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ORIGINAL PAPER

Evaluation of forest management systems under risk of wildfire

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Abstract We evaluate the economic efficiency of even- and uneven-aged management systems under risk of wildfire. The management problems are formulated for a mixed-conifer stand and approximations of the optimal solutions are obtained using simulation optimization. The Northern Idaho variant of the Forest Vegetation Simulator and its Fire and Fuels Extension is used to predict stand growth and fire effects. Interest rate and fire risk are found to be critical determinants of the superior stand management system and timber supply. Uneven-aged management is superior with higher interest rates with or without fire risk. Alterations in the interest rate affect optimal stocking levels of uneven-aged stands, but have only minor effects on the long-run timber supply. Higher interest rates reduce rotation length and regeneration investments of even-aged stands, which lead to markedly reduced timber supply. Increasing fire risk increases the relative efficiency of even-aged management because a single age cohort is less susceptible to fire damage over the course of the rotation than multiple cohorts in uneven-aged stands. Higher fire risk reduces optimal diameter limit under uneven-aged management and decreases optimal rotation length and planting density under even-aged management.

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Introduction

Wildfire poses a serious threat of damage and economic loss to forest communities and landowners. Fire risk reduces the economic potential of forestry as a source of livelihood especially in regions with hot and dry seasons (e.g., Mediterranean climate zone). Further, the increasing probability of long dry periods in other climate zones due to climate change makes fire risk a relevant factor in forest planning in a wide range of geographical locations.

The economic literature on fire effects has focused on even-aged forestry (for review see, Hesseln 2000), and the effect of fire risk on optimal rotation age is well established (e.g., Martell 1980; Routledge 1980; Reed 1984). The literature also includes optimization studies that simultaneously solve rotation age and thinning patterns (e.g., Reed and Apaloo 1991; Valsta 1992), rotation age and fire prevention activities (Reed 1987; Amacher et al. 2005), and rotation age and provision of amenity values (Englin et al. 2000).

The public interest in uneven-aged forest management has been recently growing mainly due to its ability to provide many non-timber benefits. The economic questions of uneven-aged management have been studied in several studies by employing static models (Adams and Ek 1974), dynamic optimization models (Haight 1985), and simulation-based comparisons of alternative management regimes (Schulte and Buongiorno 1998; Knoke and Plusczyk 2001). However, the effect of fire risk on optimal management or value of uneven-aged stands is largely unexplored.

The any-aged stand management formulation includes different variants of uneven- and even-aged management as special cases and offers the most general framework for evaluating the economic efficiency of alternative management strategies (Haight 1987). The control variables can be defined broadly so that the forest stand may develop an uneven-aged stand structure, an even-aged stand structure, or any intermediate structure between the two extremes depending on which gives the highest objective function value. Any-aged management problems have been formulated and solved for single-species conifer stands (e.g., Haight 1987; Wikström 2000) and mixed-species conifer stands (Haight and Monserud 1990a, b). The existing studies include sensitivity analysis with respect to different definitions of harvest controls (Haight and Monserud 1990a), initial states (Haight and Monserud 1990b), and steady-state constraints (Wikström 2000). None of these studies examine how fire risk alters the ranking of preferred management system.

Existing studies of even-aged management under fire risk make varying assumptions about how wildfire affects stand structure and management. A typical assumption is that when a wildfire occurs, it causes complete mortality that is followed by immediate replanting (e.g., Reed 1984). However, wildfires may cause only partial mortality. Mandatory replanting is not a valid assumption if only a portion of the burned trees die (Caulfield 1988). There are also studies that randomize the proportion of trees destroyed in the fire (e.g., Gassmann 1989) or the proportion of the residual timber stock that can be salvaged (e.g., Reed 1984). Some studies make fire occurrence dependent on stand characteristics or prior management (e.g., Reed and Errico 1985; González et al. 2005) or assume that the fraction of timber volume salvaged in the event of fire depends on planting density and intermediate fire prevention activity (Amacher et al. 2005). None of these studies, however, model the fire damages as functions of fuel levels, characteristics of tree canopies, species composition, and weather conditions that are the ultimate determinants of fire effects. Graetz et al. (2007) employed empirically estimated models for canopy fuels and canopy base height to determine the temporal sequence of harvests that maximize the stand's ability to avoid crown fire. However, they didn't extend their model to economic analysis of timber production.

This study builds on previous work in the areas of any-aged stand management and fire risk. We describe a modeling framework for comparing the economic efficiency of even- and uneven-aged management regimes under the risk of wildfire. The framework includes an individual-based model of stand dynamics and an empirically estimated model for fire effects. The techniques of simulation optimization are used to approximate the optimal solutions to stand management problems for a test case involving a mixed-conifer stand in Northern Idaho, USA. The computations are repeated for various rates of interest and levels of fire risk in order to elaborate economic–ecological relationships that drive rational decision making and choice of management system.

Materials and methods

Model for stand growth and fire effects

A variant of the Forest Vegetation Simulator (FVS) validated for mixed-conifer stands in Northern Idaho (Dixon 1989, 2002) and the Fire and Fuels Extension (Reinhardt and Crookston 2003) is used to predict stand growth and fire effects.[1] FVS is a family of stand management tools developed by the USDA Forest Service. At present, it consists of more than 20 variants calibrated for different locations and conditions in the USA and Canada. Each variant includes an individual-tree simulation model with thousands of state variables describing trees and fuels. The simulation model predicts tree growth and mortality as functions of natural factors (such as competition, aging, and wildfire) and human intervention (harvesting and silvicultural activities). The Northern Idaho variant also contains a full establishment model (Dixon 2002). It adds in-growth periodically during the simulation, and pulses of regeneration following significant stand disturbances. It is also possible to add trees by planting.

The FVS variants include distance-independent, individual-tree models. The stochastic features in tree growth are assigned to the distribution of errors associated with the prediction of tree diameter increment. The random component of change in tree diameter is treated by (1) adding a random deviate to the basal area increment of each tree record, and (2) augmenting (tripling) the number of tree records for consecutive periods for stands with small initial number of tree records (Dixon 2002). Simulations can be replicated with different random number seeds to obtain scenarios of stand development.

Fire and Fuels Extension to the FVS (Reinhardt and Crookston 2003) simulates fuel dynamics, fire behavior, and fire effects. The model predicts fire intensity and fire type, which can be surface fire, passive or active crown fire. Fire intensity and tree mortality are predicted as functions of vertical distribution of fuels, tree characteristics (e.g., crown length, diameter, and species), stand characteristics (e.g., slope), and environmental variables at the moment of fire (fuel moisture, wind speed, and temperature). The probability of fire arrival does not depend on stand state or

[1] The model version is RV:09.25.06.

prior management, and must be given separately to the model.

Solving stochastic stand management problems

Ideally, a stochastic forestry problem assumes that a decision maker monitors stand development and makes each decision based on the current stand state. Stochastic dynamic programing is one approach to solving such a problem. However, dynamic programing requires a small number of stand states and much simpler model structure than the FVS.

Another approach to stochastic stand management problems is simulation optimization in which the expected value of the objective function is estimated via stochastic simulation until a suitable approximation of the optimal values of the decision variables is found. The first step is to estimate the expected value of the objective function for a given set of decision variable values. This sample average is computed using a set of scenarios, where each scenario is composed of random samples from the distributions of the random variables. The second step is to search for a solution that provides a suitable approximation to the optimal values of the decision variables. The advantage of simulation optimization is that the model of stand dynamics can be used without modification in the search for the best management regime. A disadvantage is computational intensity: a large number of replications may be required to obtain a useful estimate of the expected value of the objective function for each management regime. In forestry, simulation optimization has been used to investigate the effects of stochastic prices (e.g., Caulfield 1988; Haight 1990), catastrophic risk (e.g., Valsta 1992; González et al. 2005), and uncertain regeneration success (Zhou 1999) on optimal stand management.

Applying simulation optimization with the FVS is computationally intensive. A typical simulation of harvests and wildfire requires 10–30 s on a laptop computer, and hundreds of simulations may be needed to stabilize the expected objective function value. Therefore, we made a number of simplifications in the problem formulation to reduce the computational burden. First, we defined a small number of discrete decision variables separately for even- and uneven-aged management. Second, the minimum step lengths for decision variable values were increased. Third, harvesting took place on a 20-year interval rather than the 10-year prediction interval allowed by the simulator. Fourth, wildfire occurrences were discretized such that a fire may occur once during each 20-year-period.

These simplifications reduced the set of possible harvesting regimes compared to earlier studies of any-aged stand management (e.g., Haight and Monserud 1990a) and made it possible to use FVS and its Fuels and Fire extension in our analysis. We focus on the management decision in the first period: whether the stand is retained under uneven-aged management or converted to an even-aged plantation.

Computing the forest values

Assume that the initial stand can be either retained under uneven-aged management by repeated diameter-limit harvests or converted to even-aged management with an immediate clearcut followed by artificial regeneration and an infinite series of rotations. The expected present value of the initial stand is computed separately for each management system. The optimization problem for each management system is to select the values of the decision variables (denoted by a vector x) to maximize the expected net present value of the stand, $E(\text{NPV})$, under risk of wildfires and stochastic tree diameter growth:

$$\max_x E(\text{NPV}) = \sum_{i=1}^{m}\sum_{j=1}^{n} \text{pr}_{ij}(\lambda)\text{NPV}_{ij}(x, \chi, \lambda). \tag{1}$$

The probability distribution for NPV is estimated by repeating the simulations for m fire scenarios and n sequences of tree growth predictions (see Fig. 1 for illustration on the structure of simulation optimization framework). For each set of decision variable values x, $E(\text{NPV})$ is estimated by first computing NPV_{ij} for the ijth scenario of fire and tree growth, then multiplying NPV_{ij} by the probability of occurrence of scenario ij (pr_{ij}), and finally summing the products over the mn simulations. The probability of fire occurrence in a period is denoted by λ ($0 \le \lambda < 1$). The seed random number used in diameter growth predictions, χ, is specific for each simulation.

It is assumed that fire enters the stand by spreading from outside. Thus, the occurrence of wildfire does not depend on stand characteristics or prior management. The period length w is 20 years and the number of period q is 6. Let ψ_k be a variable that has the value of 1 or 0 depending on whether a fire occurs or does not occur during the period k. The probability that a wildfire occurs in period k is $P(\psi_k = 1) = \lambda$ and the probability that the wildfire does not occur is $P(\psi_k = 0) = 1 - \lambda$. The simulations are repeated for all $m = 2^q = 64$ possible realizations of fire occurrences. The probability of each fire scenario i and sequence of diameter growth predictions, j, is:

$$\text{pr}_{ij} = \frac{1}{n}\prod_{k=1}^{q} P(\psi_k^i), \quad i = 1, \ldots, m, \quad j = 1, \ldots, n. \tag{2}$$

With uneven-aged management, the decision variable x is the diameter limit of selective cuttings (given in cm). A diameter-limit cut removes all trees above a diameter limit. In addition, 15% of smaller trees not exceeding the diameter limit are removed in selective cutting. These

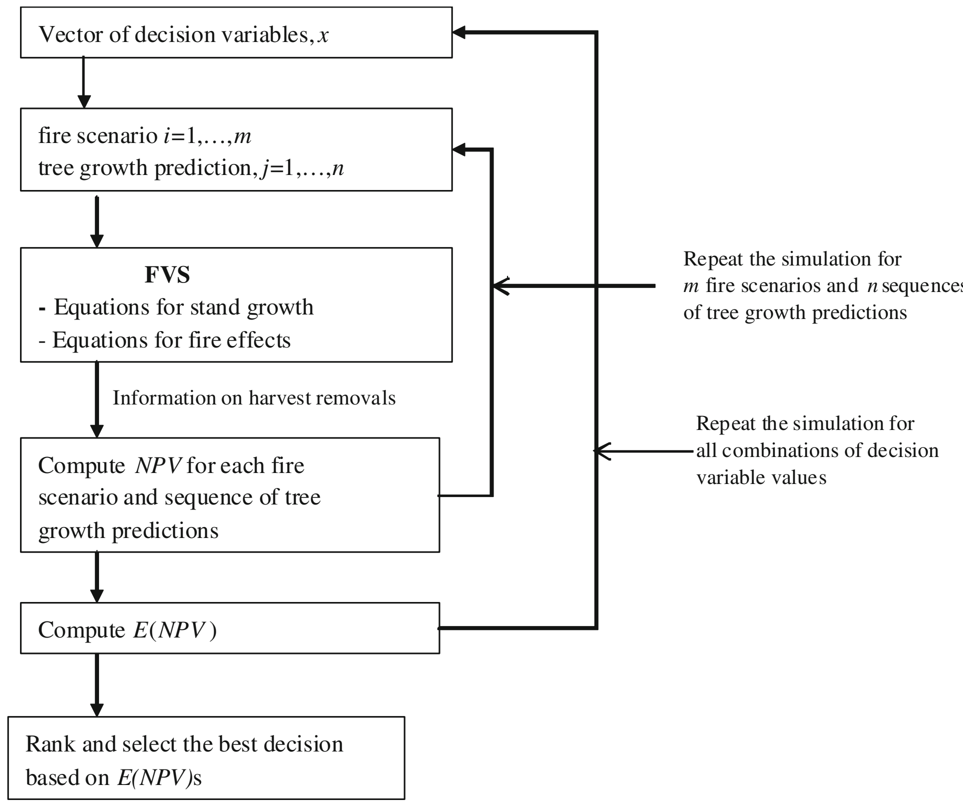

Fig. 1 Illustration of the simulation optimization framework

include inferior quality stems and those stems that are damaged during the logging operation. Cuttings are scheduled at the start of each period, and the end of the last period. The net present value for the given fire scenario, i, and sequence of diameter growth predictions, j, is approximated by discounting the simulated harvesting revenues from the first seven cuttings and assuming that the periodic revenues remain thereafter at the average level of the four last cuts.

$$\mathrm{NPV}_{ij}(x,\chi,\lambda) = \sum_{k=1}^{q+1}\sum_{l=1}^{s_k}\alpha_{kl}p_l g_{kl}\, e^{-rw(k-1)} + \frac{\sum_{k=4}^{q+1}\sum_{l=1}^{s_k}\alpha_{kl}p_l g_{kl}}{4(1-e^{-rw})}e^{-rw(q+1)}. \quad (3)$$

The rate of interest is denoted by r. The revenues from kth cutting are computed by multiplying the volume of harvested timber, g_{kl} (in MBF[2]), by its unit price, p_l (USD/MBF), and a quality premium multiplier, α_{kl}, for s_k tree records.

With even-aged management, x is a vector that consists of three decision variables: (1) planting density (trees/ha), (2) residual basal area in thinnings (m^2/ha), and (3) rotation period (years). After clearcutting, the stand is replanted immediately. The new tree regeneration is thinned to the same residual basal area after every 20 years and clearcut at rotation age. Thinnings are assumed to remove equal proportions of trees from all tree records until the target residual basal area is reached. The net present value is computed for each fire scenario, i, and sequence of diameter growth predictions, j, as a sum of harvesting revenues from immediate clearcutting of the present timber stock and the discounted net revenues from the subsequent rotation periods.

$$\mathrm{NPV}_{ij}(x,\chi,\lambda) = \sum_{l=1}^{s_1}\alpha_{1l}p_l g_{1l} + \frac{\sum_{k=2}^{q'}\sum_{l=1}^{s_k}\alpha_{kl}\,p_l\,g_{kl}\,e^{-rw(k-1)} - C(\mathrm{PL})}{1-e^{-rw(q'-1)}}. \quad (4)$$

The stand establishment costs depend on planting density, PL, and are denoted by C. The net present value from future land use is computed by discounting the net revenues for the first rotation, and assuming that similar stand management and realizations of forest fires and diameter growth rates are repeated in perpetuity. The computation was repeated for various combinations of planting density, residual basal areas, and numbers of 20-year-periods, $q' = 2,\ldots,q+1$ (i.e., rotation periods 20, 40, …,120 years).

[2] MBF denotes thousand board feet which is customary unit of timber volume in the USA.

There is an additional constraint for minimum harvested volume in each harvest for both even- and uneven-aged management problems:

$$\sum_{l=1}^{S_k} g_{kl} > 10, \quad k = 1, \ldots, q. \tag{5}$$

At least 10 MBF/ha of timber must be removed before a harvest can occur. This constraint excludes harvests with exceptionally high unit harvesting costs.

Case study computations

A real mixed-conifer stand located in Idaho Panhandle National Forest was selected as an initial state for computations. The stand consists of trees of five different species and various sizes (see detailed description of the stand in Table 1). The stand can be converted to an even-aged conifer plantation or managed with selection harvests. The stand data was obtained from the database of the Forest Inventory and Analysis Program of the USDA.[3] The stand belongs to the western hemlock habitat type with elevation 880 m above sea level. The initial basal area was 28.6 m^2/ha and average top height was 30 m.

The stumpage price levels for different species are those used in preparing the Forest Products Yield Tax Return in Idaho in 2007[4] (Table 2). The quality premium multipliers for higher dimension timber were not available for different species, and therefore a general function was assumed for all species $\alpha_{kl} = 2\left(1 - e^{-0.0394*(dbh-17.8)}\right)$, dbh ≥ 17.8, where *dbh* denotes tree diameter at breast height in cm. A tree with a *dbh* of 35.6 cm is assumed to represent the average stumpage price level. The stand establishment costs are given by $C = 247 + c_s\,\mathrm{PL}$, and consist of soil preparation (247 USD/ha) and planting cost. The combined labor and material cost for planting $c_s = 0.42$ USD/plant is the same used by Amacher et al. (2005).

The default values proposed by the FVS for wind speed (32 km/h), temperature (21°C) and other site conditions at the time of a fire were applied. Under uneven-aged management, in-growth consists entirely of naturally regenerated seedlings. Under even-aged management, in-growth consists of both natural and artificial regeneration. The percentage of plant survival in artificial regeneration is assumed to be 90%. For natural regeneration, default parameter values of FVS were applied.

Our simulation optimization procedure involved three steps. First, we constructed grids of decision variable values for both uneven- and even-aged management systems. For uneven-aged management, the minimum step length for diameter limit was 2.54 cm (1 inch). For even-aged management, the minimum step lengths for planting density, residual basal area, and rotation length were 494 trees/ha (200 trees/acre), 4.6 m^2/ha (50 sq.ft./acre), and 20 years, respectively. Next, we computed the expected present value of each point on the grid using Eq. 1. Each expected present

Table 1 Initial stand state

Tree count (trees/ha)	Species code	DBH (cm)	Live height (m)	Crown ratio
15	L	53.6	44.2	0.4
15	WH	47.0	29.0	0.5
15	WH	41.1	30.5	0.7
15	WH	37.6	24.4	0.7
15	C	37.1	29.6	0.4
15	C	35.6	22.9	0.4
15	WH	34.8	27.7	0.6
15	C	32.8	24.4	0.3
15	WH	32.3	20.1	0.6
15	C	32.0	26.8	0.2
15	L	31.8	33.5	0.3
15	C	27.4	22.3	0.4
15	WH	26.7	15.2	0.5
15	WH	25.1	21.0	0.5
15	C	24.6	15.2	0.6
15	C	23.6	19.5	0.4
15	C	21.3	16.8	0.4
15	C	20.6	14.3	0.5
15	C	20.3	16.8	0.4
15	C	19.1	16.2	0.4
15	WH	18.8	15.2	0.4
15	WH	18.3	9.1	0.5
15	C	17.8	11.3	0.4
15	WH	17.0	16.2	0.5
15	C	16.3	12.5	0.4
15	C	14.0	11.0	0.3
15	WH	14.0	9.4	0.6
15	C	11.4	9.4	0.4
185	C	4.3	3.4	0.4
185	GF	4.1	2.7	0.5
185	GF	3.8	2.7	0.6
185	GF	3.6	2.4	0.5
185	DF	3.6	2.7	0.4
185	GF	3.0	2.1	0.5
185	GF	2.5	2.7	0.6
185	GF	2.5	2.1	0.4
185	GF	2.5	2.1	0.7
7,774	GF	0.3	0.0	–
185	AF	0.3	0.0	–
3,517	C	0.3	0.0	–
4,627	WH	0.3	0.0	–

[3] http://www.fia.fs.fed.us/.

[4] http://tax.idaho.gov/propertytax/PTpdfs/EPB00035_TimberStump_102506.pdf.

Table 2 List of timber species and the average stumpage price level

Code	Common name	Scientific name	Price (USD/MBF)
DF	Douglas-fir	*Pseudotsuga menziesii*	240
S	Engelmann spruce	*Picea engelmannii*	161
GF	Grand fir	*Abies grandis*	168
LP	Lodgepole pine	*Pinus contorta*	155
PP	Ponderosa pine	*Pinus ponderosa*	213
AF	Subalpine fir	*Abies lasiocarpa*	168
WH	Western hemlock	*Tsuga heterophylla*	168
L	Western larch	*Larix occidentalis*	240
C	Western redcedar	*Thuja plicata*	542
WP	Western white pine	*Pinus monticola*	360

value was computed with 30 or more random scenarios of forest fires and diameter growth rates until the expected value was stabilized. Finally, we selected a set of solutions with the highest expected present values and performed additional simulations to determine which solution was best. It is important to note that the solutions that we report are our approximations of the best solutions obtainable from the sets of solutions that we simulated. We did not compute a probability of selecting the best of the set, although statistical procedures for screening and selection are available (e.g., Goldsman and Nelson 1998).

A matlab file was constructed to give simulation instructions to FVS and compute net present values. Three common plantation species: western white pine (*Pinus monticola*), Douglas-fir (*Pseudotsuga menziesii*), and lodgepole pine (*Pinus contorta*) were considered for even-aged management. The computations were repeated for different rates of interest varying between 1 and 7%, and four levels of fire risk ($\lambda = 0$, 0.2, 0.4, and 0.6). In the literature, fire risk is typically described as annual risk for wildfire. The risk for a 20-year-period can be converted to annual risk *ar* by solving the equation: $(1 - ar)^{20} = (1 - \lambda)$ (cf. Gassmann 1989). The risk levels of $\lambda = 0.2$, 0.4 and $\lambda = 0.6$ for a 20-year-period correspond to annual risk levels of 1.1, 2.5, and 4.5%, respectively.

Results

Table 3 shows the baseline optimization results for different rates of interest and levels of fire risk. The vectors of optimal decision variable values, x^*, net present value, NPV, and mean annual increment of commercial timber, MAI, are given for both immediate conversion of the initial stand to a white pine plantation and maintaining the uneven-aged structure of the mixed-species stand by repeated diameter-limit cuttings. The first and the ninth deciles of the probability distribution are reported for NPV and MAI in addition to expected values.

Optimal stand management without fire risk

First, consider the effects of economic factors on optimality of even-aged versus uneven-aged management without fire risk (the first four rows in Table 3). The ranking of

Table 3 Optimal solutions and probability distributions for stand values and mean annual increments

	Conversion to white pine plantation							Uneven-aged management						
	x^*	Net present value (USD/ha)			MAI (MBF/ha)			x^*	Net present value (USD/ha)			MAI (MBF/ha)		
		NPV^{d1}	$E(NPV)$	NPV^{d9}	MAI^{d1}	$E(MAI)$	MAI^{d9}		NPV^{d1}	$E(NPV)$	NPV^{d9}	MAI^{d1}	$E(MAI)$	MAI^{d9}
$\lambda = 0$														
$r = 0.01$	1,482/18.6/120	81,679	83,926	86,143	2.42	2.47	2.52	56	63,632	64,958	66,528	1.28	1.31	1.33
$r = 0.03$	1,482/13.9/100	20,568	20,817	21,086	2.27	2.32	2.35	36	19,274	19,457	19,605	1.33	1.38	1.46
$r = 0.05$	988/9.3/80	14,674	14,746	14,810	1.83	1.88	1.90	28	15,489	15,533	15,588	1.28	1.33	1.38
$r = 0.07$	0/–/60	13,714	13,719	13,723	0.94	0.96	0.99	25	14,410	14,459	14,516	1.23	1.28	1.33
$\lambda = 0.4$														
$r = 0.01$	1,482/18.6/100	31,543	50,867	69,896	0.96	1.48	1.98	41	15,123	29,904	49,136	0.47	0.81	1.23
$r = 0.03$	988/13.9/80	14,494	17,022	20,163	0.62	1.23	1.83	30	13,872	16,262	18,664	0.62	0.86	1.11
$r = 0.05$	494/–/60	13,449	14,030	14,723	0.27	0.84	1.46	25	13,410	14,514	15,383	0.77	0.86	0.86
$r = 0.07$	0/–/60	13,538	13,635	13,714	0.25	0.64	0.96	25	13,249	13,943	14,477	0.77	0.86	0.86

x^* is a vector of optimal decision variable values

Even-aged management: planting density (plants/ha)/residual basal area in thinnings (m^2/ha)/rotation length (years); uneven-aged management: diameter limit (cm)

NPV^{d1} and NPV^{d9} denote the first and the ninth deciles for probability distribution for net present values

MAI^{d1} and MAI^{d9} denote the first and the ninth deciles for probability distribution for mean annual increments preferred management system alters as the rate of interest is increased from 1 to 7%. Replacing the existing stand with a white pine plantation has higher expected present value than managing with a sequence of diameter-limit harvests for lower rates of interest (1–3%). On the other hand, uneven-aged management has higher expected present value than even-aged management for higher rates of interest (5–7%).

The change in optimal management system is a consequence of altered stand management and timber supply. Increased rate of interest reduces forestry investments and increases intensity of harvesting. With even-aged management, optimal planting density is reduced from 1,482 to 0 trees/ha and rotation from 120 to 60 years as the rate of interest increases from 1 to 7%. As a result, the expected long-run supply of commercial timber is reduced from 2.47 to 0.96 MBF/ha/year. At a high rate of interest (7%), it is optimal to clearcut the stand soon after trees reach commercial dimensions and rely on natural regeneration. With uneven-aged management, the diameter limit of harvesting is reduced from 56 to 25 cm as the rate of interest increases from 1 to 7%. Contrary to even-aged management, the change in the diameter limit has only minor effect on the level of timber production. The mean annual increment remains at about the same level (1.28–1.38 MBF/ha/year) irrespective of diameter limit varying between 25 and 56 cm. The small residual trees are able to efficiently utilize increases in growing space regardless of how many large trees are removed.

Figure 2a shows the ratios of expected present values of converting to even- and uneven-aged management under alternative rates of interest and plantation species and with no fire risk. The three plantation species are white pine, Douglas-fir, and lodgepole pine. The latter two species show similar growth rates as white pine in our case, but the stumpage prices are clearly lower (see, Table 2). Conversion to even-aged management is superior for $r \leq 0.03$ if white pine is the planted species. However, if the planted species is Douglas-fir or lodgepole pine, uneven-aged management is superior for all rates of interest. An uneven-aged stand consisting mainly of grand fir and western redcedar provides more valuable flow of timber than Douglas-fir or lodgepole pine cultures. Thus, price ratio between naturally regenerated and plantation species is another important determinant of the preferred management system.

Zero investments in planting become optimal for 7% rate of interest with white pine, for 6% and higher rates of interest for Douglas-fir and for all rates of interest with lodgepole pine. In such cases, even-aged management relies entirely on natural regeneration. Such stands develop to sparsely populated conifer mixtures that are dominated by those 250–400 trees/ha that are regenerated naturally during the first 10–20 years after clearcutting. Compared to uneven-aged management, even-aged management with natural regeneration has an inferior economic outcome. The advance regeneration is lost at clearcutting and soil preparation involves cost.

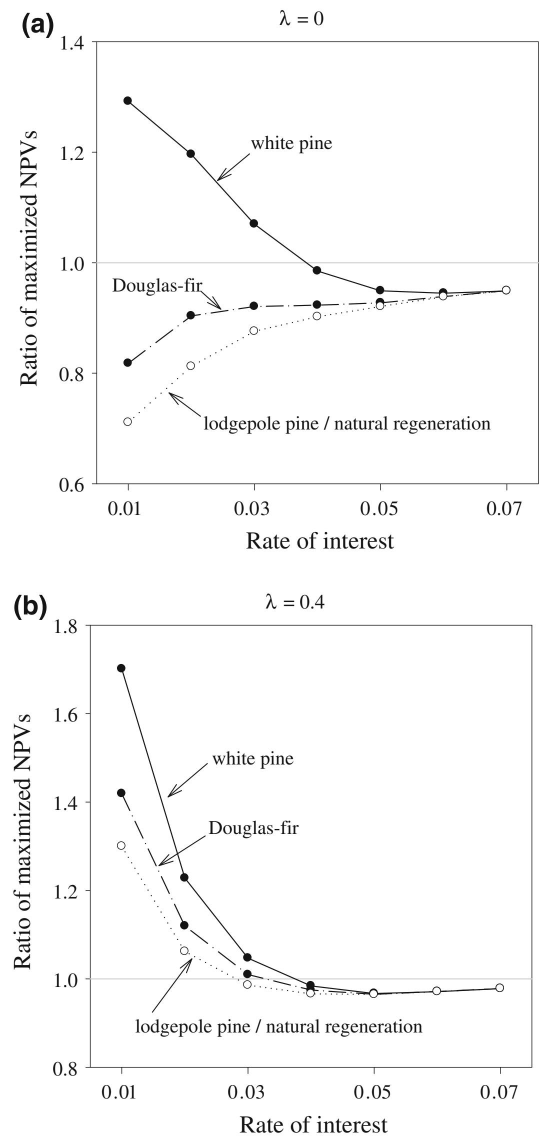

Fig. 2 The ratio of maximized E(NPV)s from conversion to even-aged management to maximized E(NPV)s from continued uneven-aged management. *Full circles* denote positive planting densities, and *open circles* zero planting densities

Fire effects on preferred management system

Inclusion of fire risk favors even-aged management especially for low rates of interest (compare Fig. 2a, b). Even-aged management allows for immediate harvesting of the initial stock without risk of losing any trees. Another explanation is that stand structures composed of an even-

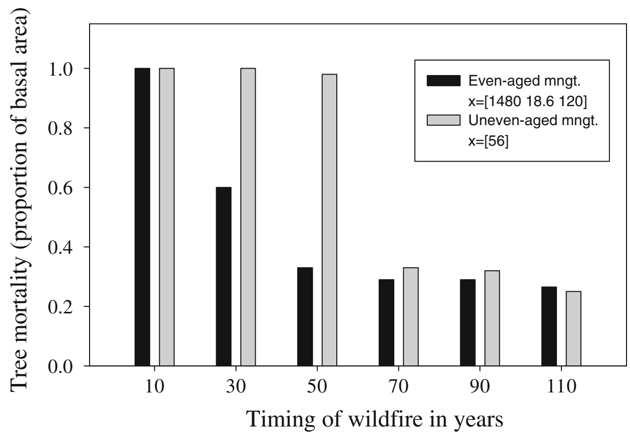

Fig. 3 Tree mortality after a wildfire

aged cohort of trees are, on average, less vulnerable to fire damage than uneven-aged stands containing more than one cohort.

Figure 3 shows tree mortality for representative regimes of both management systems (optimal solutions at $r = 0.01$ and $\lambda = 0$ in Table 3). In this illustration, it is assumed that a wildfire may occur only once during a 120-year-period. In even-aged stand, tree mortality is 100% if a wildfire occurs at a seedling stand phase. However, tree mortality reduces with higher stand age and elevated canopy base height. Using the default weather parameters of the Fire and Fuels Extension to the FVS, wildfire causes only minor damage to highly-stocked, even-aged stand that is approaching economic maturity.

Under uneven-aged management, wildfire causes complete mortality if the levels of ladder and crown fuels are high enough to trigger an active crown fire. This is the case if wildfire occurs during the first 50 years in Fig. 3. However, keeping the stocking at a high level by cutting to a high diameter limit (56 cm) reduces ladder fuels and makes the uneven-aged stand less vulnerable to fire damage. After 70 years, wildfires do not spread to active crown fires provided that the stand has not been hit by a fire before.

Fire risk reduces expected present values and widens the probability distributions. Figure 4a shows the cumulative probability distributions for a white pine plantation regime. The figure is drawn by arranging the simulated NPVs in ascending order and weighting by their probabilities. Once a wildfire occurs, it always reduces the amount of harvestable timber. Conveniently timed wildfires may also have positive effects if they reduce the numbers of less valuable species and reduce the negative effects of future fires by consuming fuels.

Figure 4b presents an example of crossing probability distributions. Without fire risk, uneven-aged management is superior to even-aged management relying on natural regeneration. However, inclusion of fire risk widens the probability

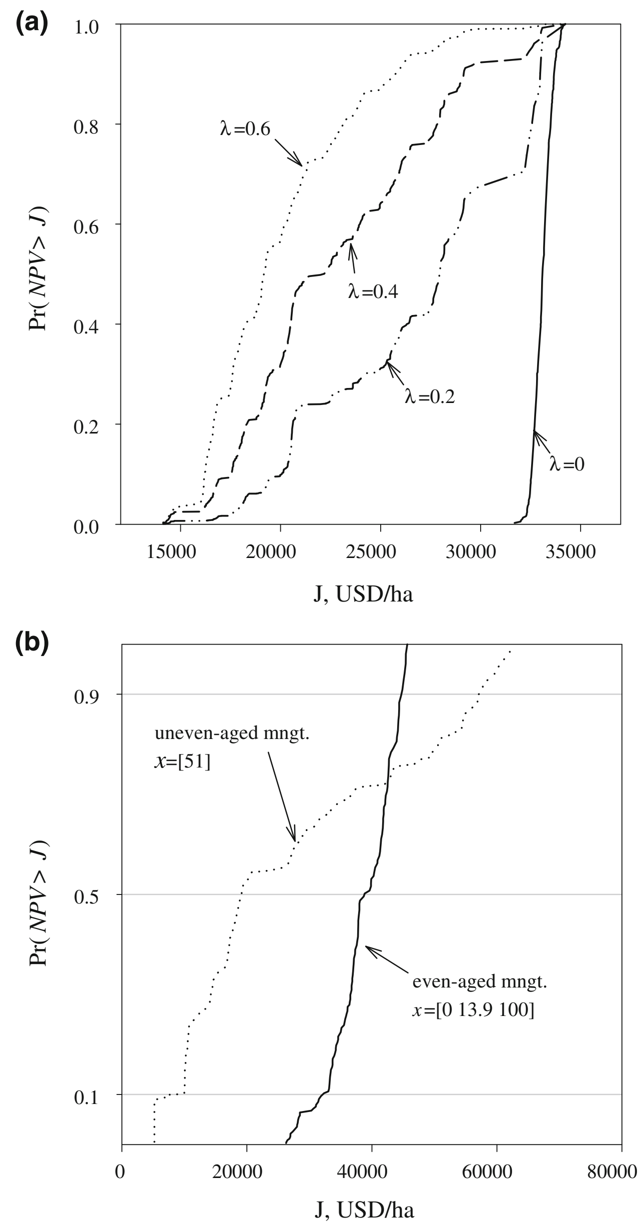

Fig. 4 Comparison of cumulative probability distributions for net present value. **a** Various levels of fire risk for a white pine plantation with $x = [1{,}480/13.9/100]$ and $r = 0.02$. **b** Exemplary regimes under even-aged management and uneven-aged management with $r = 0.01$ and $\lambda = 0.4$

distribution of net present values of uneven-aged management and changes the ranking of the management systems. The reason for crossing distributions is that an uneven-aged stand structure is more susceptible to fire damage than an even-aged cohort of naturally regenerated trees.

Fire effects on management activities

Risk of losing commercial trees to fire damage makes it rational to cut more trees earlier. Under uneven-aged management, increased fire risk reduces the diameter limit especially at low rates of interest (see, Table 3). However, a strict diameter-limit cut removing all commercial trees (dbh > 17.8 cm) is optimal only for combinations of high fire risk ($\lambda = 0.6$) and rate of interest ($r > 0.05$). For typical levels of fire risk ($0.2 \leq \lambda \leq 0.4$), and interest rates ($0.03 \leq r \leq 0.05$) the diameter limit varies between 25 and 33 cm. The benefits of growing larger trees and obtaining higher value outweigh the expected losses from fire. Value growth is high for trees that recently reached the commercial dimensions due to vigorous tree growth, high increase in board feet content of trees, and positive quality premium for higher dimension timber.

Under even-aged management, optimal levels of the decision variables are less sensitive to alterations in fire risk. This implies that possibilities for mitigating fire damages by varying planting density, thinning intensity, and rotation length are rather limited. Increased fire risk tends to reduce rotation length and planting density (see, Table 3), but the minimum intervals of decision variable values are too broad to properly identify the qualitative and quantitative fire effects.

The tendency of fire risk to reduce rotation length and planting density is better demonstrated by Fig. 5a and b that show the objective function response surface with and without fire risk. The contours are drawn by selecting the residual density that gives the highest bare land value for different combinations of rotation length and planting density. The peak denotes the optimal solution. It is changed to the left (lower planting density) and down (lower rotation length) as a result of fire risk.

Inclusion of fire risk also flattens the peak around the optimum and thus increases the number of near-optimal solutions. On the other hand, increased fire risk widens the probability distributions, which makes it less meaningful for a landowner to determine the exact optimum. The differences in E(NPV)s of the best solutions are insignificantly small compared to their probability distributions with high levels of fire risk.

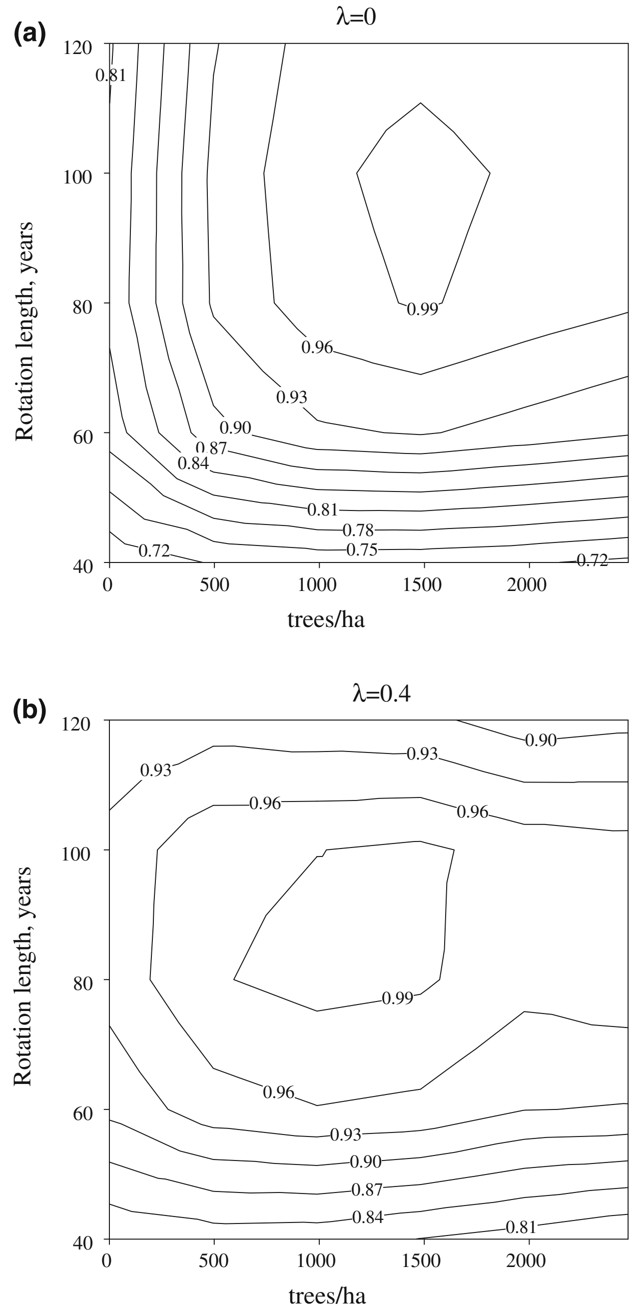

Fig. 5 Maximized bare land values relative to the maximum for combinations of rotation length and planting density in white pine plantation with $r = 0.03$

Discussion

To date, results on efficiency of even-aged versus uneven-aged management systems are mixed, and vary depending on the species, economic parameters, and assumptions of the stand growth models used to predict yield. Haight (1987) applied a diameter-class matrix model for ponderosa pine stands in Arizona, and found uneven-aged management superior to even-aged management at 3% rate of interest. Haight and Monserud (1990a, b) integrated the Prognosis model (predecessor of FVS) for mixed-conifer stands in the Northern Rocky Mountains. Both even-aged plantation management and an uneven-aged shelterwood system were capable of producing the same level of yield indefinitely, but at 4% rate of interest, uneven-aged management was superior in terms of NPV. Wikström (2000) employed individual-tree growth models to Norway spruce stands in northern Sweden. Depending on the initial stand structure, the best uneven-aged management regimes gave 4–11% lower NPVs than optimized plantation management at 3% rate of interest. Note, however, that optimal solutions for uneven-aged management were constrained by an upper bound on intensity of selection harvests (<30%) and lower bound on residual stand volume (150 m^3/ha).

Initial stand structure is another important factor affecting the relative efficiency of alternative management systems. According to Wikström (2000), the losses from uneven-aged management were higher for initial stands that deviated from the reverse *J*-shaped diameter distribution. It was the most expensive to convert an initially even-aged stand to an uneven-aged structure. According to Haight and Monserud (1990b), all initial stand structures including different initial species compositions and stocking levels converged optimally to uneven-aged stands. However, the optimal transition regime depended heavily on the initial stand structure. Fully stocked stands had repeated selection harvests to maintain the multispecies, uneven-aged structure. However, both young stands with low timber volume and old stands with inadequate natural regeneration were first clearcut and replanted and then evolved into fully stocked, uneven-aged, mixed-conifer stands.

We contribute to this literature by analyzing the efficiency of management systems under fire risk. It is demonstrated that either even-aged or uneven-aged management may be optimal depending on the rate of interest and the level of fire risk. The result that higher interest rate favors uneven-aged management was first shown by Chang (1981). He applied a whole-stand model with exogenous planting density in optimization and explained that small and frequent revenues (from uneven-aged management) become more favorable compared to higher but infrequent revenues (from even-aged management) as the rate of interest increases. The same result was obtained later by Knoke and Plusczyk (2001) that employed a spatial growth model to compare the economic performance of even-aged and uneven-aged management regimes for a spruce dominated stand in Germany. The transition regime that converts the initial two-aged stand structure into irregular age structure was superior to even-aged management especially at high rates of interest. Our results indicate that rendering harvesting and planting density as endogenous variables makes uneven-aged management even more favorable at high rates of interest. Increasing fire risk improves the relative efficiency of even-aged management because fuel structures over the course of a rotation are less likely to promote intense fires with high levels of damage compared with fuel structures over time in uneven-aged conifer mixtures. Nevertheless, even with high fire risk we found that uneven-aged management maintained its economic superiority at high interest rates.

It is important to note that the results of this study concern a mixed-conifer stand that regenerates naturally to conifer species only. In many forest ecosystems, natural regeneration consists of both conifer and broadleaf species. Broadleaf species tend to suppress the spreading of fire and mitigate fire damage particularly if a fire occurs during growing season. Thus, the computations should be repeated to various locations and initial stand structures including conifer–broadleaf mixtures before making conclusions on the efficiency of alternative management systems under fire risk.

The economic potential of uneven-aged management systems is supported by empirical studies on timber productivity. For example, O'Hara and Nagel (2006) showed that multi-aged ponderosa pine stands are either equally efficient or slightly more efficient at converting light energy to volume growth than even-aged stands. Simulations in this study and earlier studies using gap models (Botkin 1993, pp. 207–215), diameter-class matrix models (Volin and Buongiorno 1996), and individual-tree models (Monserud and Haight 1994) suggest that it is possible to obtain high and sustained flow of timber and retain the multi-aged structure in a long run. Thus, uneven-aged management seems to be a promising alternative for tree species that tolerate shade, provide enough seed frequently, and are not excessively damaged by frequent cuttings.

However, success of uneven-aged management is also conditional on several other factors that are not usually accounted for in the models. First, invasive understory vegetation may hinder natural regeneration and recruitment in some soils and climatic areas. Second, repeated selective cuttings may alter the genetic structure of forests in a manner that reduces future stand growth and potential to adapt to environmental change (Hawley et al. 2005). Third, high logging cost may render selective or selection cuttings suboptimal.

Earlier research has concentrated on analyzing the effects of fire risk on optimal rotation length under even-aged management. Routledge (1980) used a discrete-time stand model to show that inclusion of catastrophic risk shortens optimal rotation period when the risk is nondecreasing function of stand age. Reed (1984) used a continuous-time formulation and showed that fire effects on optimal rotation are equivalent to adding a premium to the discount rate. According to numerical studies, this shortening effect may vary from few years (Caulfield 1988; Valsta 1992) to several decades (González et al. 2005). On the other hand, optimal rotation period may also increase in the presence of fire risk and inclusion of thinnings (Valsta 1992), fire prevention activities (Amacher et al. 2005), and amenity values (Englin et al. 2000). According to our numerical results, presence of fire risk reduced optimal diameter limits under uneven-aged management, and decreased optimal rotation lengths and planting densities under even-aged management (see, Table 3).

This study integrates the Forest Vegetation Simulator and its Fire and Fuels extension to perform an economic analysis of even-aged and uneven-aged stand management under fire risk. The FVS also includes fuel treatments, such as prescribed burning and pre-commercial thinning, which may reduce the intensity and damage of wildfires that reach the stand. It would be interesting and useful to evaluate the cost-effectiveness of fuel treatments performed as part of even-aged and uneven-aged management regimes and to see if fuel treatments alter the present value rankings of the management systems under fire risk. The FVS offers a coherent framework for investigating these questions.

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