

Modeling Bark Beetles and Fuels on Landscapes: A Demonstration of ArcFuels and a Discussion of Possible Model Enhancements

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Abstract—The Westwide Pine Beetle Model and the Fire and Fuels Extension were used to simulate a mountain pine beetle outbreak under different fuel treatment scenarios on a 173,000 acre landscape on the Deschutes National Forest. The goal was to use these models within ArcFuels to analyze the interacting impacts of bark beetles and management activities on landscape fuel dynamics. Issues pertaining to modeling the complex inter-relationships of fire, bark beetles, and fuel dynamics are discussed, including: thinning effects on inter-stand bark beetle migration; relationships between beetle migration and survivorship; tree mortality source (e.g., fire vs. bark beetle) and its relationship to the tree's subsequent fuel deterioration dynamics; fire effects on beetles and beetle behavior in fire-affected landscapes. Ideas for future model development are presented.

Introduction

Bark beetles and wildfire play a major role in determining forest succession patterns in the extensive pine-dominated forests of the Western United States. Historically, many dry pine forest landscapes typically experienced frequent low severity fires that controlled stand densities and surface fuel loads (Graham and others 2004) and thus infrequently experienced large stand-replacing fires. Native bark beetle populations exhibited cyclic patterns of endemic and epidemic activity. During endemic periods (between outbreaks), bark beetles generally kill patches of trees weakened by fire, disease, or other stressors. Bark beetle outbreaks, which occur sporadically when conditions are favorable, cause increased mortality of trees that under endemic conditions would be considered less vulnerable. Silvicultural practices and fire suppression over the past 100+ years has resulted in landscape-scale stand structures that are experiencing an increase in both the frequency and severity of wildfire and bark beetle outbreaks in pine forests of the Western United States (Hessburg and others 1994). Future climate change may foster conditions conducive to wildfire (Meehl and others 2007) and may contribute to future increases in the severity of bark beetle outbreaks (Carroll and others 2006).

In response to concerns over the undesirable impacts of large wildfires, bark beetle outbreaks, and the potential interactions between the two, many land management agencies have adopted strategies calling for stand treatments over wide areas in the Western United States. These treatments include thinning, re-introduction of natural and prescribed fire, and mechanical fuels reductions. Many would agree that such treatments can have beneficial effects, moderating wildfire intensity and extent and, at least in the short-term, reducing within-stand beetle-caused tree mortality. However, it remains unclear what effects these treatments might have on landscape-scale bark beetle dynamics and effects on fuel load and fire behavior. Models such as the Westwide Pine Beetle Model (WWPBM) (Beukema and others 1997; Smith and others 2002, 2005)—a landscape-scale bark beetle contagion and tree-effects model—coupled with the Fire and Fuels Extension (FFE) (Reinhardt and Crookston 2003) are useful tools to investigate the landscape-scale fuels treatments and their effects on the dynamics of fire/bark beetle interactions.

Evaluating risks of tree mortality from fire and bark beetles at a landscape scale is a complex problem. Ager and others (2006) discuss many of the issues. The WWPBM and FFE can be used to help analyze possible future scenarios by projecting how, where, and to what extent fire and bark beetle “risk factors”—potential tree mortality, fuel loading, torching index, etc.—might manifest on a landscape under a variety of management scenarios.

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In this paper, we present an application of the WWPBM and the FFE on a landscape in the Deschutes National Forest on the east side of the Cascades in central Oregon. We used these models to analyze the effects of an aggressive thinning strategy on subsequent dynamics of a simulated bark beetle outbreak. We also examined the effects of these thinning regimes and a simulated beetle outbreak on near-term potential fire behavior and fuel loads. The simulations were conducted and analyzed within ArcFuels (Ager 2005), a customized ESRI ArcMap project, which facilitates the linking of Forest Vegetation Simulator (FVS) inputs and outputs with geographic information systems (GIS) and numerous post-processing applications. Our aims are to (1) foster discussion about how our models simulate the inter-relationships between fire, bark beetles, and fuel dynamics; and (2) demonstrate the types of questions that can be addressed by the models and the types of analyses that are facilitated by ArcFuels. Model strengths and weaknesses are discussed.

Analysis Area

The Five Buttes planning area spans approximately 173,000 acres of predominately forested land (90 percent) located on the Deschutes National Forest in south-central Oregon (fig. 1). The planning area encompasses the Davis Late Successional Reserve (LSR) along with designated wilderness, roadless areas, and general forest that is managed for a number of resources. The Davis LSR was established in the Northwest Forest Plan and is managed to maintain and/or create old-growth habitat for the federally listed northern spotted owl (*Strix occidentalis caurina*) (USDA Forest Service and BLM 1994). The area contains a diverse array of forest types. It is dominated by mixed conifer, lodgepole pine, and ponderosa pine plant association groups (PAG) in its eastern reaches, and dry mountain hemlock PAG in the west. The 2003 Davis fire burned approximately 24,000 acres (~15 percent of forested area) of mostly mixed conifer stands in the northeastern quadrant of the analysis area (fig. 1), destroying approximately 30 percent of the habitat of the northern spotted owl within the Davis LSR.

Simulation Details

The study area contained 5,291 mapped polygons, 135 of which were classified as non-forest (meadows, rock, and water). Polygons within the 2003 Davis fire were assumed to be bare ground. The non-forest and Davis fire polygons were excluded from the fuel treatment scenarios and the WWPBM, leaving 132,340 acres or 76 percent of the entire area being simulated as forested.

We conducted four simulation scenarios by combining a thin or no-thin treatment scenario (TRT, NoTRT) with post-treatment bark beetle outbreak or a no-beetle scenario (+B, -b). Simulations were run using the SORNEC (Southern Oregon, Northeast California) variant of FVS, together with the Parallel Processing Extension (PPE) (Crookston and Stage 1991), the FFE, the WWPBM, and the Database (Crookston and others 2007) extensions. Tree regeneration was not simulated. Simulations were run for seven 3-year cycles with an assumed starting year of 2000¹. The short cycle length invokes frequent communication between the WWPBM and the FFE, which occurs only at FVS cycle boundaries.

The thinning scenarios treated stands in the mixed conifer type where current stand density index (SDI) exceeded 55 percent of the maximum stand density index (MaxSDI) (Dixon 2007). This threshold SDI (236) (Cochran and others 1994) is generally accepted as a density above which competition can sufficiently weaken trees, causing them to be susceptible to bark beetle attack. We note that this thinning scenario is hypothetical and that operational or other constraints would prohibit treatments on such a large scale. The prescription is compatible with the management goals within and around the Davis LSR to protect large pine and Douglas-fir from bark beetles and wildfire (Maffei and Tandy 2002; USDA 2007). The thinning prescription was simulated in year 2003 and left a residual SDI of 35 percent of the MaxSDI. The prescription favored the retention of large pine and Douglas-fir.

In the beetle outbreak [+B] scenarios, a seven-year long "severe" bark beetle outbreak was imposed during simulation years 2005 through 2011. Tree mortality from endemic-levels of beetles was simulated before and after the outbreak. The no-beetle outbreak scenarios [-b] did not include either outbreak or endemic beetle-caused tree mortality.

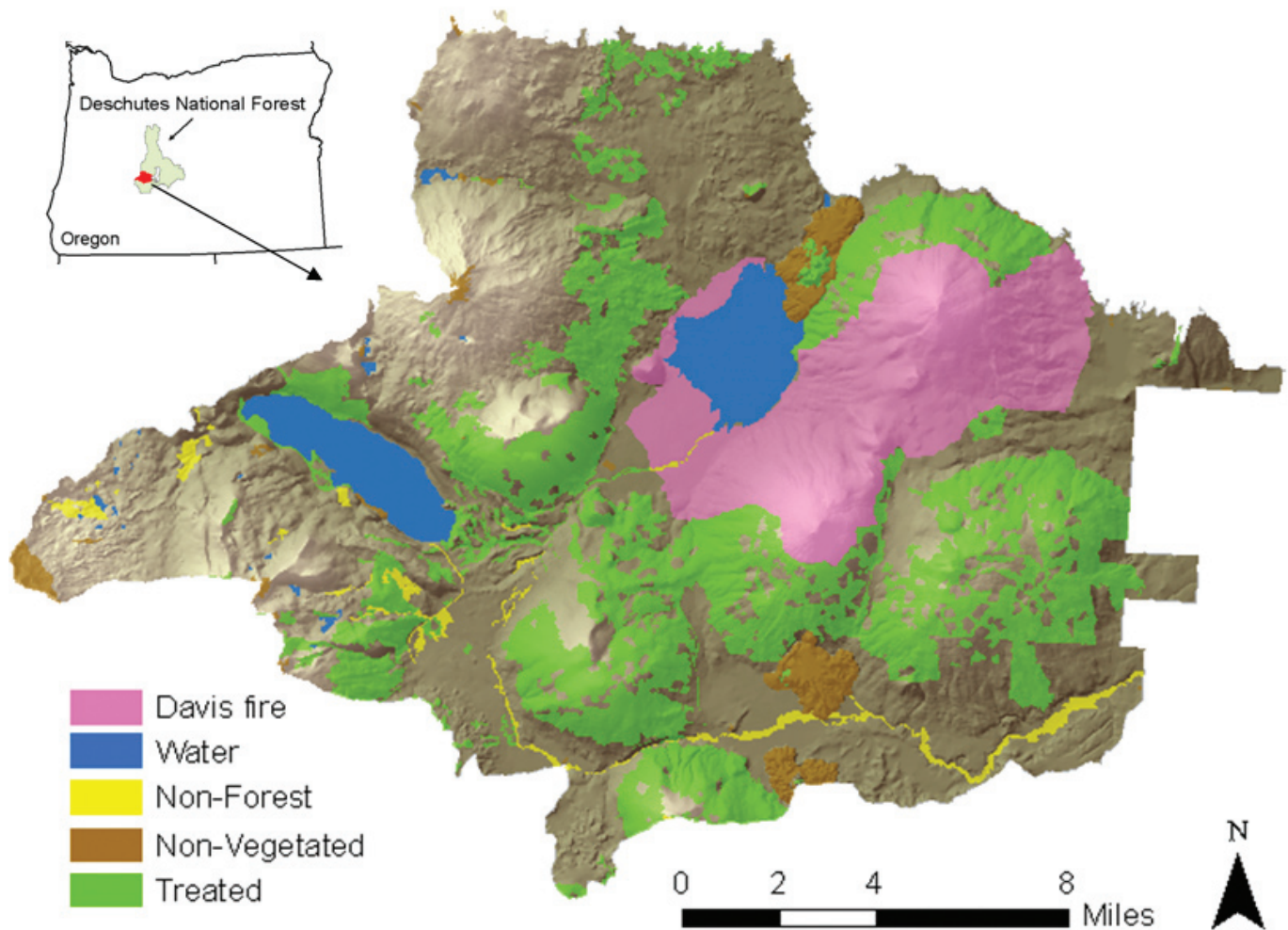


Figure 1—Five Buttes planning area showing land types and the 2003 Davis fire. Stands selected for thinning (“Treated”) in the treatment simulations (TRT) are shown in green.

In the [TRT+B] scenario, a sanitation cut (WWPBM keyword SANITIZE) concurrent with the thinning was also imposed in thinned stands to remove all recently beetle-killed trees and their beetles².

Beetle populations are simulated in the WWPBM in terms of “beetle kill potential” (BKP), expressed in units of square feet. One unit of BKP is equivalent to an amount of beetles, or “beetle pressure” capable of killing one square foot of host tree basal area. On an annual time step, the WWPBM simulates various BKP dynamics, including its re-allocation among stands (“dispersal”), reductions during dispersal (“in-flight” BKP “mortality”), tree selection and attack, and within-tree increases (“reproduction”). We initialized BKP into the landscape (keyword BMHIST) at the beginning of the simulation by assigning to stands containing significant density of host trees³ an amount of BKP equal to one percent of the host basal area in the stand. All pines were considered hosts. This BKP initialization rate approximately represents endemic levels of beetles and provides the “seed” BKP for a subsequent simulated outbreak induced via keyword VARYRAIN.

The FFE was used to generate potential fire and fuel reports. No fires were simulated. FVS keyword details are provided in the appendix. Simulations were built and analyzed within ArcFuels. This customized ArcGIS interface was used to build keyword files and to join FVS model outputs to geodatabase layers for rapid and spatial analysis of model outputs.

Results

Thinning

One-third of the forested area met the prescription criteria, resulting in 1,705 stands being treated in simulation year 2003 in the TRT+B and TRT-b scenarios. This set of stands we call the *overstocked mixed conifer* (OMC) stands. They comprise ~87 percent of the unburned mixed conifer PAG. Of these, only 47 stands met the criteria for a sanitation cut (see endnote 2). Nevertheless, sanitation removed 56 percent of landscape total BKP (from 25,656 to 11,204 ft²). Thinning reduced average stand basal area from 188 to 64 ft² acre⁻¹ in 2003 in the OMC stands; average stand basal area in all other (non-OMC) stands was 136 ft² acre⁻¹ in 2003.

Beetle Dynamics

The simulated bark beetle outbreak began in year 2005, peaked in 2010, and was nearly ended by 2012. Thinning reduced landscape average beetle-caused mortality (table 1 and fig. 2). In the TRT+B scenario, beetle-caused tree mortality was nearly eliminated in thinned (OMC) stands (fig. 3). In the NoTRT+B scenario, OMC stands (stands that would have been thinned under the TRT scenario) experienced greater beetle-caused mortality on average than other stands in the landscape (fig. 3). In the TRT+B scenario, unthinned (non-OMC) stands on average experienced beetle-caused mortality greater than they experienced in the NoTRT+B scenario (fig. 3). Over 40 percent of unthinned stands (1,092 stands) in the TRT+B scenario experienced a two percent or more increase in beetle-killed host basal area above what they experience in the NoTRT+B scenario (fig. 4c).

Fire-related Metrics

In simulations without beetles, potential volume mortality from a severe fire was reduced in thinned stands by ~77 percent, from 3,607 to 8,23 ft³ acre⁻¹ in 2003 (data not shown). The landscape average potential volume mortality was reduced in 2003 by 33 percent, from 2,728 to 1,821 ft³ acre⁻¹. Thinning completely eliminated active crown fire and conditional surface fire potential in all treated stands through 2006 (fig. 4b); active crown fire potential returned to only a few treated stands beginning in simulation year 2009. The simulated beetle outbreak caused slight increases in acres projected to have active crown fire in both of the +B scenarios (TRT+B, NoTRT+B) relative to their no-beetle (-b) counter-scenarios (TRT-b, NoTRT-b) (fig. 4a).

FFE estimates of fuel loadings and fuel model change frequently over time in response to thinning treatments and beetle dynamics. These shifts occur as BKP migrates from thinned stand to other stands across the landscape.

Discussion

Overview

In the WWPBM, BKP is dispersed among stands where it “attacks” host trees and “reproduces” in successfully killed trees. Factors controlling how BKP is allocated from one stand to another include: distance between stands, target-stand total basal area, host basal area, and a variety of stand *rating values* representing stresses to tree vigor. In our simulations, only three stressors were invoked: (a) random lightning strikes, set at the default values of two random strikes per 1,000 acres per year (this creates stressed “focus” trees for BKP); (b) dwarf mistletoe severity, provided via input tree lists; and most importantly, (c) the climate-related, outbreak-inducing stress event, invoked via keyword VARYRAIN. Other WWPBM rating values were not invoked. Stands with high total and host basal area and low vigor ratings attract BKP during dispersal; attractiveness diminishes exponentially as the distance between source and target stands increases. All stands are potential sources and targets of BKP each year. Analyses of dwarf mistletoe effects are not presented here.

The imposition of the climate-related stress event occurs landscape-wide; all stands experience the stress event. However, not all stands experience the stress to the same

Table 1—Average cumulative basal area beetle killed per acre ($\text{ft}^2 \text{ acre}^{-1}$) during simulation period 2003–2011 for two suites of stands under two simulation scenarios. The overstocked mixed conifer (OMC) stands are cut in the TRT scenarios and not cut in the NoTRT scenarios. Non-OMC stands are not cut in either scenario.

Scenario	OMC stands	Non-OMC stands
NoTRT+B	24.3	8.9
TRT+B	0.4	13.2

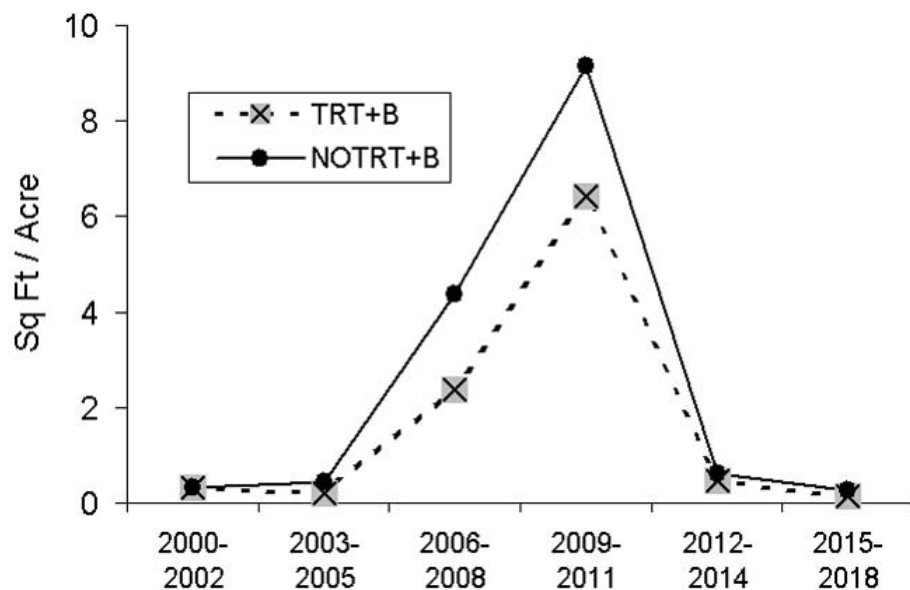
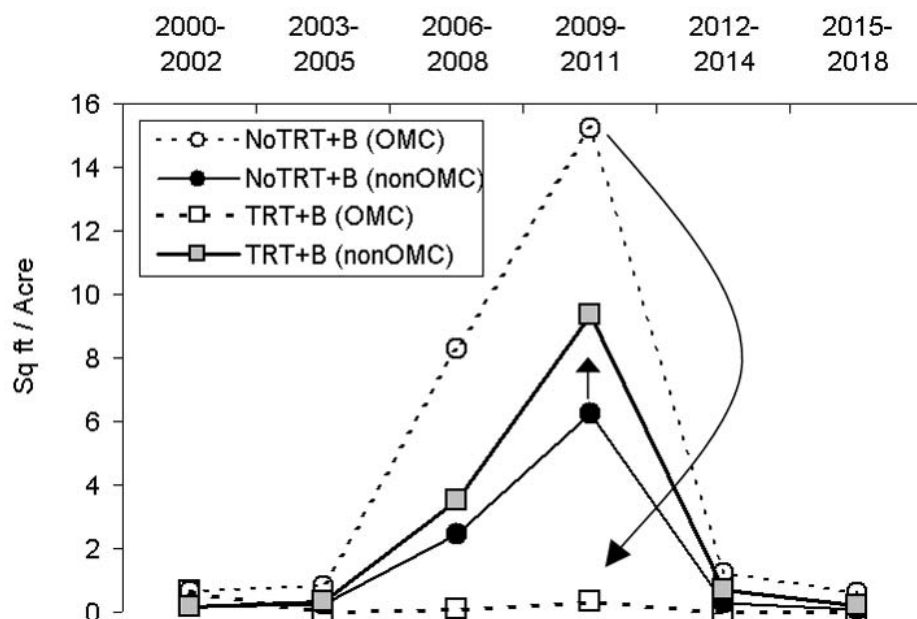


Figure 2—Landscape average basal area mortality from bark beetles during a simulated bark beetle outbreak in two different simulation scenarios. Thinning 1/3 of the landscape (TRT+B scenario) reduced simulated beetle-caused mortality by approximately 36 percent (between 2003 and 2012). Points represent 3-year cumulative basal area mortality through the end of each x-axis period-year.

Figure 3—Beetle-killed basal area ($\text{ft}^2 \text{ acre}^{-1}$) for two simulations: NoTRT+B, TRT+B. Results from each simulation are partitioned into two groups of stands: Overstocked Mixed Conifer (OMC) stands and other (non-OMC) stands. All OMC stands (dashed lines) are cut in the TRT+B scenario. Plotted values are stand-area weighted landscape averages. Points on the graph represent 3-year cumulative basal area mortality through the end of each x-axis period-year. OMC stands in the NoTRT+B scenario (open circles) experience significantly more mortality on average than other stands in the NoTRT+B scenario (filled circles). Mortality in OMC stands is reduced to negligible levels upon being thinned (long arrow). Other, non-OMC stands experience on average greater mortality in the thinned (TRT+B) scenario (filled squares) relative to what they experience in the unthinned (NoTRT+B) scenario (short arrow).



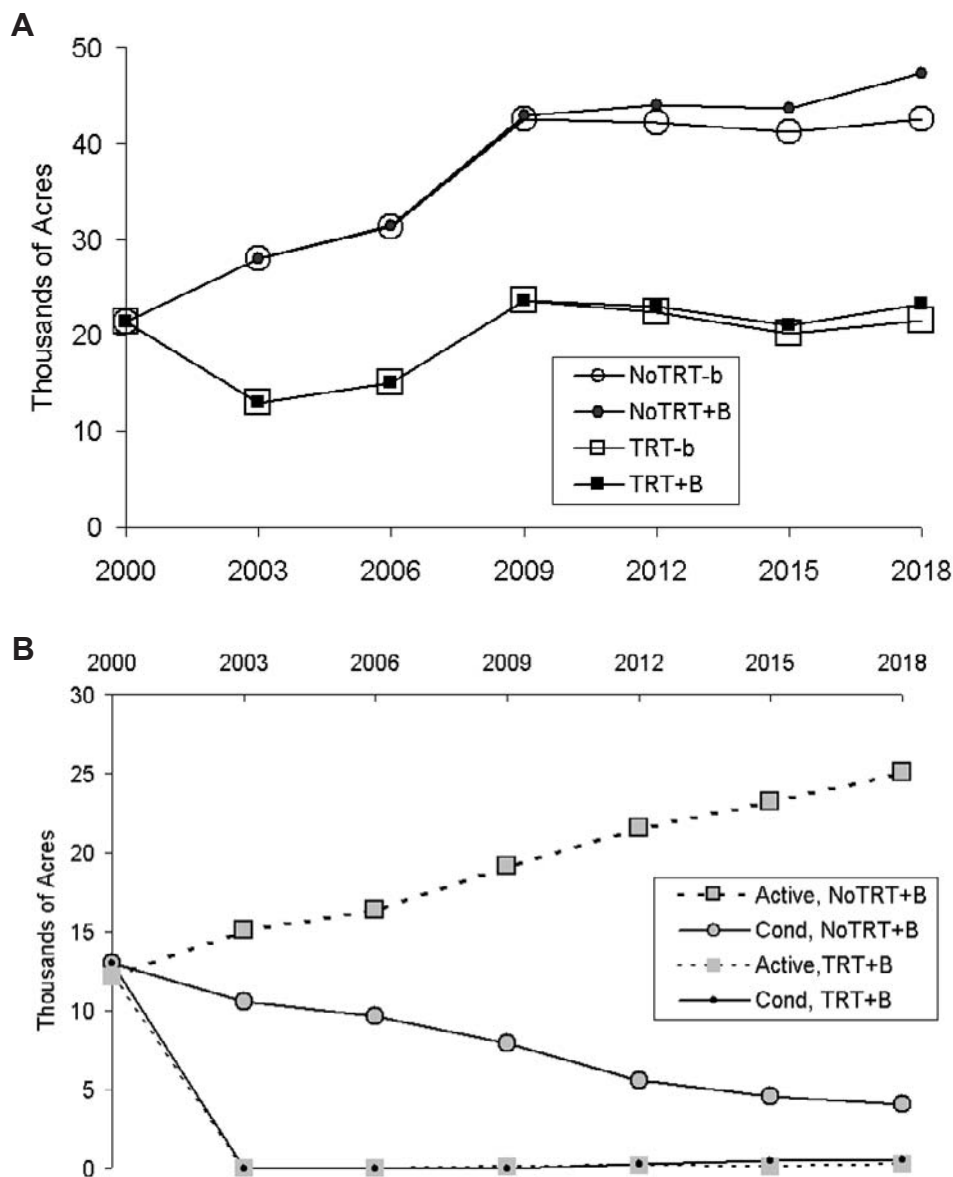


Figure 4—(A) Landscape total acres classed as having “Active” crown fire potential for the four simulation scenarios. Treatments significantly reduce “Active” acreage while beetles slightly increase “Active” acreage. (B) Acres of active crown fire (“Active”) and conditional surface fire (“Cond”) for OMC stands under TRT+B and NoTRT+B scenarios. Trajectory for untreated landscape is for increasing acres categorized as “Active” and decreasing acreage categorized as “Conditional surface.” Thinning treatments reduced both classes to negligible levels.

magnitude—more dense stands experience it more harshly. The event simulates a decrease in tree defense capabilities (the amount of BKP required to kill a tree decreases) and an increase in BKP survivorship (per unit of BKP being dispersed), thereby promoting the outbreak. The factors most strongly controlling where BKP is allocated in the landscape under these conditions are total and host basal area.

Thinning Effects on BKP “Migration”

In our simulations, thinning stands greatly reduces within-stand beetle-caused tree mortality (figs. 3 and 5b). However, because we imposed a “severe” climate-related stress event across the landscape to promote the beetle outbreak, BKP is nevertheless being

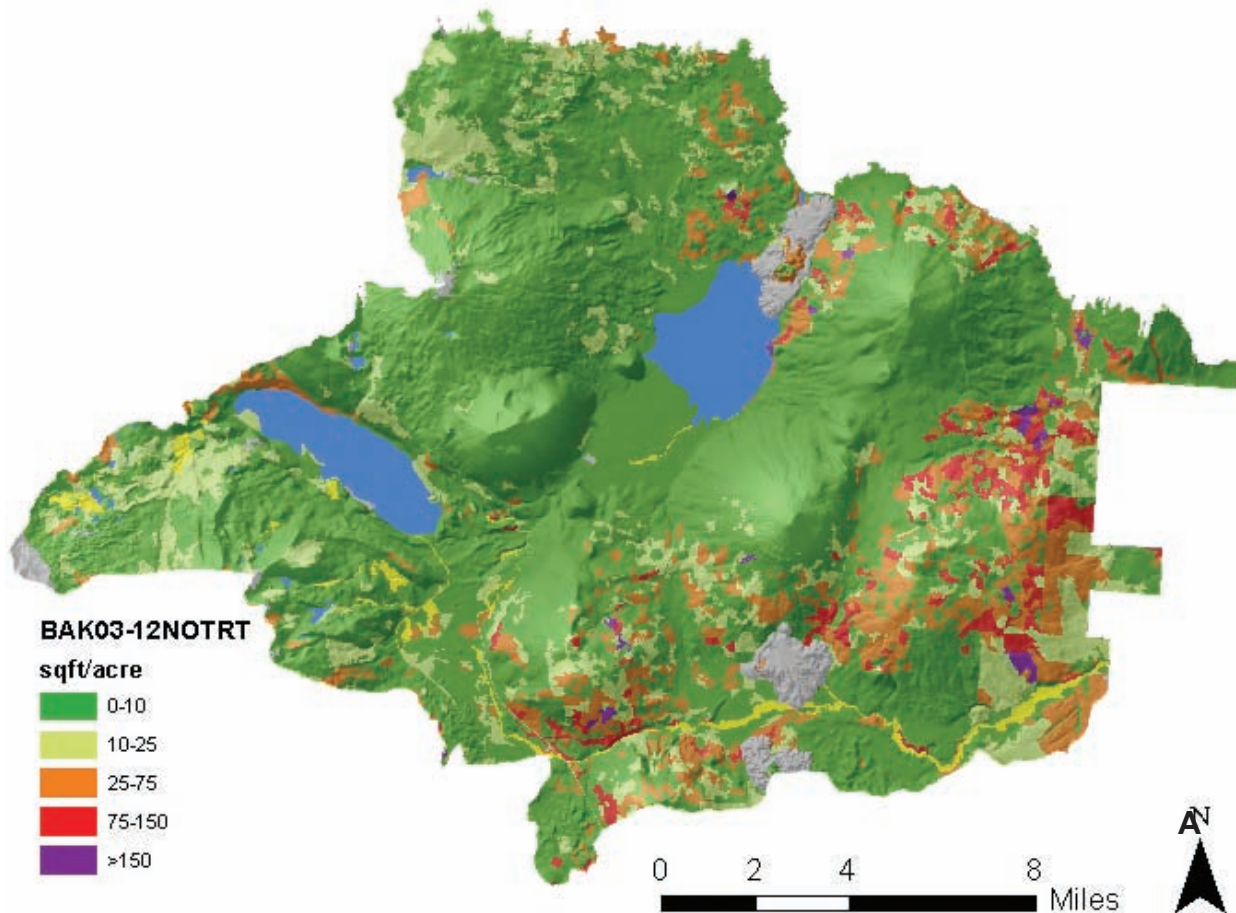


Figure 5—Simulated beetle-killed basal area (BAK, $\text{ft}^2 \text{ acre}^{-1}$) from simulation years 2003–2011 (inclusive) from two scenarios: (A) NoTRT+B; (B) TRT+B. Image (C) depicts the difference between the NoTRT and the TRT scenarios. In (C), negative values (orange) depict where beetle-killed basal area (2003–2011) has increased post-treatment (versus no treatment) by more than $15 \text{ ft}^2 \text{ acre}^{-1}$. Green and purple are where beetle-killed basal area has decreased post treatment (versus no treatment). Note: In (C), no color overlay is used to depict BAK values between -15 and $+15$ (continued on next page).

“encouraged” by the stress event to find and attack remaining host trees, even when the landscape is thinned. A striking conclusion from these simulations is that by thinning a significant portion of the landscape, BKP is effectively “pushed” into other stands where its effect was less under the NoTRT+B scenario (figs. 5a–c). Similar results are presented and discussed in Ager and others (2007).

We know of no published research designed to study the effects of thinning treatments on areas beyond the area thinned. In our simulations, BKP is able to “find” and “attack” remaining host trees in the landscape, and in some cases, at a magnitude greater than that experienced when the landscape is not thinned. Consistent with the design of the WWPBM, simulated BKP is reallocated from thinned stands to other unthinned stands. This is largely the result of the density relationships built into the model’s attractiveness algorithms. If a stand were thinned to a low enough total density, BKP would “migrate” from it to denser stands. This model behavior can be exhibited even if the absolute amount and proportion of host in the stand to which it is reallocated is less than in the source stand. What is not clear is the degree this prediction represents real-world behavior. Assuming that conditions instigating an outbreak are primarily exogenous—for example, climate-instigated—and assuming landscapes are intensively managed (our simulation thinned nearly one-third of the forested landscape), then to what degree will beetles in such a landscape find remaining hosts? If, prior to thinning, endemic beetles exist primarily in stands that are scheduled to be thinned, to what degree will remaining “unharvested” beetles remain in the thinned stands versus migrate to other stands when exogenous environmental conditions promote an outbreak? Answers to these questions could help us understand and properly interpret these model results.

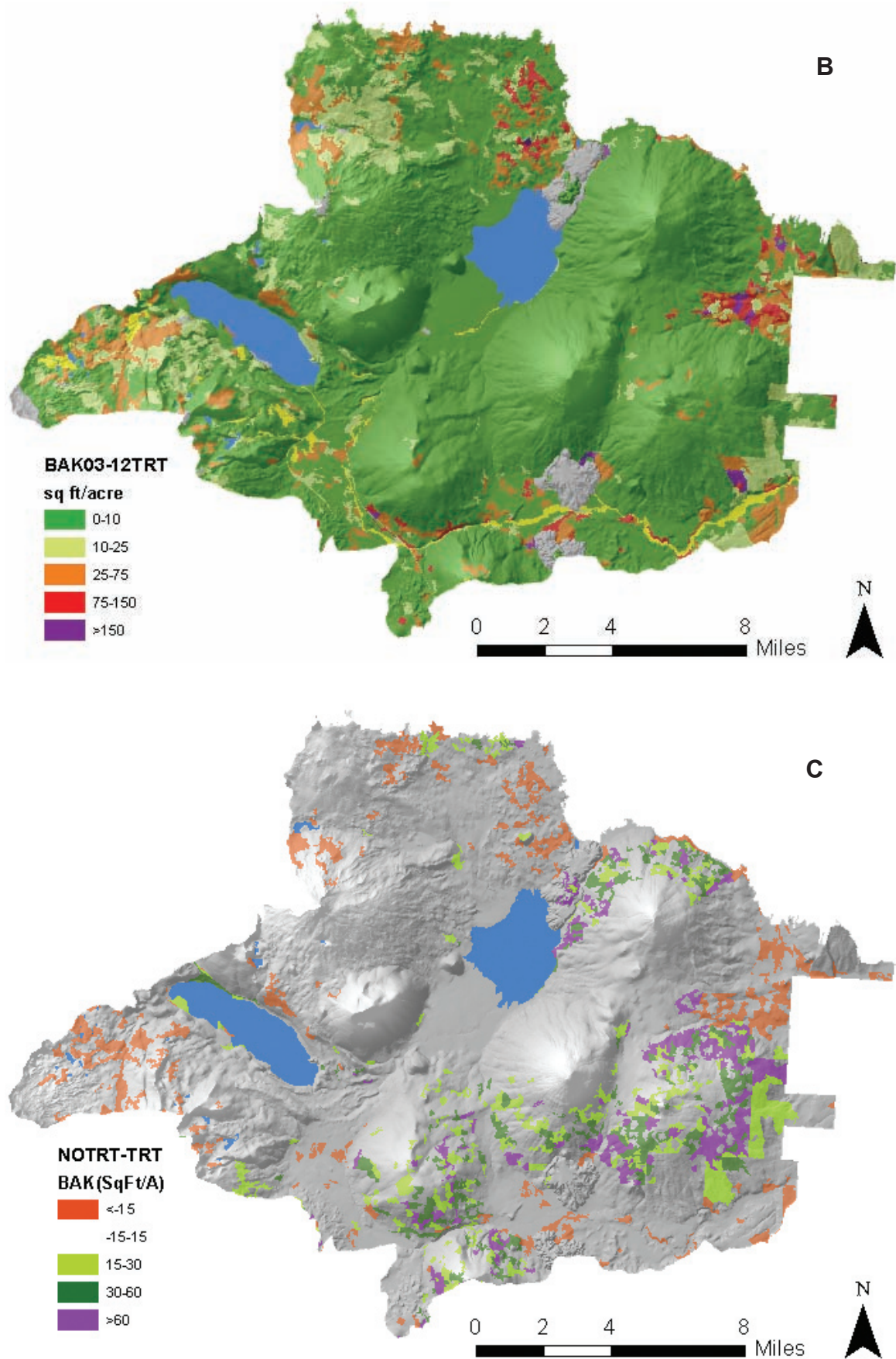


Figure 5—Simulated beetle-killed basal area (continued).

BKP Survivorship in Relation to Migration Distance

During dispersal, BKP is reduced (simulating in-flight BKP mortality). Current WWPBM structure contains algorithms that control BKP survivorship rates as a function of the severity of the VARYRAIN-induced stress event. As the severity of the event increases, BKP survivorship increases (in other words, the amount of BKP “dying” decreases). However, the WWPBM does not adjust BKP mortality as a function of the distance BKP travels as it “migrates” from stand-to-stand. In the model, potentially unlike beetles in a real-world landscape, BKP can just as efficiently “find and attack” a host that is five miles away, for example, as it can a host that is in a neighboring stand⁴. This explains in part why significantly more hosts are beetle-killed in some stands in the treated landscape than those stands experience in an unthinned landscape. Adjusting BKP to mimic beetle survivorship as it migrates long distances is a phenomenon currently not modeled in the WWPBM. Ideally this differential survivorship—assuming it exists at all—should be built into the model, but parameterization is a problem given our limited understanding of beetle survivorship over space and time.

Beetles and Fuel Dynamics

To the degree that the simulated bark beetle dynamics are valid, we found that our simulated, landscape-scale, fire behavior risk factors are significantly affected by bark beetle dynamics. Spatial distribution of standing and surface fuels significantly differs among the simulation scenarios as a result of treatments and simulated beetle activity (figs. 5c and 6). In our simulations, stands experiencing significant beetle mortality (+B scenarios) contain more snags and greater surface fuels, in the short term, than the same stands have in the no-beetle (–B) scenarios, a result of beetle-caused mortality (fig. 6). Further, because of the “redistribution” of BKP, and its concomitant tree mortality resulting from the thinning treatments (fig. 5c), the simulated thinned landscape (TRT+B) experiences significant “shifts” in patterns of beetle-caused snags and fuel loadings relative to the unthinned (NoTRT+B) landscape.

Modeling fuel loads and fuel dynamics in conjunction with disturbance agents (such as bark beetles) compels us to consider relationships between the cause of a tree’s demise and its subsequent fuel dynamics. Snag fall-down rate and deterioration has been the subject of considerable research because of the role snags play in fuel dynamics and their value to wildlife (reviewed in Laudenslayer and others 2002). While some studies have focused on deterioration of beetle-killed trees (Hinds and others 1965; Keen 1955; Mielke 1950), few comparative studies of deterioration have been completed for trees killed by other agents. Although some disturbance agents such as root disease or severe fire likely hasten fuel deterioration, there exists few data quantifying such relationships. Thus, with regard to bark beetle effects on snag and fuel dynamics, questions remain: to what degree do the mechanical injuries of attack, larval feeding on phloem, borings from associated beetles and other predators, together with infection from blue stain fungi affect snag fall-down and wood decay rates? Furthermore, other disturbance agents may have different effects on tree and snag deterioration. Incorporating these effects into our landscape projections of fuel dynamics remains a challenge.

Currently in FVS, when the FFE inherits dead trees from the WWPBM (or from any extension, for that matter) it does not “know” the source of the tree’s mortality. In the FFE, all dead trees are treated the same. Although it would be possible to build into the FFE recognition of tree mortality sources, the task is not a straightforward one, because the ultimate “cause” of tree mortality often involves more than one agent. For example, suppose a prescribed under burn kills a tree already stressed by root disease and dwarf mistletoe. To what agent is the source of mortality attributable? If mortality is attributable to more than one agent, how should that be accounted for in the FFE? These difficult issues have precluded FFE developers from making such considerations. Nevertheless, various mortality agents can and likely do play a significant role in determining snag and fuel dynamics. Elucidation and elaboration of some of these relationships into the FFE may improve its estimates of snag and fuel dynamics.

In addition to potentially affecting fall-down rates, fuel decay rates, and fuel loading, beetles affect the spatial arrangement of fuels. Stands experiencing a bark beetle infestation exhibit a rapidly changing canopy fuel dynamic, with large proportions of stand canopies (needles) changing from “green” to “red” in a span of one to two years, typically followed by relatively rapid needle fall. The spatial arrangement of fuels is an

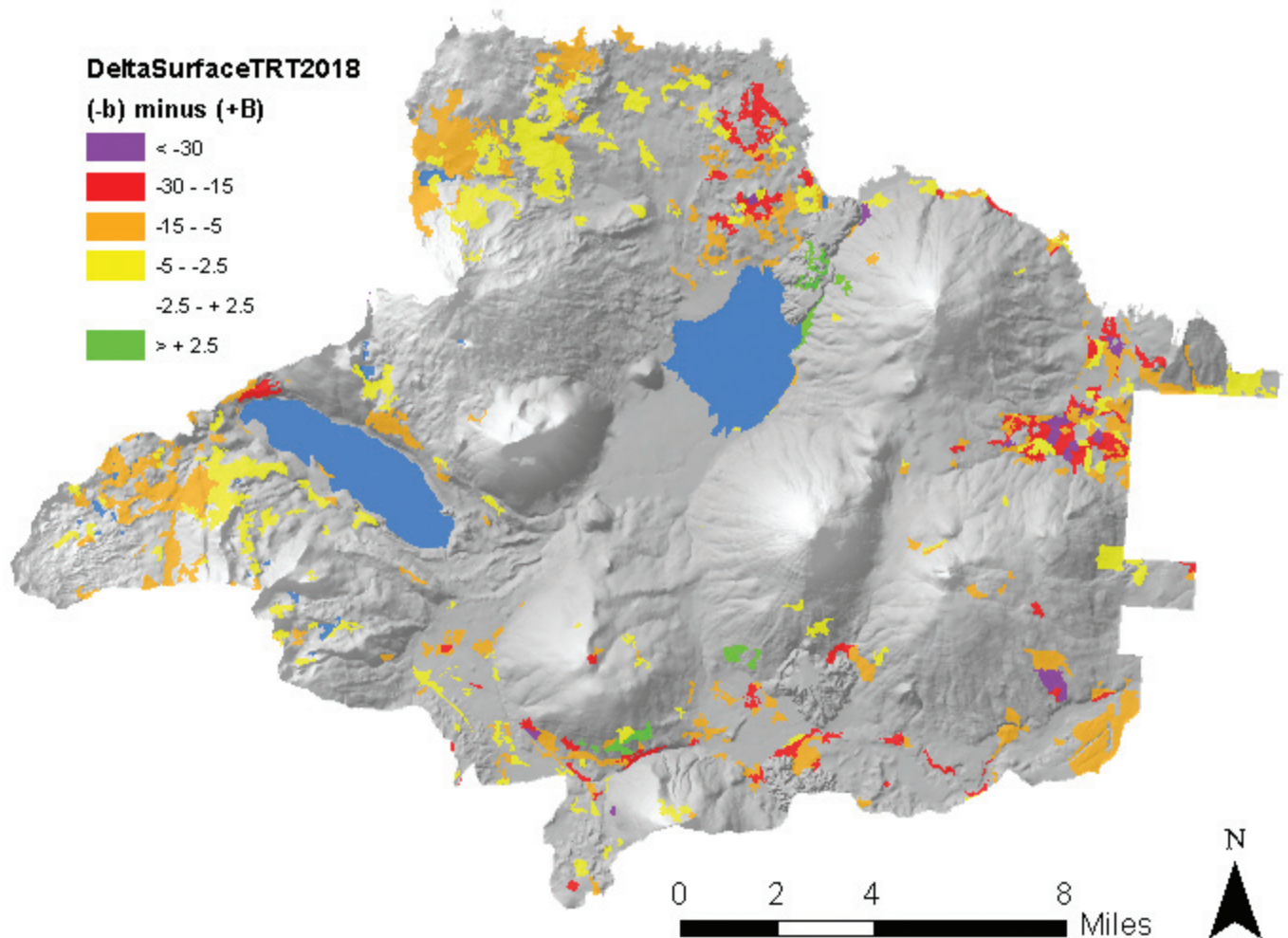


Figure 6—Difference in surface fuel loading (tons per acre) in simulation year 2018 between the TRT–b scenario and the TRT+B scenario. Negative values (yellow, orange, red, and purple) depict where surface fuels have increased due to beetle-caused tree mortality. Note: No color overlay is used to depict values between –2.5 and +2.5 tons per acre.

important component of fire behavior fuel models. Currently used fuel models may or may not be adequate to accurately model fire dynamics associated with beetle-caused canopy fuel changes. These relationships are beginning to be investigated (Page and others 2006). Again, additional studies may help us improve our modeling estimates of beetle-caused tree mortality effects on fire behavior via the development of new or modified fire behavior fuel models.

Fire Effects on Beetles

There are many questions pertaining to potential post-fire effects on beetle dynamics. A number of researchers have investigated post-fire effect relationships (for example, Amman and Ryan 1991; Boyle and others 2004; McHugh and others 2003; Ryan and Amman 1996; Sieg and others 2006; Wallin and others 2003). These effects could be at the tree or stand level. Currently, the WWPBM is designed to account for the stresses experienced by trees surviving a fire. The rating value due to fire is a function of the proportion of crown length scorched. Fire-scorched trees in the WWPBM are more attractive to BKP and are easier for BKP to kill. Although the WWPBM handles this relationship, integration with the FFE is incomplete⁶. Once complete, the relationships will need testing and refinement. A number of questions will need to be addressed, such as: Over what range of conditions will these relationships between fire-damage and beetle-attractiveness hold? Is percent crown scorch the best metric to use to calibrate a tree's rating value? Should

fire-caused root damage effects be incorporated into the model? Under what conditions does fire-stress cause trees or stands to be *less* attractive to beetles? How do fire-killed trees contribute toward a stand's attractiveness to bark beetles? How do these relationships vary amongst different tree and beetle species and across forest types? Does the seasonality of fire affect this dynamic (Ganz and others 2003)? How does fire intensity affect bark beetle brood survival (Safranyik and others 2001)? The state of knowledge in these areas is immature. Fowler and Sieg (2004) provide a good review of current research regarding fire-pest mortality relationships in ponderosa pine and Douglas-fir. A detailed discussion of these issues is beyond the scope of this paper. As our knowledge base improves, so will our models.

Concluding Remarks

Landscape scale analyses of management scenarios aimed at ascertaining risks to resources are becoming increasingly important to land managers. To support these analyses, the models and software used for multi-stand level simulation continue to develop and are increasingly accessible. The FVS and its several extensions—the PPE, FFE, Structural Stage model, and WWPBM, to name but a few—continue to evolve and be valuable modeling tools. The PPE, for example, can now be used to “pause” FVS simulations, allowing other programs to run between cycles to provide updated information for use by FVS in the next simulation cycle. The database capabilities of FVS-DB, and geodatabase capabilities of ESRI ArcGIS naturally invite connection. ArcFuels is an application that greatly facilitates the joining of these two data structures. Within ArcFuels, FVS-DB stand and tree tables are easily linked to geospatial data. Data elements such as PPE's AREALOCs⁶ supplemental records are easily derived from a GIS and readily imported into FVS via ArcFuels. Microsoft Access database tables can easily be parsed and joined to geodatabases, enabling easy map rendering of FVS model outputs. Although we did not run FLAMMAP⁷ simulations in this analysis, ArcFuels streamlines the process of moving data through FVS into FLAMMAP (Finney and others 2004). More importantly, however, are the insights gained by exploring the landscape-scale spatial dynamics of management and modeling estimations, explorations which are becoming evermore important as land managers are increasingly faced with prioritizing management activities across the landscape.

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Endnotes

- 1 Our choice of year 2000 to be our beginning-of-simulation year is based on the vintage of the inventory data. Readers should not construe our choice of simulation years to directly correspond to actual years. For example, we simulate that the Davis fire, which occurred in 2003, has already happened in simulation year 2000.
- 2 Without WWPBM sanitation cuts, BKP in beetle-killed trees would remain in thinned stands, because dead trees are not eligible to be removed via base-FVS thinning keywords. Because actual thinning activities would likely remove at least some beetle-killed trees, we imposed sanitation cuts if stands were thinned. Our sanitation cuts required a minimum sanitation removal volume of 10 cubic feet per acre (in trees greater than or equal to 6 inches DBH), and had a 90 percent removal efficiency. We also ran two additional simulations: a TRT+B *without* sanitation run and a NoTRT+B *with* sanitation, so that we could analyze the effects of the sanitation cut alone. Results from these additional scenarios are not presented here. Note that removal of dead trees via base-FVS keyword SALVAGE will not remove BKP.
- 3 In this context, “significant” amounts of host means that the stand: (a) had greater than 50 square feet of basal area per acre of host trees *and* greater than 100 square feet per acre of total basal area, if the stand was class as a “mixed conifer” PAG; *or* (b) was not a mixed conifer PAG but met the above criteria *and* had (i) greater than 100 trees per acre in lodgepole pine greater than nine inches DBH *or* (ii) greater than 50 percent of total basal area was composed of host and greater than 50 percent of the host was ponderosa pine.
- 4 This statement deserves elaboration, because it may seem counter-intuitive or inaccurate to those who understand the attractiveness algorithms built into the WWPBM. This statement is true given that the two stands in question have the same attractiveness scores. Because attractiveness decreases exponentially as distance between “source” and “target” stands increases, a stand farther away must have much more (and/or larger) host than a nearby stand for their attractiveness scores to be equal. But because the BKP survivorship function is independent of the distance over which BKP is allocated, two “target” stands having equal attractiveness scores (relative to the “source” stand) will receive the same amount of BKP regardless of the distance between the source and each of the target stands. Thus, while stand *attractiveness* is highly sensitive to distance between source and target stands, BKP “migration” (its dispersal, once allocated) is uniformly “efficient.”
- 5 Under its current structure, the WWPBM recognizes fire effects only from fires simulated within its own fire subroutines. Currently, the WWPBM does not recognize fires simulated by the FFE.
- 6 PPE keyword AREALOCs invokes reading of supplemental records containing stand spatial information: x- and y-coordinates of stand centroids and stand area.
- 7 FLAMMAP is a fire behavior mapping and analysis program that simulates potential fire behavior characteristics (spread rate, flame length, fireline intensity, etc.) over a landscape.