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Mitigating fire risk to late-successional forest reserves on the east slope of the Washington Cascade Range, USA

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Abstract

A fire-risk model was developed using a stand-structure approach for the forests of the eastern slopes of the Washington Cascade Range, USA. The model was used to evaluate effects of seven landscape-scale silvicultural regimes on fire risk at two spatial scales: (1) the risk to the entire landscape; and (2) the risk to three reserve stands with stand structures associated with high conservation priorities (layered canopy, large trees, multiple species). A 1000 ha landscape was projected five decades for each management regime using an individual tree, distance-independent growth model. Results suggest that a variety of silvicultural approaches will reduce landscape fire risk; however, reserve stand fire risk is minimally decreased by thinning treatments to neighboring stands. Intensive fuel reduction through prescribed burning and selection of reserve stands in favorable topographic positions provide substantial fire risk reductions. © 1998 Elsevier Science B.V.

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1. Introduction

In recent years, considerable attention has focused on the identification and protection of late-successional forest reserves of the Western US and Canada (FEMAT, 1993). The reserves are highly valued for their biological and social values (Swanson and Franklin, 1992).

Protecting the reserves from catastrophic disturbance requires not only understanding the susceptibility of the reserve forest, but also the susceptibility of adjacent stands and the landscape as a whole. Late-successional forests are often predisposed to destructive crown fires as a consequence of their multi-layered canopies (Oliver and Larson, 1996). Many of these reserves are located within a landscape mosaic of complex ownership and management patterns in which secondary forests and managed plantations abut the protected reserves. The risk of fires in adjacent stands will depend on their structure, weather conditions, and ignition sources (Agee, 1993). If a susceptible structure is relatively common at the landscape-scale, the risk of a catastrophic fire affecting the reserve stand may be large.

Silvicultural treatments such as thinning and prescribed burning can lessen the fire-susceptibility of a given stand (Agee, 1993), however, such intensive

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management of reserve stands is generally prohibited. One option for lessening the fire risk to reserve stands is to decrease fire risk at the landscape-scale. Silvicultural treatments could be limited to neighboring stands or applied more widely across the landscape.

In this paper, we evaluate the effectiveness of differing landscape-scale silvicultural regimes in mitigating fire risk for both the entire landscape and several fire-susceptible late-successional reserve stands. Seven landscape-scale silvicultural regimes ranging from no treatment to intensive thinning with prescribed burning are simulated for five decades. We use an individual tree, distance-independent growth model to project future stand conditions and mimic silvicultural manipulations. Projected stand conditions are evaluated using a fire-risk model developed for the eastern slopes of the Washington Cascade Range, USA. The fire-risk model incorporates equations that evaluate the potential for crown-fire ignition and crown fire spread based on forest stand conditions.

2. Methodology

2.1. Mechanics

The fire-risk model was built in Microsoft Access, a database management program, using output from the Landscape Management System (LMS; McCarter et al., 1996; McCarter, 1997), a computerized system that integrates landscape-scale data, stand-scale information, and growth models [in this case FVS[1] Northern Idaho variant (Wykoff et al., 1982)] to project changes through time across forested landscapes (Oliver and McCarter, 1996). Fig. 1 details the flow of information to the fire-risk model. We developed the fire-risk model using a synthetic landscape based on inventory data from forest stands from the east slope of the Washington Cascade Range.

The fire-risk model is based on two equations (Van Wagner, 1977). The first relates heat of ignition and flame length and average base of the live crown to the surface intensity required to initiate crown fires:

$$I_0 = (Czh)^{1.5} \qquad (1)$$

where I_0 is the critical surface intensity (kW/m), C=0.010 (Van Wagner, 1977), z the height of the base of the live crown (BLC) (m), and h the heat of ignition (largely a function of overstory foliar moisture) (kJ/kg).

Critical surface intensity (I_0) can be estimated for a range of values for foliar moisture content and height to base of live crown (BLC). Values of I_0 represent minimum levels of fireline intensity necessary to initiate crown fire (Agee, 1996) and can be used to directly calculate critical flame lengths using Byram's equation (Byram, 1959). A regression equation was developed from tables in Agee (1996) to relate foliar moisture content and BLC to the critical flame length necessary to initiate crown fires (Appendix A).

The crown-fire initiation equation (Eq. (1)) was developed in boreal forests where the majority of vegetational biomass exists in a single canopy layer. Due to the stratified nature of many of the eastside forest canopies, the movement of fire from the ground into the crown may be more complicated than that proposed in the equation. However, lacking any other quantification of crown-fire initiation based on stand structural attributes, we have adopted this method with the understanding that it is a first approximation.

The second equation relates crown bulk density and rate of spread to the ability of a crown fire to spread:

$$S = Rd \qquad (2)$$

where S is the mass flow rate (kg/m^2/s), R the rate of spread (m/s), and d the crown bulk density (kg/m^3).

The crown fire spread equation (Eq. (2)) approximates mass flow rate (S). The rate of spread (R) can be adjusted by the user through a dialog box. Regression equations for predicting crown bulk density (d) were developed from Brown (1978) in (Agee, 1996) for ponderosa pine [*Pinus ponderosa* (Dougl. ex Laws.)], Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco], and grand fir [*Abies grandis* (Lindl.)] (Appendix A).

Through a network of database queries incorporating the crown bulk density equations and stand inventory data, we established a critical flame length for crown-fire initiation and a mass flow rate for crown fire spread unique to each stand. Further queries compared the critical flame length to the flame length predicted for each stand by BEHAVE, a fire behavior program (Burgan and Rothermel, 1984). If the flame length predicted by BEHAVE exceeded the critical flame length for a given stand, a crown-initiating fire

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[1] Model formerly known as Prognosis

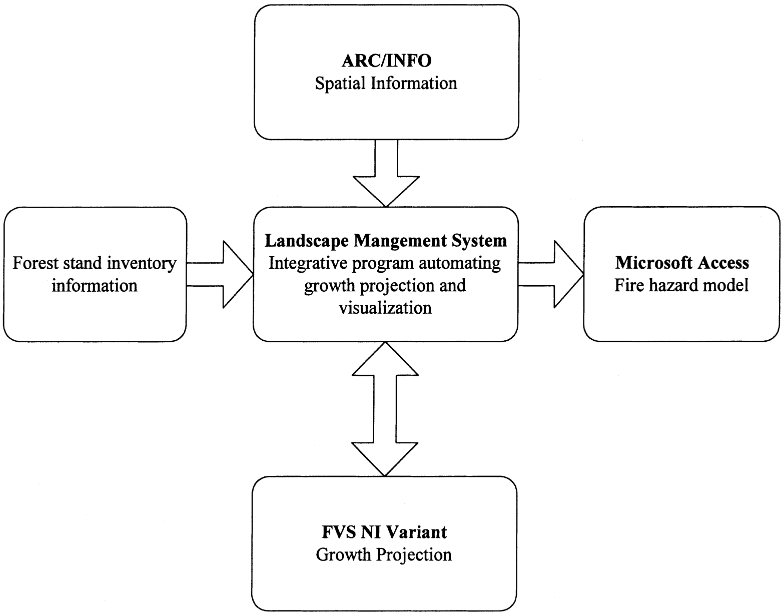

Fig. 1. Information flows into the fire-risk model. Arrows indicate the direction information flows.

could occur. Other queries compared the mass flow rate (S) of each stand with a critical mass flow rate (S_0=0.05, Van Wagner, 1977 (this variable can be adjusted by the user)). If $S > S_0$, then a fire in the crown would be likely to spread through the canopy layer of the stand.

One of 13 standard fuel models (NFFL) was dynamically assigned to each stand for each decade of the projection based on species dominance, total basal area, and the presence of an understory layer from projected inventory information. Understory layers are detected if trees with BLC <3 m account for more than 2.5% of total stand basal area. Fuel model assignments were tested by using stand visualization technology (SVS, (McGaughey, 1997)) to compare stands to photographs depicting average fuel model conditions (Anderson, 1982). The BEHAVE fire behavior model was integrated into the fire-risk module by using data from BEHAVE runs for NFFL fuel models 2, 5, 8, 9 and 10 (Burgan and Rothermel, 1984). Environmental variables for the BEHAVE runs were chosen to represent 90th percentile fire weather and are presented in Appendix B (Agee unpublished data). The slope environmental variable was adjusted according to slope values for each stand.

In designing this model, we chose to focus on the potential of a crown-fire initiating from a surface fire or of a fire spreading through the canopy of a stand, rather than on the effects of an actual fire. At the landscape scale, individual stand risk represents only a portion of the fire risk affecting each stand (Turner and Romme, 1994). The effects of neighboring stands and their fire risk need to be incorporated. Having calculated risk for each stand on the landscape, we created another set of queries to address the effect of neighboring stands. In particular, we were interested in those stands that are upwind and/or downslope from a focus stand because of the implications for fire movement across the landscape. We designed queries to identify downslope neighbors based on average elevation for each stand. A wind direction variable was created allowing the user to set the direction of the prevailing wind during severe fire weather (e.g., N, NE, E, SE,. . .). A query then identifies the adjacent polygons that are upwind from each stand. The risk from these adjacent upwind and downslope stands is then calculated. The area of stands in each risk category and their proportion across the landscape are summed and displayed in a graph as output. For this discussion, slope risk is

Stand Risk Rating

		Burn	
		N	Y
Spread	N	1	2_b
	Y	2_s	3

Wind or Slope Risk Rating

		Neighbor burn or spread into focus	
		N	Y
Stand Risk	1	1	2
	2_b	1	2
	2_s	1	3
	3	1	3

Fig. 2. Matrices showing details of the fire risk rating system. Stands are assigned a rating from 1–3 based on whether they can burn, spread, or both. Each stand is also assigned upwind and downslope risk ratings from 1–3. Ratings are based on whether neighboring stands can burn or spread into the focus stand and the stand risk rating for the focus stand. Total Stand Risk=(Stand Risk+Wind Risk+Slope Risk)−2; where 2 is a scalar that moves the range of risks from 3–9 to 1–7.

defined as the risk to the focus polygon associated with its downslope neighbor and wind risk is defined as the risk to the focus polygon associated with its upwind neighbor (Fig. 2). The total risk to a polygon is defined as:

$$\text{Total fire risk} = (\text{polygon risk} + \text{wind risk} + \text{slope risk}) - 2 \qquad (3)$$

Two is subtracted from the ranking to scale values from 1–7 instead of 3–9.

The rating method described in Fig. 2 weights the importance of polygon, slope, and wind risk equally. Stand risk factors are only half as important as landscape risk factors. In a landscape with large polygons, the importance of neighboring stand attributes to total risk diminishes. Larger polygons have reduced edge-to-area ratios, thus increasing the probability of internal compared to external ignition. Weights of polygon vs. neighbor risk factors can be adjusted to account for the size of individual polygons in a landscape. To test the model's sensitivity to risk factor weights, we evaluated the scenarios with stand risk factors of equal importance to landscape risk factors, and stand risk factors being twice as important as landscape risk factors.

The proportions of the landscape in each risk level through time can be estimated by analyzing the projected information from LMS in the fire-risk module. Landscape-scale silvicultural treatment scenarios can be applied in LMS and then analyzed for fire risk at the landscape scale (graphical output) and at the individual stand scale (tabular output of polygon, wind, slope, and total risk).

2.2. Model assumptions and limitations

In any modeling effort there are inherent limitations that arise as a consequence of trade-offs between efficiency and thoroughness. We attempted to make assumptions as realistic as possible, based on current knowledge of fire ecology and forest stand dynamics. Nonetheless, in simplifying such a broad category as fire risk across a landscape through time to a manageable computational problem, we sacrificed complexity. We will discuss these sacrifices briefly, justifying our assumptions and trying to identify the limitations as they relate to the fire-risk module.

2.2.1. The stand inventory database

The module was developed using composite data from an eastside database. The stands were chosen to represent a relatively homogenous landscape typical of mid-elevation forests from the eastern slope of the Washington Cascade range. The dominant species include ponderosa pine, Douglas-fir, and grand fir. Results from a more heterogeneous landscape may be somewhat different, particularly with respect to combinations of fuel models and variability in adjacent stand structures.

2.2.2. BEHAVE models

The BEHAVE fire behavior model includes a standardized set of 13 NFFL fuel models. These models are designed to represent four major fuel types: grassland; shrubland; timber; and slash (Anderson, 1982). For eastside forests, fuel models 2, 8, 9, and 10 are generally applied. We have added NFFL fuel model 5 to address dense stands of regeneration. In order to use stand inventory data for assigning fuel models, we established a set of decision rules based on dominant species, basal area, and the presence of an understory. We chose values for basal area and height of understory trees based on field estimates. These variables can be adjusted to reflect better estimates of fire fuel behavior.

2.2.3. Base of the live crown

The regression equation for crown-fire initiation is based on two variables: overstory foliar moisture; and the average height of the base of the live crown for the stand. The foliar moisture can be adjusted as a variable in the model to mimic seasonal fluctuations in water availability. The height of the BLC presents several problems. The theory for the crown-fire initiation model was developed in boreal forests where the stand canopy is typically a monolayer (Van Wagner, 1977). In the eastside stands that we used in developing the fire-risk module, multi-layered stands are common. Using the average height of the BLC for these stands may not provide a realistic result. For example, consider a stand with two distinct layers: an overstory with an average height of the BLC at 25 m; and an understory with an average height of the BLC of 1 m. If the number of trees in each layer is equal, the average height of the BLC for the stand will be 13 m. The risk of crown-fire initiation may be grossly underestimated if it is based on this calculation. In order to address this issue, we used the midpoint between the minimum and average height of the BLC instead of the average for calculating crown-fire initiation risk. In addition, adapting the crown-fire initiation model to multi-layered stands was problematic due to the lack of information on the effects of fire initiation in one layer on the potential for fire in another layer. In the two-layered stand example used above, the ability of a fire to crown will depend on the height of the understory trees and the length of the flames generated as the understory trees burn. FVS growth projections generate a rapid increase in the minimum height of the BLC under most stand conditions. Consequently, the risk of crown-fire initiation inevitably decreases through time unless natural regeneration is simulated or the fuel model changes to one with a higher flame length.

2.2.4. Species mixtures

The regression equations to calculate crown bulk density are based on data from three species: ponderosa pine; Douglas-fir; and grand fir. Several other species for which crown bulk density information was unavailable are included in the stand inventories. For these species, we used crown bulk density values for Douglas-fir as they were intermediate between those of ponderosa pine and grand fir. In reality, the bulk density of the crowns for these species may be higher or lower. If these unknown crown bulk densities are higher, crown fire would tend to spread more readily for constant stocking and average tree diameter; if they were lower, crown fires would be less likely to spread through the canopy.

2.2.5. Stand layering

The crown bulk density is calculated from stand stocking (trees/ha) and average tree diameter. In multilayered stands these numbers may not provide an accurate reflection of mass flow rates through the canopy. The crown fire spread rate is more a function of the overstory trees than the total number of trees in the stand. The crown bulk density may be overestimated by including the understory trees in the stand averages. Given various rates of spread (R) this may represent the difference between a crown fire spreading or not spreading. To address this, we have incorporated a user-defined landscape-scale variable, height of the understory (HU), that allows for flexibility in isolating the overstory trees for crown bulk density calculations.

2.2.6. The influence of proportion of neighbor's flame length on total risk

In assessing the risk of neighboring stands on focus stands, we have incorporated the effect of the neighboring stand's flame length, as assigned by the BEHAVE model, on initiating crown fires in the focus stand. Sensitivity analysis showed that using the full flame length of the neighboring stand overwhelmed all

Table 1
Treatments applied in each management scenario

Treatment	Focus stands [a]	Adjacent stands [b]	Non-adjacent stands [c]
None	none	none	none
Light	none	none	thin 30%
Mix1	none	thin 30% [d]	thin 70%
PB	none	thin 30% and PB [e]	thin 70% and PB
Mix 2	none	thin 70%	thin 30%
FocusPB	PB	none	none
Intense	thin 70%	thin 70%	thin 70%

[a] Reserve stands with desirable late-successional structural characteristics to protect.

[b] Stands immediately adjacent to the reserve stands.

[c] Stands that do not share a border with the reserve stands.

[d] All thinning is from below (i.e. small trees first) as percent removed in trees per unit area.

[e] PB stands for prescribed burn.

other considerations of risk from adjacent stands. To limit this problem, we used the average of the flame lengths for the focus stand and the neighboring stand. We are unaware of any data describing the change in flame length as it moves from one stand structure to another.

2.3. Management scenarios

We ran a variety of management scenarios using LMS to assess the utility and flexibility of the model (Table 1). We chose three stands (Fig. 3(A)–(C)) with multi-layered canopies to represent late-successional reserves and designed scenarios with the goal of reducing reserve stand fire risk. The protected stands were either isolated or surrounded by a buffer zone comprised of adjacent stands. Each scenario will be described in turn, from the least intensive (no treatment) to the most intensive treatment (heavy thinning across the entire landscape, reserves included). Throughout these analyses two factors will be considered: the level of risk for the entire landscape; and the level of risk for the reserve stands.

All scenarios were projected five decades. The thinning and prescribed burning treatments were applied to half of the treated stands in each decade; therefore, individual stands were treated every two decades. Natural regeneration was simulated by adding 50 shade tolerant saplings (Douglas-fir and grand fir) to the tree list in each decade. Foliar moisture levels were set at 90% (Agee, unpublished data). Spread rate (R) was set to 0.5 m s^{-1}, which is considered well in the range of wind-driven crown fires. Winds were assumed from the south, for actual landscapes the primary wind direction during extreme fire weather should be derived from historic data. The critical value for S_0 was 0.05 (Van Wagner, 1977), and the height above which trees were included in the crown fire spread calculations was 3 m. These variables were kept constant for all scenarios to isolate treatment effects.

Seven management scenarios were simulated in this analysis (Table 1). The first scenario (None) included no treatment of any stand throughout the projection. In the second scenario (Light), stands outside the buffer zone surrounding the reserve stands were lightly thinned. Treated stands were thinned 30% from below (based on trees per acre, not basal area). In the third scenario (Mix1), a mixed thinning treatment, reserve stands were isolated and two levels of thinning intensity were applied to the landscape. The mixed thinning scenario isolated the reserve stands within a clump of moderately treated stands which are in turn surrounded by heavily treated stands. The moderately treated stands were thinned 30% from below and the heavily treated stands were thinned 70% from below. In the fourth scenario (PB), thinning treatments were identical to Mix1, but included a simulated prescribed burn in the thinned stands. The prescribed burn was simulated by adjusting fuel loads in the NFFL fuel models of BEHAVE. The load and depth of surface fuels were reduced by 50% (van Wagtendonk, 1974,

Fig. 3. Planimetric map showing stand boundaries and elevation contours. Reserve stands are identified.

1996). In the fifth scenario (Mix2), stands adjacent to the reserve stands were thinned 70% from below. All other stands were thinned 30% from below. The goal was, through moderate-to-intense thinnings, to reduce the fire risk of those stands adjacent to the reserve stands to minimize the risk of the reserve stands. Other stands on the landscape were treated less intensively as their influence on the reserve stands was less direct. In the sixth scenario (FocusPB), fuel loads in the NFFL fuel models of BEHAVE were adjusted to simulate a prescribed burn in reserve stands. The load and depth of surface fuels were reduced by 50% (van Wagtendonk, 1974, 1996). No treatment was simulated in non-reserve stands. In the seventh scenario (Intense), the entire landscape, reserve stands included, were thinned 70% from below.

3. Results

3.1. Management scenarios

3.1.1. No treatment (none)

Landscape risk can be evaluated by examining the proportions of landscape area that fall in each risk category. In the no treatment scenario, landscape risk increases with time (Fig. 4). In presenting the results we refer to stand fire risk scores of 1 or 2 as ‘low risk’ and scores of 6 or 7 as ‘high risk’. In the first decade, 15% of the landscape is composed of high-risk stands, and ≈40% is low risk. By the third decade stands with a risk of 1 occur on less than 10% of the landscape. By the fifth decade, nearly 30% of the landscape is in the high-risk category. Reserve stands A and C had risks

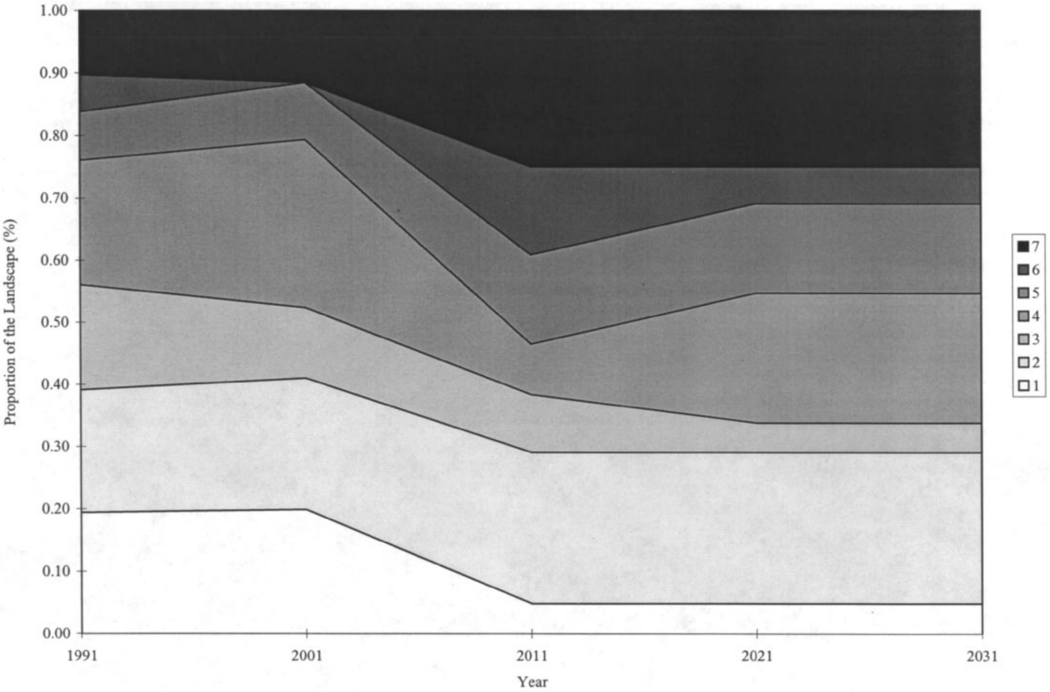

Fig. 4. Proportions of the landscape in different risk classes through time with no treatment. Risk ratings range from 1–7, 7 being highest risk.

of 5 to 7 in every time period. The reserves have high potential for both crown-fire initiation and crown fire spread due to their multi-layered canopy (Table 2). While the fire-risk model does not explicitly take layering into account, the low base of the live crown typical of multi-layered stands increases the potential for crown-fire initiation. Neighboring stands also influence the risk of the reserve stands. Longer flame lengths from different fuel models in neighboring stands will increase the risk in the focus stand. Reserve stand B is located in a valley and, therefore, has few downslope neighbors. The slope risk rating is low and the total risk which started as a 3 in the first decade increased to 5 for the rest of the projection (Table 2).

3.1.2. *Light thinning treatment (light)*

Results (Fig. 5) suggest that a light thinning regime across a portion of the landscape considerably reduces fire risk across the landscape as a whole, but has little-to-no effect on the particular stands chosen for protection. The proportion of the landscape in low-risk categories varies ca. 40% throughout the scenario. Areas with high-risk scores occupy ca. 15% or less of the landscape throughout the 40 year projection. Fire risk in the reserve stands under this treatment are almost identical with fire risks in the no treatment scenario with the exception of the stand A, which had a score of 5 for the light treatment in the fifth decade instead of a 7 with no treatment in the fifth decade. This minor reduction was due to stand A being upwind from a treated stand.

3.1.3. *Mixed thinning treatment with light thinning in reserve buffer (Mix1)*

Greater proportions of the landscape are at high and low risks compared to the light thinning treatment (Fig. 6). The proportion of the landscape composed of low risk stands increases to 50% by the third decade. The amount of landscape in high-risk categories also increases to 25% by the fifth decade.

The reserve stands maintain the same risk as the no treatment reserve stands, and are worse than the light thinning treatment in one time period (in the fifth decade stand A has a 7 for this treatment and a 5 for the light thinning). The partial thinning of adjacent stands in the first mixed thinning scenario does not reduce the

Table 2
Risk ratings for reserve stands A, B, and C for each projected year in each of the 7 management scenarios[a]

	None	Light	Mix 1	PB	Mix2	FocusPB	Intense
A							
1991	5	5	5	5	5	4	5
2001	7	7	7	5	5	4	2
2011	7	7	7	5	5	6	2
2021	7	7	7	5	7	6	2
2031	7	5	7	5	5	6	2
B							
1991	3	3	3	3	3	2	3
2001	5	5	5	3	5	2	2
2011	5	5	5	3	5	2	2
2021	5	5	5	3	5	2	2
2031	5	5	5	3	5	2	2
C							
1991	5	5	5	5	5	4	4
2001	5	5	5	5	5	4	4
2011	5	5	5	5	5	2	2
2021	5	5	5	3	5	2	2
2031	5	3	3	3	3	2	2

[a] The risk rating system ranges from 1–7, 7 being highest.

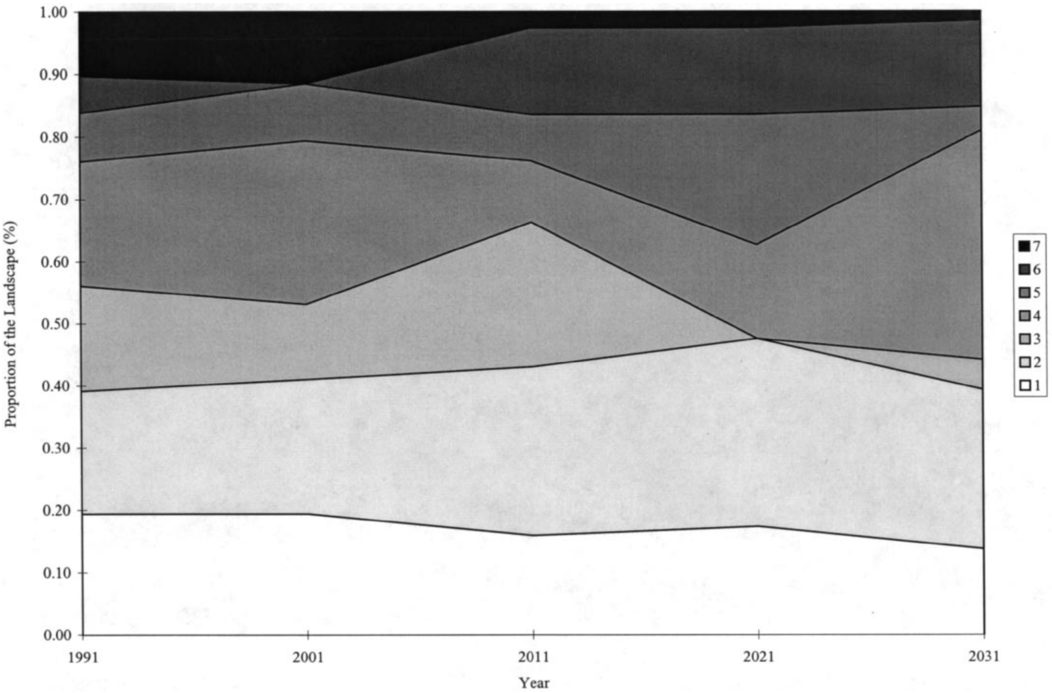

Fig. 5. Proportions of the landscape in different risk classes through time with light thinning.

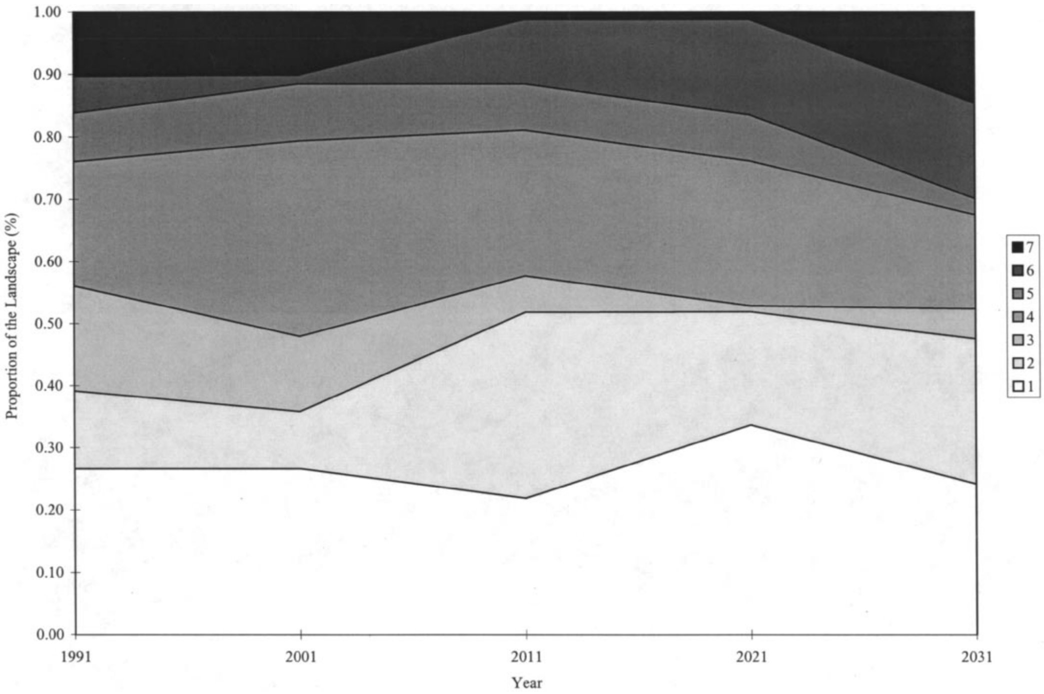

Fig. 6. Proportions of the landscape in different risk classes through time with mixed thinning, light thinning in the reserve buffers.

risk of the reserve stands. By removing only 30% of the stand from below, sufficient basal area and understory trees are kept to maintain the original fire fuel models. The flame lengths from the fuel models of the adjacent stand appear great enough to initiate crown fires in the reserve stands. The reserve stands are sufficiently dense to have mass flow rates in excess of the critical value and can be expected to support crown fires. The combination of these two factors, neighboring stand flame lengths and reserve stand crown fire spread risk, keep the scores for upwind and downslope neighbors at 3 throughout the 5 decade scenario.

3.1.4. Thinning treatment (Mix1) with prescribed burning (PB)

Landscape risk is dramatically reduced in this scenario (Fig. 7). Low-risk ratings comprise 55% of the landscape throughout most of the projections. High-risk ratings averaged 15% of the landscape.

Fire risk in reserve stand C was unchanged from the previous scenario; however, prescribed burning reduced risk in stand A from 7 to 5 and stand B from 5 to 3.

3.1.5. Mixed thinning treatment with moderate thinning of reserve buffers (Mix2)

Landscape-scale risk for this scenario was considerably less than in the no treatment scenario (Fig. 8). Over the entire 40-year period, fire risk was relatively consistent. By the third decade over 60% of the landscape is in the low-risk category, while 10% of the landscape is in the high-risk categories. Reserve stands, B and C, maintained the same risk as in the no treatment scenario. The risk in stand A was reduced because of decreased risk in an upwind stand.

3.1.6. Prescribed burning in focus stands with no thinning (FocusPB)

There is a large reduction in landscape fire risk in this scenario compared to the no treatment scenario (Fig. 9). Prescribed burning lowers reserve stand risk which in turn lowers wind and slope risk in adjacent stands. Over 50% of the landscape is in the low-risk categories throughout the projection. The landscape proportion in high-risk categories is initially less than 1% and climbs to 15% at the end of the projection.

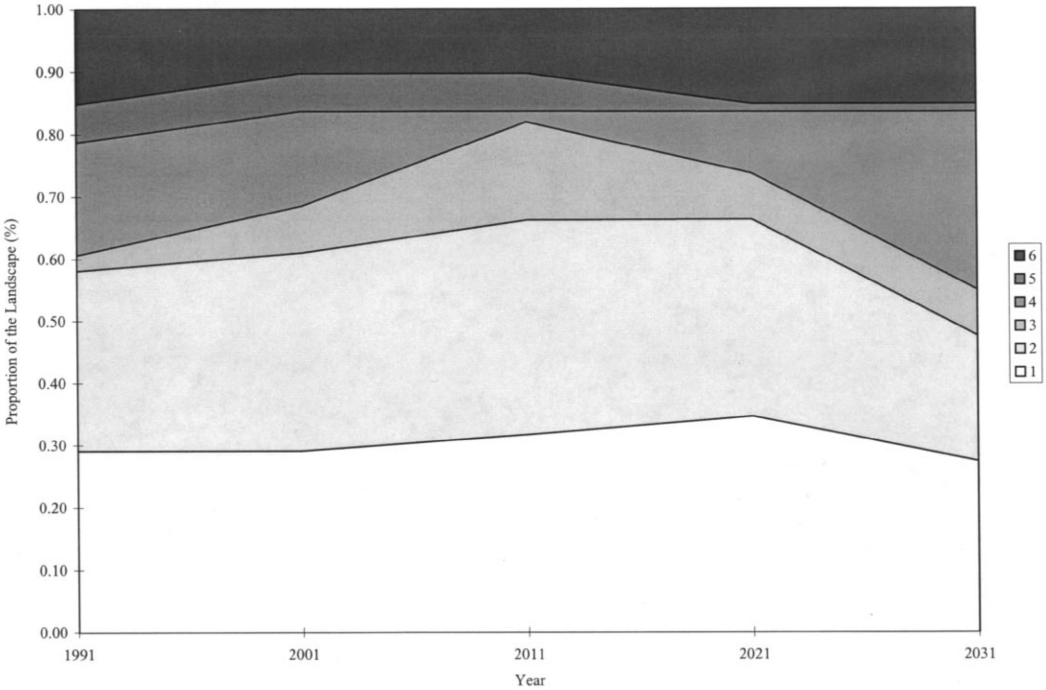

Fig. 7. Proportions of the landscape in different risk classes through time with mixed thinning, light thinning and prescribed burning in the reserve buffers.

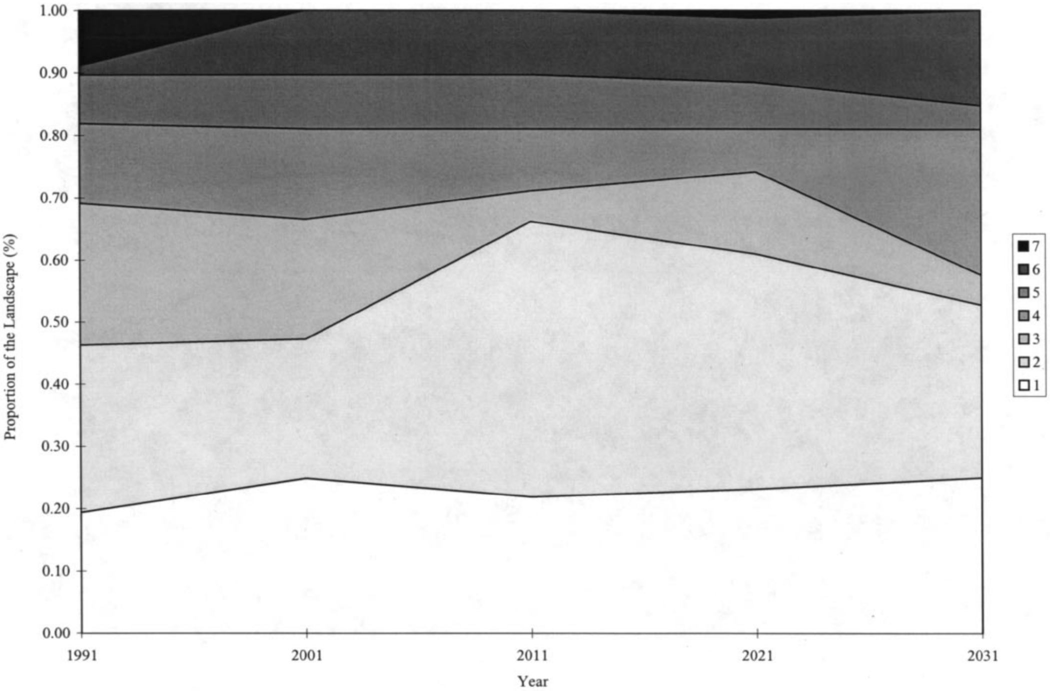

Fig. 8. Proportions of the landscape in different risk classes through time with mixed thinning, moderate thinning in the reserve buffers.

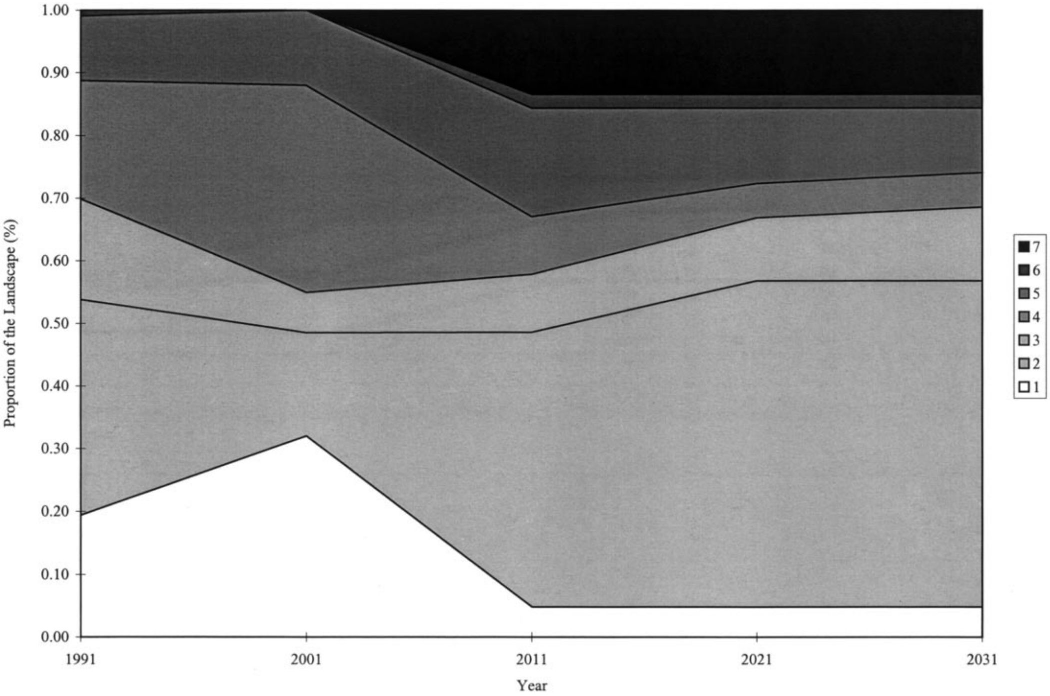

Fig. 9. Proportions of the landscape in different risk classes through time with prescribed burning in reserve stands.

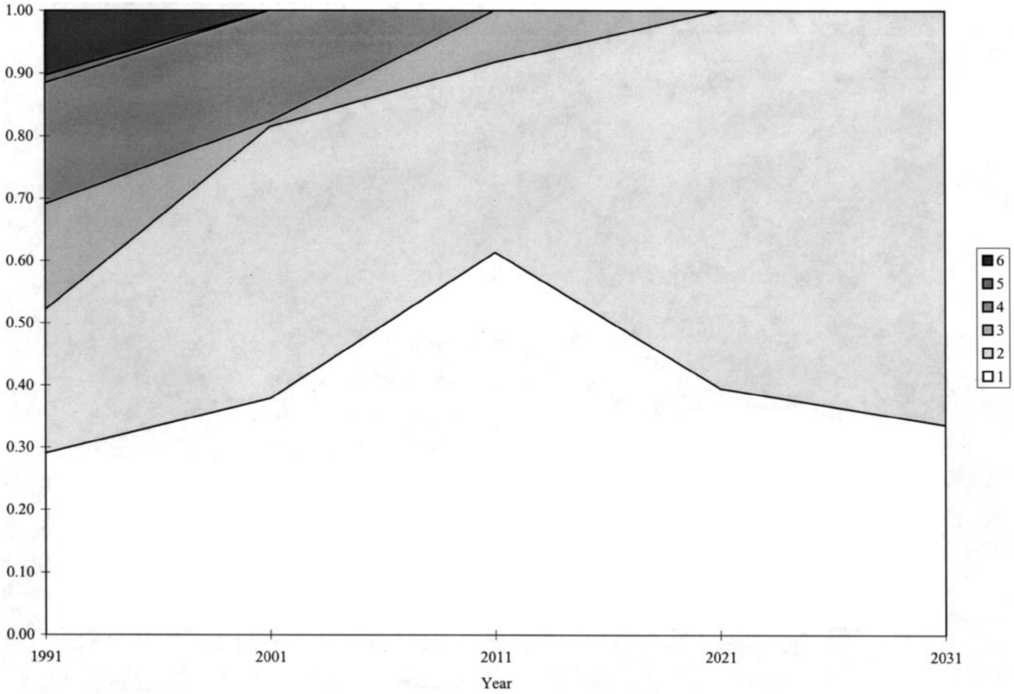

Fig. 10. Proportions of the landscape in different risk classes through time with heavy thinning in all stands, including reserves.

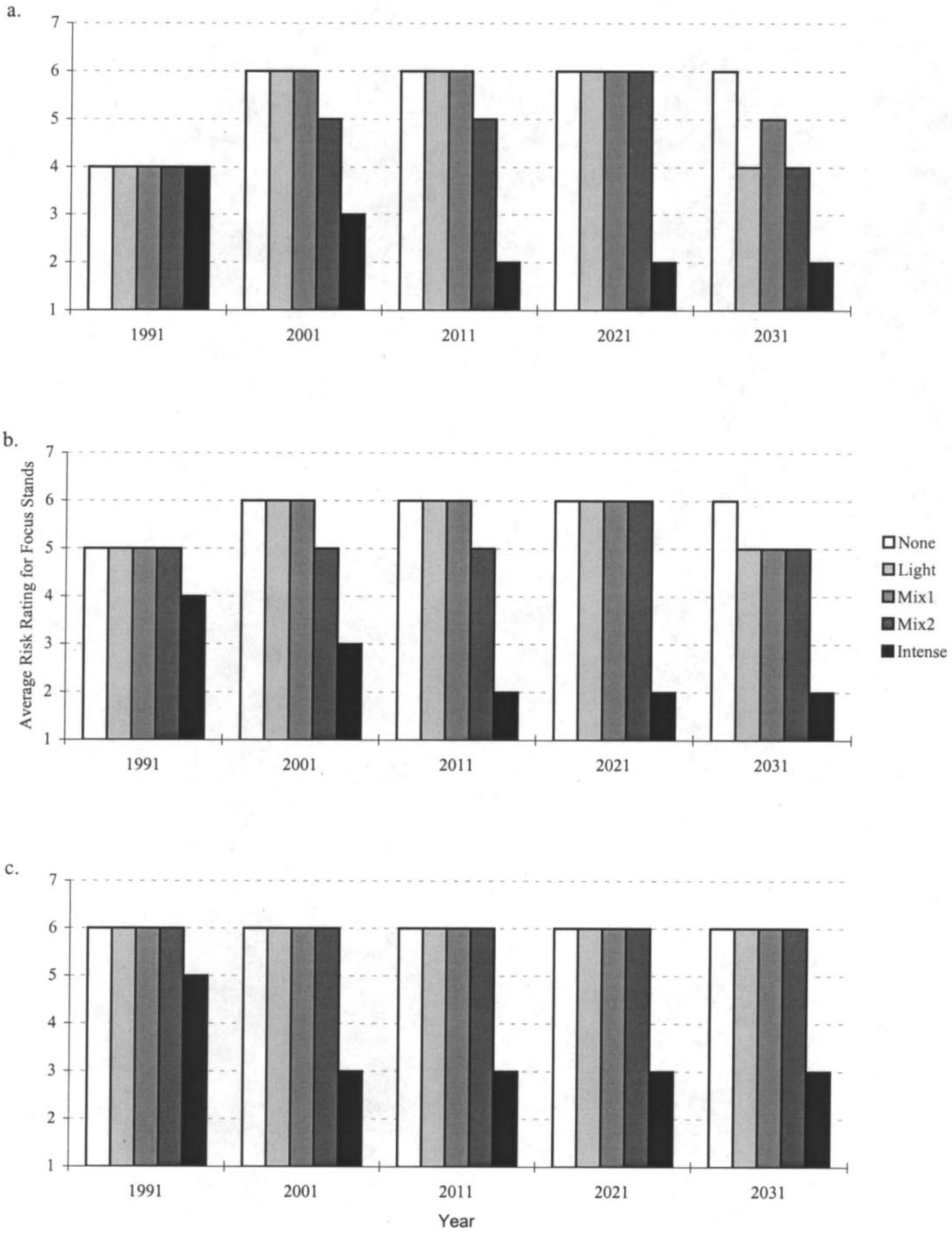

Fig. 11. Average risk rating in reserve stands for each scenario in each year (prescribed burn scenario is not included in this figure). Levels include (% total risk): (a) polygon risk (33%), neighbor risk (66%); (b) polygon risk (50%), neighbor risk (50%); (c) polygon risk (66%), neighbor risk (33%).

In each reserve stand, risk is less than that in the no treatment scenario. This decrease was more substantial for stands B and C than A.

3.1.7. Intensive treatment (intense)

Fire risk was reduced to low categories on 100% of the landscape for the fourth and fifth decade (Fig. 10). The proportion of stands in high-risk categories was small (10%) in the first decade and had entirely disappeared by the second decade. The fire risk to the individual reserve stands varied in the first year (5, 3, and 4 for stands A, B, and C, respectively) in all other years the risk was 2.

The advantage of the minimized risk to the reserve stands is offset by the loss of desired structural qualities. However, thinning from below would leave the largest trees, and for cases in which ample regeneration existed, some understory may persist.

3.2. Sensitivity of the model to size of polygons

To analyze the sensitivity of the model to the relative importance of individual polygon risk vs. the risk associated with neighbors (upwind, downslope) in assessing total risk, the 5 thinning scenarios were run at 3 polygon risk/neighbor risk weighting levels. These levels include (% total risk): (1) polygon risk (33%), neighbor risk (66%); (2) polygon risk (50%), neighbor risk (50%); (3) polygon risk (66%), neighbor risk (33%).

Landscape risk increases only slightly as greater emphasis is placed on individual stand risk factors; however, individual reserve stand risk rises more substantially as the relative importance of polygon risk is increased. Average reserve stand risk in the first decade for the thinning treatments equals 4 in the first weighting level, but climb to 6 when polygon risks are weighed twice as heavily as landscape risks (Fig. 11).

4. Discussion

The seven scenarios presented above address a wide spectrum of management intensities ranging from no treatment to various degrees of thinning and prescribed burning to total treatment at the landscape scale. The fire risk for the landscape decreases steadily as the intensity of management increases. The no treatment scenario has nearly 30% of the landscape in high-risk categories (6 and 7) by the fifth decade, whereas the intensive treatment of all stands has 100% of the landscape in the low-risk categories (1 and 2) by the fifth decade. The light and middle thinning treatments have decreasing proportions of the landscape in high-risk categories and increasing proportions in low-risk categories. In contrast to the landscape-scale fire risk, the stand-scale risk of specific reserve stands identified for protection either does not change with increasing severity of thinning treatment (stands B and C) or changes only slightly (stand A). Thinning with prescribed burning of non-reserve stands provides a moderate reduction of both landscape and individual reserve stand risk. The intensive thinning treatment and prescribed burning in focus stands scenarios both dramatically reduce fire risk in each of the reserve stands, but at the cost of altering the reserve stand structures through manipulations, a consequence which may be incompatible with the goal of conserving late-successional habitat.

Fire risk in individual reserve stands is difficult to mitigate due to the highly multi-layered qualities that characterize late-successional habitat and make them high conservation priorities. The presence of an understory layer increases the risk of crown-fire initiation by lowering the base of the live crown and providing a fire ladder. The presence of both overstory and understory trees increases the number of trees per unit area which, in turn, will increase the crown bulk density of the stand, leading to a higher risk of crown fire spread. In assessing the risk from neighboring stands, the fire-risk module compares the average of the flame lengths from the focus stand and the neighboring stands to the critical flame length of the focus stand. In order to receive a risk of 3 from the upwind or downslope neighbor, the focus stand must be able to have crown fire spread (which most multi-layer stands have due to their high stocking) and the average flame length of the two stands must be higher than the critical flame length of the focus stand (which typically occurs because of the low BLC of the understory species). The only opportunity to reduce this risk would be to have fewer trees in the stand which would require thinning from above and/or below, raising the base of the live crown which would require thinning from below, or reducing the flame length of either the reserve or neighboring stands. Thinning reserve stands to raise the base of the live crown is likely to be unacceptable from a habitat preservation perspective. Prescribed burning to reduce flame lengths in reserve stands may preserve habitat better than thinning; however, the multi-layered nature of the stands may make controlled burning difficult. A combination of thinning treatments and prescribed burning in neighboring stands ensures reserve habitat preservation. Even with thinning and prescribed burning of neighbors two of the reserve stands still had moderate to high fire-risk ratings (5).

Stand B, a designated reserve stand, had a relatively low fire risk scores (3–5) due to its position in a valley bottom. With few downslope neighbors chances for high slope risk were reduced; however, the potential funnel effect that a valley can have on wind movement, might offset the reduced risk by increasing the fire spread rate and crown fire spread risk. In designating reserve stands such topographical considerations may be useful in anticipating fire risks (Camp, 1995).

Intensive treatment may have the unintended consequence of altering the fuel models. Although this situation did not arise in the scenarios we ran, it is conceivable that by thinning too intensively the basal area would decrease sufficiently to assign the stand to NFFL fuel models 2 and 5 which have the longest flame length. If thinning resulted in a stand being assigned fuel models 2 or 5, the risk for neighboring un-thinned reserves could be increased.

5. Conclusion

Management of landscape fire risk involves tradeoffs between individual stand- and landscape-scale considerations (Oliver, 1992). In this analysis individual stand- and landscape-scale risk were given equal weight. Our analyses suggest that even light treatments across a portion of the landscape provide a considerable reduction in overall landscape fire risk, although they may not lower the risk to unmanaged reserve stands with large trees and multi-layered canopies. Increasingly intense treatments will decrease the landscape fire risk further. In contrast, efforts to protect the individual reserve stands through moderate or intense management of adjacent stands provide minimal reductions of individual reserve stand fire risk. Thinning or prescribed burning in reserve stands lowers their fire risk substantially; however, the stand's multi-layered canopy is altered. The combination of thinning and prescribed burning in adjacent stands, to reduce surface fuel loads, is the only treatment tested that provides a moderate decrease in unmanaged reserve stand risk The simulations also suggest that selecting existing or developing new reserve stands in topographically protected areas may abet fire risk management of reserve stands by reducing the number of neighbors that need to be treated.

In landscapes with large stands (i.e. polygons) the importance of neighbor characteristics to fire risk diminishes. Overall landscape fire risk can still be lowered substantially by treating stands; however, treatment of surrounding polygons to protect a large reserve stand will provide little risk reduction for the individual reserve stand.

5.1. Areas for further development

There are many facets of fire behavior and its relation to stand structure that require further research. Exploration of the following questions would most directly benefit future iterations of the fire-risk module that we have described in this paper.

1. How do fires behave in multi-layered stands? Are shorter flame lengths required to initiate a crown fire due to the laddering effect of the vegetation?
2. How do flame lengths alter when they reach the stand edge and how does this relate to the movement of fire between stands?
3. How much of a stand must be adjacent to a focus stand to pose a significant fire risk to the adjacent stand (1, 10, 100 m)? And at what scale should this be measured (i.e. edge to total area ratio, edge alone)?
4. How do mixtures of species affect measures of crown bulk density?
5. At what height do understory trees begin to play an important role in calculating crown bulk density for the model?
6. How should the base of the live crown be calculated in multi-layered stands?

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Appendix A

A.1. Crown-fire initiation regression

Crown-fire initiation regression equations:

$$\begin{aligned}&\text{Critical flame length (m)}\\&\quad = -1.11229 + 0.26883^{*}(\text{Height of crown base})\\&\qquad +0.02274^{*}(\text{Foliar moisture content})\quad r^2 = 0.983\end{aligned}$$

A.2. Bulk density regression

Bulk density regression equations:

$$\begin{aligned}&\text{Ponderosa pine crown bulk density (kg/m}^3)\\&\quad = 0.00051^{*}(\text{mean DBH}) + 0.000024^{*}(\text{TPA})\\&\qquad + 0.000004^{*}(\text{mean DBH})^{*}(\text{TPA})\quad R = 0.950\end{aligned}$$

$$\begin{aligned}&\text{Douglas} - \text{fir crown bulk density (kg/m}^3)\\&\quad = 0.000589^{*}(\text{mean DBH}) + 0.000042^{*}(\text{TPA})\\&\qquad +0.000004^{*}(\text{mean DBH})^{*}(\text{TPA})\quad R = 0.914\end{aligned}$$

$$\begin{aligned}&\text{Grand} - \text{fir crown bulk density (kg/m}^3)\\&\quad = 0.001251^{*}(\text{mean DBH}) + 0.000065^{*}(\text{TPA})\\&\qquad +0.000002^{*}(\text{mean DBH})^{*}(\text{TPA})\quad R = 0.886\end{aligned}$$

Units: Height of the BLC (m); Foliar moisture content (%); Mean DBH (cm); TPA (number of trees per hectare).

Appendix B

B.1. Fire weather environment

90% fire weather environment variables used for BEHAVE runs (Agee unpublished data).

	Models 2 and 5	Models 8, 9, and 10
1 h fuel moisture (%)	3	4
10 h fuel moisture	4	5
100 h fuel moisture	6	6
Live herb fuel moisture	50	50
Live woody fuel moisture	90	90
Wind speed (m/s)	2.74	1.52
Slope	based on stand	based on stand

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