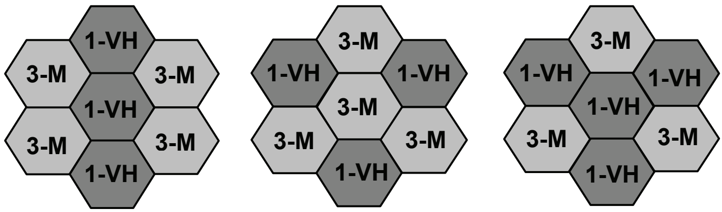
Figure 4. Spatial configuration of age class and fuel condition for each of initial 26 landscapes after optimal decision is applied, but before fire event occurs in the current period. Each MU is labeled "age class—fuel condition."

To illustrate, we define a "threshold risk level" as the level of fire risk (i.e., the probability that an MU will burn) that induces a land manager to harvest at age class 3 rather than at age class 4. In a non-spatial model, using our growth projections, the threshold risk level for a single MU without spatial interdependency is 0.068. If the probability that an MU will burn exceeds this level, the MU will be harvested at age class 3 rather than age class 4. We then solved the spatial model for a subset of three initial landscapes (Figure 5A). We selected these landscapes because they illustrate various cases where "3-M" MUs are adjacent to "1-VH" MUs and, therefore, face the risk of fire spreading. We added a constraint to the model limiting the number of MUs that can be treated to one. This constraint ensures that the risk in each MU cannot be reduced to a low level by treating several MUs and forces a land manager to face trade-offs between harvesting and fuel treatment. If, in the spatial model, the threshold risk level for an MU is higher than in the non-spatial model, spatial externalities lead land managers to hold stands longer than they would if they did not consider spatial externalities.

In the three solutions, the center MU was chosen for treatment (Figure 5B) and none of the "3-M" units were harvested. That treatment and harvest pattern means that the risk levels in those MUs were insufficiently high to justify harvest at age class 3 rather than at age class 4. The risk levels - the probability the MU would burn - are 0.073, 0.094, and 0.115 for landscapes 1, 2, and 3 respectively. These levels exceed the risk threshold in the non-spatial model of 0.068, indicating that a land manager who considers the spatial externality associated with timber harvest will be less likely to harvest timber "early" than one who does not.

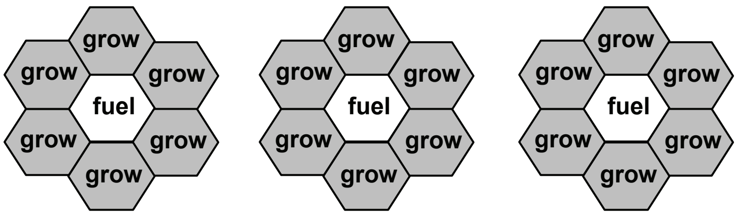
In addition, this harvest externality can create a heterogeneous harvest strategy among homogeneous MUs. Without the spatial externality, at high enough interest rates a price-taking land manager will harvest all MUs that are financially near matured. With the spatial externality, at higher interest rates, a land manager harvests some but not all MUs at that lower age class. For example, Figure 6B depicts the optimal decisions for the three initial landscapes in Figure 6A at a discount rate that induces a spatial land manager to harvest only some of the MUs at age class 3 rather than age class 4. In landscapes 1 and 2, some “3-M” MUs are harvested at the discount rate of 4.6%, while the others are treated without harvesting. In landscape 3, two “3-M” MUs are harvested at the discount rate of 4.9%, while one “3-M” MU is treated without harvesting. This heterogeneous harvest pattern within age classes is optimal when spatial interactions are considered because harvesting all valuable MUs without fuel treatment yields a landscape prone to larger fires due to connected MUs with high fire spread rates. By treating “3-M” MUs that are adjacent to harvested “3-M” MUs, a land manager can reduce overall fire risk on the landscape.

A: (1) (2) (3)



Fuel Conditions – Fire Spread Rate (Table 1)				
VL=Very Low	L=Low	M=Medium	H=High	VH=Very High

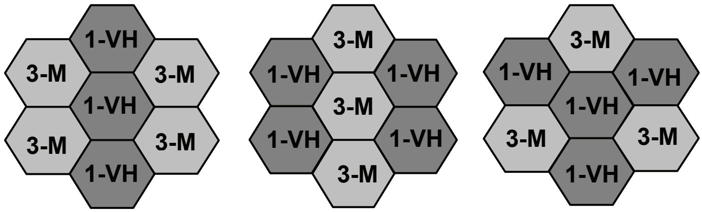
B: (1) (2) (3)



Decisions – Management Activities Applied			
Fuel	Cut & Fuel	Grow	Cut

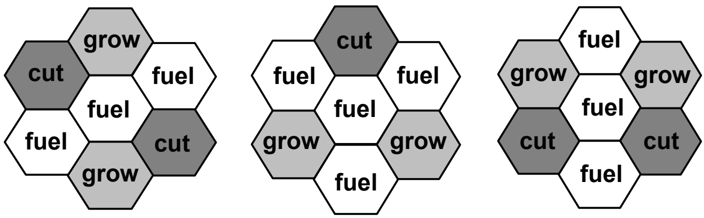
Figure 5. Spatial configuration of (A) age class and fuel condition class and (B) optimal decisions for 3 selected initial landscapes used to demonstrate effect of spatial externality on likelihood of early timber harvest. Each MU is labeled (A) “age class—fuel condition” and (B) “action.”

A: (1) (2) (3)



Fuel Conditions – Fire Spread Rate (Table 1)				
VL=Very Low	L=Low	M=Medium	H=High	VH=Very High

B: (1) 4.6% (2) 4.6% (3) 4.9%



Decisions – Management Activities Applied			
Fuel	Cut & Fuel	Grow	Cut

Figure 6. Spatial configuration of (A) age class and fuel condition class and (B) optimal decisions for 3 selected initial landscapes used to demonstrate effect of increasing discount rate on stand age at timber harvest. Each MU is labeled (A) "age class—fuel condition" and (B) "action."

4. Discussion and Conclusions

This paper extends the forest economics literature by combining: (1) an evaluation of harvest and fuel management decisions on a spatial rather than a single-stand level; (2) a fire behavior model that characterizes spatial endogenous risk; and (3) a model of uncertain fire events rather than assuming a particular type or pattern of fire. This framework forms a platform for evaluating and improving current fuel management to efficiently manage forests at risk of catastrophic fires.

The results presented here confirm the appropriateness of a commonly pursued management strategy. Fire and forest scientists often suggest policies that limit the ability of fires to grow, such as policies that create firebreaks between areas of high spread rates (Finney, 2001; Hirsch *et al*., 2001; Finney and Cohen, 2003). A non-spatial analysis cannot comment on such policies, but it can state whether fuel treatment is beneficial on a given unit. The optimal spatial allocation of fuel management derived in this paper confirms this rule of thumb policy because the optimal patterns often follow a "separation" strategy that uses fuel treatments to separate high spread rate forests from each other, thereby limiting the spatial extent of fires. Those treatments may prove optimal in areas that a non-spatial analysis does not treat.

Our analysis also dispels two commonly held ideas about forest management in the face of fire risk. First, although the Forest Ecosystem Management Assessment Team (FEMAT, 1993) proposed to focus treatment on young stands to reduce fire hazard (Committee on Environmental Issues in Pacific Northwest Forest Management, 2000), a triage style of determining where to locate fuel management that targets young stands with high fire spread rates often wastes time and money. Because areas with young trees of little short-term value often have the highest spread rates, whether to treat those areas depends critically on neighboring areas' fuel conditions and timber values. The spatially explicit model determines that the optimal solution lies in between a triage policy that looks just at spread rates and a single-stand perspective that ignores spread rates and simply protects standing timber value.

Second, despite a recent study of salvage logging and fuel treatments by Amacher *et al*. (2005), traditional forest economics calls for harvesting younger trees in the face of fire risk. Again, this perspective derives from a stand-level analysis. The spatial analysis here shows that because harvesting can increase spread rates and increase risk to neighboring areas, spatial endogenous fire risk increases harvest age when spatial externalities matter. Similarly, this analysis finds that identically stocked areas will be harvested at different times depending on their location and the condition of neighboring areas in an effort to manage fire risk.

Although this stylized framework considers only seven management units and uses other simplifying assumptions, it provides some general rules of thumb for forest managers. For example, this analysis encourages managers to recognize the impact of actions on one land unit on the risk and appropriate management of other land units - fire's ability to spread implies tradeoffs between protecting an individual management unit's value and protecting a group of management units from fire spread. In addition, the results about the interior management unit here suggest that, in a real forest setting, forest managers should pay special attention to any management units that act as gateways to other management units. Similarly, separating areas of high fire spread rates can prove more important than targeting the highest spread rate areas. Implementation of a "separation" strategy requires a land manager to have flexibility in choosing areas for fuel treatment depending on initial spatial configurations and spatial fire risk generated on them. Therefore, any political or management restriction that constrains the allocation patterns of fuel management efforts may increase the risk of fire damage. For example, the Endangered Species Act (1973) may limit the area that can be treated, which can conflict with a land manager's objective to mitigate the risk of fire damage.

Recent studies in the forest planning literature that recognize fire spread, but assume given ignition points and weather conditions, provide a framework for analyzing "what if" scenarios for a particular spatial fire pattern (Finney, 2001; Sessions *et al*., 1999; Hof *et al*., 2000; Stratton, 2004). A land manager will be better off implementing the resulting fuel management strategy only if that particular fire occurs. If a land manager ignores uncertainty about fire events, the loss to fire could be high if an unexpected fire pattern occurs.

Our framework provides a foundation to research other fire risk management issues. Areas of current research include salvage logging, effectiveness of fuel treatments, tradeoffs between fuel treatment costs and fire suppression costs, non-timber values and fuel management, and ownership patterns. In all of these policy-relevant research questions - as in the basic analysis presented here - the spatial relationships and connections across management units dominate the optimal solutions and lead to different patterns of forest management than derive from stand-level analyses.

Because forest fire suppression policy in the United States has led to an accumulation of forest fire fuel in the last century, fire poses an enormous threat to forest values, particularly in the western states. The limited budgets for preventive measures to mitigate fire loss risk increase the importance of making cost-effective location decisions about fuel management. This paper provides a framework for making those decisions and identifies priorities for managers undertaking those activities.

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[i] After some experimentation, we chose an MU size of 370 ha. While this is unrealistically large for a timber harvest unit (Oregon forest practice regulations restrict maximum clearcut size to 48 ha (Oregon Department of Forestry, http://egov.oregon.gov/ODF/lawsrules.shtml#rulesubject, accessed August 2006), it allows us to demonstrate the effect of spatial externalities on optimal fuel treatment. In addition, we consider a ten-year period, which brings this MU size assumption into alignment with 10 years of 48 ha harvests.

[ii] Other research performs wide sensitivity analysis on the parameter values used here and describes other types of forests, but the spatial results presented here are quite general.

[iii] Although fuel moisture contributes to fire growth and can vary with weather, we assume constant fuel moisture for simplicity and because our results are weather-dependent (Hartford and Rothermel, 1991; Rothermel *et al*., 1986; Finney, 2004).

[iv] To simulate the fire front, 360 points are expanded for the duration of the fire, at the spread rate corresponding to the fuel condition of the MU where it occurs, using equations developed by Richards (1990).

[v] Fire does not necessarily kill trees. Tree death by fire is a function of crown scorch height and tree diameter (Agee, 1993). Under conditions where litter and understory fuel build up due to long fire-return intervals, crown fires with high intensity occur in ponderosa pine type forests (Agee, 1993; Pollet and Omi, 2002). Because we are interested in cases where fires destroy timber value and causes financial loss for landowners, we only consider cases where fires initiate crown fires, damage trees, and results in total loss of timber value. For a public land manager, this scenario could mimic a situation in which a fire removes all timber values because salvage logging following fire is prohibited.

[vi] Precise information on an annual ignition probability for specific areas is not readily available. There are studies focused on estimating the risk of fire. Preisler *et al*. (2004) defined the probabilities of fire for different fire sizes. However, in this study, we used the average fire arrival rate to represent an ignition probability, as in studies by Amacher, Malik, and Haight (2005) and Reed (1984). Reed used three different average fire arrival rates, 1%, 2% and 5%. According to Bork (1985) the average fire arrival rate ranges from 2% to 6% for ponderosa pine forests in Oregon. We also assume that fuel treatment conducted is effective for the duration of the 10-year decision period. Several studies suggest this assumption is reasonable (Loehle, 2004; Fiedler and Keegan, 2003).

[vii] Graetz (2000) examined three weather conditions: wet, moderate, and severe. His project's science team suggested these weather conditions occur with the probability of 0.1, 0.65, and 0.25 respectively, based on precipitation data obtained from a weather station in Medford,

Oregon. Because we would like to model our case in drier conditions than his study area, we set a higher probability for severe weather conditions and consider only moderate and severe weather conditions.

[viii] Stumpage price of ponderosa pine has fluctuated from about \$50/mbf to \$600/mbf (in nominal dollars) between the years 1973 to 1995 (Haynes, 1998).

[ix] Sessions *et al*. (2004) estimated regeneration cost to successfully establish 500 conifer trees per ha, considering probability of success and cost of restocking failures on different slopes. They report regeneration costs that range from \$625 to \$1,108 per ha.

“空間的外部性”が火種管理の効率的配置問題に及ぼす影響

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要約 ： 本研究では，森林火災中に発生する“空間的外部性”が，火種管理の効率的配置問題に及ぼす影響を研究した．ここでは，空間的外部性を空間的かつ内因的リスク構造により現わした．分析には，森林火災シュミレーションモデルと空間的確率動的最適化モデルを組み合わせたフレームワークを使用した．様々な仮想の物理的経済的に一様でない森林ランドスケープに対して最適解を数値計算的に求めることにより，効率的森林管理の空間配置に関して一般的な洞察を与えた.

キーワード ： 森林火災，確率動的計画法，空間的モデル，空間内因的リスク，空間的外部性