Modeling the effects of thinning on bark beetle impacts and wildfire potential in the Blue Mountains of eastern Oregon

Alan A. Ager [a,*], Andrew McMahan [b], Jane L. Hayes [a], Eric L. Smith [c]

[a] *USDA Forest Service, Forestry and Range Sciences Laboratory, 1401 Gekeler Lane, La Grande, OR 97850, USA*
[b] *INTECS International, Inc., Forest Health Technology Enterprise Team, 2150A Centre Avenue, Fort Collins, CO 80526, USA*
[c] *USDA Forest Service, Forest Health Technology Enterprise Team, 2150A Centre Avenue, Fort Collins, CO 80526, USA*

Available online 14 December 2006

Abstract

We simulated management scenarios with and without thinning over 60 years, coupled with a mountain pine beetle outbreak (at 30 years) to examine how thinning might affect bark beetle impacts, potential fire behavior, and their interactions on a 16,000-ha landscape in northeastern Oregon. We employed the Forest Vegetation Simulator, along with sub-models including the Parallel Processing Extension, Fire and Fuels Extension, and Westwide Pine Beetle Model (WPBM). We also compared responses to treatment scenarios of two bark beetle-caused tree mortality susceptibility rating systems. As hypothesized, thinning treatments led to substantial reduction in potential wildfire severity over time. However, contrary to expectations, the WPBM predicted higher bark beetle-caused mortality from an outbreak in thinned versus unthinned scenarios. Likewise, susceptibility ratings were also higher for thinned stands. Thinning treatments favored retention of early seral species such as ponderosa pine, leading to increases in proportion and average diameter of host trees. Increased surface fuel loadings and incidence of potential crown fire behavior were predicted post-outbreak; however, these effects on potential wildfire behavior were minor relative to effects of thinning. We discuss apparent inconsistencies between simulation outputs and literature, and identify improvements needed in the modeling framework to better address bark beetle-wildfire interactions.
© 2006 Elsevier B.V. All rights reserved.

Keywords: Landscape simulation modeling; Forest Vegetation Simulator; Thinning; Bark beetles; Wildfire behavior; Westwide Pine Beetle Model

1. Introduction

Historically, bark beetle infestations and wildfire were dominant influences over successional processes in the dry ponderosa pine forests in the western United States (Agee, 2003). In general, frequent, low-severity fires maintained stand densities and fuels, and bark beetles attacked patches of mature trees weakened by fire, disease, or other factors. These stand dynamics caused patchy, cyclic mortality, and an equilibrium age class distribution at the landscape scale (Agee, 2003). Fire suppression and other management over the past 100 years have altered succession and disturbance regimes, and created forest conditions that are prone to severe wildfire and bark beetle outbreaks (Hessburg et al., 1994). In response, forest management strate-

gies have been adopted by Federal land management agencies to accelerate treatment of hazardous forest conditions over wide areas in the western United States. Treatments include mechanical thinning, surface fuels reduction, the re-introduction of prescribed fire and natural fire. Although these treatments can significantly reduce wildfire severity (Kalabodkidis and Omi, 1998; Pollet and Omi, 2002), their effects on bark beetle dynamics and bark beetle-caused tree mortality are less clear. Treatments may reduce stand-scale susceptibility to beetle infestation by reducing stand density, increasing tree vigor, and removing weakened "focus" trees (Eckberg et al., 1994; Kaufman and Stevens, 1984; Larsson et al., 1983; Negron and Popp, 2004; Sartwell and Dolph, 1976; Sartwell and Stevens, 1975). However, site disturbance, wounding, and mortality from mechanical or prescribed fire treatments may create more "focus" trees, which act as magnets for bark beetles (reviewed in McCullough et al., 1998). Further, prescribed fire and thinning prescriptions in the dry forest types favor retention of tree species such as ponderosa pine (*Pinus ponderosa*) that are hosts

* Corresponding author. Tel.: +1 541 278 3740; fax: +1 541 278 3730.
E-mail addresses: aager@fs.fed.us (A.A. Ager), dmcmahan@fs.fed.us
(A. McMahan), jlhayes@fs.fed.us (J.L. Hayes), elsmith@fs.fed.us (E.L. Smith).

for a suite of bark beetles (including mountain pine beetle, *Dendroctonus ponderosae*, western pine beetle, *D. brevicomis*, and engraver beetles, *Ips* spp.), potentially leading to increased mortality if an outbreak occurs.

Interactions between long-term fuels management activities and bark beetle dynamics at the landscape scale are complex and have received little attention. We report results of model simulations designed to examine how thinning treatments to reduce stand density might affect bark beetle-caused tree mortality. We simulated long-term (60-year) effects of repeated thinning treatments on species composition, basal area, wildfire behavior, and susceptibility to bark beetle-caused tree mortality across forest stands within a ca. 16,000-ha area encompassing a wildland–urban interface near La Grande, Oregon. We used several extensions of the Forest Vegetation Simulator (FVS; Wykoff et al., 1982) to simulate forest dynamics, fuels, thinning treatments (Crookston and Stage, 1991), potential fire behav-

ior (Reinhardt and Crookston, 2003), and bark beetle-caused tree mortality using the Westwide Pine Beetle Model (WPBM) (Beukema et al., 1994, 1997; Smith et al., 2002, in press-a,b). The WPBM is a landscape-scale model that has seen limited application (Eager and Angwin, 1997; Smith et al., 2002). We used the WPBM to examine differences in bark beetle-caused tree mortality between a thinning versus a no thinning scenario. We also examined the effects of thinning and beetles on potential stand-scale fire behavior. We hypothesized that by maintaining low stand density, effects of simulated bark beetle outbreaks would be moderated, as would fire behavior.

1.1. Materials and methods

A simulation study of long-term fuels management of a wildland–urban interface in the Blue Mountains of northeastern Oregon provided the background and opportunity for this
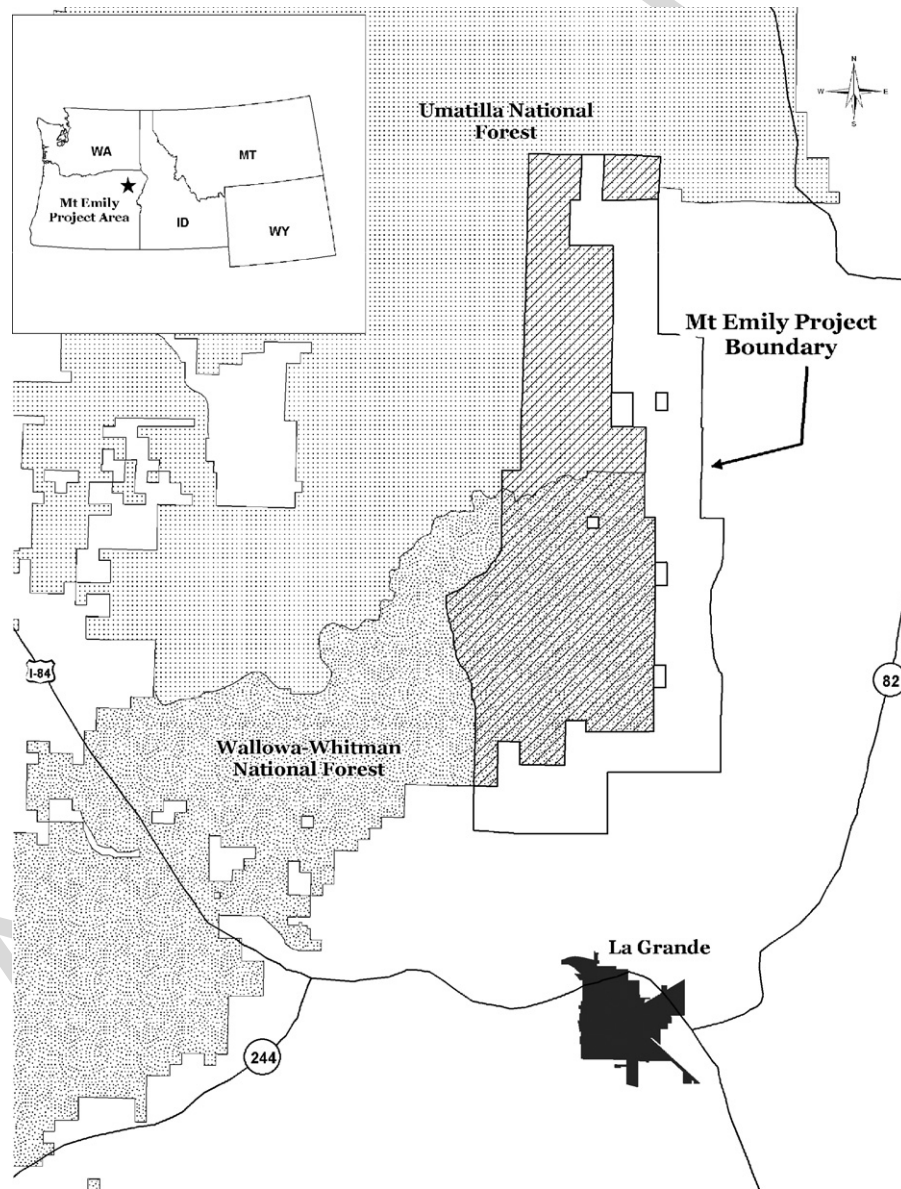

Fig. 1. Vicinity map of the Mt. Emily project area showing land ownership and National Forest boundaries.

study (Ager et al., 2007). We briefly describe the study area, vegetation and fuels data, along with the vegetation and fire and fuels models here. Additional details are provided in Ager et al. (2007).

1.2. Study area

The Mt. Emily wildland–urban interface is north of La Grande, Oregon, and contains 16,343 ha of Federal, state, and privately owned lands (Fig. 1). Based on plant association data (Hall, 1998), approximately 75% of the area is classified as forested lands (unpublished data, La Grande Ranger District, Wallowa-Whitman National Forest, La Grande, Oregon). The area includes a variety of forest types from low-elevation dry and warm forests of ponderosa pine with grand fir (*Abies grandis)* and Douglas-fir (*Pseudotsuga menziesii*), to mid-elevation mesic mixed-conifer forests, which includes lodgepole pine (*Pinus contorta*), subalpine-fir (*Abies lasiocarpa*), western larch (*Larix occidentalis*), and Engelmann spruce (*Picea engelmannii*). Private lands are located on the southern and eastern, lower slopes of the study area and contain about 100 year-round residences. Forest Service lands make up approximately 60% of the total analysis area and are valued for a number of resources including old-growth forests, wildlife habitat, and recreational opportunities. At the time of our study, surface and ladder fuels exceeded management guidelines and the entire area was being analyzed for fuel-reduction treatments by the La Grande Ranger District of the Wallowa-Whitman National Forest. Accumulation of downed and dead woody fuels has resulted from weather events and mortality caused by local to widespread outbreaks of various insects and diseases (Gast et al., 1991). Understory vegetation density has increased following many decades of fire exclusion.

1.3. Vegetation and fuels data

Within the Forest Service boundary, stand delineations were obtained from vegetation geographical information system (GIS) layers on file at the La Grande Ranger District. Outside of the Forest Service boundary, stands were digitized by using aerial orthophotos of an area flown in 2000. A simulation unit layer and associated database were created by intersecting stand and ownership layers. By using data obtained from pre-existing stand exams, and photo-interpretation of 1:12,000 color aerial photos from 1998, a vegetation database was compiled containing the density of each tree species categorized into 2.54 cm (1 in.) size class for each stand.

Stand-specific data on surface fuels loadings were obtained from field inventories for about 1500 ha of the study area. The field inventory data were extrapolated to other stands based on canopy closure, species composition, plant association, stand structure, and local knowledge of stand conditions. Additional fuels sampling using the methods of Brown et al. (1982) was completed on six stands to obtain estimates of the surface fuel loadings for the old-forest structure stands in the cold-forest plant association group. Conditions for this particular stratum were not well represented in the existing field inventories in the study area.

1.4. Vegetation, fire and fuels modeling

We simulated vegetation treatments and succession using the Blue Mountains variant of the Forest Vegetation Simulator, a distance-independent, forest growth model, with the Parallel Processing Extension (FVS-PPE, Crookston and Stage, 1991). The FVS-PPE allows multiple stands to be simulated in a parallel fashion, i.e., the simulation is completed for all stands each time step before cycling to the next time period. FVS-PPE can model spatially explicit management activities among stands in a given landscape (Ager, 2005; Crookston and Stage, 1991).

We simulated forest dynamics and thinning treatments on decadal time steps for 60 years (2000–2060) and report outputs for the beginning year of each decade (2000–2050). We reported the post-thin condition for the first year of each decade (FVS executes thinning in the first year of a cycle) for all variables except the beetle-susceptibility rating variables. A forest regeneration model (Robinson, 2004; Wilson and Maguire, 2002) was developed from survey data obtained from the La Grande Ranger District and used for the simulations.

The Fire and Fuels Extension (FFE) to FVS (Reinhardt and Crookston, 2003) was used to simulate surface fuel dynamics and potential fire behavior for individual stands. Weather conditions for simulating potential wildfire effects were derived from three nearby weather stations and processed to generate 97th percentile temperature, wind speed, and fuel moisture values (see Table 2 in Ager et al., 2007). Outputs were analyzed for crown fire activity, flame length, crowning and torching index, and fire-related mortality.

1.5. Scenarios and prescriptions

We modeled two thinning scenarios (thin and no thin) with and without bark beetles, resulting in a 2×2 factorial design (THN, NOTHN, THN + B, NOTHN + B). The scenarios including mountain pine beetle (THN + B, NOTHN + B) included endemic mortality over the entire simulation and a beetle outbreak during the fourth decade (2030–2039). The thinning scenarios implemented selective, mechanical thinning from below, i.e., starting with the smallest trees, and with removal of progressively larger trees until the thinning threshold was reached. Specifically, stands were thinned when they exceeded 65% of maximum stand density index (SDI) thresholds (Cochran et al., 1994), and trees were removed until the SDI was reduced to 35% of the maximum SDI for the stand. Maximum SDI values for each plant association and target tree species in the study area were obtained from Cochran et al. (1994). We used an FVS thinning efficiency (Dixon, 2003) of 90%, so that 10% of the trees selected for removal were retained. The thinning prescriptions favored retention of early seral species such as ponderosa pine, western larch, and Douglas-fir and targeted removal of late-seral, fire-intolerant species like grand fir in mixed-species stands (Ager et al., 2007).

1.6. Bark beetle model

We used the WPBM (Beukema et al., 1997; Smith et al., 2002, 2005, in press-a,b), an extension to FVS, to simulate endemic mountain pine beetle-caused tree mortality and a mountain pine beetle outbreak. The WPBM simulates beetle populations in terms of amount of "beetle kill potential" (BKP), a surrogate for beetles, where one unit of BKP is an amount of beetles sufficient to kill and occupy 0.0929 m^2 (1 ft^2) of host tree basal area (Smith et al., 2005). The WPBM simulates beetle dynamics such as dispersal, tree selection, attack, and reproduction on an annual time step (Beukema et al., 1997, and reviewed in Smith et al., 2005). Briefly, the model assumes that beetles emerge and disperse, and choose stands to attack based on distance and stand attributes. A proportion of the beetles that choose a stand survive and contribute to the successful attack of host trees, beginning with already weakened ("focus") trees, such as trees struck by lightning. The number of beetles needed to kill a tree varies with tree health ("rating value") and diameter. After the initial attack of 2.5 focus trees/ha (one focus tree per acre), more and healthier trees are attacked, with a preference for large diameter trees. Attacked tree size distribution varies with beetle density; a higher proportion of large trees are attacked when beetle populations are high. The number of newly emerging brood from colonized trees is a function of tree diameter, to an upper limit. Model parameters were developed by a large group of experts and supported by scientific literature; for complete details see Smith et al. (2005).

Note that although the WPBM can simulate the effects of mountain pine beetle, western pine beetle, and pine engraver beetles, it cannot model the effects of mountain pine beetle and western pine beetle simultaneously. Consequently, we focused our analyses solely on the effects of mountain pine beetle, widely considered one of the most destructive bark beetles in the western U.S. (Furniss and Carolin, 1977). We simulated endemic mountain pine beetle population activity for 30 years using WPBM, followed by a mountain pine beetle outbreak during the first half of the fourth simulated decade (2030), and a subsidence of the outbreak beyond the fourth decade. The impact of the outbreak was compared between a thinned landscape (THN + B) and an unthinned (NOTHN + B) landscape.

The WPBM keywords and associated parameters (entered into the simulation file in specific columns called "fields") used in our simulations are presented in Table 1. Keyword BMPARM defines the beetle type (mountain pine beetle), the number of generations per year (1), and the host tree species (lodgepole and ponderosa pine). Keyword BMHIST initializes beetles into the landscape. We initialized BKP into approximately 46% of the landscape, into stands with an amount of mortality greater than 0.23 m^2/ha (1 ft^2/acre) in any of five simulated decades in preliminary calibration simulations. The result is that BKP was put into almost every host-containing stand. BKP was initialized into these stands in the amount of 0.015 m^2/ha (0.07 ft^2/acre) at the beginning of the simulation. Specifically, the BMHIST keyword's supplemental records "establish" 0.123 trees/ha in size class 5 (30.5–38.1 cm diameter at breast height [DBH]) and 0.123 trees/ha in size class 3 (15.2–22.9 cm DBH) as recently

Table 1

Keywords and their parameters used with the Westwide Pine Beetle Model to simulate an outbreak of mountain pine beetle

Keyword	Keyword parameters					
	Field 1	Field 2	Field 3	Field 4	Field 5	Field 6
BMPARM	1	1	7	10	–	–
BMHIST	63	1	–	–	–	–
ATTRACT	1	6	1	(10)	1	(5)
REPRODN	1	6	(5)	(18)	–	–
VARYRAIN	2030	1	−3	–	–	–
VARYRAIN	2035	1	3	–	–	–
VARYRAIN	2039	−1	–	–	–	–
BKPKILL	2036	2	0.5	0.035	–	–
OWVALUES	2030	(0.5)	*	*	*	*
OWVALUES	2031	(1)	*	*	*	*
OWVALUES	2033	(0.5)	*	*	*	*
OWVALUES	2035	*	*	*	*	*
LIGHTN	2000	0.002	–	–	–	–

See text for description and function of keywords. Values that were changed from the model defaults are shown in parentheses. Asterisk indicates that landscape average conditions at the beginning of the simulation were used for the parameter. Units are English to conform to the model parameters.

attacked trees, which become the sources of BKP for the landscape in the first year of the simulation. The simulated landscape-average BKP immediately decreased (within 1 simulated year) and equilibrated at lower levels prior to the outbreak (data not shown), so the initialization amount of BKP had little net effect on the long-term dynamics of the simulation. The ATTRACT keyword (Table 1) specified parameters used to calculate stand attractiveness scores, which determine how BKP is assigned to individual stands. The scalar used to weight the importance of distance (field 4) was lowered from the default of 100 to 10. The maximum per-year BKP dispersal distance (field 6) was lowered from the default of 24 km (15 miles) to 8 km (5 miles).

The keyword REPRODN defines BKP annual reproduction rates specifying the amount of BKP emerging from trees per unit of attacking BKP. We changed the default maximum from 4 to 5 units of BKP emerging per unit of BKP attacking at DBH of 45.7 cm (18 in.) to more accurately reflect BKP dynamics based on previous experience with the model.

Beetle outbreaks are initiated in the model by simulating a stress event (keyword VARYRAIN, Table 1). Different stress events, such as drought, may be specified for each year, thus stresses of different intensities and durations can be specified. We used keyword VARYRAIN to simulate a stress event in simulation year 2030 (field 3 = −3). Negative values in the keyword's field 3 represent stress events that cause tree vigor to decrease and BKP survivorship to increase. The stress event was "reversed" via a second instance of keyword VARYRAIN in simulation year 2035, by using +3 in field 3. This "reverse-stress" event simulates conditions that are favorable to trees and unfavorable to beetles, and promotes the decline of the simulated outbreak. The "reverse-stress" event ends in 2039 (keyword VARYRAIN field 2 = −1).

The BKPKILL keyword was then used to collapse the outbreak in 2036. BKPKILL represents forces that depress

beetle reproduction and in-tree brood survival, including build-up in populations of predators and parasites, and cold winter temperatures. Both the intensity and duration of the beetle outbreak were coarsely modeled after observed trends in the Blue Mountains as captured in historical pest surveys (Ager et al., 2004). The OWVALUES keyword slightly raises the BKP densities during the period of the simulated outbreak in the area surrounding the simulated landscape, which, in the model, serves as a potential source and sink for landscape BKP. The LIGHTN keyword sets the density of lightning strikes per year, which creates focus trees that increase stand attractiveness and are first chosen for attack by beetles. We estimated the lightning strikes per year using lightning detection data obtained from the La Grande Ranger District. Both treatment scenarios were simulated with (THN + B and NOTHN + B) and without (THN and NOTHN) the bark beetles.

During a simulation, mortality estimates from the WPBM are reconciled with base-FVS estimates of mortality at the end of each decade, and standing and downed dead wood fuel pools within the FFE are updated. Thus, the fuel information in the FFE reflects additions to and subtractions from live and dead fuel pools as modified by simulated tree growth and senescence, tree management (thinning), dead fuel management, tree mortality, and regeneration.

1.7. Stand susceptibility rating

We estimated the potential for bark beetle-caused tree mortality using stand classification systems developed by Steele et al. (1996; hereafter referred to as the Steele system) and Stevens et al. (1980; hereafter referred to as the Stevens system) to examine how susceptibility varied with the different scenarios and compared their predictions with the outcome of the simulated outbreak. Rating systems such as Stevens' and Steele's are often referred to as stand "risk" or "hazard" rating systems and have been developed to provide land managers with a means of classifying or rating stands by their vulnerability or susceptibility to sustained bark beetle-caused tree mortality. We use the term "susceptibility" to refer to these rating systems and the indices they generate, and reserve "risk" for the probability or likelihood of an outbreak occurring and the ability to sustain an outbreak (Bentz et al., 1993; Chojnacky et al., 2000), which these rating systems do not address.

The Stevens system was developed for mountain pine beetle attacking ponderosa pine in the Black Hills of South Dakota. It relies on average tree diameter, stand density, and stand structure data. The classification system described by Steele was developed as part of a composite rating system for central Idaho forests with 11 major disturbance agents, including insects, diseases, and wildfire. The component dealing with mountain and western pine beetle in ponderosa pine was based on the Stevens system, but modified to account for the findings of Schmid and Mata (1992), who observed that lower basal areas can reduce mountain pine beetle-caused mortality in ponderosa pine. Otherwise, the Steele system considers average diameter, percentage of ponderosa pine in the stand, and age structure of the stand.
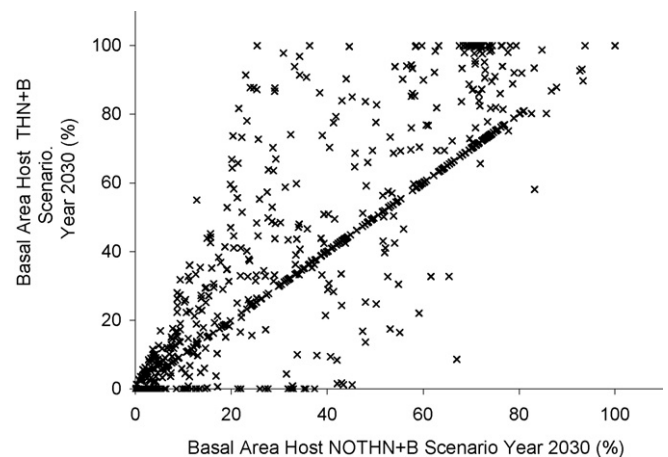

Fig. 2. Basal area of host trees as a percentage of total stand basal area in the thinned (THN + B) vs. unthinned (NOTHN + B) scenario in year 2030 (post-thin) immediately prior to the beetle outbreak. Plotted values are individual stands. Points above the diagonal are stands that have increased basal area of host trees in the THN + B scenario relative to NOTHN + B.

Ratings were calculated by using decadal FVS outputs for each of the four scenarios.

2. Results

2.1. Stand development

At year 2000, the FVS outputs indicated that basal area of ponderosa pine and lodgepole pine averaged 6.4 m²/ha in the forested stands, although the latter species is a relatively minor component (0.38 m²/ha). The thinning treatments resulted in large reductions in stand basal area (Table 2) and the magnitude of the difference between the NOTHN and THN scenarios remained at about 13 m²/ha over the simulation. By the year 2030 when the outbreak was initiated, the thinning treatments in the THN scenario increased the percentage of composition of host pine species by nearly 10% of the total basal area (Table 2; Fig. 2). A similar increase in percentage of composition of host pine was also observed for the THN + B compared to the NOTHN + B scenario (Table 2; Fig. 2). A number of stands that had a minor amount (e.g., 20–40%) of host basal area in year 2030 in the NOTHN + B scenario had over 60% host under the THN + B scenario (Fig. 2). The THN + B scenario resulted in a 4.5-cm increase in the average stand quadratic mean DBH of the host species compared to the NOTHN + B scenario at the beginning of the simulated outbreak (year 2030, Table 2; Fig. 3). Without endemic beetle mortality (THN and NOTHN scenarios) the thinning resulted in a substantially larger host diameter difference (8.2 cm, Table 2). Thus the thinning treatments, which favored the retention of ponderosa and lodgepole pine, resulted in an overall increase of host percentage composition, average DBH, and the proportion of larger host trees.

2.2. Bark beetle-caused tree mortality

The simulated bark beetle outbreak in the NOTHN + B scenario showed a sharp increase in host tree mortality

Table 2
Results of simulation showing area treated and changes in vegetation for the four scenarios included in the study

Variable	Scenario	Year					
		2000	2010	2020	2030	2040	2050
Area thinned (ha) (percentage of total)	THN	7897 (64.4)	2152 (17.6)	5422 (44.2)	4918 (40.1)	5375 (43.8)	3136 (25.6)
	THN + B	7897 (64.4)	2152 (17.6)	5385 (43.9)	4734 (38.6)	3774 (30.8)	2732 (22.3)
Stand density index (percentage of maximum)	NOTHN	286 (67)	337 (80)	351 (85)	356 (86)	360 (87)	359 (87)
	NOTHN + B	286 (67)	337 (80)	351 (85)	356 (86)	330 (81)	343 (83)
	THN	148 (36)	200 (48)	194 (46)	196 (47)	190 (46)	216 (52)
	THN + B	148 (36)	200 (48)	194 (46)	197 (47)	150 (36)	180 (43)
Total stand basal area (m^2/ha)	NOTHN	31.5	35.0	36.7	37.8	38.7	39.2
	NOTHN + B	31.5	35.0	36.7	37.8	34.9	36.8
	THN	18.9	22.4	24.1	24.7	25.6	27.1
	THN + B	18.9	22.4	24.1	24.6	19.0	21.2
Host-tree basal area (m^2/ha) (percentage of stand)	NOTHN	6.4 (20.2	8.1 (23.2)	9.3 (25.5)	10.1 (26.6)	10.5 (27.0)	10.6 (27.1)
	NOTHN + B	6.4 (20.2)	8.1 (23.2)	9.3 (25.5)	10.0 (26.6)	6.7 (19.0)	7.5 (20.3)
	THN	5.2 (27.4)	6.9 (30.6)	8.1 (33.4)	8.9 (36.0)	9.7 (37.8)	10.3 (38.0)
	THN + B	5.2 (27.4)	6.9 (30.6)	8.1 (33.4)	8.7 (35.1)	2.5 (13.1)	3.2 (15.2)
Host-tree quadratic mean diameter (cm)	NOTHN	20.6	23.0	25.2	27.6	30.0	32.2
	NOTHN + B	22.0	28.1	29.4	34.8	33.3	35.2
	THN	24.1	28.1	31.3	35.8	38.8	43.2
	THN + B	26.4	32.1	34.5	39.3	38.0	38.6
Crown base height (m)	NOTHN	3.7	3.9	3.0	2.7	2.6	2.7
	NOTHN + B	3.7	3.9	3.0	2.7	2.6	2.6
	THN	7.7	7.9	6.8	8.4	9.4	7.9
	THN + B	7.7	7.9	6.8	8.2	8.0	6.2
Crown bulk density (kg/m^3)	NOTHN	0.20	0.18	0.16	0.14	0.13	0.13
	NOTHN + B	0.20	0.18	0.16	0.14	0.13	0.13
	THN	0.09	0.09	0.07	0.06	0.06	0.06
Potential tree mortality from wildfire (m^3/ha) (percentage of total volume)	THN + B	0.09	0.09	0.07	0.06	0.05	0.06
	NOTHN	117.0 (51.6)	127.8 (48.0)	198.1 (67.5)	259.5 (81.8)	299.9 (88.6)	325.4 (92.4)
	NOTHN + B	117.0 (51.6)	127.8 (48.0)	198.0 (67.5)	259.6 (81.9)	283.8 (92.2)	316.2 (96.0)
	THN	95.6 (64.6)	59.5 (32.1)	87.4 (41.4)	69.6 (30.5)	65.4 (26.8)	87.7 (32.9)
	THN + B	95.6 (64.6)	59.5 (32.1)	87.9 (41.4)	72.8 (32.0)	67.6 (35.8)	94.6 (45.2)
Tree mortality from beetles (m^3/ha/decade) (percentage of total volume)	NOTHN + B	–	0.1 (0.1)	0.1 (0.1)	0.3 (0.1)	31.9 (10.1)	0.3 (0.1)
	THN + B	–	0.1 (0.1)	0.2 (0.1)	2.2 (1.1)	50.8 (22.3)	0.2 (0.1)
Total surface fuel loading (kg/ha $\times 10^3$)	NOTHN	21.1	18.4	24.8	35.4	47.9	60.1
	NOTHN + B	21.1	18.4	24.8	35.4	49.3	71.8
	THN	21.8	16.4	16.6	18.3	19.3	21.1
	THN + B	21.8	16.4	16.6	18.3	22.2	47.7

NOTHN: no thinning; THN: thin stands exceeding 65% of maximum stand density index; NOTHN: B and THN: B are the same as the previous two scenarios, but with endemic beetle mortality and a simulated bark beetle outbreak between years 2030 and 2040. Values reported are landscape average values (stand area-weighted) as of the first year of each decadal cycle, post-thinning.

between 2030 and 2034 when the simulated outbreak or beetle kill pressure (BKP) peaked (Fig. 4). The total volume of beetle-caused mortality for the THN + B scenario was about 50.8 m^3/ha/decade during the outbreak (2030–2040), compared with only 31.9 m^3/ha/decade for the NOTHN + B scenario (Table 2). Tree mortality from beetles during the decade in which the outbreak occurred was substantially higher for many individual stands for the THN + B scenario compared to NOTHN + B (Fig. 5). Among stands that exhibited relatively high levels of mortality (>500 m^3/ha/decade) in the NOTHN + B scenario, only 32 experienced less mortality in the THN + B versus

NOTHN + B scenario (Fig. 5). Although the mortality for the THN + B versus NOTHN + B scenario varied widely, high mortality in one scenario was generally associated with high mortality in the other.

2.3. Stand susceptibility ratings

Both the Steele and the Stevens susceptibility rating systems showed an increase in the area of moderate or high susceptibility over time for the NOTHN and THN scenarios (Figs. 6 and 7). The percentage of the area ranked as moderate or high suscep-
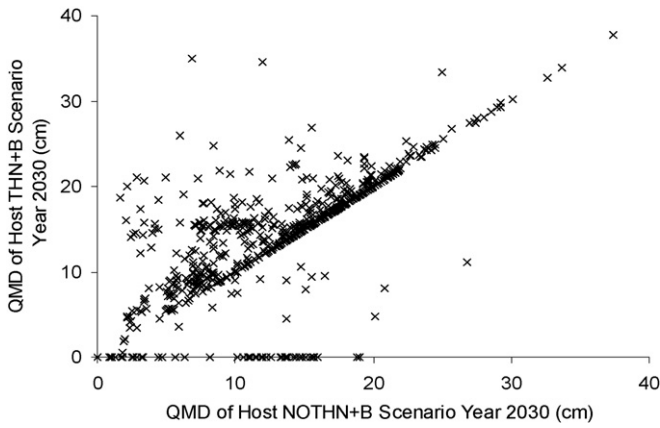
Fig. 3. Quadratic mean diameter (QMD) of host trees in the thinned (THN + B) vs. unthinned (NOTHN + B) scenario in year 2030 (post-thin) prior to the beetle outbreak. Plotted values represent individual stands.
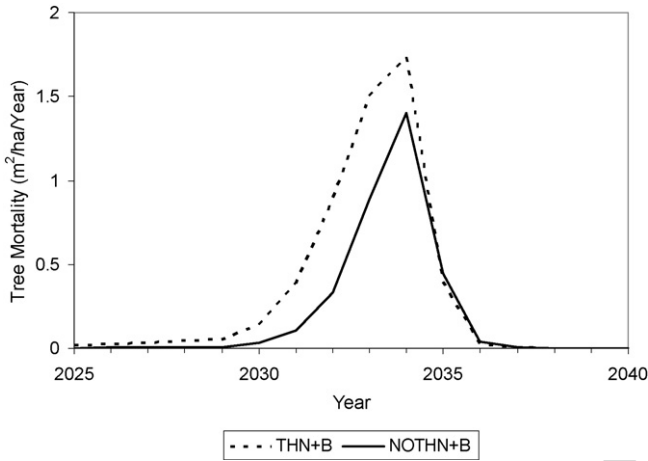

Fig. 4. Host-tree mortality from a simulated mountain pine beetle outbreak for the NOTHN + B and THN + B scenarios. The outbreak was initiated in year 2030, and collapsed in 2038.
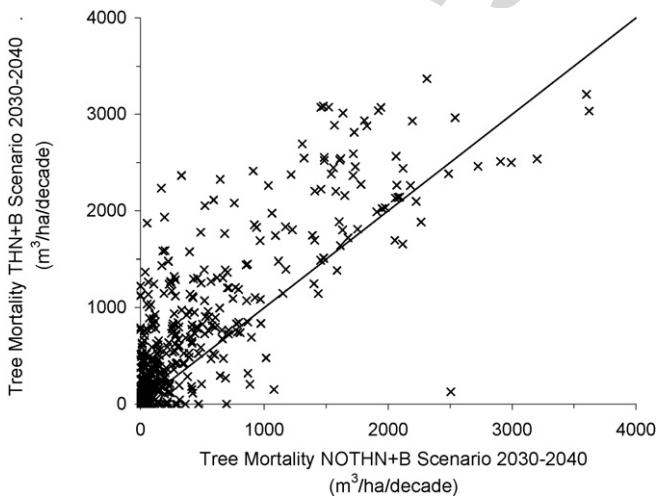

Fig. 5. Comparison of host-tree mortality from a simulated mountain pine beetle outbreak for the THN + B and NOTHN + B scenarios from years 2030 through 2039 for each stand. Points above the diagonal indicate stands where mortality due to beetles was higher in the THN + B vs. NOTHN + B scenario.
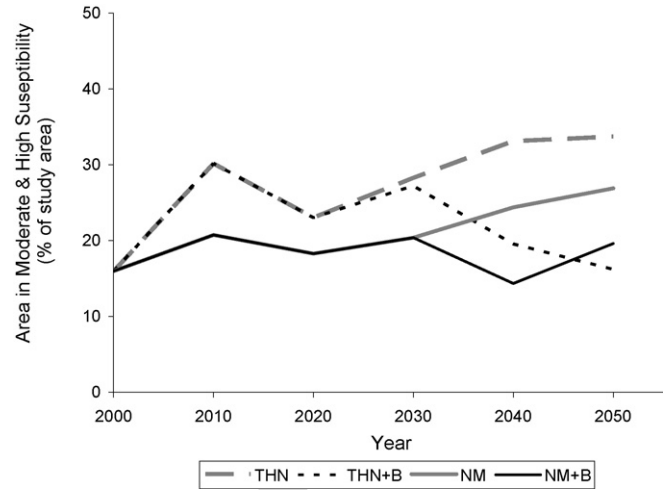

Fig. 6. Percentage of the study area rated moderate or high susceptibility to mountain pine beetles according to the Stevens et al. (1980) stand rating system. Values are reported for the beginning of each decade.

tibility according to the Stevens system changed from about 16% to 27% over the simulation for the NOTHN scenario, and increased to about 34% for the THN scenario (Fig. 6). Compared to Stevens, the Steele system showed a similar difference in area in moderate to high susceptibility for the THN versus NOTHN scenario (5–8%), and a higher overall area rated moderately or highly susceptible throughout the simulation (Fig. 7). Thus, both projections showed increased average susceptibility for the THN scenario compared to the NOTHN scenario, with the difference between scenarios persisting throughout the simulations. Both rating systems showed a rapid decrease in susceptibility after the simulated beetle outbreak was initiated in year 2030, with the decrease being more pronounced for the THN + B scenarios (Figs. 6 and 7).

2.4. Potential wildfire behavior

Over time, the thinning treatments substantially reduced the potential tree mortality from a wildfire as projected by the
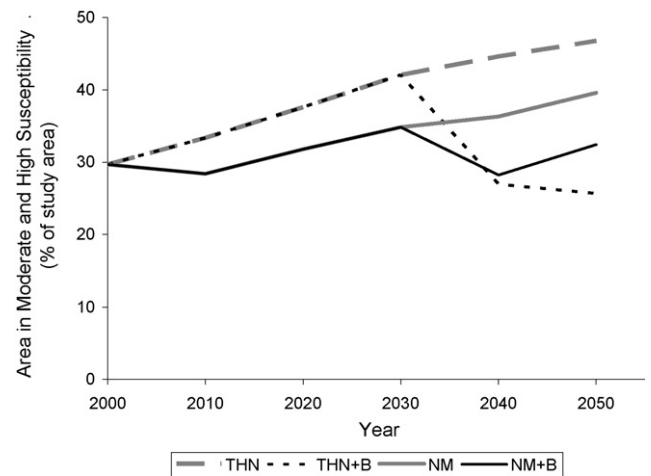

Fig. 7. Percentage of the study area rated moderate or high susceptibility to mountain pine beetles according to the Steele et al. (1996) stand rating system. Values are reported for the beginning of each decade.
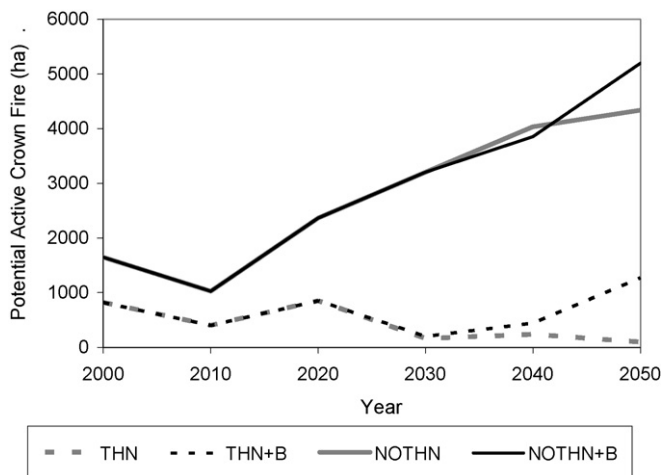
Fig. 8. Potential active crown fire behavior for the THN, NOTHN, THN + B, and NOTHN + B scenarios. Data are shown for stands that have at least 1 m²/ha of ponderosa pine and/or lodgepole pine in trees greater than 12.7 cm diameter at breast height in any simulation cycle prior to the outbreak in 2030.

FFE. For the NOTHN scenario, potential mortality continued to increase through time, reaching 92% of the total volume in year 2050 (Table 2). The increase was non-linear, the most substantial changes occurred between year 2010 and 2020. In contrast, potential mortality from a wildfire for the THN scenario was much lower, ranging from 31% to 41% throughout the simulation after the initial thinning in year 2000 (Table 2). The thinning treatments resulted in substantial reductions in crown bulk density and increases in crown base height, which should moderate potential fire behavior (Table 2).

The effect of the beetle outbreak on potential wildfire behavior was relatively minor compared to the effect of the thinning treatments (Fig. 8). FFE outputs indicated that hectares of potential active crown fire increased by about 1170 ha in the THN + B scenario after the outbreak relative to the THN scenario. The NOTHN + B scenario also showed an increase in hectares of potential active crown fire relative to the NOTHN scenario, although the increase was somewhat less at about 850 ha (Fig. 8). Simulation outputs on surface fuel loading generated by the FFE following the bark beetle outbreak showed that loadings in 2050 increased from about 21,100 kg/ha for the THN scenario to about 47,700 kg/ha for THN + B (Table 2). Overall fuel loadings were larger for the NOTHN and NOTHN + B scenarios, and the increase in surface fuels in 2050 from the beetle-caused tree mortality was relatively small at about 11,700 kg/ha (Table 2).

3. Discussion

Our simulations suggested that susceptibility and potential tree mortality from a future mountain pine beetle outbreak could increase after intensive thinning treatments. The simulated treatments selectively thinned stands, which decreased stand density and increased proportion of susceptible pine host trees. Although it is reasonable to expect that vulnerability to beetle attack might increase with a treatment scenario that creates large host trees, we did not anticipate increased beetle-caused mortality

with decreasing stand density. To the contrary, our expectation based on the literature was to find substantially reduced mortality in the thinned scenario (e.g., Amman and Logan, 1998; Cochran and Barrett, 1995, 1999; Negron and Popp, 2004). Our analysis of the WPBM outputs suggested the following hypotheses to explain the results: (1) Simulated beetle kill pressure (BKP) may disperse more efficiently than real-world beetle populations; thus simulated "populations" may be more effective in finding scattered, mixed-species stands containing small amounts of host trees. (2) In contrast to an actual thinning treatment, where beetle infested trees would likely be thinned and removed from the site, the simulated thinning did not remove beetle-attacked trees and their associated BKP, because these trees are considered dead by FVS, and are not available for removal with the thinning keywords we used; thus the thinned landscape has an amount of pre-dispersal BKP equal to what the landscape would have were it not cut. (3) Beetle-attacked stands in the thinned landscape contain, on average, trees of larger DBH than beetle-attacked stands in the unthinned landscape.

Although the increase in quadratic mean diameter (QMD) of 4.6 cm may seem small, bark beetle-host interactions are non-linear, and thus even a small diameter difference between the scenarios may change overall host susceptibility. Several factors are important to consider. First, bark beetle often exhibit a marked preference for larger trees, and mountain pine beetle reproduction and survivorship rates are typically higher in larger trees with thicker phloem and bark (e.g., Amman and Pasek, 1986; reviewed in Amman and Cole, 1983). Second, there usually exists a lower diameter threshold-typically 10–12.5 cm (4–5 in.) DBH depending on the host species (Furniss and Carolin, 1977)-below which trees are considered not susceptible to beetle attack. Thus, an increase of 4.6 cm in average host diameter could translate into both a substantial increase in the number of susceptible trees as well as an increase in the numbers of beetles emerging from attacked trees. We see this effect in our results where the WPBM simulated higher beetle reproduction rates in the larger trees present in the thinned landscape, and more severe mortality under outbreak conditions. Finally, our use of the mean diameter for comparing the scenarios may mask the true difference in the host tree populations, and in retrospect a diameter distribution might have provided a better metric.

It is also important to note our simulations did not examine the likelihood or risk of a severe mountain pine beetle outbreak between the unthinned and thinned landscapes. We explicitly triggered an outbreak with the WPBM VARYRAIN keyword, i.e., with the introduction of environmental stress such as would be experienced with severe drought. Inducing an environmental stress in our model may have effectively nullified the increase in vigor as well as resistance that typically occur over time with thinning (Kaufman and Stevens, 1984; Kolb et al., 1998; Larsson et al., 1983).

In support of the WPBM model outputs, we also found that the two frequently used susceptibility rating systems also predicted higher susceptibility in the thinned scenario (although see Bentz et al., 1993; Chojnacky et al., 2000 for critical reviews

of susceptibility rating systems). Furthermore, historical information indicates that large outbreaks of mountain pine beetle were common in forests of northeastern Oregon in the early 1900s following drought (Filip et al., 1996) and is consistent with increased beetle activity in the southwest associated with long-term drought conditions. Thus, the outbreak scenario was probably not unreasonable in terms of mountain pine beetle-caused tree mortality for a forest that resembles pre-suppression stand structure and composition.

Part of the problem with interpreting the model results is that existing mountain pine beetle literature points to a complex relationship between stand conditions and susceptibility. As summarized by Negron and Popp (2004), one consistent observation in ponderosa pine stands is that beetle-caused mortality is positively related to density, although the role (and interaction with density) of tree size is less clear. Although Negron and Popp (2004) found a larger proportion of large diameter trees were killed, Eckberg et al. (1994) and Olsen et al. (1996) found that mountain pine beetle did not exhibit a preference for large diameter ponderosa pine. In lodgepole pine, the literature is more consistent, and suggests that mountain pine beetle prefer large diameter host trees in lodgepole stands (e.g., Bentz et al., 1996; Mitchell and Preisler, 1991). Mitchell and Preisler (1991) found that the probability of a tree being colonized in a stand was higher when larger diameter trees were available. Preisler and Mitchell (1993) found mountain pine beetle colonization occurred more slowly in thinned plots, but once infestation began, the preference for large diameter trees was observed in both thinned and unthinned plots. However, while they also found the magnitude of attack was lower in thinned plots, Borden et al. (submitted for publication) manipulated beetle densities with pheromones in field plots and observed that mortality increased with increasing DBH and decreasing density.

The effects of thinning on potential mountain pine beetle impacts include immediate changes in stand microclimate (increased temperatures, light, and wind movement) that make a stand less attractive to beetles (reviewed in Amman and Logan, 1998). Tree vigor (Larsson et al., 1983; but see Sanchez-Martinez and Wagner, 2002) and resistance (Kolb et al., 1998) also may improve after thinning. Thus, thinning is frequently reported to have immediate, positive impacts in terms of reducing bark beetle-caused tree mortality. Reducing stand density, however, also has a longer term effect of generating large trees, and some studies have shown increased beetle attractiveness under outbreak conditions (Borden, personal communication; Preisler and Mitchell, 1993). This longer term effect appears to be reflected in the simulation results presented here.

The effect of the simulated beetle outbreak on surface fuels and fire behavior showed an increase in area of potential crown fire activity after the beetle outbreak, in both thinned and unthinned stands, primarily as a result of increased regeneration. The effect of the beetle outbreak on crown fire activity was minor compared to the thinning, however. The potential impact of beetles was limited by the percentage of host trees in the landscape, which in the present study ranges from about 20% to 35% of the total basal area.

Improvements are needed in the current WPBM to fully study interactions between fire and bark beetles. At present, it is only possible to simulate the effect of beetles on potential wildfire, and not the reciprocal interaction. Specifically, the current version of WPBM does not use crown and bole scorch outputs from the FFE in the calculation of beetle attractiveness. Thus, we were not able to model short-term increased risk of bark beetle impacts associated with certain types of fuels treatments and low-intensity wildfire, despite the fact that many studies have shown that fire scorching can promote bark beetle activity (Bradley and Tueller, 2001; McHugh et al., 2003; Mitchell and Martin, 1980; Wallin et al., 2003). Additionally, a robust tradeoff analysis of management options needs to consider the simultaneous impacts of other bark and engraver beetles and defoliators. We speculate that such analysis would show the thinning treatments used in this study will dramatically reduce the potential impacts of mortality from Douglas-fir beetle (*Dendroctonus pseudotsugae*) and fir engraver (*Scolytus ventralis*) and defoliators like western spruce budworm (*Choristoneura occidentalis*) and Douglas-fir tussock moth (*Orgyia pseudotsugata*) as pine species replace fir species.

References

Agee, J.K., 2003. Historical range of variability in eastern Cascades forests, Washington, USA. Landsc. Ecol. 18, 725–740.

Ager, A.A., 2005. ArcFuels: forest planning tools for managing wildland fuels. In: Proceedings of the 25th ESRI International Users Conference, San Diego, CA, 25–29 July, p. 5, http://gis.esri.com/library/userconf/proc05/papers/pap1296.pdf.

Ager, A.A., Hayes, J.L., Schmitt, C., 2004. Methods to model insect and disease mortality in landscape simulation and planning models. In: Hayes, J., Ager, A., Barbour, R. (Tech. Eds.), Methods for Integrated Modeling of Landscape Change. Gen. Tech. Rep. PNW-GTR-610. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR, pp. 104–116.

Ager, A.A., McMahan, A.J., Barrett, J.J., McHugh, C., 2007. A simulation study of forest restoration and fuels treatments on a wildland–urban interface. Landsc. Urban Plann. 80, 292–300.

Amman, G.D., Cole, W.E., 1983. Mountain pine beetle dynamics in lodgepole pine forests. Part II: Population dynamics. Gen Tech. Rep. GTR-INT-145. U.S. Department of Agriculture, Forest Service, Intermountain Forest & Range Exp. Sta., Ogden, UT, 59 pp.

Amman, G.D., Logan, J.A., 1998. Silvicultural control of mountain pine beetle: prescriptions and the influence of microclimate. Am. Entomol. 44, 166–177.

Amman, G.D., Pasek, J.E. 1986. Mountain pine beetle in ponderosa pine: effects of phloem thickness and egg gallery density. Res. Pap. INT-367. U.S. Department of Agriculture, Forest Service, Intermountain Research Station, Ogden, UT, 7 pp.

Bentz, B.J., Amman, G.D., Logan, J.A., 1993. A critical assessment of risk classification systems for the mountain pine beetle. For. Ecol. Manage. 61, 349–366.

Bentz, B.J., Powell, J.A., Logan, J.A., 1996. Localized spatial and temporal attack dynamics of the mountain pine beetle in lodgepole pine. Res. Pap. INT-RP-494. U.S. Department of Agriculture, Forest Service, Intermountain Research Station, Ogden, UT, 8 pp.

Beukema, S.J., Greenough, J.A., Robinson, D.C.E., Kurz, W.A., Smith, E.L., Eav, B.B., 1997. The Westwide Pine Beetle Model: a spatially-explicit contagion model. In: Teck, R., Moeur, M., Adams, J. (Comps.), Proceedings of the Forest Vegetation Simulator Conference. Gen. Tech. Rep. INT-GTR-373. U.S. Department of Agriculture, Forest Service, Intermountain Research Station, Ogden, UT, pp. 126–130.

Beukema, S.J., Robinson, D.C., Greenough, J.A., McNamee, P.J., Kurz, W.A., 1994. Westwide Pine Beetle Model: detailed description. Final report prepared for U.S. Department of Agriculture, Forest Service, Forest Pest Management. Methods Application Group, Fort Collins, CO, 92 pp.

Borden, J.H., Birmingham, A.L., Burleigh, J.S. Evaluation of the push-pull tactic against the mountain pine beetle using verbenone and non-host volatiles in combination with pheromone-baited trees. Forest Chronicles, submitted for publication.

Bradley, T., Tueller, P., 2001. Effects of fire on bark beetle presence on Jeffrey pine in the Lake Tahoe Basin. For. Ecol. Manage. 142, 205–214.

Brown, J.K., Oberheu, R.D., Johnson, C.M., 1982. Handbook for inventorying surface fuels and biomass in the Interior West. Gen. Tech. Rep. INT-129. U.S. Department of Agriculture, Forest Service, Intermountain Research Station, Ogden, UT, 48 pp.

Chojnacky, D.C., Bentz, B.J., Logan, J.A., 2000. Mountain pine beetle attack in ponderosa pine: comparing methods for rating susceptibility. Res. Pap. RMRS-RP-26. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Ft. Collins, CO, 10 pp.

Cochran, P.H., Barrett, J.W., 1995. Growth and morality of ponderosa pine poles thinned to various densities in the Blue Mountains of Oregon. Res. Pap. PNW-RP-483. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR, 27 pp.

Cochran, P.H., Barrett, J.W., 1999. Growth of ponderosa pine thinned to stocking levels in central Oregon: 30-year results. Res. Pap. PNW-RP-508. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR, 27 pp.

Cochran, P.H., Geist, J.M., Clemens, D.L., Clausnitzer, R.R., Powell, D.C., 1994. Suggested stocking levels for forest stands of northeastern Oregon and southeastern Washington. Res. Note PNW-RN-513. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR, 21 pp.

Crookston, N.L., Stage, A.R., 1991. User's guide to the Parallel Processing Extension of the Prognosis model. Gen. Tech. Rep. INT-281. U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT, 87 pp.

Dixon, G.E. (Comp.), 2003. Essential FVS: A user's guide to the Forest Vegetation Simulator. Internal Rep. Fort Collins, CO. U.S. Department of Agriculture, Forest Service, Forest Management Service Center, 193 pp.

Eager, T.J., Angwin, P.A., 1997. Forest health assessment—Piney analysis area, Holy Cross Ranger District, White River National Forest. In: Teck, R., Moeur, M., Adams, J. (Comps.), Proceedings of the Forest Vegetation Simulator Conference. Gen. Tech. Rep. INT-GTR-373. U.S. Department of Agriculture, Forest Service, Intermountain Research Station, Ogden, UT, pp. 116–120.

Eckberg, T.B., Schmid, J.M., Mata, S.A., Lundquist, J.E., 1994. Primary focus trees for the mountain pine beetle in the Black Hills. Res. Note RM-RN-531. U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO, 11 pp.

Filip, G.M., Torgersen, T.R., Parks, C.A., Mason, R.R., Wickman, B., 1996. Insects and disease factors in the Blue Mountains. In: Jaindl, R.G., Quigley, T.M. (Eds.), Search for a Solution: Sustaining the Land, People, and Economy of the Blue Mountains, American Forests. Washington, DC, pp. 169–202.

Furniss, R.L., Carolin, V.M., 1977 (reprinted in 1992). Western Forest Insects. Misc. Publ. No. 8. U.S. Department of Agriculture, Forest Service, Washington, DC, 654 pp.

Gast Jr., W.R., Scott, D.W., Schmitt, C., Clemens, D., Howes, S., Johnson Jr., C.G., Mason, R., Mohr, F., Clapp Jr., A.R., 1991. Blue Mountains Forest Health Report: New Perspectives in Forest Health. U.S. Department of Agriculture, Forest Service, Malheur, Umatilla, and Wallowa-Whitman National Forests (Unconventional pagination).

Hall, F.C., 1998. Pacific Northwest ecoclass codes for seral and potential natural communities. Gen. Tech. Rep. PNW-GTR-418. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. Portland, OR, 290 pp.

Hessburg, P.F., Mitchell, G.R., Filip, G.M., 1994. Historical and current roles of insects and pathogens in eastern Oregon and Washington forested landscapes. Gen. Tech. Rep. PNW-GTR-327. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR, 72 pp.

Kalabodkidis, K.D., Omi, P.N., 1998. Reductions in fire hazard through thinning/residue disposal in the urban interface. Int. J. Wildland Fire 8, 29–35.

Kaufman, M.R., Stevens, R.E., 1984. Vigor of ponderosa pine trees surviving mountain pine beetle attack. Res. Note RM-448, U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Ft. Collins, CO, 5 pp.

Kolb, T.E, Holmberg, K.M., Wagner, M.R., Stone, J.E., 1998. Regulation of ponderosa pine foliar physiology and insect resistance mechanisms by basal area treatments. Tree Phys. 18, 375–381.

Larsson, S., Oren, R., Waring, R.H., Barrett, J.W., 1983. Attacks of mountain pine beetle as related to tree vigor of ponderosa pine. For. Sci. 29, 395–402.

McCullough, D.G., Werner, R.A., Newmann, D., 1998. Fire and insects in northern and boreal forest ecosystems of North America. Annu. Rev. Entomol. 43, 107–127.

McHugh, C., Kolb, T., Wilson, J.L., 2003. Bark beetle attacks on ponderosa pine following fire in northern Arizona. Environ. Entomol. 32, 1–13.

Mitchell, R.G., Martin, R.E., 1980. Fire and insects in pine culture of the Pacific Northwest. In: Proceedings of the sixth conference on fire and forest meteorology, Society of American Foresters, 22–24 April, pp. 82–190.

Mitchell, R.G., Preisler, H.K., 1991. Analysis of spatial patterns of lodgepole pine attacked by outbreak populations of the mountain pine beetle. For. Sci. 37, 1390–1408.

Negron, J.F., Popp, J.B., 2004. Probability of ponderosa pine infestation by mountain pine beetle in the Colorado Front Range. For. Ecol. Manage. 191, 17–27.

Olsen, W.K., Schmid, J.M., Mata, S.A., 1996. Stand characteristics associated with mountain pine beetle infestations in ponderosa pine. For. Sci. 42, 310–327.

Pollet, J., Omi, P.N., 2002. Effect of thinning and prescribed burning on crown fire severity in ponderosa pine forests. Int. J. Wildland Fire 11, 1–10.

Preisler, H.K., Mitchell, R.G., 1993. Colonization patterns of the mountain pine beetle in thinned and unthinned lodgepole pine stands. For. Sci. 39, 528–545.

Reinhardt, E., Crookston, N.L., 2003. The Fire and Fuels Extension to the Forest Vegetation Simulator. Gen. Tech. Rep. RMRS-GTR-116. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Ft. Collins, CO, 209 pp.

Robinson, D.C.E., 2004. The Blue Mountains Establishment Model: An Externally Executed Program Linked to the Forest Vegetation Simulator Establishment System. Tech. Rep. ESSA Technologies, Ltd., Vancouver, BC, Canada, 9 pp.

Sanchez-Martinez, G., Wagner, M.R., 2002. Bark beetle community structure under four ponderosa pine forest stand conditions in northern Arizona. For. Ecol. Manage. 170, 145–160.

Sartwell, C., Dolph Jr., R.E., 1976. Silvicultural and direct control of mountain pine beetle in second-growth ponderosa pine. Res. Note 268. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR, 8 pp.

Sartwell, C., Stevens, R.E., 1975. Mountain pine beetle in ponderosa pine: prospects for silvicultural control in second growth stands. J. For. 73, 136–140.

Schmid, J.M., Mata, S.A., 1992. Natural variability of specific forest insect populations and their associated effects in Colorado. Gen. Tech. Rep. RM-GTR-275. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Ft. Collins, CO, 14 pp.

Smith, E.L., McMahan, A.J., Eager, T., 2002. Landscape analysis application of the Westwide Pine Beetle FVS extension. In: Crookston, N.L., Havis, R.N. (Comps.), Second Forest Vegetation Simulator Conference. Proc. RMRS-P-25. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO, pp. 62–67.

Smith, E.L., McMahan, A.J., David, L., Beukema, S.J.; Robinson, D.C., 2005. Westwide Pine Beetle Model Version 2.0: Detailed Description. FHTET 05-06. U.S. Department of Agriculture, Forest Service, Forest Health Protection, Forest Health Technology Enterprise Team, Fort Collins, CO, 101 pp.

Smith, E.L., McMahan, A.J., David, L., Havis, R., Crookston, N.L., Beukema, S.J., Robinson, D.C. Westwide Pine Beetle Model Version 2.0: Keyword Guide. FHTET 05-XX. U.S. Department of Agriculture, Forest Service, Forest Health Protection, Forest Health Technology Enterprise Team. Fort Collins, CO, 55 pp., in press-a.

Smith, E.L., McMahan, A.J., David, L., Oberle, M., Crookston, N.L., Beukema, S.J. Westwide Pine Beetle Model Version 2.0: User's Guide. FHTET 05-XX. U.S. Department of Agriculture, Forest Service, Forest Health Protection, Forest Health Technology Enterprise Team, Fort Collins, CO, 102 pp., in press-b.

Steele, R., Williams, R.E., Weatherby, J.C., Reinhardt, E.D., Hoffman, J.T., Thier, R.W., 1996. Stand hazard rating for central Idaho forests. Gen. Tech. Rep. INT-GTR-332. U.S. Department of Agriculture, Forest Service, Intermountain Research Station, Ogden, UT, 29 pp.

Stevens, R.E., McCambridge, W.F., Edminster, C.B., 1980. Risk rating guide for mountain pine beetle in Black Hills ponderosa pine. Res. Note RM-385. U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Ft. Collins, CO, 2 pp.

Wallin, K.F., Kolb, T.E., Skov, K.R., Wagner, M.R., 2003. Effects of crown scorch on ponderosa pine resistance to bark beetles in northern Arizona. Environ. Entomol. 32, 652–661.

Wilson, D., Maguire, D., 2002. A regeneration model for the Upper Grande Ronde Watershed. Unpublished Report. Oregon State University, Department of Forest Sciences, Corvallis, OR.

Wykoff, W.R., Crookston, N.L., Stage, A.R., 1982. User's guide to the stand Prognosis model. Gen. Tech. Rep. INT-133. U.S. Department of Agriculture, Forest Service, Intermountain Research Station, Ogden, UT, 112 pp.