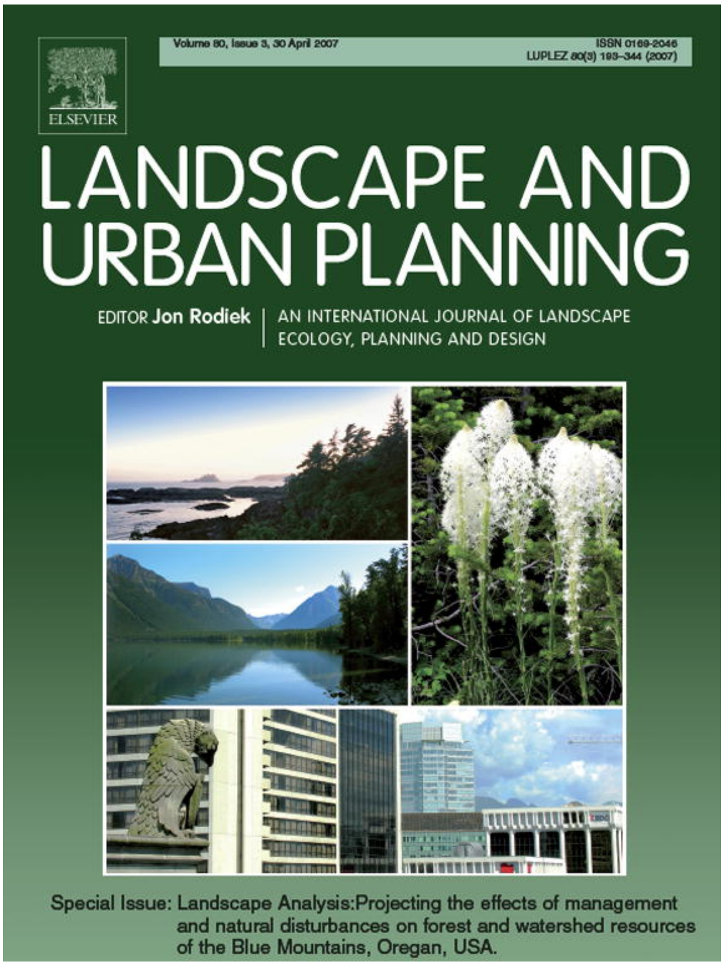
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A simulation study of thinning and fuel treatments on a wildland–urban interface in eastern Oregon, USA

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Abstract

We simulated long-term forest management activities on a 16,000-ha wildland–urban interface in the Blue Mountains near La Grande, Oregon. The study area is targeted for thinning and fuels treatments on both private and Federally managed lands to address forest health and sustainability concerns and reduce the risk of severe wildfire. We modeled a number of benchmark management scenarios through time and examined potential wildfire behavior, stand structure, species composition, and other forest characteristics over the study area. The simulation models indicated that substantial area would require repeated thinning over time to meet desired forest density guidelines for the landscape as a whole. Fire models predicted significant reductions in crown fire activity for a specific weather scenario as a result of thinning and treatment of surface fuels. Substantial changes in stand structure and other characteristics were noted for the thinning versus no-treatment scenarios. The study provided a template of modeling methods and information for forest planners concerned with forest and fuel management issues in the Western United States.

Keywords: Landscape simulation; Fuels treatment; Stand density index; FVS; Wildfire

1. Introduction

Forest thinning and fuel reduction treatments have become a high priority for forest managers throughout the Western United States to address a wide range of forest health and sustainability issues. However, few studies have closely examined the long-term effectiveness of management strategies in terms of mitigating the impacts from natural disturbances, and achieving desired future forest condition. Although case studies show that stand-scale treatments can create desired stand structures that are more resilient to wildfire and insects (Kalabodkidis and Omi, 1998; Negron and Popp, 2004; Pollet and Omi, 2002; Stephens, 1998), the effectiveness and feasibility of these treatments at larger scales is dependent on many factors including climate, vegetation dynamics, treatment rate and type, spatial arrangement, operational and resource constraints, financial considerations, and key resource values (Finney and Cohen, 2002; Schoennagel et al., 2004). Interactions among disturbances, such as fire and bark beetles (*Dendroctonus* spp.), must also be considered (Mitchell and Martin, 1980). The problem of long-term forest planning in disturbance-prone forests is a complex spatiotemporal problem that warrants attention.

We simulated forest management scenarios on a wildland–urban interface (WUI) near La Grande, OR, USA. The La Grande Ranger District identified the Mount Emily area as high risk because of the intermingling of homes with forest vegetation and the potential for extreme fires. The design of an extensive fuel treatment project was initiated by the La Grande Ranger District. Like many areas in the Blue Mountains, the forests have high surface and ladder fuel loadings resulting from decades of fire exclusion and multiple insect epidemics (Quigley et al., 2001). We simulated five management alternatives and examined them for the following: (1) What treatment rate is required over time to achieve and maintain national forest density guidelines? (2) How well do widely used density management prescriptions address fire behavior issues at the stand scale? (3) What are the net effects

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of long-term treatments on fire behavior, forest structure, and species composition?

2. Materials and methods

2.1. Study area

The Mount Emily wildland urban interface is an area 30 km long immediately north of La Grande, Oregon, where the forested slopes of Mount Emily and adjacent ridges descend to the agricultural lands in the Grande Ronde Valley (Fig. 1). For analysis purposes, a boundary was established around the area following major drainages, natural breaks in vegetation, and land ownership boundaries, and the area within contained 16,343 ha of federal, state, and privately owned lands (Fig. 1). About 12,259 ha of the study area is forested based on the definitions used in the Wallowa-Whitman and Umatilla Forest Plans. Approximately 9432 ha is managed by the USDA Forest Service. The forest composition ranges from dry forests of ponderosa pine (*Pinus ponderosa*), cold forests dominated by subalpine-fir (*Abies lasiocarpa*) and Engelmann spruce (*Picea engelmannii*), and a transition zone containing grand fir (*Abies grandis*), Douglas-fir (*Pseudotsuga menziesii*), and western larch (*Larix occidentalis*). Forest Service lands are managed for a number of resources including summer and winter range for Rocky Mountain elk (*Cervus elaphus*), habitat for Lynx (*Lynx canadensis*), old growth, recreation, and scenery. Surface fuel loadings exceed 140 metric tonnes/ha in some areas, with high loading of dead ladder fuels in a large number of the stands. Fuel accumulations accelerated after the 1980–1986 western spruce budworm (*Choristoneura occidentalis*) epidemic that caused extensive mortality within the stands in the project area.

2.2. Vegetation and fuel data

Stand delineations were obtained from existing vegetation GIS layers on file at the La Grande Ranger District. Stands outside the Forest Service boundary were digitized by using digital orthophotos from 2000. We built a database consisting of stand density by species and 2.5 cm diameter class for each stand by using data obtained from stand exams and photo-interpretation of 1:12000 aerial color photos taken in 1998.

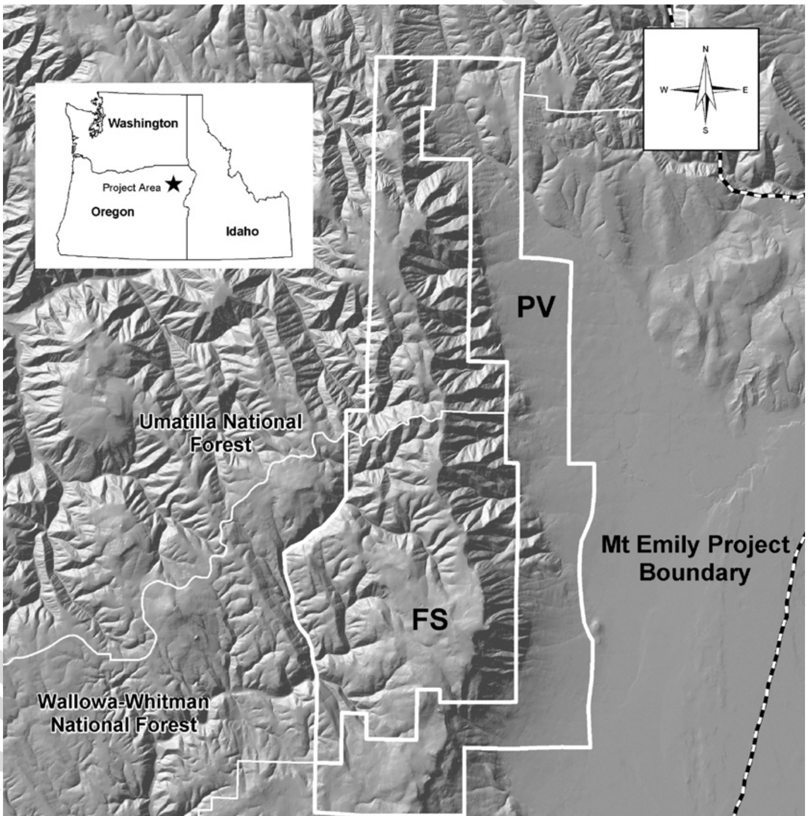

Fig. 1. Vicinity map of the Mount Emily area showing study area and land ownership boundaries. Bold white line indicates study area boundary. FS denotes lands managed by the Forest Service. PV denotes privately owned land. Several small tracts owned by the State of Oregon within the study area are not shown.

Stand-specific data on surface fuel loadings were derived in several ways. The fuel loadings on about 1500 ha of the study area were estimated in the field as part of prescription development for a proposed fuel reduction project. In this process, stand surface fuel conditions were matched to the photo series of Fischer (1981). These fuel loadings were then extrapolated to the remaining stands by using aerial photo-interpretation, stand exam data on plant association and stand structure, as well as local knowledge of stand conditions. Line transect sampling of six stands by using the Hilbruner and Wordell (1992) procedure was used to calibrate the photo series for extremely high fuel loadings found within many of the old forest stands.

2.3. Modeling overview

We simulated stand dynamics by using the Blue Mountains variant of the Forest Vegetation Simulator linked to the Parallel Processing Extension (FVS-PPE, Crookston and Stage, 1991) and the Fire and Fuels Extension (Reinhardt and Crookston, 2003). The FVS-PPE simulates multiple stands in a parallel fashion (i.e., the simulation is completed for all stands each period before cycling to the next period). A forest regeneration model developed by Wilson and Maguire (A regeneration model for the Upper Grande Ronde watershed. Unpublished Report 2002, Oregon State University, Department of Forest Sciences, Corvallis, OR) was used for the simulations. This regeneration model was developed from extensive forest regeneration survey data obtained from the La Grande Ranger District.

We simulated forest vegetation dynamics on decadal time steps starting in year 2000 and ending in year 2070. Surface fuel dynamics were simulated with the Fire and Fuels Extension (FFE) to FVS (Reinhardt and Crookston, 2003) on annual time steps and reported by decade. We reported both the initial prethin as well as the postthin conditions for the year 2000. For all other decades we reported the postthin condition in the first year of each decade (FVS executes thinning in the first year of the cycle). Yearly averages for selected output variables were calculated by summing over the postthin, decadal outputs and dividing by 70 years.

2.4. Treatment scenarios and prescriptions

We simulated stand-level treatments that consisted of selective thinning, and, depending on the scenario, followed the thinning with mechanical fuel treatment, underburning, and maintenance underburns every 10 years until the next thinning. Using these treatments, we modeled five scenarios: (1) repeated thinning (THN), (2) thinning with underburning and maintenance burns every 10 years (THNBRN), (3) the THNBRN scenario simulated for only the first decade with no treatments thereafter (THNBRN1), (4) the THN scenario implemented only on private lands (THNP), and (5) no treatment (NOTRT). We included scenarios with and without underburning because the extensive use of fire on a wildland urban interface is the subject of considerable debate.

The thinning prescription used the stand density index (SDI) (Reineke, 1933), a relative measure of density where the stand's existing density is converted into a density at a reference tree size of 25 cm diameter at 137 cm bole height (DBH). The SDI is calculated by FVS (Stage, 1968) as:

$$\mathrm{SDI} = \sum \mathrm{TPH}_i \left[\frac{\mathrm{DBH}_i}{25}\right]^{1.6}$$

where TPH_i is the number of trees/ha of the ith DBH class.

Maximum values for SDI have been established in the Blue Mountains for each target tree species and plant association (Cochran et al., 1994; Hall, 1998; Johnson and Clausnitzer, 1992). Following thinning guidelines on the La Grande Ranger District, we triggered a thin in FVS when a stand's SDI exceeded 65% of the maximum. Removal of trees was ordered from smallest to largest so that the thinning treatments were effective at reducing ladder fuels. Stands were thinned to 35% of the maximum SDI for the stand. We used an FVS thinning efficiency (Dixon, 2003) of 90%, so that 10% of the trees in each thinned size class were retained for crop trees. The thinning prescriptions targeted removal of late-seral, fire-intolerant species like grand fir in mixed-species stands, favoring early seral species such as ponderosa pine, western larch and Douglas-fir. The species preferences differed by plant association group, which are aggregates of plant associations defined by Hall (1998). Preferred leave species are:

Cold dry—western larch, Englemann spruce, grand fir.
Cool moist—western larch, ponderosa pine, Douglas-fir.
Warm dry—ponderosa pine, Douglas-fir, western larch.

2.5. Fire and fuels modeling

Potential fire effects, dead and down fuel dynamics, and underburns were simulated with the FVS FFE (Reinhardt and Crookston, 2003). The FFE uses relationships developed by Albini (1976), Van Wagner (1977), Andrews (1986), and Scott and Reinhardt (2001) to model surface fire behavior and the onset of crown fires. Fuel loadings were initialized in FFE for each stand by using the surface fuel data in the vegetation database. We simulated mechanical treatment of surface fuel by using the same operational parameters as the Mount Emily fuel reduction project (Wallace, La Grande Ranger District, personal communication). Specifically, we simulated site removal of 90% of the 7.6–14.8 cm diameter, and 40% of the 2.5–7.6 cm diameter surface fuels. Underburning was simulated by using weather conditions and fuel moisture guidelines provided by fuel specialists on the La Grande Ranger District for fall burning (Johnson, La Grande Ranger District, personal communication) (Table 1). We scheduled the fuel removal for the year following thinning, and the underburning 2 years after. The underburn model was scrutinized by simulating underburns in several hundred stands, and then examining the postburn tree list in the Stand Visualization System (McGaughey, 1997) to ensure that overstory mortality averaged less than about 2 trees/ha.

Weather conditions for simulating potential wildfire effects were derived from the J-Ridge (Station 351414), Black Mountain (Station 351314), and Black Mountain 2 (Station 351317)

Table 1
Weather and fuel moisture parameters used in potential wildfire and prescribed fire simulations

Variable	Wildfire	Underburn
Temperature (°C)	32.2	21.1
1-h fuel (0–0.64 cm) (%)	3	6
10-h fuel (0.64–2.54 cm) (%)	4	8
100-h fuel (2.54–7.62 cm) (%)	6	10
1000-h fuel (>7.62 cm) (%)	7	20
Live woody fuel (%)	64	125
Duff (%)	20	20
10-min average windspeed at 6.1 m above ground (km/h)	4	<4
Maximum wind gusts (km/h)	10.7	NA

Values for wildfire are 97th percentile weather conditions and were calculated from local weather station data. Underburn conditions were obtained from fuel specialists in the Blue Mountains. See Section 2 for additional details on weather station data and calculation of percentile values and velocity of wind gusts. NA: not applicable.

remote automated weather stations. The Black Mountain stations are located 16 km east, and the J-Ridge station is located 40 km south of the project area. Weather data for June to September from the years 1986 to 2002 were analyzed in FireFamily Plus (Bradshaw and McCormick, 2000) to generate upper 97th-percentile temperature, windspeed, and fuel moisture (Table 1). The 10 min average windspeed generated in FireFamily Plus were adjusted upward by using tables developed by National Oceanic and Atmospheric Administration (NOAA) to model actual gust windspeed rather than average velocities (http://www.wrh.noaa.gov/sew/fire/olm/fire/10togust.htm).

2.6. Forest structure and composition

We analyzed forest structure (O'Hara et al., 1996) for the scenarios by using canopy and stand structure classification built into FVS (Crookston and Stage, 1999). Changes were made to default parameters in an attempt to replicate structural classification used in the Blue Mountains. Specifically, we adjusted the definition of a canopy layer by increasing the minimum canopy closure from 5 to 20%, and decreasing the threshold DBH of a stratum to qualify as old forest structure from 63.5 to 53.3 cm (21 in). This corresponds to the large tree class in Wales et al. (this volume) and Hemstrom et al. (2007). Changes in tree species composition over time was analyzed by creating FVS Event Monitor variables (Crookston, 1990) for average basal area (m^2) by species.

3. Results

3.1. Treatment areas and stand development

The THN scenario, which called for thinning all stands that exceeded 65% of the maximum SDI, resulted in the treatment of 8090 ha in the first decade, and on average treated 471 ha/year over the simulation period, or 3.8% of the forested area (Table 2). When thinning was followed by underburning and decadal maintenance underburns (THNBRN), the area thinned was reduced to 177 ha/year, or 1.4% of the forested area. The THNBRN scenario resulted in extensive underburn treatments, and after the second decade most of the study area received a burning treatment each decade (Table 2). The THN scenario removed a large amount of wood (1,099,203 m^3) in the first thinning, after which thin volumes declined to 114,307–469,982 m^3 per decade. The THNP and THNBRN1 scenarios removed relatively small amounts of wood compared to the other scenarios.

Average SDI stabilized at 36–48% of the maximum for the THN and THNBRN alternatives (Fig. 2). Average SDI for the NOTRT scenario increased until about year 2020, and then tapered off at about 87% of the maximum for the remaining periods (Fig. 2). Stand density index for the THNBRN1 scenario decreased in response to thinning in year 2000, and thereafter

Table 2
Area treated, total wood volume harvested, area underburned, and average basal area over time for management scenarios simulated for the Mount Emily study area

Variable	Scenario	Decade								Average per year
		2000	2010	2020	2030	2040	2050	2060	Total	
Area thinned (ha)	THNP	2,760	878	1,689	1,963	1,096	1,301	2,036	11,723	167
	THN	8,090	1,963	4,386	5,380	3,699	4,064	5,354	32,938	471
	THNBRN1	8,090	0	0	0	0	0	0	8,090	116
	THNBRN	8,090	1,911	1,326	681	254	121	34	12,418	177
Area underburned (ha)	THNBRN1	7,963	0	0	0	0	0	0	7,963	114
	THNBRN	7,963	9,842	11,154	11,794	11,968	12,038	12,072	76,831	1,098
Volume removed (m^3)	THNP	278,640	47,677	77,879	182,188	63,025	113,998	179,106	942,513	13,464
	THN	1,099,203	114,307	274,646	469,982	264,475	317,674	407,750	2,948,037	42,115
	THNBRN1	1,099,203	0	0	0	0	0	0	1,099,203	15,703
	THNBRN	1,099,203	112,810	64,476	35,252	17,377	9,378	2,340	1,340,837	19,155
Average stand basal area (m^2/ha)	NOTRT	31.5	34.9	36.5	37.8	38.8	39.4	39.8	–	–
	THNP	27.2	30.3	31.5	32.1	33.5	33.8	33.6	–	–
	THN	17.7	21.1	22.7	22.3	23.5	23.7	23.1	–	–
	THNBRN1	17.7	19.0	23.6	27.8	31.2	33.9	35.8	–	–
	THNBRN	17.7	17.4	17.3	17.4	17.7	18.3	19.1	–	–

Stand basal area is postthin for the treatment scenarios. Table shows outputs for the decade label following the specified year. Average per year is calculated by using a 70-year simulation period (2000–2070). THNP: thin only on private lands; THN: repeated thinning; THNBRN1: thin and burn once; THNBRN: repeated thinning and burning; NOTRT: no treatment.

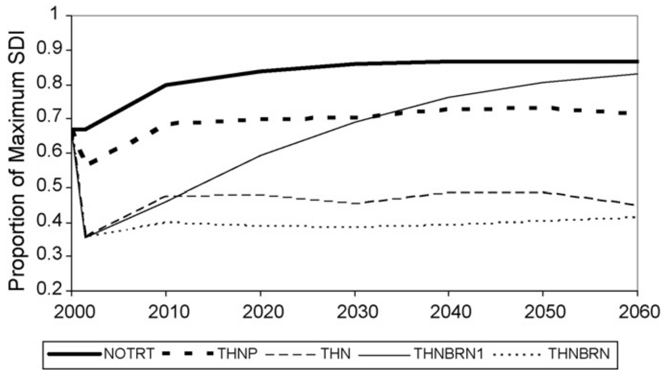

Fig. 2. Average proportion of maximum stand density index (SDI) over time for five scenarios simulated for the Mount Emily study area. NOTRT: no treatment; THNP: thin only on private lands; THN: repeated thinning; THNBRN1: thin and burn once; THNBRN: thin and repeated.

rapidly increased to equal about 70% of the maximum by year 2030, compared to 87% for the no management and 45% for the THN scenario.

Average stand basal area was substantially reduced after the first thinning from 31.5 m^2/ha for the NOTRT scenario to 17.7 m^2/ha for the THN, THNBRN, and THNBRN1 scenarios (Table 2). The difference between the NOTRT and THN basal area increased slightly over time (Table 2). After the first treatment, the basal area for the THNBRN scenario was consistently lower than the THN by about 4–6 m^2/ha.

Stand structure showed rapid changes over time for all thinning scenarios, and large differences among the scenarios (Fig. 3). A large increase in the stand initiation structure was observed for the treatment scenarios after the initial thinning (Fig. 3). The NOTRT scenario showed a gradual loss of the stand initiation (SI) structure, and a slight increase in the old forest multistratum (OM) and old forest single stratum (OS) structure through time (Fig. 3). About 60% of the landscape was in the stem exclusion (SE) class for the NOTRT scenario in year 2060. The THN and THNBRN scenarios converted about half of the landscape to old forest single stratum by the year 2060. All of the treatment scenarios created more old forest structure (OM + OS) than the NOTRT scenario (Fig. 3).

The thinning treatments resulted in modest changes in species composition (Fig. 4). Over the simulation period, the basal area of ponderosa pine in the THN scenario increased from 19 to 40% of the total basal area. Conversely, the percentage of grand fir basal area decreased from 39 to 20%. Tree species composition on a relative basis was nearly constant for other species and scenarios.

The thinning treatments had a marked effect on stand characteristics that determine wildfire behavior. For instance, the THN scenario reduced average crown bulk density from 0.20 to 0.09 kg/m^3 after the first thinning treatment (Fig. 5). Although the NOTRT scenario showed a decreasing crown bulk density over time, the difference between the thinning and NOTRT scenarios persisted (Fig. 5) and averaged about 0.09 kg/m^3 in the later decades. The crown bulk density for the THNBRN1 scenario increased after the thinning treatment in year 2000, and nearly equaled values for the NOTRT scenario (0.13 kg/m^3) by year 2040. Area distribution for the NOTRT scenario showed that over 4700 ha of the study area had crown bulk densities above 0.20 kg/m^3 in year 2000 (Fig. 6). The postthin crown bulk densities for the THN scenario in year 2000 were clustered around 0.06–0.08 kg/m^3, but still remained spread over a range of values (Fig. 6). In year 2060, the THN scenario distribution was narrower, and a large majority of the study area had crown bulk densities in the range 0.02–0.06 kg/m^3.

Average crown base height decreased slightly for the NOTRT scenario over the simulation period, from 3.7 to 2.7 m (Fig. 7). The THN scenario increased crown base height by 1.7 m on

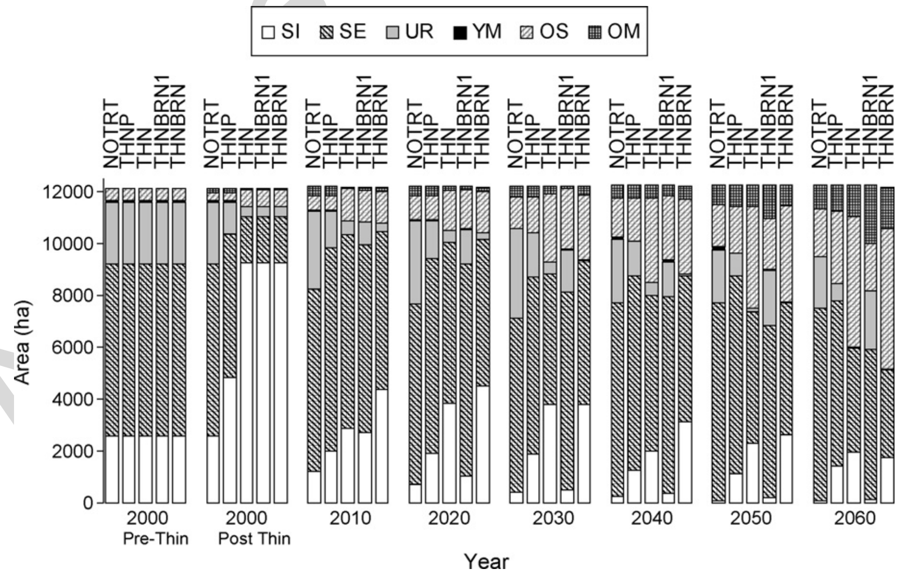

Fig. 3. Area in different forest structure classes by decade for five management scenarios simulated for the Mount Emily study area. Structure modeling follows Crookston and Stage (1999). OM: old forest multistrata; OS: old forest single story; SI: stand initialization; SE: stem exclusion; UR: understory reinitiation; NOTRT: no treatment; THNP: thin only on private lands; THN: repeated thinning; THNBRN1: thin and burn once; THNBRN: thin and repeated.

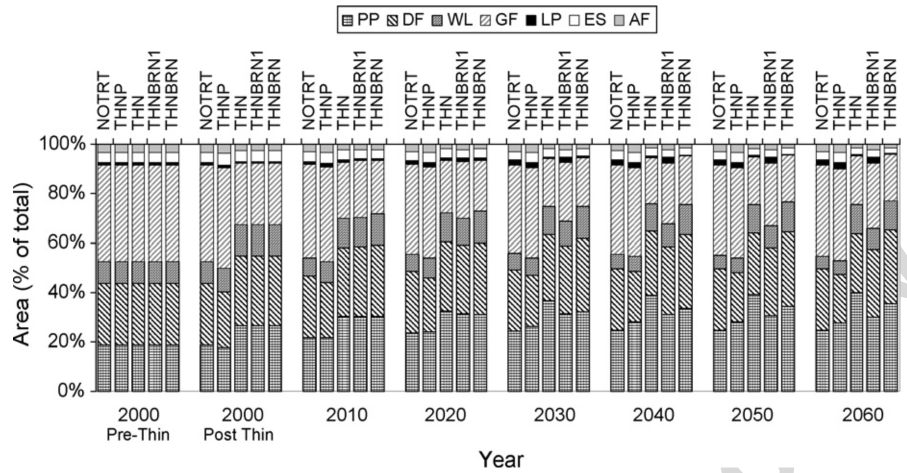

Fig. 4. Average percentage of basal area by species over time for five management scenarios simulated for the Mount Emily study area. PP: ponderosa pine; DF: Douglas-fir; WL: western larch; GF: grand fir; LP: lodgepole pine; ES: Engelmann spruce; AF: subalpine fir; NOTRT: no treatment; THNP: thin only on private lands; THN: repeated thinning; THNBRN1: thin and burn once; THNBRN: thin and repeated.

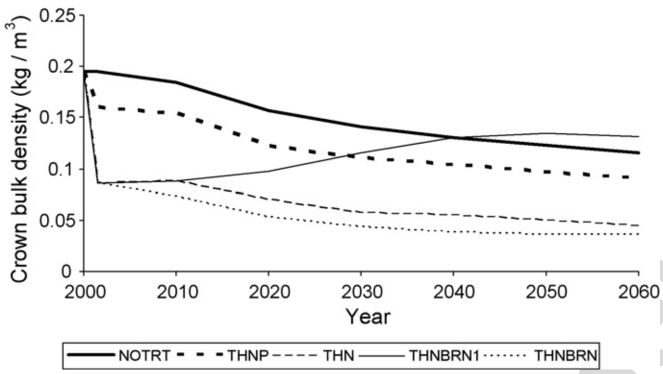

Fig. 5. Average crown bulk density over time for five management scenarios simulated for the Mount Emily study area. NOTRT: no treatment; THNP: thin only on private lands; THN: repeated thinning; THNBRN1: thin and burn once; THNBRN: thin and repeated.

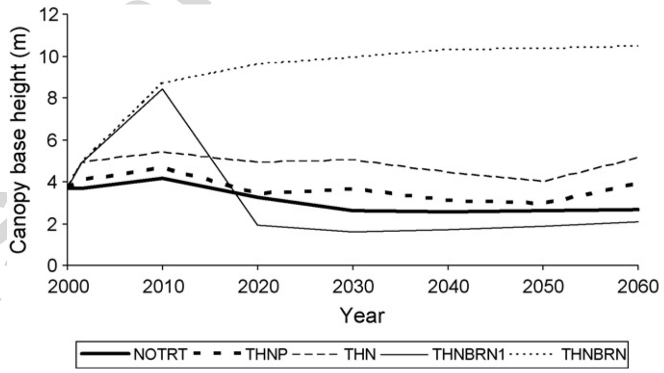

Fig. 7. Average crown base height over time for five management scenarios in the Mount Emily study area. NOTRT: no treatment; THNP: thin only on private lands; THN: repeated thinning; THNBRN1: thin and burn once; THNBRN: thin and repeated.

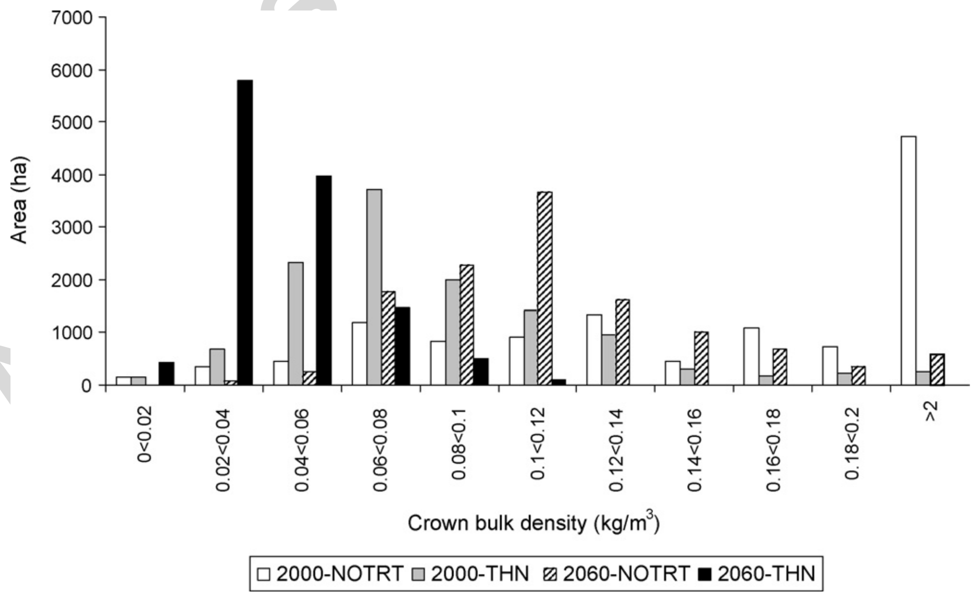

Fig. 6. Distribution of crown bulk density values for the no treatment (NOTRT) and thin repeatedly (THN) scenarios in years 2000 and 2060. Values for the THN in year 2000 are postthinning.

average over the simulation period relative to the NOTRT scenario. The THNBRN scenario resulted in dramatic increases in crown base height after year 2010. The THNBRN1 scenario showed an initial increase in crown base height in year 2010 in response to the thinning treatment, and rapidly decreased thereafter, reaching a minimum of 1.6 m in year 2020. Interestingly, the crown base height for the THNBRN1 scenario was lower than the NOTRT scenario after 2020.

3.2. Potential fire analysis

The simulation of potential fire-caused tree mortality revealed large differences among the scenarios that were consistent with the observed changes in crown bulk density and crown base height. For the NOTRT scenario, potential tree mortality continued to increase through time, reaching 91% of the total volume by year 2060 (Fig. 8). Potential tree mortality from a wildfire for the THN and THNBRN scenarios steadily declined through time, and equaled 34 and 16%, respectively, in year 2060 (Fig. 8). The THNBRN1 scenario resulted in a rapid decrease in potential volume mortality after the initial thinning in year 2000, and then steadily increased over time to reach 63% at year 2060.

Crowning index, which estimates the windspeed required to sustain an active crown fire (Scott and Reinhardt, 2001), was relatively constant for the NOTRT scenario at around 44 km/h (Fig. 9). Crowning index for the THN and THNBRN scenarios were substantially higher, and steadily increased over time. After the initial treatments in year 2000, the crowning index was between 11 and 23 km/h higher for the THNBRN versus the THN scenario. The THNBRN1 scenario resulted in an initial increase of 24 km/h in the crowning index after the initial thinning treatment, and decreased thereafter until year 2040 where it equaled the NOTRT values (Fig. 9). Area distributions for the crowning index (Fig. 10) showed that for the NOTRT scenario in year 2000, most of the area had a crowning index between 10 and 40 km/h. The initial thinning treatment shifted the distribution to higher values, primarily for areas that had crowning indices less than 40 km/h; in year 2060, the distribution of crowning index values was highly asymmetrical and most of the area had values that exceeded 100 km/h.

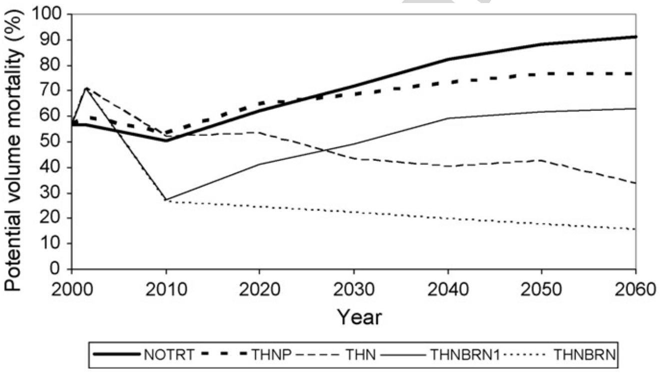

Fig. 8. Average percentage of wood volume consumed by a simulated wildfire in every stand for five management scenarios in the Mount Emily study area. Weather conditions for the wildfire simulation are described in the text. Wildfire was simulated at the stand scale with the Fire and Fuels Extension (FVS). NOTRT: no treatment; THNP: thin only on private lands; THN: repeated thinning; THNBRN1: thin and burn once; THNBRN: thin and repeated.

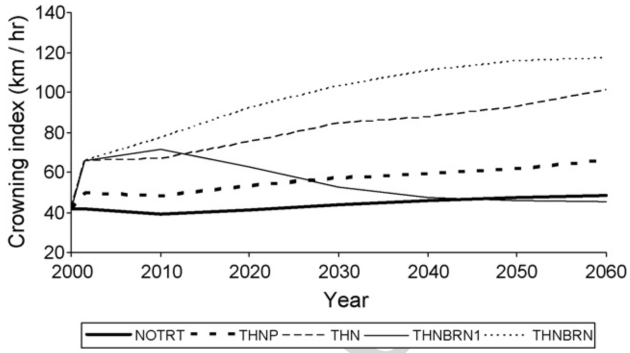

Fig. 9. Average crowning index over time for five management scenarios simulated for the Mount Emily study area. The crowning index is the windspeed that will sustain an active crown fire under a given set of weather conditions. NOTRT: no treatment; THNP: thin only on private lands; THN: repeated thinning; THNBRN1: thin and burn once; THNBRN: thin and repeated.

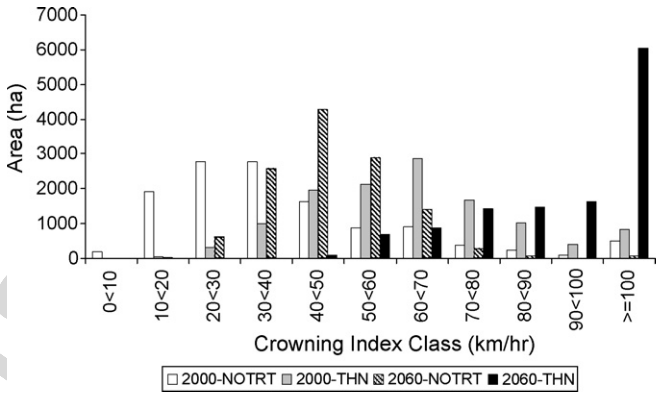

Fig. 10. Area distribution of the crowning index for the no treatment (NOTRT) and thin repeatedly (THN) scenarios in years 2000 and 2060.

4. Discussion

Our study area is a representative sample of forest conditions in much of the Blue Mountains, and thus the results show the magnitude of the gap between the desired (Cochran et al., 1994) and current stand density in the Blue Mountains of eastern Oregon. The simulations provide a more detailed analysis compared to previous broad-scale assessments of the surrounding Blue Mountains (Quigley et al., 2001; Wickman, 1992) and show that a significant area requires repeated treatment over the long term to achieve and maintain long-term density management goals on landscapes like the Mount Emily area. A wide array of operational and resource constraints on national forests make our scenarios infeasible to implement, including old-growth networks, lynx habitat, visual concerns, and financial considerations. Nevertheless, the simulations serve as useful management benchmarks for strategic planning.

Overall, the simulations indicated that thinning to meet stand density goals on the entire Mount Emily landscape would reduce stand-level potential crown fire behavior and associated mortality, increase the area of old forests with single-story structure, and to some extent change forest species composition to the earlier seral species like ponderosa pine and western larch. The effect of thinning treatments had marked effects on parameters like crown bulk density and live crown height, both of which are strong determinants of crown fire activity (Scott and Reinhardt, 2001; Van Wagner, 1977). For instance, for the THN alternative, the average crown bulk density for the THN scenario was 0.06 kg/m^3, which is below the 0.10 kg/m^3 threshold commonly cited as that required to sustain active crown fires (Keyes and O'Hara, 2002).

We observed large differences between the THN and THNBRN scenarios for some of the measured variables (crown base height, crowning index, potential tree mortality from wildfire) but not others (crown bulk density, species composition). The decadal maintenance burns resulted in significant seedling mortality in the THNBRN scenario, resulting in a higher crown base height. Seedlings persisted in the THN scenario as long as the stand SDI was below the thinning threshold. In addition, not all seedlings were removed in the thinning treatments because we used a 90% thinning efficiency.

The THNBRN1 scenario where thinning and burning were carried out only once at the beginning of the simulation showed that treatment effects persist for a long time (i.e., 20–40 years) for most but not all of the variables examined. Crowning index and other variables reverted back to values similar to the NOTRT scenario within 40 years or less. However, average canopy height actually decreased in the THNBRN1 scenario, the result of seedling regeneration after the thinning. Thus, thinning once without later treatments may result in conditions that are less desirable in terms of fire behavior as compared to a no-treatment scenario over the long run. The long-term management of fuels is difficult in the Blue Mountains because many fuel treatments generally have negative net values (Barbour et al., 2007), and a variety of resource values and constraints must be considered on the Federally managed land base.

Both the THNBRN and THNBRN1 scenarios generated a large percentage of old forest structure at the end of the simulation (Fig. 4). The omission of endemic insect and disease agents in our simulations, and perhaps optimistic tree growth rates in FVS, may have led to unrealistic rates of old forest development. The structure projections in this study can be coarsely compared to those reported by Hemstrom et al. (2007) in the adjacent Upper Grande Ronde watershed. The Hemstrom et al. study used a state-and-transition model with a 200-year simulation period and considered three scenarios: background natural disturbances (insects, wildfire), fire suppression, and active fuel treatments. The Hemstrom et al. active-fuel-treatment scenario is not comparable to the treatment scenarios in the present study, as different assumptions were made about the levels and intensity of fuel treatments. However, a comparison of the projected area of old forest structure between our NOTRT scenario and the two other Hemstrom et al. scenarios (fire suppression and active background natural disturbance) showed that we predicted more old forest structure (20%, versus 7–10% of the respective study areas) after 60 years. The magnitude of the observed difference is not large considering the different modeling approaches and study areas.

The simulations also demonstrated the implications of extensive treatment on private land without treatments on Forest Service land. Over time, a sharp contrast is created between the different ownerships in potential fire behavior, forest structure, and species composition. Treatments on private land may be less effective in terms of reducing wildfire risk when adjacent Forest Service land is not treated.

Although the models used indicated that the treatment scenarios had a moderating effect on overall potential fire behavior, a robust assessment of the alternatives needs to examine other disturbance agents. Insect defoliators are a major disturbance agent in the Blue Mountains (Torgersen, 2001) and the thinning treatments we simulated removed host species such as grand fir, and would likely reduce the impact from these insects. At the same time, selection for species like ponderosa pine may lead to increased impacts from bark beetles even when stand density is controlled with thinning (Ager et al., this volume). Of concern are the impacts of mountain (*Dendroctonus ponderosae*) and western pine beetle (*Dendroctonus brevicomis*) under a management regime that includes frequent underburning, as literature suggests increased activity by these beetles in fire-damaged trees (Mitchell and Martin, 1980).

Many issues can be explored with the simulation system we used, such as optimal spatial pattern of fuel treatments (Finney, 2004), interactions between wildfire and other disturbances (Ager et al., this volume; Quigley et al., 2001; Wallin et al., 2003), and secondary effects of fuel treatments on other resources including wildlife and forest productivity (Johnson and Miyanishi, 1995; Tiedemann et al., 2000). Future analyses on the Mount Emily WUI should examine how treatment rate and spatial arrangement affect wildfire behavior (Finney, 2004). Economic questions about the kinds of investments that will be needed in the long term to finance fuel reduction treatments need to be addressed in a way that reflects spatially explicit harvesting and transportation costs. All of these issues contribute to long-term landscape design questions of how to achieve management goals in the Blue Mountains and elsewhere in the intermountain West.

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