Modeling trade-offs between fire threat reduction and late-seral forest structure

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Abstract: Evaluating the effects of managing for one forest resource in terms of associated impacts on other resources is not easy. Yet methods to identify potential trade-offs among forest resources are necessary to inform people about the implications of management options on public land. This paper uses a case study from a forest reserve in the northwestern United States to quantify trade-offs between fire threat (FT) and late-seral forest (LSF) structure at stand and landscape levels. Simulation of forest dynamics was done with and without silvicultural treatments. A landscape optimization algorithm maximized FT reduction subject to constraints on amount of LSF structure and total area treated. Results suggest that compatibility between the two objectives is possible at the landscape level when LSF structure is about 45% or less of the total reserve area. Conflict can exist between them at the stand level and when more area is required to be in LSF structure in the reserve landscape.

Résumé : Il est difficile d'évaluer les effets de l'aménagement d'une ressource forestière en termes d'impacts sur les autres ressources. Toutefois, des méthodes visant à déterminer les compromis possibles entre les ressources forestières sont nécessaires pour informer la population des implications des différentes options d'aménagement sur les terres publiques. Cet article part d'une étude de cas faite dans une réserve forestière du nord-ouest des États-Unis pour quantifier les compromis entre les risques d'incendie et la structure de la forêt de fin de succession aux échelles du peuplement et du paysage. La simulation de la dynamique forestière a été effectuée avec ou sans traitements sylvicoles. Un algorithme d'optimisation à l'échelle du paysage a maximisé la réduction des risques d'incendie conditionnellement à des contraintes quant à la proportion de forêt ayant une structure de fin de succession et de la superficie totale traitée. Les résultats indiquent que les deux objectifs peuvent être compatibles à l'échelle du paysage lorsque la forêt ayant une structure de fin de succession occupe environ 45 % ou moins de la superficie totale de la réserve. À l'échelle du peuplement, la situation peut devenir conflictuelle lorsqu'il est nécessaire d'avoir une plus grande superficie de forêt ayant une structure de fin de succession dans le paysage de la réserve.

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Introduction

The production of multiple forest resources from public land is desired, yet the resources can appear to compete with each other. Trade-offs among them are often unclear. For example, the Northwest Forest Plan (Plan) created a network of forest reserves to provide habitat for species associated with late-seral forests within the range of the northern spotted owl (*Strix occidentalis caurina*) (USDA–USDI 1994). In these "late-successional" reserves (LSR), federal land managers are to protect late seral forest ecosystems from "loss due to large-scale fire, insect and disease epidemics, and major human impacts" (USDA–USDI 1994, p. B-1). Little information is available, however, to help reserve managers evaluate the relative effects to habitat associated with silvicultural treatments that reduce the likelihood of large-scale disturbances.

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Research into the compatibility of different management objectives can inform public debate by identifying production relationships between forest resources that people value (Haynes and Monserud 2002; Stevens and Montgomery 2002). Compatibility implies that joint production of outputs is feasible. One method for investigating compatibility is production possibility analysis (Stevens and Montgomery 2002; Montgomery 2003), and several studies (Montgomery et al. 1994; Marshall et al. 2000; Calkin et al. 2002) have used production possibility frontiers (PPF) to define relationships between different resources and to identify the opportunity cost of providing one resource in terms of another. We extended this work by using a stand-level simulation model and optimization techniques to develop production relationships between the dual objectives of fire threat reduction and late-seral forest (LSF) structure for one LSR.

Optimization techniques are useful for identifying efficient allocations of resources and for investigating trade-offs of potentially competing outputs in forest planning problems (Hof and Raphael 1997). New optimization techniques, such as heuristics, allow for increased complexity (Boston and Bettinger 1999; Bettinger et al. 2002; and Calkin et al. 2002). This is useful because planning problems with spatial and temporal considerations, like those including fire, are

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complex. The evolution of spatial forest planning methods, from linear programming to classical integer programming to heuristics, has developed from a need for solutions that incorporate complex spatial relationships and that can be implemented operationally (Brodie and Sessions 1991). The public is demanding more from public forests (Murray and Snyder 2000), and as such, integer formulations are useful for representing the desired spatial restriction or conditions necessary for decision modeling.

In the Plan area, which extends from the Pacific Ocean to the eastern side of the Cascade Mountain Range in the United States, debate about public forest management encompasses the roles of fire and of silvicultural treatments to alter its severity or behavior. Regional differences in fire regimes, climate, and management history between forests on the eastern slopes of the Cascade Range (eastside) and those on the westside, translate into different issues for LSR management (USDA–USDI 1994). The eastside, mixed-conifer forests occupy a transitional zone between coastal forests dominated by Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and interior forests of ponderosa pine (*Pinus ponderosa* Dougl. ex P. & C. Laws.), or lodgepole pine (*Pinus contorta* Dougl. ex Loud.). These transitional forests, which lie in a north–south strip extending from British Columbia to California, were historically characterized by mixed-severity fire regimes (Agee 1993). Successful fire suppression in the late 20th century (Dana and Fairfax 1980, p. 199), coupled with grazing and selective logging, are altering the structure, species composition, and disturbance dynamics of these eastside forests. Such changes in forest structure have potential implications both for wildlife habitat and for fire behavior (Hummel and Agee 2003). For example, the northern spotted owl (owl) is a federally listed endangered species in the United States, whose habitat is associated with forest structural complexity (Buchanan et al. 1995; Everett et al. 1992, 1997). Key elements of owl habitat include large trees, downed wood, and multilayered forest canopies (Thomas et al. 1990). Forest structure also interacts with fire behavior, which is a function of fuels, weather, and topography. Increased complexity of forest structures can increase the likelihood of severe, stand-replacing fires (Agee 1997).

Within eastside LSRs, active management may be required to achieve Plan goals, but may impose a cost on other resource objectives (Agee 1997). By examining LSR goals, potential impacts on these goals, and administrative and operational constraints at the LSR (landscape) level, the trade-offs among goals can be better identified, and potential effects of active management within eastside LSRs can be better understood.

Our goal in this study was to quantify the relationship between LSF structure and fire threat. We accomplished this by

(*i*) Developing a spatially explicit fire threat index to capture threats associated with wildfire at the scale of an individual forest unit and the landscape;
(*ii*) Scheduling silvicultural treatments for an eastside LSR to maintain LSF structure while maximizing fire threat reduction over a 30-year planning horizon (three decadal planning periods) using heuristic optimization techniques;
(*iii*) Developing production possibility frontiers by exploring a range of values for our goals within the scheduling algorithm.

Methods

We were guided by a need to develop methods for quantifying trade-offs between two forest management objectives. Our approach uses a combination of sample data, the forest vegetation simulator (FVS), GIS software, and optimization techniques.

Developing a fire threat index

We developed a fire threat index that integrated components of fire threat at the individual unit level ("reference unit") plus the characteristics of neighboring units with high fire threat potential. It is a spatially explicit approach similar to Wilson and Baker (1998). We use the term "threat" to define our index rather than "risk" or "hazard", because risk refers to the chance of a fire occurring and hazard focuses on fuel parameters. Empirical evidence from wildfires (Agee 1996; Agee et al. 2000; Agee and Skinner 2005) and results from simulation modeling (Wilson and Baker 1998) indicate that fire behavior in adjacent units can create additional fire effects in the reference unit. Accordingly, our threat index includes surface fire behavior, torching, and active crown fire potential within the unit, and torching and active crown fire potential in neighboring units that produce additional heat loads into it.

We used three variables: flame length, a wind speed necessary to initiate a crown fire (torching), and a wind speed necessary to sustain independent crown fire activity (crowning) for each unit in each period (Scott and Reinhardt 2001). The first variable, flame length, is mostly applicable to the unit in which the fire is burning. The second, torching, affects the unit in which the fire is burning, but will also affect adjacent units because of spotting potential (firebrands are lifted from the torching action and blown downwind). Torching potential is calculated partly on the basis of flame length, so the two are not independent. The third, crown fire activity, affects the unit in which the fire is burning, and affects adjacent units from firebrand activity plus the heat load from the crown fire that can scorch the crowns of adjacent units. We compared estimated wind speeds required to initiate torching and crown fire in individual units against a local 95-percentile wind speed. For each unit, torching and crown fire spread were either turned "on" if the estimated wind speed was less than the local wind speed or "off" if it exceeded that speed. Although canopy bulk density, a major input to crowning index, may be high, it is weighted as a threat factor only when torching is possible. This is relevant to wildlife habitat, as it means that units with high canopy cover may be retained with low fire threat, if surface fuels and understory layers have low fire potential.

Although we assumed that active crowning was not possible if torching within the unit was not enabled, in theory an active crown fire is possible (Scott and Reinhardt 2001). Van Wagner (1977) noted that usually active crowning requires the additional heat support of an intense surface fire. There are empirical examples where such independent crown fire has apparently occurred, but the mechanisms of crown fire transitioning back to surface fire are not well understood

Table 1. Example fire threat calculation for two representative units.

Reference unit	Upwind units		Fire threat index	Category
Unit 1	One neighbor (100% edge)		2+0+0	Moderate
Flame = 1.0 m	Flame = 1.8 m		+1.0(1+1) =	
Torch = 55 km/h	Torch = 8 km/h		4	
Crown = 43 km/h	Crown = 0 km/h			
Unit 2	Two neighbors (60% and 40% edge)			
Flame = 2.1 m	Neighbor 1	Neighbor 2	5+1.5+1.5	High
Torch = 10 km/h	Flame = 1.8 m	1.1 m	+0.6(1+1)+0.4(0+0) =	
Crown = 5 km/h	Torch = 0 km/h	70 km/h	9.2	
	Crown = 8km/h	40 km/h		

(Scott and Reinhardt 2001). The canopy bulk densities in parts of our study area (averaging 0.12 $kg \cdot m^{-3}$; Hummel and Agee 2003) are low enough that active crown fire activity would be minimal without energetic support from below, given the worst-case wind speeds in our study area.

Mathematically fire threat on a 10-point scale was defined as

$$[1] \qquad \text{Threat10}_i = \text{FL}_i + w_1(\text{Torch}_i + \text{Crown}_i) + \frac{w_2 \sum_{\text{adj}} [\text{Edge}_{\text{adj}} (\text{Torch}_{\text{adj}} + \text{Crown}_{\text{adj}})]}{\sum_{\text{adj}} \text{Edge}_{\text{adj}}(1)}$$

where

i is the reference unit for which fire threat is being calculated;

adj references adjacent units to unit i;

FL_i = 1 if flame length for reference unit i <0.92 m;

FL_i = 2 if flame length is between 0.92 and 1.22 m;

FL_i = 3 if flame length is between 1.23 and 1.51 m;

FL_i = 4 if flame length is between 1.52 and 1.82 m;

FL_i = 5 if flame length is ≥1.83 m;

Torch is 1, if torching potential wind speed is <95% local wind speed; 0, otherwise;

Crown is 1, if crowning potential wind speed <95% local wind speed and Torch is 1; 0, otherwise;

Edge_{adj} is the amount of perimeter accounted for by adjacent unit adj; and

w_1 and w_2 are relative weighting variables.

We weighted in-unit variables more heavily than adjacent unit variables. Within a unit, the flame length was weighted more than torching and crown fire potential based on a 1–5 point scale. The in-unit Crown and Torch variables were given a weight (w_1) of 1.5, while adjacent torch and crown fire threat were given a weight (w_2) equal to 1.0. The weighting of these factors was subjective, and is not meant to be a linear function of fire risk.

This fire threat index (Threat10) is a continuous scale ranging from 1 to 10. However, we collapsed this index into a three-point scale to make it easier to compare results directly with area in reduced threat categories. Where:

Threat is 1, if Threat10 < 3 (low threat, control likely, fair survival of residual trees); 2, if Threat10 is 3–5.99 (moderate threat, control problematical, some residuals survive); 3, if Threat10 ≥ 6, (high threat, control unlikely, high mortality likely).

By using eq. 1 to define fire threat indices for two hypothetical units, we illustrate the contribution from the three fire variables and the influence of neighboring units in defining stand level fire threat (Table 1). Fire threat was evaluated by identifying the proportion of the LSR landscape in each of the low, moderate, and high fire threat categories. We assessed the effectiveness of the simulated silvicultural treatments by identifying if treatments reduced existing threat levels for treated units as well as their neighbors.

Table 2. Structural definitions of late-successional forest and owl nesting habitat.

Late-successional forest	
1	BA at least 55.2 m^2/ha
2	BA trees greater than 61.0 cm DBH ≥ 8.3 m^2/ha
3	BA trees greater than 35.6 cm DBH ≥ 33.1 m^2/ha
4	BA trees less than 35.6 cm DBH ≥ 8.3 m^2/ha
Nesting habitat	
1	BA at least 55.2 m^2/ha
2	BA trees greater than 61.0 cm DBH ≥ 13.8 m^2/ha
3	BA trees greater than 35.6 cm DBH ≥ 11.0 m^2/ha
4	BA trees less than 35.6 cm DBH ≥ 8.3 m^2/ha
5	BA Douglas-fir trees greater than 61.0 cm DBH ≥ 1.2 m^2/ha

Note: BA, basal area.

Defining LSF

Structure-based definitions for LSF and owl nesting habitat were developed (Table 2) (Hummel and Calkin 2005). Despite considerable research in recent decades on forest ecology and northern spotted owl biology in the Pacific Northwest, unified definitions for LSF structure and owl nesting habitat have not emerged, particularly for eastside forests. Our definition of nesting habitat was more restrictive than that for LSF structure: in addition to the required large trees and minimum basal area by diameter class, it included a requirement for large Douglas-fir trees (Buchanan et al. 1995; Everett et al. 1992).

Sampling vegetation conditions and simulating forest development

We used aerial resource photos to identify lsandscape vegetation patches, which were then spatially described in a GIS database. The patches were stratified into a summary matrix of stand types based on structure class and potential vegetation (details in Hummel et al. 2001). In combination, these two attributes yield information on the current forest structure in any given patch and the conditions influencing change over time. We next randomly selected patches for field sampling in 2000 and 2001 to cover the range of stand types. The number of sample exams done within each patch depended on the patch size. Exam data were used to create “tree lists” for that patch using procedures for FVS (Dixon 2003). Any unsampled patches were randomly assigned a FVS tree list within the same stand type. Some photo-interpreted patches were further divided to refine our GIS coverage into units. In the final analysis, a unit was the smallest area to which a treatment could be applied and was our unit of analysis for simulating forest development over time. All of them were assigned the FVS tree list associated with their original patch and linked in the GIS database (for details see Hummel and Calkin 2005). We assumed that the structural conditions within stand types are similar and that within-stand type variation is lower than among-stand type variation.

By using the East Cascades FVS variant (Johnson 1990), the Western Root Disease Model (Frankel 1998), and the Fire and Fuels Extension to FVS (FFE-FVS) (Reinhardt and Crookston 2003), we simulate forest development in each unit over three 10-year cycles (details in Hummel and Calkin 2005). The 30-year simulation period reflects fire return intervals in the region. It creates a baseline case for forest growth in the absence of fire.

Scheduling silvicultural treatments

We used a stand-level simulation process (FVS and FFE-FVS) to develop alternative management prescriptions for a landscape level optimization process. Silvicultural treatments were applied to units according to a rule set based on Plan objectives and management concerns. We simulated the results of multiple treatments on the units; however, only one treatment could be selected for each unit in a decade. By applying all relevant treatments to all eligible units and saving the simulated outcomes, we could then evaluate the conditions in a specific unit relative to conditions in neighboring units before selecting the treatment that best achieved the landscape objectives using a simulated annealing (SA) algorithm. This approach expands silvicultural decision making beyond a unit-by-unit approach and instead develops methods for considering adjacent units and landscape objectives explicitly in such decisions.

Heuristics optimization techniques apply randomness or intelligent programming to limit the search space while maintaining the inherent integer nature of forest planning problems. Several different heuristic techniques have been developed and applied to forest planning problems including SA, great deluge, and tabu search (see Reeves 1993 for a review of these different heuristic techniques). Typically, heuristic solutions cannot assure global optimality of the identified solutions. However, heuristic techniques attempt to find “good” (i.e., close to the global optima) solutions, at a substantial decrease in computational effort. This decreased computational effort allows researchers to analyze more complex problems than could be reasonably analyzed using traditional integer programming techniques.

Bettinger et al. (2002) found that SA produced very good solutions with fast computational times applied to complex forest planning problems compared with seven alternative heuristic algorithms. SA is considered a neighborhood search technique that evaluates the effect of small perturbations, or neighborhood moves, on a current proposed solution (Kirkpatrick et al. 1983). The achievement of the objective function and constraints are evaluated, and the perturbation is either accepted or rejected based on a probabilistic acceptance criterion. By accepting nonimproving solutions, the algorithm is able to effectively search a large portion of a problem’s solution space. As the algorithm progresses, nonimproving solutions are less likely to be accepted, and the algorithm concentrates search efforts in particular high-quality neighborhoods. The acceptance criterion is typically defined as follows:

$$[2] \qquad \text{If } \Delta\text{Obj} \geq 0, \text{ accept new solution}$$

$$[3] \qquad \text{Else if } \Delta\text{Obj} < 0, \quad \text{accept if } e^{(\Delta\text{Obj}/\text{Temp})} > \text{Rand}(0,1)$$

where nObj is defined as the change in the objective function, Temp is the SA temperature parameter, and Rand(0,1) is a randomly drawn number between 0 and 1.

Initially the temperature parameter is set relatively high, allowing a large number of nonimproving solutions to be accepted. The temperature parameter is then slowly lowered or “cooled”, thus decreasing the likelihood that the algorithm will accept nonimproving solutions. Near the completion of the algorithm, the temperature parameter is so low that typically only improving solutions will be accepted. Figure 1 displays the flow chart for our algorithm. The quality of solutions and the computational effort are influenced by the initial and final temperature, cooling rate, and the number of iterations per temperatures; however, there are few guidelines to help determine the appropriate levels for these variables (Boston and Bettinger 1999).

The silvicultural treatment scheduling problem was defined as follows:

$$[4] \qquad \text{Maximize} \sum_t \sum_i \{\text{Threat}_{i,t}(\text{no treatment}) - \text{Threat}_{i,t}\,[j, \text{adj}_i(j)]\}\ \text{Area}_i - B_1\ \text{LSF Penalty} - B_2\ \text{Total Area Penalty}$$

$$[5] \qquad \text{If } \Sigma_t\Sigma_i\ \text{Area}_i \times \text{LSF}_{i,t} < X$$

$$\text{LSF Penalty} = X - \Sigma_t\Sigma_i\ \text{Area}_i \times \text{LSF}_{i,t}$$

$$\text{Else LSF Penalty} = 0$$

$$[6] \qquad \text{If } \Sigma_i\ \text{Area}_i \times \text{Period}_{i,t} > Y \text{ for } t = 1, 2, 3$$

$$\text{Area Penalty}_t = \Sigma_i\ \text{Area}_i \times \text{Period}_{i,t} - Y$$

$$\text{Else Area Penalty}_t = 0$$

$$\text{Total Area Penalty} = \Sigma_t\ \text{Area Penalty}_t$$

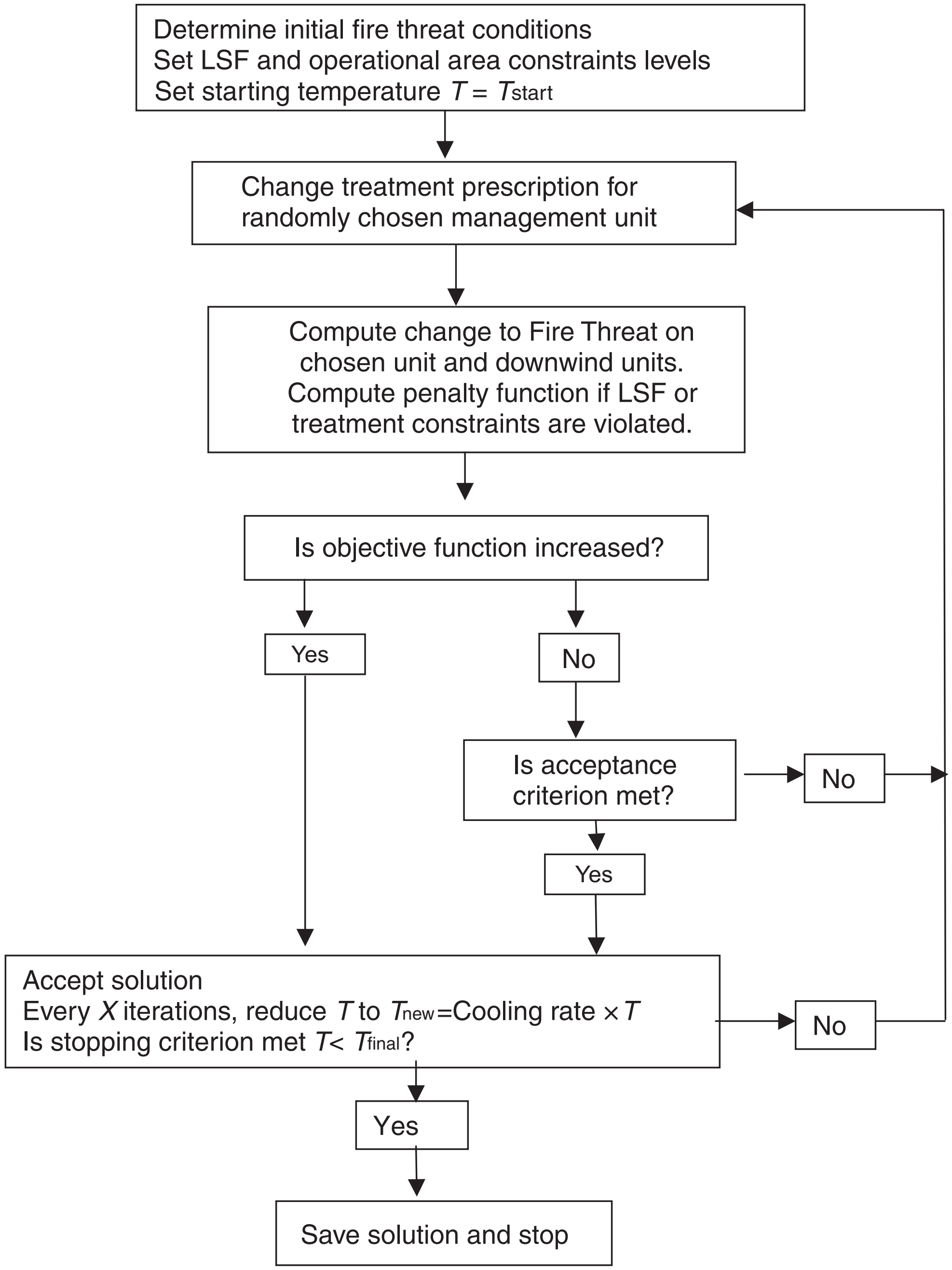
where

i indexes the individual projection units;

j indexes the set of treatment alternatives including no treatment;

t indexes the planning horizon periods 1–3 (three decade planning horizon);

Fig. 1. Simulated annealing flow chart.



$\text{Threat}_{i,t}$ is the fire threat class of unit i in period t described in eq. 1;

$\text{adj}_i(j)$ is the set of treatment selected for adjacent units that affect the threat index for unit I;

LSF Penalty is the penalty for violating the minimum area required to meet the LSF definition; Total Area Penalty is the aggregate penalty for violating the maximum area treated in each period;

B_1 is the weighting factor for the LSF penalty;

B_2 is the weighting factor for the area penalty;

Area Penalty_t is the periodic penalty for violating the maximum area treated;

Area_i is the size of unit i in hectares;

$\text{LSF}_{i,t}$ = 1, if unit i meets the LSF definition in period t; 0, otherwise;

$\text{Period}_{i,t}$ = 1, if unit i is scheduled for an active treatment in period t; 0, otherwise;

X is the minimum amount of LSF structure required, aggregated for all three periods; and

Y is the maximum amount of area that could be treated in a single period.

The SA algorithm was formulated to maximize fire threat reduction on the landscape (minimize fire threat) while meeting goals for the minimum amount of LSF present (eq. 5) and not exceeding a maximum area treated in each planning period (eq. 6). Equation 4 maximizes the area in a

Table 3. Example of fire threat reduction calculation for alternative treatments on a given unit (unit A: 50 ha) with a single downwind unit (unit B: 40 ha).

Unit	Year	Passive management	Fire threat class treatment Y1	Fire threat reduction	Fire threat class treatment Y2	Fire threat reduction
A	2001	Moderate	Moderate	0	Low	50
A	2011	High	Moderate	50	Low	100
A	2021	High	High	0	Moderate	50
B	2001	Moderate	Moderate	0	Low	40
B	2011	Moderate	Moderate	0	Moderate	0
B	2021	High	High	0	High	0
Total fire threat reduction				50		240

reduced fire threat class times the number of classes reduced while minimizing the penalty functions in eqs. 5 and 6. The threat index for an individual unit is determined by the treatment selected for the individual unit (j), as well as the treatments selected for adjacent units ($\text{adj}_i(j)$). The penalty weights (B_1 and B_2) were selected to be as small as possible yet still meet the established constraints based on the levels of the penalty goals (X and Y). In this formulation, a reduction of fire threat from high to medium is equivalent to a reduction from medium to low for an equivalent area, while a reduction from high to low is valued twice as much as a reduction from high to medium or medium to low. The amount of fire threat reduced in each period was weighted equally as was the area meeting the LSF definition. Aggregating resources over the analysis period could create the potential for extreme solutions where resource conditions are substantially worse in one period relative to other periods. However, the periodic treatment area penalty helps to reduce the likelihood of extreme solutions. If extreme solutions occur, alternative specifications such as maximizing the resource levels for the worst period or requiring a minimum periodic resource level could be explored. For the initial solution, no units were scheduled for treatment.

The fire threat reduction goal (eq. 4) is equivalent to the sum, across all units and time, of the area times the number of hazard classes (1 or 2) reduced in comparison with no active management with reductions associated with not meeting required LSF and area treated goals. When a given unit is treated, not only can the fire threat to the treated unit be reduced, but, in addition, adjacent units may experience a reduction in their fire threat level because of the changes in torching and crown fire potential of the treated unit. Table 3 presents an example of the application of eq. 4. Assume there is an option to schedule an active treatment on unit A in 2011 using treatment Y1, or in 2001 using treatment Y2. unit A is 50 ha in size and has one adjacent neighbor, unit B, which is 40 ha. In this example, treatment Y1 causes a reduction in fire threat in unit A in 2011 from high to moderate, and no reduction in unit A in 2021, and no reduction in neighboring unit B. Therefore, total fire threat reduction from applying treatment Y1 to unit A equals 50. Alternatively, applying treatment Y2 in 2001 lowers the fire threat in unit A one step in 2001 (moderate to low), two steps in 2011 (high to low), and one step in 2021 (high to moderate). Additionally, fire threat is reduced in unit B in 2001 (moderate to low) because of reduced torching and crown fire threat from unit A. Total fire threat reduction from applying treatment Y2 to unit A is 240.

Quantifying the relationship between LSF structure and fire threat reduction

By varying the amount of LSF structure required in eq. 5, the relationship between fire threat reduction and LSF structure was identified for a variety of treatment levels (eq. 6). This relationship traces out the productive potential to reduce fire threat while maintaining a specified level of LSF structure. By mapping the relationship between these objectives in two-dimensional space, we can identify portions of the curves where increases in fire threat reduction can be achieved at relatively low cost in terms of LSF structure lost.

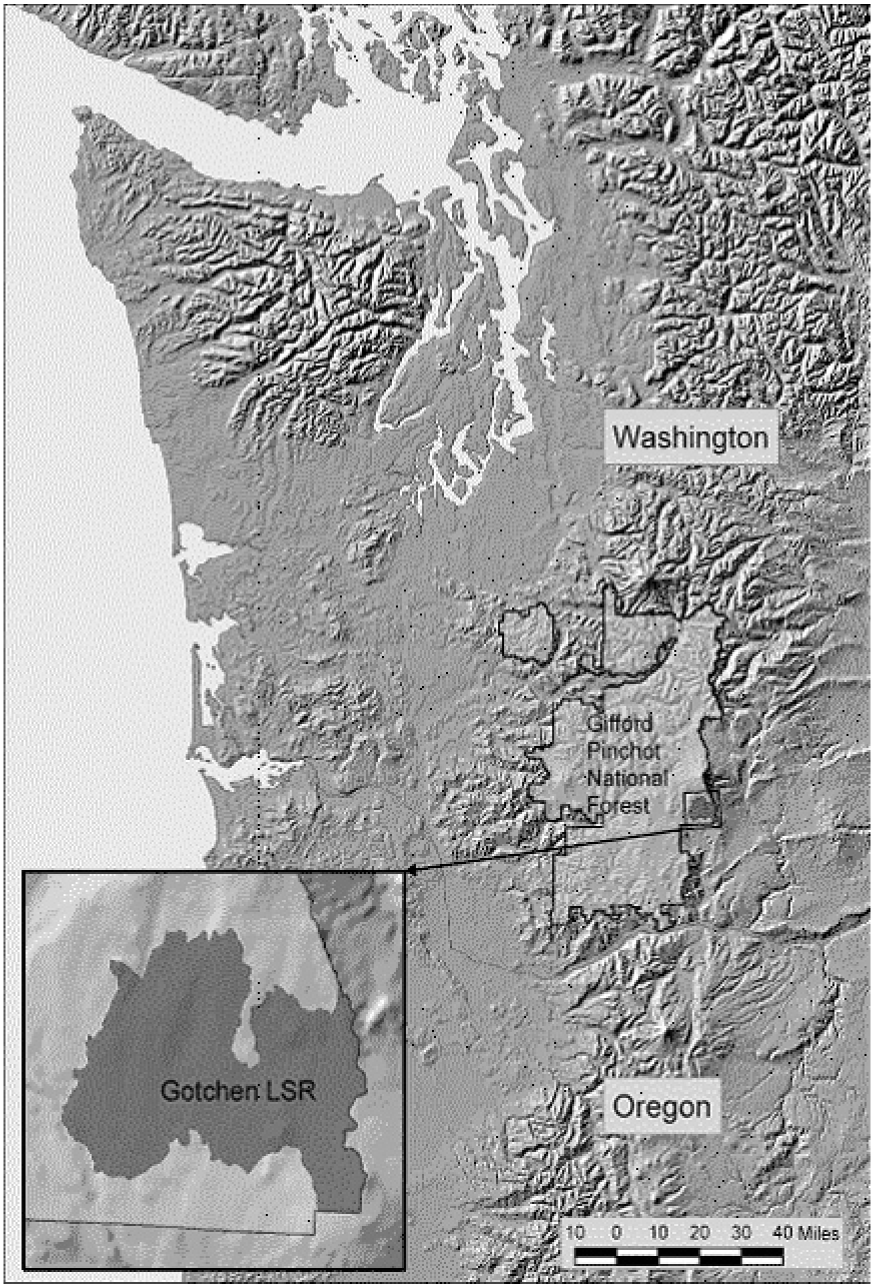
Data and analysis

We selected the Gotchen Late Successional Reserve (Gotchen LSR or reserve), a 6070-ha LSR located east of the Cascade Mountains in the Gifford Pinchot National Forest (Fig. 2) to apply our methodology. Reserve managers were interested in information on the relationship between fire threat and LSF structure because of ongoing landscape planning. Six documented spotted owl nest sites exist in the Gotchen LSR (Mendez-Treneman 2002). Studies of the Gotchen LSR, much of which lies in the grand fir zone (*Abies grandis* (Dougl. ex D. Don) Lindl.) suggest that current forest structure is more homogeneous than in the past (Hummel et al. 2001) and that it is being altered by an ongoing outbreak of western spruce budworm (*Choristoneura occidentalis* Freeman) (Willhite 1999). Budworm defoliation of true firs (*Abies* spp.) appears to be directly affecting habitat for the owl through reduced cover (Hummel and Agee 2003).

Characterizing existing conditions

Interpretation of 1995 aerial resource photos (1 : 12 000) of the Gotchen LSR resulted in 159 patches, which were contained in 15 stand types (Hummel et al. 2001). The size of the photo-interpreted patches ranged from 2 to 837 ha with an average of 40 ha. Most large patches (>200 ha) were subsequently split into smaller units to reduce within-patch heterogeneity (Hummel et al. 2001) and to reflect areas of special concern to personnel of both the USDA Forest Service and the US Fish and Wildlife Service. Maps of these special status areas were provided by agency personnel (B. Babb, V. Harke, and R. Mendez-Treneman, personal com-

Fig. 2. Location of the Gotchen late-seral forest (LSR) (1 mi. = 1.609 km).



munication, 2001) and included spotted owl nest sites, culturally and biologically significant sites, riparian corridors, and sites without roads. The process of sub-stratifying the photo-interpreted patches resulted in 340 smaller "projection units", which averaged 18 ha and ranged in size from 0.8 to 464 ha.

In 2000 and 2001, we conducted stand exams. The number of exams done within each patch depended on the patch size. Plots per exam ranged from 4 to 72, with an average of 19. The total number of exams was 327. In all, 35 patches were sampled, covering the range of stand types. The assigned root disease ratings for *Armillaria ostoyea*, *Phellinus weirii*, and *Heterobasidion annosum* (S-type) in each stand type reflect both the main tree species affected and the pathogen severity (E. Goheen and E. Willhite, personal communication, 2002).

Simulating future conditions

The silvicultural treatments we applied by using FVS varied in their intensity and type of thinning, in species removed, the residual basal area, and the residual fuel levels (Table 4). The rules for determining eligibility of a unit for treatment were as follows:

(1) Units could have an active treatment applied only once in the 30-year analysis period;
(2) Only units in PVT 10 (warm, dry Douglas-fir or grand fir) were eligible for treatment;

Table 4. Silvicultural treatment descriptions.

Prescription objective	Silvicultural treatment applied in FVS	Citation for prescription references
No prescription		
Minimize human disturbance	No activity scheduled	
Reduce prescription		
Reduce crown fire potential in historically low fire-severity forest ecosystems	40% canopy cover	Agee 1996
	Thin from below to DBH 50.8 cm	Agee et al. 2000
	Preferentially remove ABGR	Graham et al. 1999
	Pile and burn	
	Plant PSME, PIPO, LAOC	
Restore prescription		
Reduce density of shade-tolerant true fir trees (*Abies*) that have established since the 1920s	Thin from below to DBH 38.1 cm	Hummel et al. 2002
	Keep at least 23 m^2/ha basal area	
	Retain PSME, PIPO, LAOC, PIEN	
	Pile and burn	
Protect prescription		
Protect large trees (DBH >53.3 cm) and retain sufficient basal area to meet late-seral forest definition	If more than 55.2 m^2/ha in unit, then thin trees	Johnson and O'Neil 2001 (pp. 140–153, 213, 238)
	DBH 0–35.6 cm to basal area 8.3m^2/ha	Brown 2000
Diameter prescription	Pile and burn	Mendez-Treneman 2002
Reduce density of shade-tolerant understory true fir trees (*Abies*)	Thin from below to DBH 25.4 cm	
	Keep at least 23 m^2/ha basal area	
	Retain PSME, PIPO, LAOC, PIEN	
	Pile and burn	

Note: FVS, forest vegetation simulator; ABGR, grand fir; PSME, Douglas-fir; PICO, lodgepole pine; LAOC, western larch; PIPO, ponderosa pine.

(3) No unit characterized as nesting habitat (NH) was eligible in the period in which it is NH;
(4) No unit that is projected to become NH within three periods was eligible for treatment;
(5) Units within owl circles were not eligible in the first two periods, however, they were eligible in the third period, provided they were not restricted because of any of the other rules; and
(6) Special concern areas were excluded from treatment.

These rules reduced the number of units to which active treatments could be applied to 237. For these units, 10 potential treatment alternatives were simulated.

We focused on simulating treatments in PVT 10, because it appears to have been most altered in forest structure and composition during decades of fire suppression and logging (Hessburg et al. 1999; Hummel et al. 2001, 2002). Seventy percent of the units in the Gotchen LSR are in PVT 10. In contrast, the cool, moist subalpine fir PVT 13 has missed fewer fire return intervals and has had correspondingly less change in structure and composition. We used compute commands in FVS to compare the existing vegetation structure and simulate structure for each unit in each cycle under each treatment type according to the definitions established for LSF, nesting habitat, and fire threat. Results of the comparisons were saved in FVS output (.cp2) files.

Localizing the planning problem

We compared FVS and FFE-FVS output against our established definitions of LSF, owl nesting habitat, and fire threat for each of the 340 projection units with no active management simulated. These results were calculated for the three-decade planning horizon.

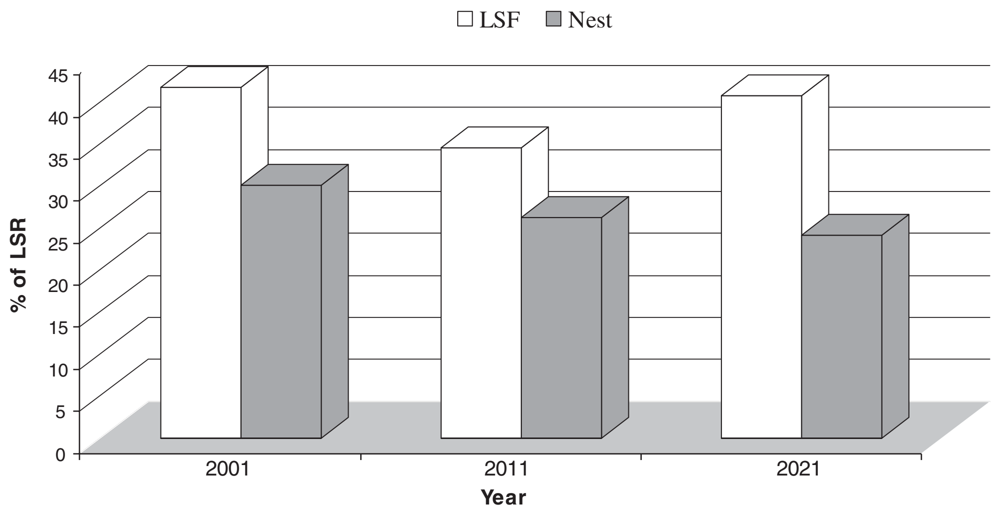
The fire threat index was parameterized based on local conditions. The influence of adjacent units on fire threat was incorporated by considering the conditions under which severe fire weather usually occurs. In the Gotchen LSR, severe weather typically comes from east winds that have low humidity. Slope was not considered because of the moderate terrain. The 95th percentile wind speed for Trout Lake, the nearest weather station to the Gotchen LSR, is 22.5 km/h (Hummel and Agee 2003). Measuring the northern- and southern-most points on the east boundary using a GIS coverage identified the primary upwind units for each reference unit on the landscape. These adjacent units were the ones for which torching and crown fire estimates were incorporated into the fire threat for the downwind unit. We limited the number of adjacent units to the three units with the longest easterly edge. This limit captured a large majority of unit influence and avoided the need to identify all adjacent units no matter how limited the shared border.

Fire threat values from an initial weighting system were

Table 5. Area by fire threat class and late-seral forest (LSF) and nesting habitat over time with no active management (percentage of landscape in parentheses).

	Area by fire threat class (ha)			Area by structure class (ha)	
Year	High	Moderate	Low	LSF	Nest
2001	3153 (53%)	1962 (33%)	862 (14%)	2492 (42%)	1797 (30%)
2011	5236 (88%)	644 (11%)	97 (2%)	2060 (34%)	1568 (26%)
2021	5246 (88%)	682 (12%)	49 (1%)	2430 (41%)	1437 (24%)

Fig. 3. Late-seral forest (LSR) and owl nesting habitat by simulation period under the no-action alternative.



evaluated during a field visit by comparing results from the baseline calculations with field observations. The weighting system was then adjusted to account for increased levels of down wood associated with the budworm outbreak (Hummel and Agee 2003) and thus current hazard. Fire threat was then reevaluated, and these results provided the baseline conditions.

Treatment restrictions were varied for different optimization runs through the use of penalty functions. Penalty functions in our analysis included a penalty on the amount of LSF that must be maintained over the entire planning horizon (eq. 5), and a penalty on the area that could be treated in a given period (eq. 6). The area treated ranged from the no action (passive management) alternative (0 ha), to no treatment penalty (all nonrestricted units could be treated in any period without incurring a penalty). Intermediate treatment goals included 304 ha per period (approximately 5% of the entire Gotchen LSR), and 607 ha per period (10% of the Gotchen LSR). The LSF structure penalty was bound from below by allowing any treatment to occur in any unit that qualified as LSF structure but not nesting habitat, and was bound from above by the maximum area that qualified as LSF structure over the three time periods (6982 ha). This maximum potential area of LSF represented 38% of the total available area of the Gotchen LSR over the three planning periods (6982 ha vs. 3 × 6070 ha).

Solution times for the simulated annealing algorithm ranged from 25 to 27 min depending on the penalty functions. The algorithm was written in C++© using Windows 2000 Professional© operating system, and run on an 863-Mhz Pentium processor with 264 Mb of memory (algorithm code on file with lead author).

Testing the quality of solutions

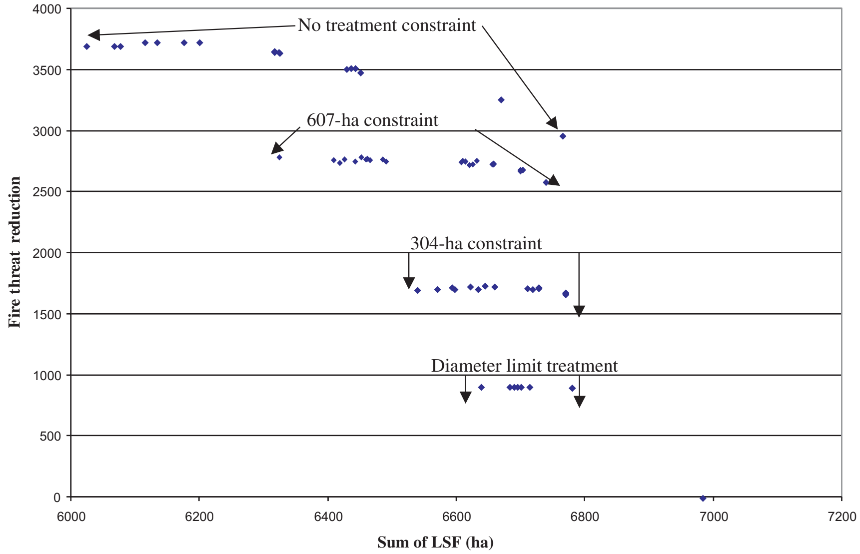
We compared the ability of the proposed treatments to reduce fire threat to a common fuel reduction treatment that is often proposed for Forest Service lands. A diameter limit thinning treatment, in which only trees less than a specified diameter were removed (we used a 25.4 cm diameter limit), was modeled for all eligible units using FVS. We then used the SA algorithm to select treatment units within the Gotchen LSR, and compared these results with the results from optimization runs with all treatment options available.

Although SA may identify suboptimal solutions, it has been shown to identify good solutions in a number of previous problems (see, for example, Boston and Bettinger 1999; Bettinger et al. 2002). We compared the solutions generated from our SA algorithm with a simple Monte Carlo algorithm equivalent to running the SA algorithm with a constant temperature of 0. For the Monte Carlo algorithm, a unit was selected at random, and a randomly chosen treatment was applied to the unit. If the result of the new treatment resulted in a decrease in landscape fire threat and the penalty goals were not violated (now set as strict constraints), the new treatment was accepted, if not, the existing treatment alternative remained. This random selection process was repeated for 20 million iterations. We ran this Monte Carlo algorithm 100 times to identify an average solution value and a best solution.

Results

Under the passive management scenario, fire threat levels in the Gotchen LSR increased over time; a large number of units increased from the low and moderate fire threat classes

Fig. 4. Production possibility frontier for fire threat reduction and late-successional forest.



to the high fire threat class between 2001 and 2011, and stayed in the high fire threat class in 2021. Initially in 2001, 53% of the landscape is in a high fire threat class increasing to 88% in 2011 and staying at 88% in 2021. The LSF structure and owl nesting habitat shows a different trend. Between 2001 and 2011, 411 ha drop out of the LSF structure category followed by an increase of 369 ha between 2011 and 2021. Nesting habitat shows a more modest decline between 2001 and 2011 of 229 ha; however, the decline of nesting habitat continues in 2021; an additional 131 ha no longer qualify as owl nesting habitat (Table 5). Figure 3 portrays LSF structure and owl nesting habitat as a percentage of LSR area for 2001, 2011, and 2021. Overall, these results indicate a landscape with an increasing fire threat over the next 30 years, but a stable or slightly downward trending area in LSF structure and nesting habitat. These trends are consistent with ongoing tree mortality in the LSR associated with the recent western spruce budworm outbreak. In parts of the Gotchen LSR, the per hectare live tree basal area by size class is declining below definition requirements, and fuel loads are increasing significantly (Hummel and Agee 2003).

Since we solved the SA algorithm for a variety of LSF and area treated goals, no single cooling schedule (initial and final temperature, cooling rate, and iterations per temperature) identified the best solution set for all goal sets. We examined initial temperatures of 100, 200, and 400, cooling rates of 0.97, 0.98, and 0.99, and iterations per temperature of 100 000, 250 000, and 350 000 for several representative goal sets. The final temperature was selected such that solutions had stabilized. The selected cooling schedule (initial temperature: 200; final temperature: 0.004; cooling rate: 0.99; iterations: 250 000) provided high fire threat (FT) reduction with low levels of variability compared with other cooling schedules over the range of goal sets.

Figure 4 displays several production possibility frontiers for the Gotchen LSR planning problem. The three individual curves can be thought of as production curves for a given treatment goal (304 ha per period, 607 ha per period, and no area restriction). Penalty goals for LSF structure ranged from no goal to 6982 ha (the maximum estimated), with differing intermediate values depending on the operational penalty, so that the production relationships were fully developed. We produced six solutions for each penalty goal set using the SA algorithm. All six solutions for each goal set are displayed in Fig. 4; however, because of the scale of the figure and proximity of solutions within a goal set, they may appear as single points on the graph. The most interesting result from this analysis is the relative flatness of the production curve, at least over a majority of LSF structure values. The curve does get steep past the 6880 ha of LSF structure (maintaining 98.5% of the maximum potential LSF) for the 304-ha treatment goal and around 6800 ha of LSF structure (97.4% of the maximum potential LSF) for the 607-ha goal. The flat portion of the production curve implies that in this range, treating non-LSF units is as effective in reducing landscape fire threat as treating LSF units. The steep portion of the curve implies that there are a small number of LSF units that, if treated, could substantially reduce landscape-wide fire threat.

The 304-ha treatment penalty was the most effective on a per area basis. The best solution identified for the 304-ha treatment penalty and a maximum LSF structure goal (no unit meeting the LSF definition could be scheduled for active treatment) showed fire threat reduced by a total of 1665 points, or an average of 1.83 points/ha treated (304 ha treated in each of three periods equals 912 ha total treated). The best solution identified for the 607-ha treatment penalty (1821 ha total) and the strict LSF structure penalty was 2581 points for an average reduction of 1.42 points/ha. The decreasing marginal effectiveness as the allowable area treated is increased was not surprising. The most effective treatments (in terms of reducing FT while meeting other landscape goals) were selected in both the 304- and 607-ha solutions, while the additional area treated in the 607-ha solution comprised marginally less effective treatments.

The treatment schedules were able to reduce fire threat on the landscape; however, fire threat still increased over time for all of the relevant penalty goals. Examples for the best solution for the 6880 LSF structure goal and the 304- and

Table 6. Area by fire threat class and late-seral forest (LSF) per decade (difference from no active management case in parentheses) and aggregate fire threat reduced for two solutions.

	304 ha treated, 6880 ha LSF					607 ha treated, 6880 ha LSF				
Year	High	Medium	Low	Fire threat reduced	LSF	High	Medium	Low	Fire threat reduced	LSF
2001	3006(−147)	2195(232)	776(−86)	61	2436(−56)	2643(−510)	2499(536)	836(−26)	484	2454(−38)
2011	4737(−499)	933(289)	308(211)	710	2056(−4)	4438(−800)	1291(647)	249(152)	952	2043(−17)
2021	4525(−721)	1100(418)	352(304)	1025	2400(−30)	4111(−989)	1365(682)	356(307)	1296	2387(−43)

607-ha treatment goal are provided in Table 6. Not surprisingly, fire threat reduction was higher in later time periods because of the effects of treatments occurring in earlier periods and the higher baseline threat levels in periods 2 and 3 associated with the no-action alternative. Interestingly, treatment reduced the area in the low fire threat class in the first planning period for both of these solutions. This happened because there were several units that were scheduled for treatment in the initial planning period that, because of treatment, increased from low to moderate threat. However, threat reduction on these units occurred in both of the subsequent periods causing a net decrease in threat. For many other units, the effectiveness of treatments in reducing fire threat was short-lived. For the scenario with a 607-ha treatment goal and an LSF goal of 6880 ha, 35 units were selected to have treatments applied in 2001, and 51 units were selected in 2011. Of the 35 units receiving treatment in 2001, 14 of them had a reduced fire threat class in 2011, with 10 of these 14 maintaining reduced fire threat in 2021. Of the 51 units selected for treatment in 2011, only 16 of them had a reduction in fire threat class in 2021.

For many units, simulation of the diameter limit treatment did not result in a reduction of fire threat. Therefore, restricting treatment options to only the diameter limit treatment in the landscape optimization algorithm substantially reduced the level of fire threat reduction achieved. We found that the full set of treatment options produced solutions 110% above the diameter limit treatment for the goal set of 304 ha treated per decade and 6880 ha of LSF structure (fire threat reduction equaled 1818 for the full set of treatment options versus 846 for the diameter limit option).

The SA algorithm developed scheduling solutions with higher levels of fire threat reduction than the Monte Carlo algorithm for a given LSF structure goal. The average fire threat reduction for the 100 runs using the Monte Carlo algorithm on the problem with 304 ha treated per decade and 6880 ha of LSF structure was 1178 with the best solution resulting in a reduction value of 1462. For the same goal set, the six solutions from the SA algorithm had a range of solutions between 1796 and 1823 with an average reduction of 1815 (24% above the best Monte Carlo solution). The Monte Carlo algorithm is a coarse method to solve this scheduling problem; however, it shows that selecting treatment units that experience FT reduction, without considering the interaction of the units within the landscape, results in significantly less reduction in fire threat compared with solutions generated using the SA algorithm.

Discussion

Our results suggest that maintaining the existing proportion of LSF structure (ca. 40%) and reducing wildfire threat in the Gotchen LSR can be achieved using a mixture of variable-intensity silvicultural treatments. Further, if reducing fire threat is an objective, our results indicate that moving among the production curves (Fig. 4) would be more effective than moving along any single one. These results imply that a few units meeting the LSF structure definition exist that, if treated, would contribute to reducing landscape fire threat. However, greater gains in fire threat reduction could be achieved by increasing the area treated, composed of units that did not meet our definition of LSF structure, rather than by treating additional units that met the definition. A contemporary proposition about compatibility among landscape management objectives suggests that the scale of observation is influential (Spies and Johnson 2003). Our results are consistent with this proposition, which borrows from hierarchy theory, because we would expect that compatibility between reducing fire threat and maintaining owl habitat structures would diminish either if a larger portion of the reserve landscape was in LSF structure or if the size of the analysis area were decreased.

The 6070-ha analysis area is a result of administrative and legal boundaries rather than of biological and physical ones. We assumed that the information used by Plan architects reliably depicted owl life history requirements in the study area and that the size of the Gotchen LSR represents an appropriate scale at which to evaluate owl habitat. A lack of consensus exists, however, among wildlife biologists and forest ecologists about the characteristics of LSF structure, particularly in eastside conditions. Similarly, knowledge is limited about how within- and between-unit variation in forest structure relates to organisms (like owls) or to phenomena (like wildfire) that occur over multiple units (DeStefano 2002) and whether contemporary silvicultural treatments to create structural and compositional diversity will indeed sustain biological diversity (Hummel 2003). As empirical evidence about LSF structure and its relationship to habitat accumulates, our structural definitions for owl habitat can be modified. The same is true for our weighted index of fire threat, which reflects conditions in adjacent units that influence fire effects in reference units. The specific weights can be adjusted, either for use in different forest types, or as data on adjacency and interaction effects become available. The methods we describe in this paper are adaptable to other forest resource objectives that can be defined structurally, although our results are only applicable in the Gotchen LSR over the period of our analysis. The potential value of the approach is supported by its contribution to management planning for the reserve (USDA 2003).

Models create opportunities even as they introduce limitations. We used FVS, a publicly available simulation model, because it has extensions for fire and root disease and because we could localize the East Cascades variant for conditions in the Gotchen LSR using empirical data. Simulated annealing has been shown to generate feasible high-quality solutions for complex integer programming problems; however, solution optimality cannot be assured. Both models have their limits, however. In particular, estimating error in FVS model predictions associated with sampling is not yet automated (Gregg and Hummel 2002) nor easily included in optimization. Individually and collectively, these limitations affect the multiple solutions we obtained to our scheduling problems and thus the production curves between landscape fire threat reduction and the area of LSF structure in the Gotchen LSR. For this reason, we emphasize the importance of considering the relative differences among the production curves rather than their absolute values.

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