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Costs of landscape silviculture for fire and habitat management

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Abstract

In forest reserves of the U.S. Pacific Northwest, management objectives include protecting late-seral habitat structure by reducing the threat of large-scale disturbances like wildfire. We simulated how altering within- and among-stand structure with silvicultural treatments of differing intensity affected late-seral forest (LSF) structure and fire threat (FT) reduction over 30 years in a 6070-ha reserve. We then evaluated how different financial requirements influenced the treatment mix selected for each decade, the associated effects on FT reduction and LSF structure in the reserve, and treatment costs. Requirements for treatments to earn money (NPV+), break even (NPV0), or to not meet any financial goal at the scale of the entire reserve (landscape) affected the predicted reduction of FT and the total area of LSF structure in different ways. With or without a requirement to break even, treatments accomplished about the same landscape level of FT reduction and LSF structure. Although treatment effects were similar, their associated net revenues ranged from negative $1 million to positive $3000 over 30 years. In contrast, a requirement for landscape treatments to earn money ($0.5 to $1.5 million NPV) over the same period had a negative effect on FT reduction and carried a cost in terms of both FT reduction and LSF structure. Results suggest that the spatial scale at which silvicultural treatments were evaluated was influential because the lowest cost to the reserve objectives was accomplished by a mix of treatments that earned or lost money at the stand level but that collectively broke even at the landscape scale. Results also indicate that the timeframe over which treatments were evaluated was important because if breaking even was required within each decade instead of cumulatively over all three, the cost in terms of FT reduction and LSF structure was similar to requiring landscape treatments to earn $0.5 million NPV.

Keywords: Northwest Forest Plan; Late-successional reserve; Northern spotted owl; Simulated annealing; Ecosystem management

1. Introduction

Headline issues about federal forest management in the United States change frequently but share a common theme: how human activities that remove commodities from the forest affect values for which a market price is not readily available, like wildlife habitat, water quality, and biological diversity. Fire management is one contemporary issue with implications for these and other non-market values. Debate currently exists on the effects of both pre-fire and post-fire silvicultural treatments on non-market forest

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values. If proposed treatments involve harvesting trees of merchantable size, then concerns that public agency decisions have more to do with making money than with principles of forest ecology spice the debate with controversy (Thomas, 2002).

In an attempt to balance non-market values with commodity production in the US Pacific Northwest, federal land within the range of the northern spotted owl (*Strix occidentalis caurina*) was zoned by a 1994 forest management plan (Plan) (USDA and USDI, 1994). There are seven zones, or "land allocations", in the Plan; in some allocations the focus is on commodities whereas in others it is on non-market values. In one of the latter, called "late-successional reserves" (reserves), a key objective is to provide habitat for species, like the spotted owl, that are associated with later seral stages of forest development (USDA and USDI, 1994). Within reserves there is also an emphasis on restoring or maintaining ecosystem processes associated with older forests (USDA and USDI, 1994). If, however, the scale or intensity of disturbance processes could adversely affect late-seral habitat, the Plan permits using silvicultural treatments to moderate the potential impact.

In the first decade of the Plan, approximately 10% of the total forested area in reserves in Washington and Oregon burned (Cohen et al., 2002). The impact, or total cost, of these fires to an individual reserve or spotted owl differs from the cost to the network of reserves or to the population of owls in the Plan area. Our working hypothesis is that the geographic and temporal scales at which total costs are evaluated themselves affect non-market forest values by influencing silvicultural options. We use the phrase "landscape silviculture" for treatments applied to a stand but evaluated collectively according to objectives for an entire reserve.

Because of regional differences in climate, vegetation, and management history, the Plan distinguished between silvicultural treatments permitted in reserves lying to the west or to the east of the Cascade Range (USDA and USDI, 1994). More silvicultural flexibility is permitted in the eastern region (east-side), which is characterized by mixed-severity fire regimes with shorter average fire return intervals than is the western region (Agee, 1993). The east-side forests occupy a transitional zone between coastal forests dominated by Douglas fir (*Pseudotsuga menziesii*) and interior forests of ponderosa pine (*Pinus ponderosa*), or lodgepole pine (*P. contorta*). In these transitional forests, which lie in a north–south strip extending from British Columbia to California, forest structures that facilitate the spread of crown fires, such as layered canopies and downed wood, are the same structures favored by owls or by their prey (Buchanan et al., 1995; Everett et al., 1997). Thus, silvicultural treatments that modify forest structure to alter fire behavior also affect owl habitat. Since fire control and habitat provision are both desired non-market values in east-side reserves, one question is whether they can be achieved simultaneously and at what total cost.

The Plan referred to the financial costs of silvicultural treatments, but it was not explicit about the scale at which related assumptions were made. Some treatments were expected to generate enough money through wood removals to cover the costs of their implementation. Other treatments, however, were expected to have these costs subsidized with appropriated funds (FEMAT, 1993, p. III-35; USDA and USDI, 1994). Documents underlying the Plan specified it would be undesirable to conduct "only those activities that generate a commercial return and ignore the needs of stands that cannot be treated commercially" (FEMAT, 1993, p. III-35). This hints that a stand was the expected scale of analysis. However, in the decade since the Plan was adopted, there has been increasing recognition that the measurement of spatial patterns for processes like fire should match the scale at which they occur (Spies and Johnson, 2003; Swanson et al., 2003). Similarly, a collection of stands may offer a more appropriate scale at which to evaluate the impact of management activities for fire control and spotted owl habitat than does a single stand because in the Plan area these phenomena are spatially extensive.

In addition to financial costs, other treatment costs exist that are not readily expressed in dollars. Landscape silviculture alters forest structure both within- and among-stands and thus affects ecosystem processes, functions, and non-market values. Measuring and evaluating these effects is daunting, not the least because of the logistical and statistical challenges associated with large-scale management experiments (Monserud, 2002). Simulation, optimization, and hybrid models offer ways to explore potential treatment effects, although the accuracy of such models relies ultimately on empirical data. Production possibility curves (Calkin et al., 2002; Montgomery, 2003) are one way to display the cost of one value in terms of another and the potential unit change in one from a corresponding change in the other (marginal cost). We developed a landscape treatment scheduling algorithm to determine the production relationship between owl habitat and fire threat reduction using forest structure as a common denominator. Forest structure was used because it can be measured and managed, and because it is physically and biologically relevant to fire and to owl habitat. In this paper, we report how the addition of a financial requirement to landscape silviculture treatments affected fire threat and late-seral habitat structure over 30 years in an east-side reserve. For comparison, we examine how imposing the financial requirement within each decade rather than summed over all three decades affected these two reserve objectives.

2. Methods and analysis

2.1. Choosing a study site

We selected as our study site the 6070 ha Gotchen Late-Successional Reserve (Gotchen Reserve), south-east of Mount Adams on the Gifford Pinchot National Forest in Washington (Fig. 1). Vegetation differs by aspect and elevation, but much of the reserve resembles the grand fir/creeping snowberry/vanilla-leaf (*Abies grandis/Symphoricarpos mollis/Achlys triphylla*) or grand fir/big huckleberry (*A. grandis/Vaccinium membranaceum*) associations described in Franklin and Dyrness (1988) and Topik (1989). Subalpine fir (*A. lasiocarpa*) is a significant component of higher elevation forests. The nearest weather records are from the USDA Forest Service Mount Adams Ranger Station in Trout Lake, Washington, which receives about 116 cm of annual precipitation.

After the first decade of the Plan, we measured significant decreases in canopy closure and increases in tree mortality and down wood within the Gotchen Reserve. These structural changes, which contributed to doubled fuel loads and thus to significant changes in predicted fire behavior (Hummel and Agee, 2003), were associated with an outbreak of western spruce budworm (*Choristoneura occidentalis*) that affected hundreds of hectares (Willhite, 1999). Concurrent with the structural changes, declines in nest site occupancy and reproductive success of spotted owls were documented (Mendez-Treneman, 2001). Barred owls (*S. varia varia*), a territorial competitor of spotted owls, were also observed in the vicinity (Harke, 2003). Taken together, the observed changes suggested that the Gotchen Reserve offered an opportunity to simulate forest development with and without silvicultural treatments and to evaluate how treatment options and reserve objectives were affected by different financial assumptions.

2.2. Developing a database of existing vegetation conditions

We first stratified and sampled the Gotchen Reserve to create a database with which we could characterize existing forest conditions. Recent aerial photos and methods described in Hessburg et al. (1999) were used to identify 159 patches of vegetation in the reserve and to create an ArcView® geographic information system (GIS) database. The size of the patches ranged from 2 to 837 ha with an average of 40 ha. Two photo-interpreted attributes, structure class and potential vegetation (PVT), became the basis of a summary matrix (Hummel et al., 2001) because in combination these attributes provide information on the growing conditions in any given patch and its current forest structure. Fifteen matrix cells (5 × 3) contained all 159 patches with each cell representing a stand type (Hummel et al., 2001). Seventy percent of the area in the Gotchen Reserve was classified as warm/dry Douglas-fir/grand fir (*P. menziesii/A. grandis*) or PVT 10. In contrast to other PVT types present, the structure and composition of PVT 10 appear to have changed the most over previous decades of harvest and fire suppression activities (Hummel et al., 2001, 2002).

Several large patches (>200 ha) were subsequently divided into smaller units to reduce within-patch variability associated with the photointerpretation rules for tree species (Hummel et al., 2001) and management concerns (Hummel et al., 2002). The process of dividing the original patches resulted in 330 smaller units, which averaged 18 ha and ranged in size

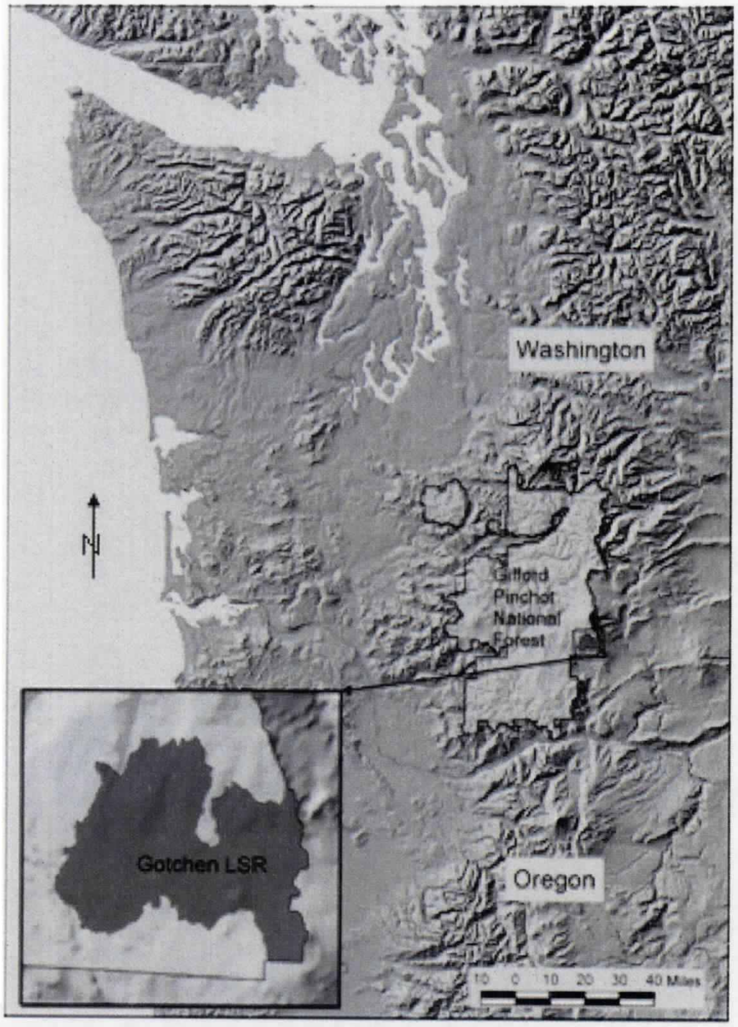


Fig. 1. Location of Gotchen Reserve in the northwestern United States (1 mile = 1.6 km).

from 0.8 to 464 ha. Each unit was linked with the features of its original patch and stand type, plus any added management codes, in the GIS database. These units, the conditions within which we assumed to be uniform, were our unit of analysis for characterizing existing conditions. In this paper, a unit is synonymous with a stand. We used the Forest Vegetation Simulator (FVS, Dixon, 2003; Stage, 1973), an individual tree growth model, to simulate forest dynamics over three decades.

Root diseases are prevalent in the study area and influence forest dynamics (Filip, 1980). The effects of root diseases on forest dynamics can be included in FVS simulations by using the Western Root Disease Model (WRDM) (Frankel, 1998). Because *Armillaria ostoyae*, *Phellinus weirii*, and *Heterobasidion annosum* are all present in the Gotchen Reserve, we assigned each stand type, and its associated units, a root disease severity rating by using methods from Goheen (1997). Although the severity and effects of root diseases vary and interact within a unit, the rating system applied the single most prevalent disease to each stand type, consistent with requirements of the WRDM.

To populate each unit with tree data, we measured variable radius plots in 1999, 2000, and 2001 by using stand exam procedures from the Pacific Northwest Region of the USDA Forest Service. In 2000 and 2001, patches were randomly selected for sampling with probability proportional to size. Number of plots per exam ranged from 4 to 72, with an average of 19; the number depended on the patch size. In all, we sampled 35 patches with 327 exams, covering 10 strata that together represent over 97% of the landscape. Exam data were used to create FVS input data files, or tree lists (Dixon, 2003), for each sampled patch and its associated units. We assumed that the structural conditions within stand types were similar and that within-stand type variation was lower than among-stand type variation. Unsampled patches and their associated units were randomly assigned an FVS tree list from the same stand type. Each FVS tree list was linked in the GIS database to connect the existing spatial and managerial information with the exam data.

2.3. Characterizing forest structure relative to reserve objectives of fire and habitat management

We next evaluated the initial conditions in each unit, as represented by the tree list, against structural definitions for spotted owl nesting habitat, late-seral forest (LSF structure), and fire threat (FT). For the definitions of nesting habitat and LSF structure, we relied on published data and knowledge of local conditions (Thomas et al., 1990; Buchanan et al., 1995; Forsman, USDA Forest Service, pers. comm. 18 Oct 2001; Mendez-Treneman, 2002). Both the nesting habitat and the LSF structure definition were based on the basal area of trees in specific size classes and a total basal area per hectare across all size classes (Table 1). If conditions in a unit met or exceeded the requirements of the definition, it received a code of "1" in the database; otherwise it was coded "0". The total hectares in each unit were then multiplied by the code and the total hectares summed to estimate the proportion of the Gotchen Reserve in nesting habitat and in LSF structure.

Table 1
Structural definitions of late-seral forest and nesting habitat

Late-seral forest
Basal area (BA) at least 55.2 m^2/ha
BA trees greater than 61.0 cm dbh $\geq$ 8.3 m^2/ha
BA trees greater than 35.6 cm dbh $\geq$ 33.1 m^2/ha
BA trees less than 35.6 cm dbh $\geq$ 8.3 m^2/ha
Nesting habitat
BA at least 55.2 m^2/ha
BA trees greater that 61.0 cm dbh $\geq$ 13.8 m^2/ha
BA trees greater than 35.6 cm dbh $\geq$ 33.1 m^2/ha
BA trees less than 35.6 cm dbh $\geq$ 11.0 m^2/ha
BA Douglas-fir trees greater than 61.0 cm dbh $\geq$ 1.2 m^2/ha

For the FT definition we used three fire variables: flame length, a wind speed necessary to begin the torching process (crown fire initiation), and a wind speed necessary to sustain independent crown fire activity (crown fire spread). We estimated these three variables for each unit in each decade by using the fire and fuels extension (FFE) of FVS (Reinhardt and Crookston, 2003) and local 95% fire weather information. We weighted the within-unit (reference unit) estimates by the estimates from units adjoining to the east (adjacent unit), because east winds historically drove the extensive and severe fires recorded in the area of the Gotchen Reserve. We included adjacent units in our index, using an approach similar to Wilson and Baker (1998), so that treating one unit could influence FT in neighboring units and vice versa (Calkin et al., submitted for publication; Hummel et al., 2002). We used FVS-FFE both because of its direct compatibility with the FVS model and because fire spread models like FARSITE (Finney, 1998) assume spatial independence of landscape units.

The initial FT index value calculated for each unit was on a 1–10 point scale, based on the estimated values from FVS-FFE for the three fire variables. The first variable, flame length, affected the reference unit. The second, crown fire initiation (torching), affected the reference unit plus adjacent units because of spotting potential. The third, crown fire spread, also affected the reference unit and adjacent units. Estimates for reference unit variables were weighted more heavily than those for adjacent units in the index. For example, the reference unit crown fire initiation and spread variables were given a weight of 1.5, while in adjacent units they were given a weight of 1.0. Flame length (FL) was weighted on a 0–5 point scale (e.g., if FL < 0.91 m = 1 to if FL $\geq$ 1.83 m = 5). For each reference unit, crown fire initiation and spread variables were "on" if the estimated wind speed was less than the local wind speed (22.5 km/h) or "off" if it exceeded that speed. Units in which torching and crown fire spread were "on" also contributed to the FT index values in adjacent units.

The initial FT index value calculated for each unit was on a 1–10 point scale but we grouped the results into three categories: <3, low threat (control likely, fair survival of residual trees); 3–5.99 moderate threat (control problematical, some residuals survive); 6+, high threat (control unlikely, high mortality likely). Collapsing the 10-point scale to a 3-point scale made the results more descriptive of the area in reduced threat categories after treatment and characterized fire behavior in a manner relevant for suppression efforts. All of the hectares in a unit were assigned the same FT index value.

The effectiveness of the simulated silvicultural treatments was assessed by identifying if treatments reduced existing FT levels for treated units as well as their neighbors. A landscape FT was computed from the proportion of the Gotchen Reserve in each of the low, moderate, and high FT categories for every decade.

2.4. Simulating forest development

We simulated the structural development of each unit over three 10-year periods by using the east Cascades FVS variant (Johnson, 1990), the WRDM (Frankel, 1998), and the FVS fuels and fire extension (FFE) (Reinhardt and Crookston, 2003). Conditions in each unit were compared against the definitions for LSF structure and FT in each decade, values assigned as described above, and output for each unit saved in a

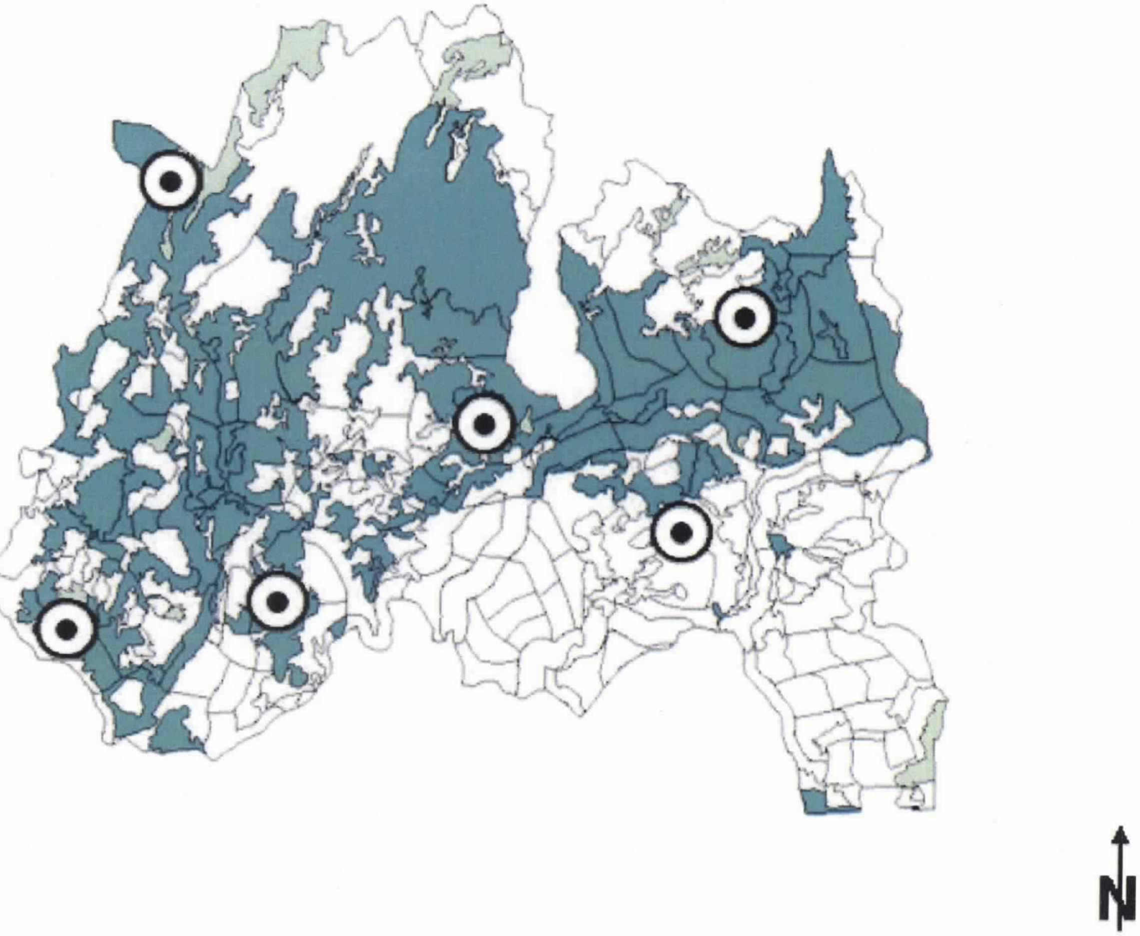


Fig. 2. Simulated area of late-seral forest structure (LSF) in the Gotchen Reserve (6070 ha) in 2001 (dark shaded units), relative to the six documented northern spotted owl nest sites (circles). Light shaded units lack sample data; white units are non-LSF structure.

Microsoft Excel® file. We used the EMAP software (MacMahan, 2002) to link the FVS output files (.cp2) to ArcView® shape files (.shp) and to display the spatial pattern of forest structure in the Gotchen Reserve (e.g., Fig. 2). Although some units began with the same initial tree list, their development varied because of the random number generator invoked with a keyword in the FVS simulations (Van Dyck, 2000). We used other FVS keywords to bring the 3 years of sample data to a common year (2001); modify the large-tree-diameter-growth equation based on local calibration statistics; change default values for down wood and fuel moisture based on field samples (Hummel and Agee, 2003); classify each unit according to definitions for LSF structure and FT; set wind speed values; and simulate natural regeneration and survivorship based on the PVT. In PVT 11, for example, the FVS regeneration file included 20 grand fir and 40 subalpine fir trees per acre with 40% survival each decade while in PVT 10 the regeneration was 30 Douglas fir and 100 grand fir trees per acre, survivorship on the former was 40% while for the latter it was 80%.

We then repeated the FVS simulations but this time applied silvicultural treatments to the units. The treatments differ in their main objective and, accordingly, in their target structure. Hence, the intensity and type of thinning, tree species removed, residual basal area, and residual down fuel levels vary (Table 2). Treatments reflect the capabilities and limitations of FVS, combined with available literature and site-specific information. The least intensive treatment (ProtectRx) was designed to protect LSF structure, as defined in Table 1. Therefore, thinning occurred only if the unit had over 55.2 m^2/ha of basal area and all large trees (>35.6 cm) were retained. A unit treated with ProtectRx still met the definition for LSF structure, which was not true for the other two treatments, RestoreRx and ReduceRx. The treatment of intermediate intensity (RestoreRx) was designed to decrease the density of grand fir trees that have established since successful fire exclusion practices began. Application of the diameter limit was coupled with a residual basal area requirement of 23 m^2/ha and preferential retention of early-seral species like ponderosa pine (*P. ponderosa*) or western larch (*Larix occidentalis*). The most intensive treatment in terms of basal area removed (ReduceRx) was designed to minimize crown fire potential. Therefore, crown bulk density was reduced by allowing canopy cover to drop to 40% and by increasing the maximum diameter limit of trees removed to 51 cm dbh. All treatments were followed by piling and burning of residual slash. The ReduceRx and RestoreRx also planted early-seral species that historically were more extensive in the study area (Bright, 1941) but because of previous

Table 2
Silvicultural treatment descriptions and associated net present values (NPV) per hectare

Treatment	Description	Citation	NPV ($)	
			Lowest	Highest
No Rx	No activity scheduled			
ReduceRx	40% canopy cover Thin from below to 51 cm dbh Preferentially remove ABGR[a] Pile and burn Plant PSME, PIPO, LAOC	Agee (1996) Graham et al. (1999)	−2470	3663
RestoreRx	Thin from below to 38.1 cm dbh Keep at least 23 m^2/ha basal area Retain PSME, PIPO, LAOC; PIEN Pile and burn	Hummel et al. (2002)	−2534	−12
ProtectRx	If more than 55.2 m^2/ha in unit then thin trees 0–35.6 cm dbh to 8.3 m^2/ha Pile and burn	Johnson and O'Neil (2001) Brown (2000) Mendez-Treneman (2001)	−1339	−563

[a] ABGR: Grand fir (*A. grandis*); PSME: Douglas fir (*P. menziesii*); PICO: Lodgepole pine (*P. contorta*); LAOC: Western larch (*L. occidentalis*); PIPO: Ponderosa pine (*P. ponderosa*); PIEN: Engelmann spruce (*Picea englemannii*).

Table 3
Additional harvest costs and contract requirements treatments modeled

	RestoreRx		ReduceRx		ProtectRx	
	Dollars/ha	Dollars/m^3	Dollars/ha	Dollars/m^3	Dollars/ha	Dollars/m^3
Hauling		280		280		280
Road maintenance		35		35		35
Temporary development						
Required reforestation	480		480			
Slash live trees < 7.6 cm	480		480		200	
Pile and burn	600		600		250	

logging now lack a reliable seed source. The planted regeneration included 50 Douglas fir, 50 ponderosa pine, and 30 western larch trees per acre. In summary, the treatments comprise a thinning gradient, from the most intense (ReduceRx) to the least (ProtectRx).

We did not determine in advance which treatment to apply to which unit, but instead based application eligibility on a set of rules. We simulated the results of multiple treatments on many of the units; however, only one treatment could be selected for each unit in a decade. The rules were as follows: (1) only units in PVT 10 were eligible for treatment; (2) no unit classified as nesting habitat (NH) could be treated in the same decade; (3) no unit projected to become NH within 30 years was ever eligible; (4) units within owl circles were not eligible for treatment in the first two decades but could be eligible in the third provided they were not restricted by other rules; and (5) special areas of agency concern were not eligible for treatment.

We compared the simulated conditions in each unit in each decade under each treatment according to the nesting habitat, LSF structure, and FT definitions given earlier and saved all values in a Microsoft Excel® file. Treatments were applied to a total of 237 units.

2.5. Accounting for treatment costs and revenues

When a silvicultural treatment is applied in FVS, it is possible to request a list of the trees cut in the process (Van Dyck, 2000). We did this for all treated units in all decades and entered the resulting "cut tree" lists into the Financial Evaluation of Ecosystem Management Activities (FEEMA) model (Fight and Chmelik, 1998). By using the cut tree list together with additional input data, the FEEMA software first estimated wood volume by tree species, lumber grade recovery, and corresponding product value and then subtracted manufacturing, hauling, and harvesting costs to calculate the expected net revenue per unit associated with any given treatment.

The additional input data required by FEEMA included price assumptions for harvest costs, fuel treatments, and wood products. We obtained estimates of the costs of harvest and fuel treatments, including hauling, road maintenance, contractual requirements, reforestation, slashing, and piling and burning, from managers of the Gotchen Reserve (Table 3). Direct harvest costs were differentiated by the diameter at breast height of cut trees and the cubic volume of wood removed (Table 4). Defect is common in grand fir, the main species cut in all treatments (Aho, 1977), and so we estimated the amount of defect by log size class by using local timber sale records (Table 5). Wood product prices from a stable high market (fourth quarter 1999) and a stable low market (fourth quarter 2001) (Warren, 2001, 2003) were averaged (Table 6). Manufacturing costs by small-end diameter for stud, random length, and veneer are displayed in Table 7 (from Wagner et al., 1998). We assumed that product prices and all harvest and operational costs were constant over time and discounted future costs and revenues by 4% (Row et al., 1981).

Table 4
Harvest costs (dollars/m^3 removed)

Diameter at breast height (cm)	Volume per hectare (m^3/ha)			
	27.9	48.93	69.9	104.8
15.24	83	81	79	76
20.32	74	72	71	68
25.40	66	64	62	59
30.48	57	55	53	50
35.56	48	46	44	41
40.64	48	46	44	41

Source: Barbour et al. (2004).

Table 5
Estimate of defect by diameter class

Diameter at breast height (cm)	Defect (%)	Chipable (%)
2.5–12.8	4	100
12.9–25.4	4	100
25.5–38.1	6	85
38.2–50.8	15	70
>50.9	25	60

2.6. *Developing a production function for FT and LSF structure with financial constraints*

In combination, the FVS and FEEMA models allowed us to create a database that included all values for LSF structure, FT, and net revenue computed for each unit, in each decade, and for each treatment, and the GIS layer enabled us to link these values spatially. We used this spatial database and a simulated annealing algorithm (Kirkpatrick et al., 1983) to identify tradeoffs between FTR and LSF structure for given targets for net present value (NPV) and limits on area treated in each decade. By varying constraints, we constructed a set of two-dimensional production curves for the Gotchen Reserve (Calkin et al., submitted for publication). We used these curves to identify a range within which silvicultural treatments could achieve relatively high FT reduction at relatively low cost to LSF structure. Within this range, we added financial constraints to the algorithm to evaluate the effect on FT reduction levels.

We set NPV constraint levels of USD $0, $0.5 million, $1 million and $1.5 million over 30 years to develop a three-dimensional production function in terms of NPV, LSF structure, and FT. We also included an unconstrained case, in which no financial requirement was set. The objective function was to reduce landscape FT while the area in LSF structure, the NPV, and the maximum area treated with ReduceRx, RestoreRx, ProtectRx, or a mixture thereof, were set as constraints. The $1.5 million NPV constraint was infeasible at the highest levels of the LSF

Table 6
Wood product prices by species and grade

	Douglas fir and Larch	Hemlock[a] and fir	Ponderosa pine	Lodgepole pine
Dollars/thousand board feet				
Select and shop				
Moulding and better	1092	923	1516	
No. 1 Shop			740	
No. 2 Shop			900	
No. 3 Shop			692	
Visual dimension				
Select structural	410	360		360
No. 2 & better	356	322	281	319
Stud	338	325		314
No. 3 & Utility	214	303	174	208
Economy	127	134	133	143
Commons				
2 Common and better common			579	
3 Commons			395	
4 Commons			275	
5 Commons			126	
Dollars/bone dry unit[b]				
Other				
Chips	54	71	61	71
Residue chips	54	71	61	71
Other residues	10	10	10	10

[a] Tsuga.

[b] Bone dry unit (Bdu): 1088.6 kg (oven-dry).

Table 7
Manufacturing costs by processing technology and product

Small end diameter (cm)	Stud dimension (dollars/m^3)	Random length (dollars/m^3)	Veneer (dollars/m^3)
Common technology			
12.7	194	254	45
13.97	164	218	45
15.24	142	175	45
16.51	122	147	45
17.78	106	133	45
22.86	80	93	45
27.94	77	75	45
35.56		65	45
Advanced technology			
12.7	219		
13.97		181	
15.24		157	
16.51		136	
17.78		123	
22.86		91	
27.94		73	
35.56		63	

Note: metric conversion assumptions: stud: 2 × 4 dry, and random length = 2 × 6 dry.

structure constraint and so we used a \$1.45 million maximum NPV constraint instead. The LSF structure constraint was bound by using values from the simulations run without treatments applied. These values bound the constraint from below by the total area in nesting habitat and from above by the maximum potential LSF structure, which was 6985 ha summed over 3 decades. We included intermediate constraints of 6678, 6780, and 6880 ha of LSF structure. The constraint on the maximum area treated in each decade was based on guidelines for silvicultural activities in reserves identified in Plan documents (FEMAT, 1993, p. III-35). We included both a NPV constraint and an area treated constraint in our formulation due to the large variation in NPV of individual treatment alternatives. Treatment effects were assessed by calculating if FT index values were reduced in treated units and adjacent units and then calculating the overall effect on the landscape FT index over the 30-year analysis period.

We explored a variety of constraint formulations including penalty functions, strict constraints, and combinations of these two. In the end, a combination of two penalty functions and a strict constraint produced the most consistent solutions for the range of constraint levels. Treatment area and NPV constraints were achieved using penalty functions while the LSF constraint was achieved using a strict constraint. The final form was

$$\text{Max}\quad \left[\sum_t\sum_i\{\text{Threat}_{i,t}(\text{no treatment}) - \text{Threat}_{i,t}(j,\text{adj}_i(j))\} * \text{Area}_i\right] - \text{Tot Area Penalty} - \text{Revenue Penalty} \tag{1}$$

$$\text{If}\quad \sum_i \text{Area}_i * \text{Period}_{i,t} > 608 \quad \text{for} \quad t = 1,2,3$$

$$\text{Area Penalty}_t = \left(\sum_i \text{Area}_i * \text{Period}_{i,t}\right) - 608$$

$$= 0 \text{ otherwise}$$

$$\text{Tot Area Penalty} = B_1 * \sum_t \text{Area Penalty}_t \tag{2}$$

$$\text{If} \sum_t\sum_i \text{Area}_i * \text{Revenue}_{i,j,t} < \text{Y}$$

$$\text{Revenue Penalty} = B_2 * \left(\text{Y} - \sum_t\sum_i \text{Area}_i * \text{Revenue}_{i,j,t}\right)$$

$$= 0 \text{ otherwise} \tag{3}$$

$$\text{Subject to}: \quad \sum_t\sum_i \text{Area}_i * \text{LSF}_{i,j,t} \geq \text{X} \tag{4}$$

where i indexes the 340 projection units and j indexes the 10 treatment alternatives: (0 = no action, 1 = apply ReduceRx in first decade, 2 = apply ReduceRx in second decade, 3 = apply ReduceRx in third decade, 4 = apply ProtectRx in first decade, 5 = apply ProtectRx in second decade, 6 = apply ProtectRx in third decade, 7 = apply RestoreRx in first decade, 8 = apply RestoreRx in second decade, 9 = apply RestoreRx in third decade); and $\text{adj}_i(j)$ is the treatment set for units adjacent to unit i; t indexes the three decades; $\text{Threat}_{i,t}$ is the fire threat class for unit i in period t; Area_i is the size of unit i in hectares; $\text{LSF}_{i,j,t}$ equals 1 when unit i with treatment j meets the LSF structure definition in decade t; but otherwise equals 0; $\text{Period}_{i,t}$ equals 1 if unit i is treated in decade t but otherwise equals 0; Area Penalty_t is when the periodic area constraint is violated in decade t; Tot Area Penalty is Area Penalty summed over three decades; $\text{Revenue}_{i,j,t}$ is the discounted net revenue (NPV) when treatment j is applied to unit i in decade t; Revenue Penalty occurs when the aggregated NPV constraint is not met, X is the minimum area of LSF structure summed over three decades; Y is the minimum NPV value (\$0, \$0.5, \$1, and \$1.5 million); B_1 is the area constraint coefficient (range 2.5–5.0); and B_2 is the NPV constraint coefficient (range 0.005–0.02).

To examine the potential influence of time, we also examined the effect of requiring the landscape silviculture treatments to break even (\$NPV = 0) in each of the three decades, rather than summed over the entire 30-year analysis period. For this, the penalty function described in Eq. (3) was replaced with the strict constraint:

$$\sum_i \text{Area}_i * \text{Revenue}_{i,j,t} < Y \quad \text{for } t = 1, 2, 3 \qquad (5)$$

3. Results

With no treatment, the hectares projected to be in LSF structure remained below 50% of the reserve area (Fig. 3), whereas the area projected to be in high fire threat increased to over 80% (Fig. 3). Several units changed from low or moderate FT to a high FT level between the first two decades and remained high in the third decade. These trends are consistent with ongoing tree mortality associated with the western spruce budworm outbreak. In parts of the Gotchen Reserve, the per hectare live tree basal area by size class is declining and fuel loads are increasing significantly (Hummel and Agee, 2003).

When treatments were applied, financial requirements for landscape silviculture over 30 years affected the predicted reduction of fire threat and the total area of late-seral forest structure in different ways. The amount of FT reduction and LSF structure in the reserve decreased with increasing financial requirements, as illustrated in Fig. 4, wherein the highest financial constraint (NPV $\geq$ \$1.5 million) is the most interior curve and the curves shift outward as the NPV constraint is reduced to no constraint. A positive financial constraint imposed costs on landscape objectives because the NPV of the silvicultural treatments ranged from a low of negative \$2534 to a high of \$3663 per hectare (Table 2). Therefore, treatments that lost money at the scale of an individual unit were rarely selected by

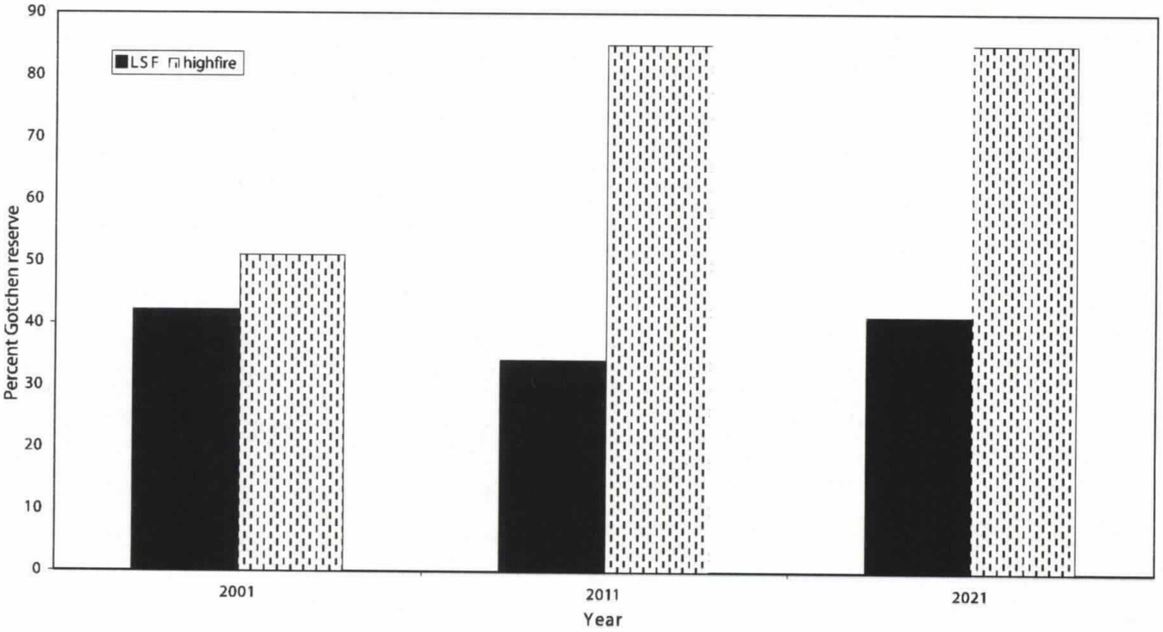


Fig. 3. Projected late-seral forest (LSF) structure (black) and area in high fire threat (stippled) (total area as percent of Gotchen Reserve, no treatment).

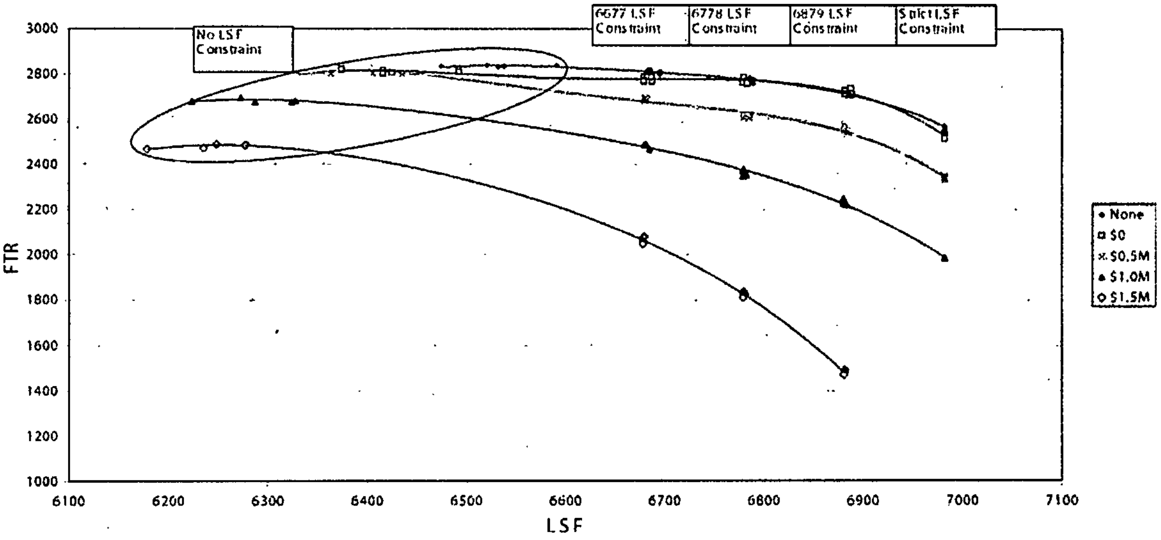


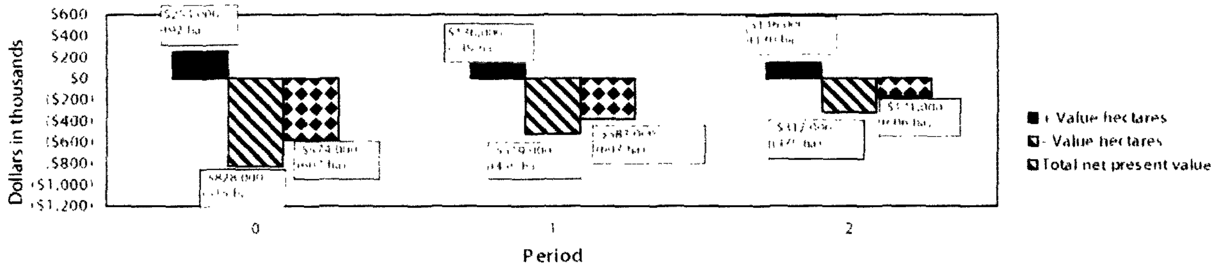
Fig. 4. Fire threat reduction (FTR) (weighted index values) versus late-seral forest (LSF) structure (hectares) for a range of net present value (NPV) requirements over 30 years in the Gotchen Reserve. The ellipse highlights the unconstrained option.

the algorithm during runs with high NPV constraints even though they reduced the landscape threat of fire at low cost to LSF structure.

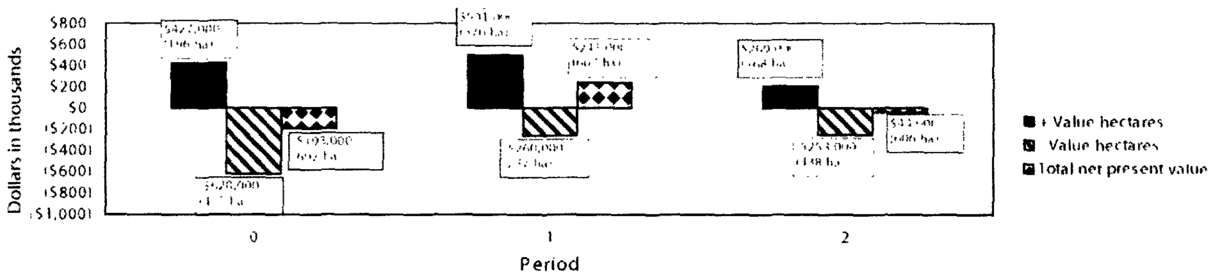
Compared to the financially unconstrained solution, the breakeven NPV constraints imposed a very small cost in terms of FTR and LSF structure relative to the positive NPV constraints. The mix of silvicultural treatments in the breakeven and unconstrained solution sets accomplished about the same level of FT reduction and LSF structure (Fig. 4) but although the treatment results were similar the net revenues were not (Fig. 5a and b). Indeed, their associated NPV ranged from negative $1,000,000 to positive $3000 over 30 years. Thus, the breakeven NPV constraint imposed a relatively low cost in terms of fire threat reduction and avoided the financial losses associated with the unconstrained case. Relative costs are perhaps more informative than absolute ones for non-market objectives. As an example, for the breakeven NPV constraint, results suggest that the cost of an 8% improvement in FT reduction is a 1.5% reduction in LSF structure within the study reserve.

The paired graphs (Figs. 5a–e and 6a–e) reveal some trends about the effects of financial constraints on landscape silviculture treatments. The net revenue by decade for different NPV constraints given an LSF structure constraint of 6880 ha are shown in Fig. 5a–e and the corresponding silvicultural treatments each decade are shown in Fig. 6a–e. For example, Fig. 5a indicates that the total NPV of the financially unconstrained case was negative in all decades and Fig. 6a shows the various proportions of the three treatments that comprise this case. The least intensive treatments (RestoreRx, ProtectRx) resulted in a negative NPV for all units in all decades, whereas the most intensive treatment (ReduceRx) had large negative net returns in some units and large positive returns in others (Table 2). More treated acres lost money than made money in each decade, and the largest losses occurred in the first decade, in which RestoreRx and ReduceRx were each applied to approximately half of the area eligible for treatment. By decade 2, the area treated by ReduceRx dropped to one-third. In the last decade, ProtectRx was applied to approximately 40 ha, and the area in ReduceRx was about half. Similarly, the other paired graphs (Figs. 5 and 6b–d, etc.) illustrate the NPV per decade for the different financial constraint levels and the associated mix of silvicultural treatments given the same landscape objective. For example, although the unconstrained case (Fig. 6a) and the breakeven case (Fig. 6b) resulted in similar levels of FT reduction in the Gotchen Reserve (Fig. 4) it was accomplished with different treatment mixtures and total area treated. In the breakeven case, the most intensive treatment (ReduceRx) was applied more often and to more area

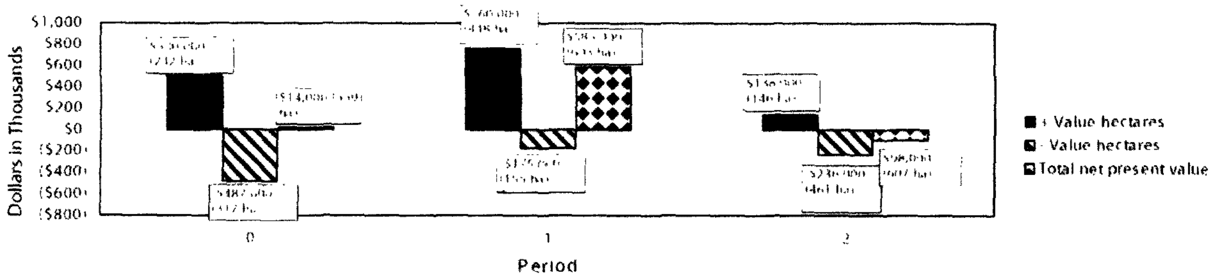
(a) no npv constraint



(b) $0 npv constraint



(c) $0.5 million constraint



(d) $1.0 million constraint

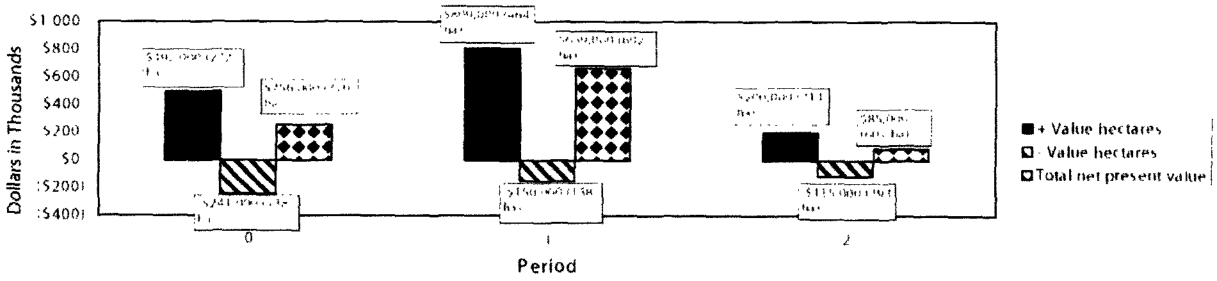


Fig. 5. Financial returns per decade for five different net present value (NPV) constraints and a constant 6880 ha LSF structure constraint in the Gotchen Reserve. (a) No NPV constraint (unconstrained); (b) $0 NPV constraint (breakeven); (c) $0.5 million NPV constraint; (d) $1.0 million NPV constraint; (e) $1.5 million NPV constraint.

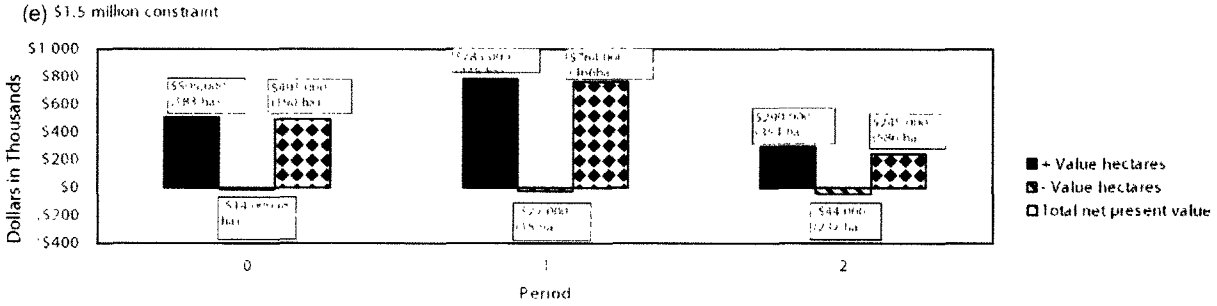


Fig. 5. (*Continued*).

than in the unconstrained case. The ReduceRx treatment sometimes earned money (Table 2) which made it possible to apply the least intensive treatment (ProtectRx) earlier in the breakeven case (the second decade) than in the unconstrained case (the third decade) and still meet the NPV constraint.

The financial constraints also affected whether the maximum area eligible for treatment imposed by the area constraint (608 ha) was indeed treated. Clearly, the constraint to earn positive NPV imposed an additional limitation beyond what the area constraint allowed (Fig. 6c–e). This trend increased with increasing financial requirements, because once the hectares that returned positive net revenue were treated it did not make financial sense to treat any others. Together, Fig. 6c–e reveals a trend to apply the

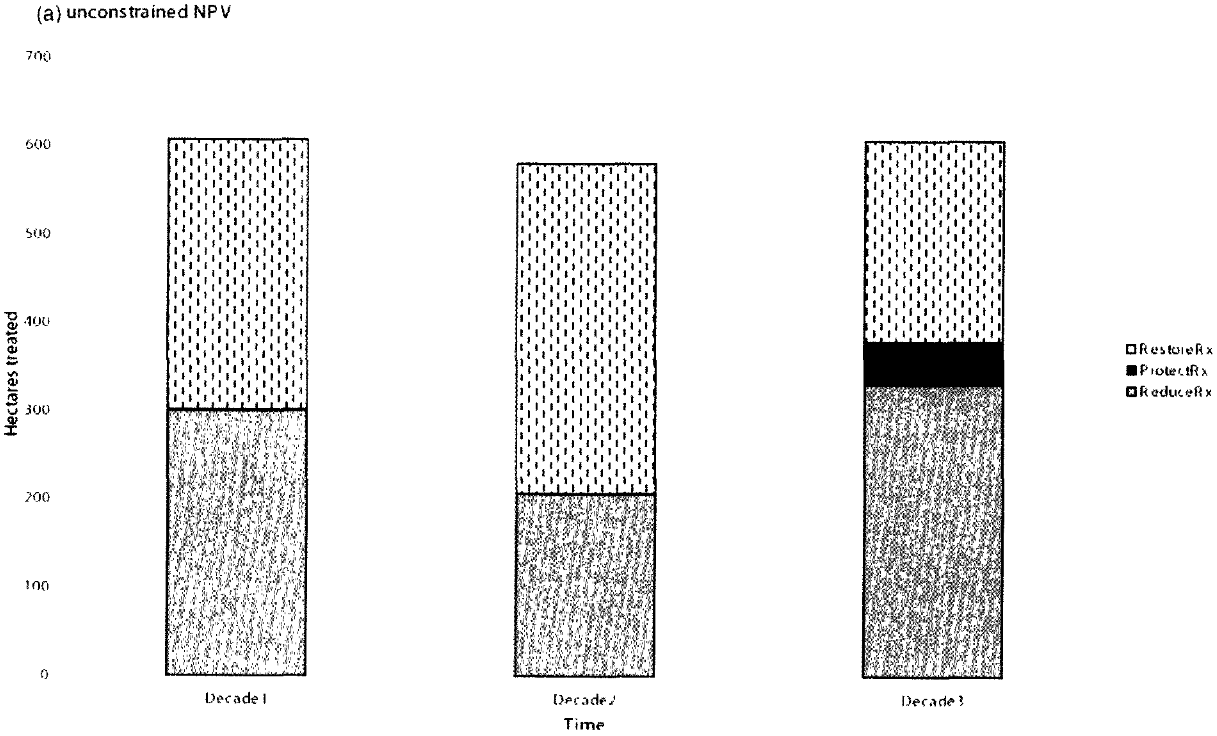
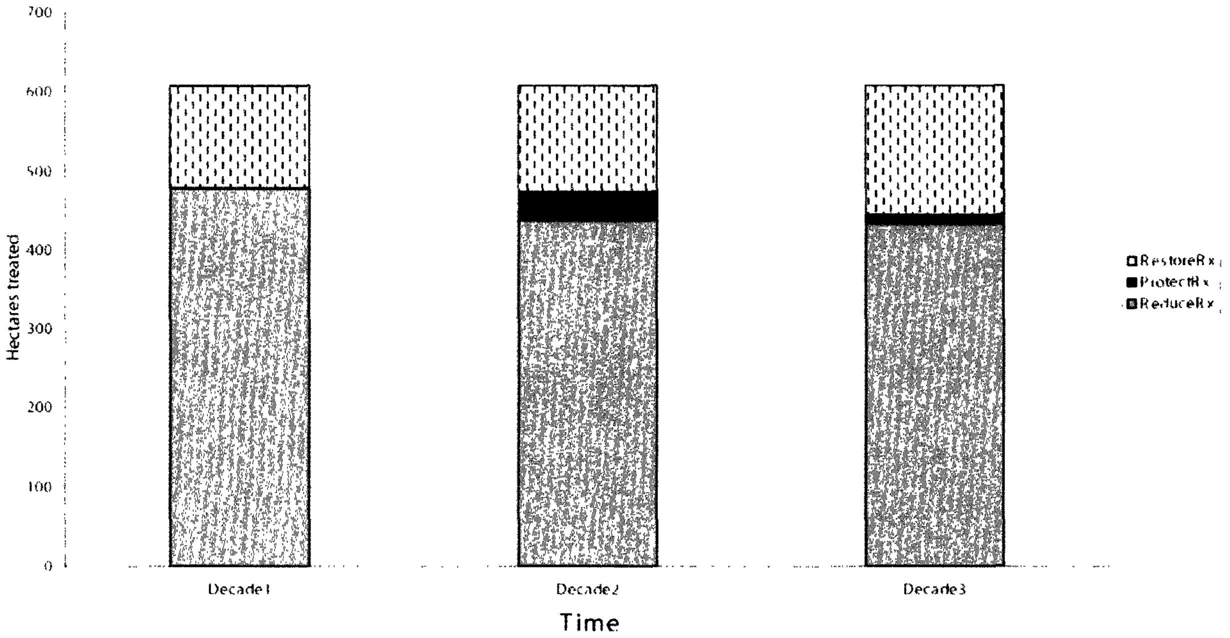


Fig. 6. Proportion of silvicultural treatments (RestoreRx, ProtectRx, ReduceRx) applied in each of 3 decades to maximize fire threat reduction in the Gotchen Reserve given constraints on late-seral forest (LSF) structure maintained (6880 ha), on area treated per decade (10% of reserve), and on net revenues (NPV): (a) no NPV constraint (unconstrained); (b) $0 NPV constraint (breakeven); (c) $0.5 million NPV constraint; (d) $1.0 million NPV constraint; (e) $1.5 million NPV constraint.

(b) Breakeven NPV



(c) $0.5 million NPV

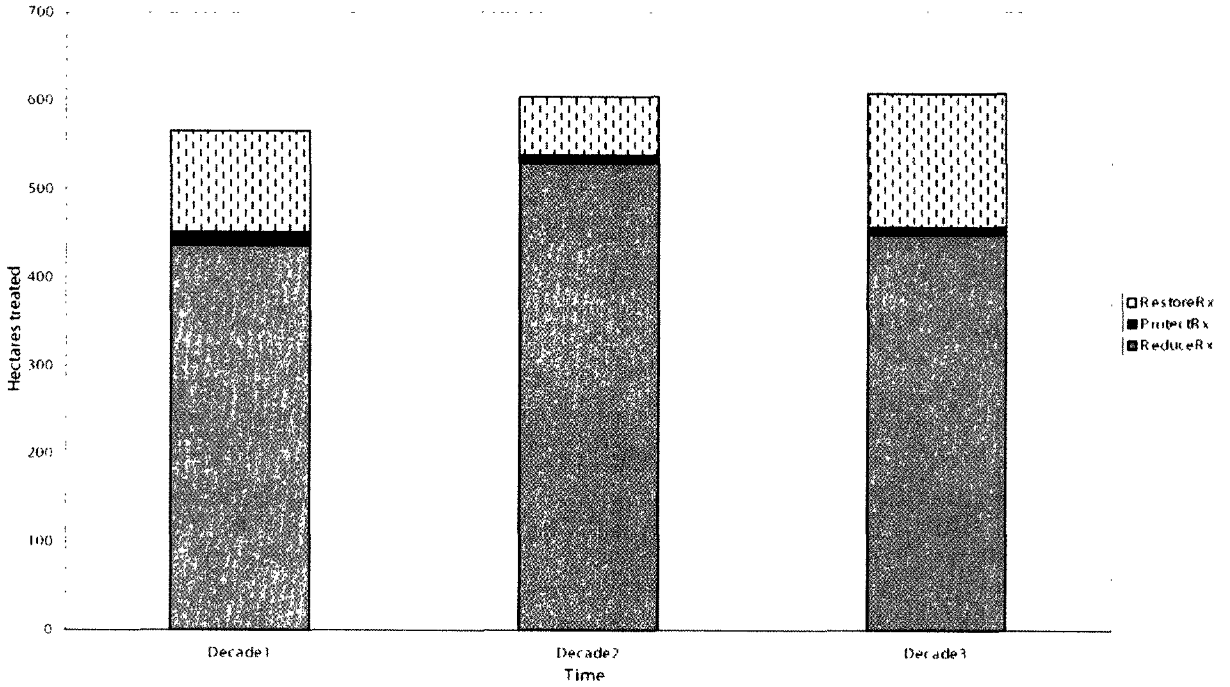
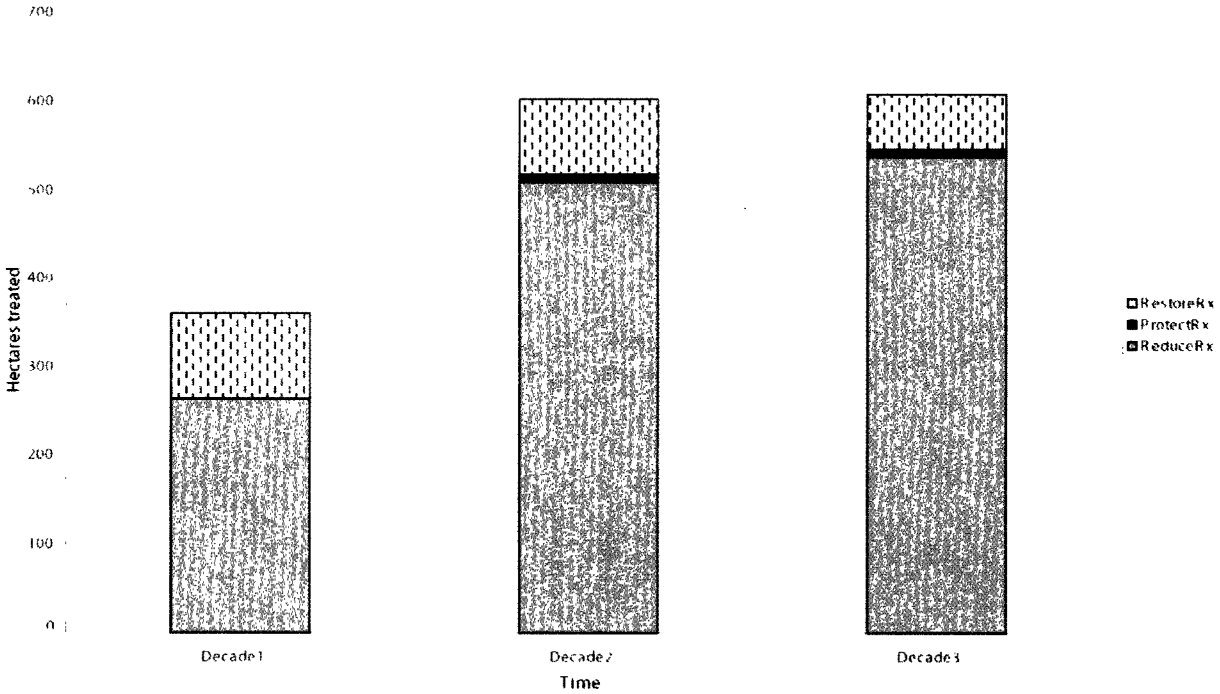


Fig. 6. (*Continued*).

(d) $1.0 million NPV



(e) $1.5 million NPV

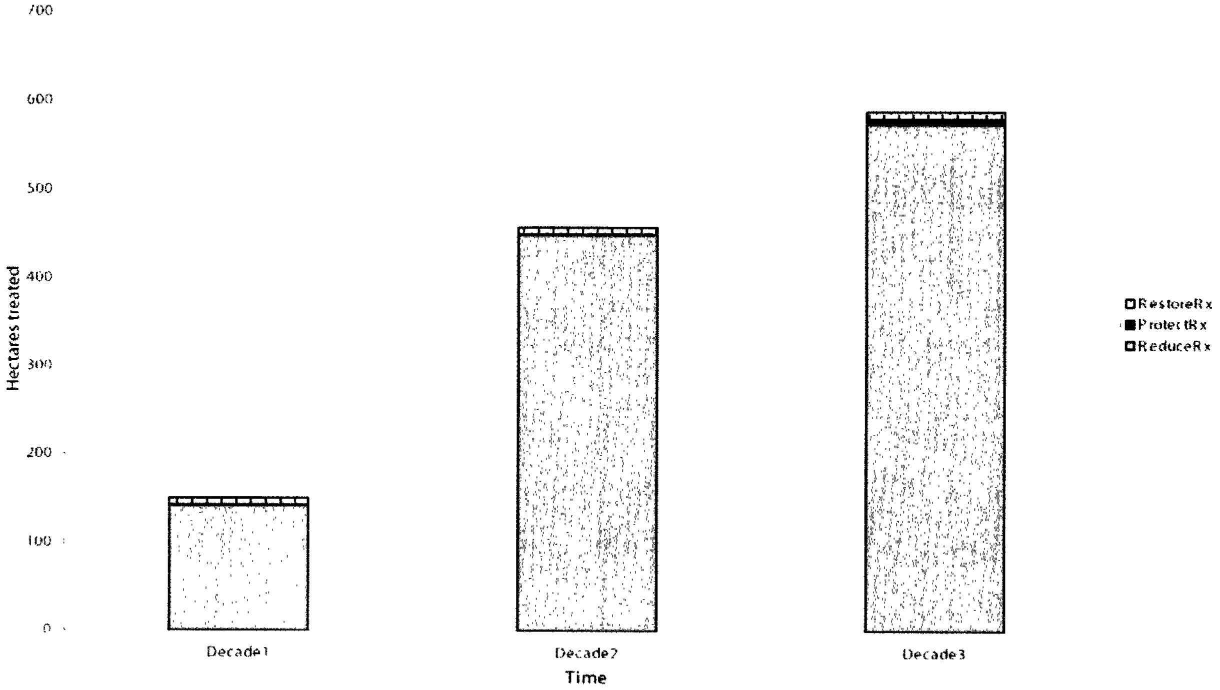


Fig. 6. (*Continued*).

most intensive treatment and to apply it heavily in the second and third decades when the trees have grown and become even more valuable. Fig. 6d and e also illustrates that the higher the required NPV, the less opportunity exists to apply any treatment that loses money on an individual unit.

Estimates of net revenues from landscape silviculture varied widely. The maximum potential NPV, restricted to the treatments modeled and with an area constraint of 608 ha per decade, was a positive $2.25 million. In contrast, NPV from the unconstrained case ranged between negative $1.6 million to negative $714,000 with constraints of 6985 and 6680 ha, respectively, for the area of LSF structure to be maintained. The second decade consistently contributed more revenue to total NPV than the first despite the discount rate of 4%. The discount rate diminished the contribution of returns in the last decade relative to the first two.

The time over which the NPV constraint was applied imposed a cost on FT reduction in the Gotchen Reserve. When the financial constraint to break even was imposed in each decade instead of being aggregated over the 30-year analysis period, results suggest that breaking even in each decade was comparable to making $0.5 million over 30 years. By implication, imposing the decadal constraint lowers the total FT reduction in comparison to what would be possible over 30 years because the aggregated $0.5 million constraint has a lower FT reduction level than the aggregated unconstrained or breakeven constraints (Fig. 4).

A mixture of silvicultural treatments always resulted in higher levels of FT reduction for the same level of LSF structure than did any one single treatment. This suggests that any treatment applied universally would impose a cost on both non-market values when the units were aggregated. Further, it implies that a collection of stands may confer non-market values not included in any individual stand. This is logical, given that different treatments result in different forest structures, and a mix of structures over an area may confer values not contained in any single structure.

4. Discussion

In landscape silviculture, conditions in a treated unit can only be evaluated within the context of objectives for a larger area. What appears to support landscape objectives in isolation may change when considered in total because the gestalt of a forest landscape is more than the sum of its units. We therefore abandoned a unit-by-unit approach to silvicultural decision-making in this analysis and instead developed methods to consider all units when selecting treatments to support fire and habitat management objectives for the Gotchen Reserve. Results from this analysis indicate that objectives for the reserve could be achieved with a mixture of treatments that returned both positive and negative net revenue at the scale of an individual unit. The study results also suggest that the objectives could be achieved either with treatment mixtures that lost money or that broke even at the scale of the reserve.

The skills on which silviculturists rely to understand forest dynamics and to design treatments at the stand scale can be relevant as the scale of management changes. Site-specific knowledge remains critical, yet identifying and testing principles of landscape silviculture requires interaction with disciplines that are focused at larger spatial scales. Forest simulation models are tools that are available when it is difficult or impossible to install, replicate, and maintain landscape silviculture experiments.

Prudence dictates that public forest management objectives be achieved at the lowest cost. Rather than focus on absolute costs, however, it can be useful instead to consider opportunity costs when evaluating the effects of silvicultural treatments at any spatial or temporal scale. This is particularly true when forest management objectives include non-market values, because the total cost of silvicultural treatments will include impacts not measurable in dollars. One way to evaluate these impacts is by identifying production relations between non-market values and then estimating the relative cost of managing one in terms of the other. Although production curves can increase our understanding of the potential tradeoffs between non-market values, two or three dimensions are likely insufficient to capture biologically and socially important variables. In this analysis, for example, uncertainty over the relation of forest structure to persistence of the northern spotted owl will affect perceptions of the risk to owls from different silvicultural treatments. This, in turn, will introduce other constraints that are outside the scope of this analysis. The large negative NPVs of unconstrained solutions and the proximity of breakeven constraints suggests that if important values are not included in scheduling optimization programs, the solutions may have large costs in terms of values not modeled. Similarly, extreme constraints had high marginal costs on the values that were modeled. This argues for including additional values in modeling efforts and avoiding strict constraint levels. Our results suggest that focusing on one non-market value to the exclusion of others can carry high opportunity costs. Economic efficiency is not the only factor considered by managers of public lands, but economic methods can be used to provide information on costs and tradeoffs associated with different options for landscape silviculture.

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