The Westwide Pine Beetle Model: A Spatially-Explicit Contagion Model

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Abstract—The Westwide Pine Beetle Model provides a means to project the impact of 3 pine beetle species in FVS simulations of susceptible landscapes. The model simulates the movement of beetles (contagion) between the stands in the landscape, as well as to and from the forests of the "outside world" beyond this landscape. Incorporating the model's projections of beetle impacts on each stand in a section of the Nez Perce National Forest results in a more rapid loss of pine basal area from the landscape than is projected by FVS alone. This successional change in species composition over time better matches the conditions observed in the real world. The spatial dynamics of the beetle infestation may be observed in the model results, as well as the importance of properly accounting for conditions in the "outside world".

Together, the Forest Vegetation Simulator (FVS) (Wykoff and others 1982) and the Parallel Processing Extension (PPE) (Crookston and Stage 1991) model the growth of trees in stands across an entire landscape. The Westwide Pine Beetle Model simulates the movement of beetles within the landscape and beyond, and projects beetle impacts on each stand. As is shown below, this can increase the realism of FVS vegetation projection in forests that are potentially affected by pine beetles.

The following paper provides an overview of the Westwide Pine Beetle Model. A more detailed technical description is available in Beukema and others (1994). As well, a model user's guide and keyword reference guide are available to assist model users (Beukema and Kurz 1994; Beukema and Robinson 1994).

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Objectives

The Westwide Pine Beetle Model (WTBM) was designed to:

- Incorporate the impact of pine beetles on FVS projections of stand dynamics
- Model the shift between endemic and epidemic beetle population levels
- Capture the spatial effects of contagion processes operating in the landscape and beyond
- Simulate three beetle species—the mountain pine beetle (*Dendroctonus ponderosae* Hopkins), western pine beetle (*Dendroctonus brevicomis* LeConte), and *Ips* spp.

The resulting model can support silvicultural planning and pest-management efforts in forests that are susceptible to pine beetles.

Methods

The WPBM was developed through a series of collaborative workshops with entomologists, forest scientists, and potential model users. This workshop approach, based on the protocols developed by Holling (1978) for Adaptive Environmental Assessment, has been used successfully in the development of other forest health extensions to FVS (such as the Western Root Disease Model; Shaw and others 1991). This approach allowed the design and parameterization of the model to benefit from a broad pool of expert knowledge, including the 42 scientists listed in the Acknowledgments.

Model Components

The WPBM uses the Forest Vegetation Simulator (FVS)to project stand development and represent timber management activities. The Parallel Processing Extension (PPE) is used to manage the simultaneous projection of hundreds of stands in a landscape. The Westwide Pine Beetle Model itself simulates the impact of pine beetles and other disturbance agents on each stand, and modifies the FVS tree list to account for these effects.

In addition, the WPBM incorporates within itself a model of all the forest land outside the simulated landscape that is near enough to affect beetle dispersal—the so-called "outside world". The model assumes that the stockable portion of the outside world consists of homogenous forests in a specified condition. It then calculates the quantity of beetles that will disperse between the forests of the outside world and each stand in the landscape. The calculation is mathematically precise, respects all the spatial variation of the landscape, and is based on the same assumptions about beetle movements as is dispersal within the landscape.

Simulated Beetle Activity

The WPBM projects beetle population levels and forest impacts by conducting the following operations in each year of the simulation:

1. *Calculate the quantity of beetles emerging from infested trees.* This depends on the number and size of killed, strip-killed, or top-killed trees in the previous year; the density of *Ips* infestation in slash; and the number of beetle generations per year.
2. *Simulate the dispersal of beetles between stands, and between each stand and the outside world.* Dispersal depends on the average distance between the source and destination areas, and numerous characteristics of the destination (including total area, basal area and size of host pine, stand basal area, and the condition of individual host trees).
3. *Estimate beetle mortality,* based on the quantity of beetles in each stand, the basal area of host trees, and the proportion of total basal area that is host above a minimum size.
4. *Simulate the selection and attack of individual host trees within each stand.* This depends on the number and condition of host trees in each size class and the density of beetles present in the stand. *Ips* is assumed to attack any available slash before attacking live trees.
5. *Determine the result of each attack* (tree death, strip-kill, top-kill, or pitch-out) based on the quantity of beetles attacking each tree, and the size and condition of the tree.

The WPBM then removes beetle-killed trees from the FVS tree-list.

User Controls

The model user may control all of the model's assumptions about beetle behavior (for example, dispersal distances, reproductive rates, and so forth) by way of FVS-style model keywords. In addition, the WPBM provides a number of pest-management options under user-control. These options include pheromone baiting, use of repelling pheromones, pesticide application, sanitation cutting, salvage cutting, and slash management.

The WPBM user may also activate numerous other disease and disturbance agents, including fire, drought, lightning, other beetles, defoliators, mistletoe, root disease, and stem rust. In the WPBM, these "driving variables" act to kill host and nonhost trees, consume woody fuels, kill beetles, reduce tree health, and create "special" trees that attract more beetles. The driving variables are implemented as simple sub-models that are not intended to replace more detailed independent disturbance and health extensions where such extensions are available. The purpose of these driving variables in the WPBM is to allow the model to simulate, in an approximate manner, the interacting effects of multiple disturbance agents.

The WPBM allows the user to choose from three different assumptions about beetle population levels and host abundance outside the landscape. At the user's discretion, conditions in the "outside world" (beyond the immediate landscape that is simulated in detail) may be assumed to be changing in parallel with changes in the landscape, staying constant in the same condition as the landscape average at the start of the simulation, or varying as prescribed by the user at one or more points in time. These different assumptions will influence the quantity of beetles moving between each stand in the simulated landscape and the outside world.

Finally, the WPBM provides output data on numerous indicators selected by the user. The available indicators include the volume, basal area, and size of beetle-killed trees; the condition of remaining live host trees; an index of beetle population level; the amount of slash and standing dead wood in each stand; the amounts of dead woody material in each of three different decay classes, and so forth. Data on these indicators may be obtained as landscape averages as well as for each individual stand.

Test Results

The model results shown here are for the Trapper Creek Quadrangle of the Nez Perce National Forest. This is an area of 279 contiguous stands with a total area of about 6,400 acres. At the beginning of the simulations in 1990, lodgepole pine dominates other species in the intermediate size classes, but not in the smaller and larger size classes. All simulations were run for a 100 year time period using a 5 year FVS cycle. The Northern Idaho variant of FVS was used, as is appropriate for the Nez Perce.

Two main alternative scenarios are considered here. In scenario 1, "without beetles", the model is run as if no pine beetles are present in the landscape. That is, the dynamics of each stand are projected by FVS in the usual way.

In the second scenario, "with beetles", the model is run with mountain pine beetles active on host lodgepole pine. Beetles are "initialized" in three stands by labeling five trees per acre in each stand as beetle-killed trees from the previous year. All of the model parameters controlling beetle behavior and impact were set to the default values established for this FVS variant in consultation with many of the entomologists and forest scientists listed in the Acknowledgments. A number of variations of the "with beetles" scenario were constructed by varying the conditions assigned to the outside world. In the baseline variation (used to produce all the maps shown in figure 1), host basal area and beetle population density in the outside world are both held constant at 70 percent of the landscape average value at the start of the simulation. In the subsequent variations (used to produce the graph in figure 2), the outside world is either removed from the simulation or made less attractive to beetles by reducing the host basal area to 50 percent of the initial landscape average, with the beetle population density set to either 50 or 70 percent of the landscape average.

The maps in figure 1 show how the basal area of pine changes over time in each stand in the landscape according to whether or not pine beetle impacts are taken into account. The graphs in figure 1 show the size class distribution of pine in one sample stand at each point in time. The following effects may be seen:

- The basal area of host pine decreases over the course of the simulations. This is projected to occur as a natural consequence of stand development, even in the absence of pine beetles.
- The decrease in pine basal area is significantly larger and more rapid when the effects of pine beetles are taken into account.
- As stands develop, the remaining pine trees are larger in the absence of beetles. When beetles are present, they preferentially attack larger host trees.
- In the presence of beetles, the fate of a stand depends on its location relative to other stands. The beetle outbreak shown here began first in the northwest section of the landscape; stands here experience a greater early loss of pine.

Figure 2 shows the importance of the outside world to simulation results in the presence of beetles. The loss of pine basal area in the landscape is greatly exaggerated when the simulation is run with no outside world at all. Once beetles in this simulation reach epidemic levels in the landscape, they remain at high levels until essentially all large enough host trees have been eradicated-the artificial world of the simulation provides nowhere else for them to "go". As the outside world is made more attractive to beetles, the rate of pine loss decreases.

Discussion

The results highlight the importance of accounting for pine beetle impacts in projections of susceptible landscapes: expected future conditions are quite different when the likely impacts of beetles are considered. The long-tem persistence of old, dense pine stands that is projected in the absence of beetles is not observed in the real world. The more rapid decline in pine basal area, the decline projected by the WPBM when beetles were included in the simulation, appears to be closer to the actual observed course of stand development in these forests.

Moreover, the results show the importance of accounting for spatial effects when dealing with contagion processes. It is clearly unrealistic to attempt to predict the probability that a stand will catch fire without considering the condition and fate of adjacent stands. It is just as unrealistic to attempt to predict beetle impacts on a target stand without considering the location of that stand relative to sources of infection and concentrations of host trees. The results also show the importance of accounting for the "outside world"

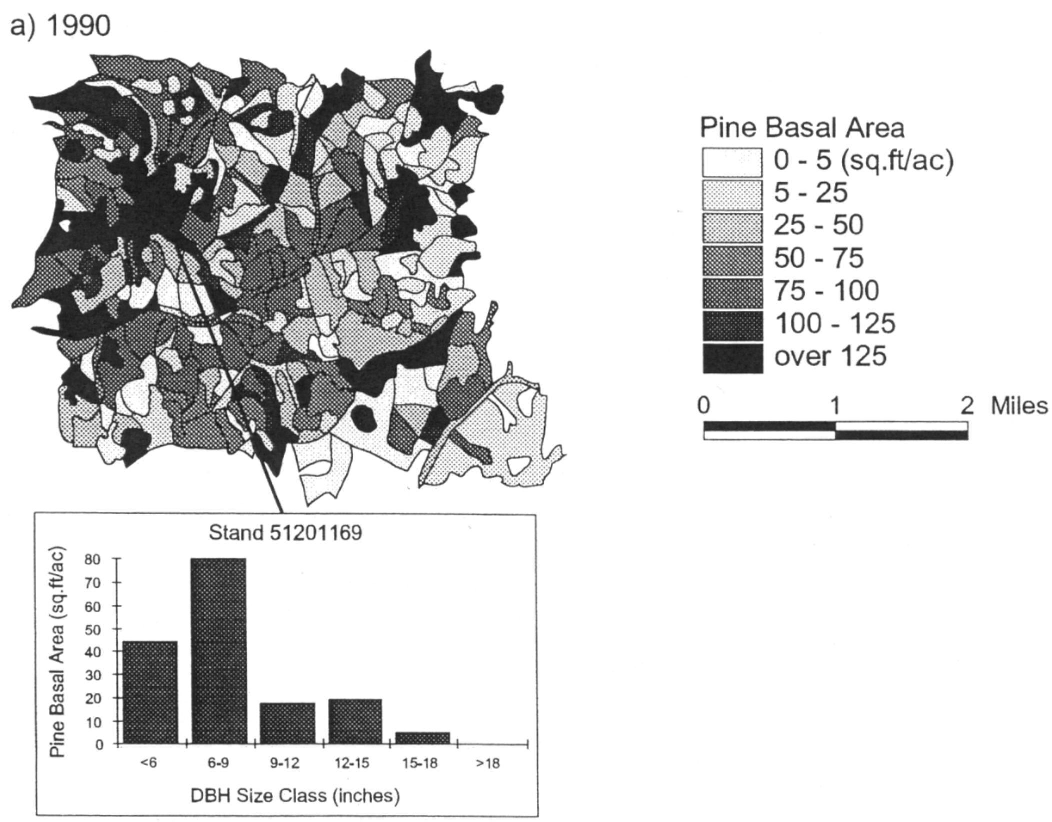
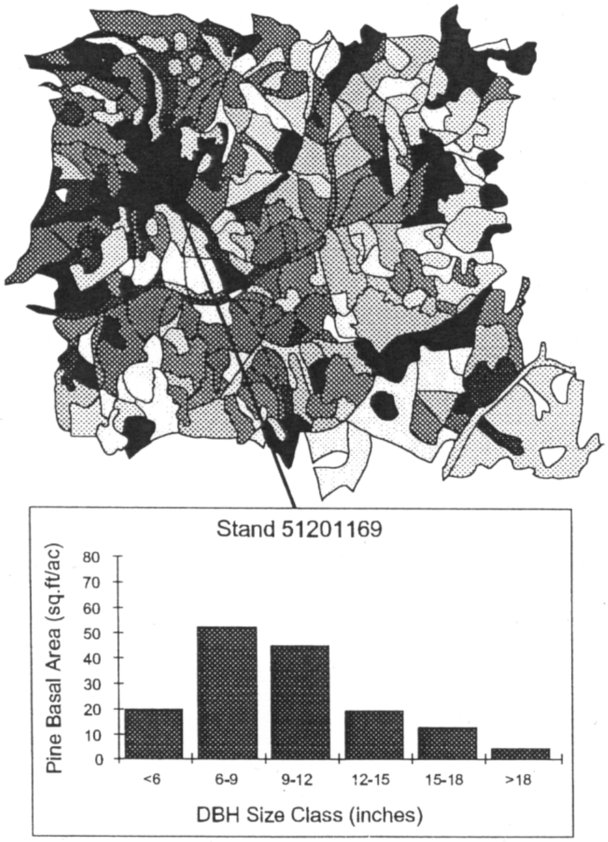
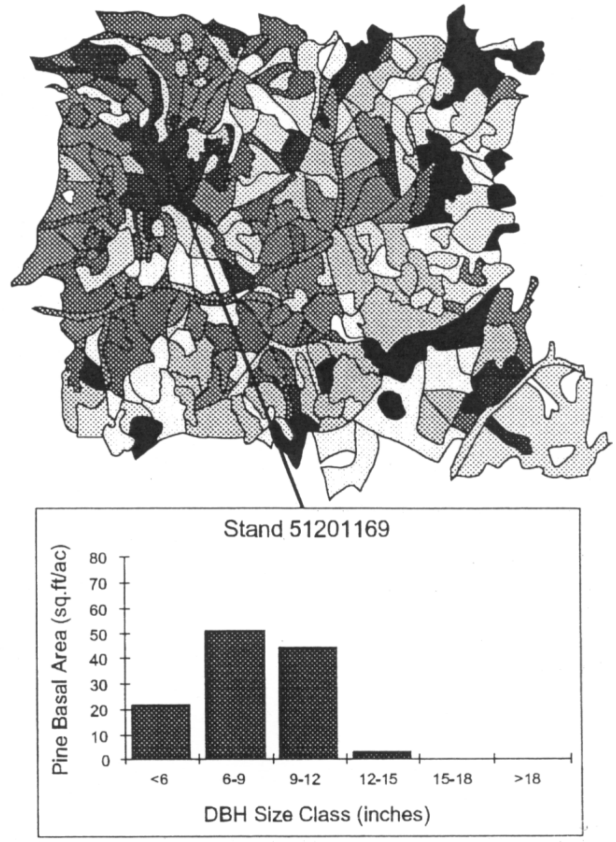


Figure 1—Projected change in pine basal area in the presence and absence of pine beetles. The maps show the amount of host basal area in each stand in the landscape a) at the start of the simulation in 1990; b) projected for the year 2020 without accounting for possible beetle impacts; c) projected for 2080 without beetles; d) projected for 2020 with probable beetle impacts taken into account; and e) projected for 2080 with beetles. The graphs show the pine size class distribution, by basal area, in the same sample stand in each situation.

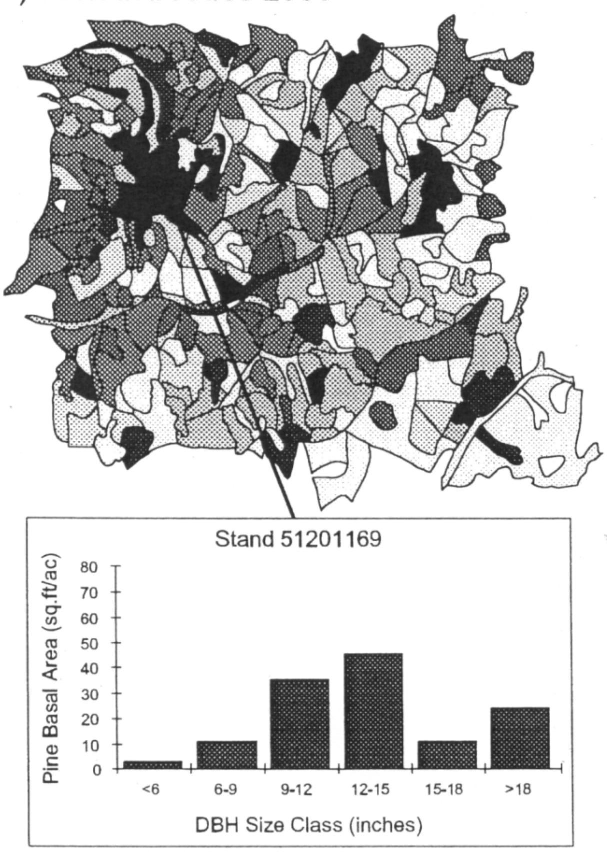
b) without beetles 2020



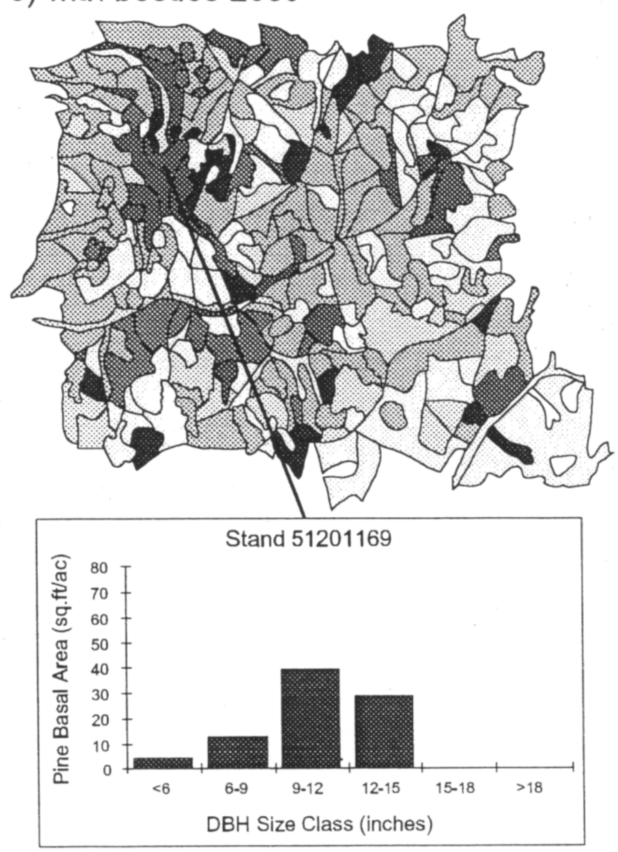
d) with beetles 2020



c) without beetles 2080



e) with beetles 2080



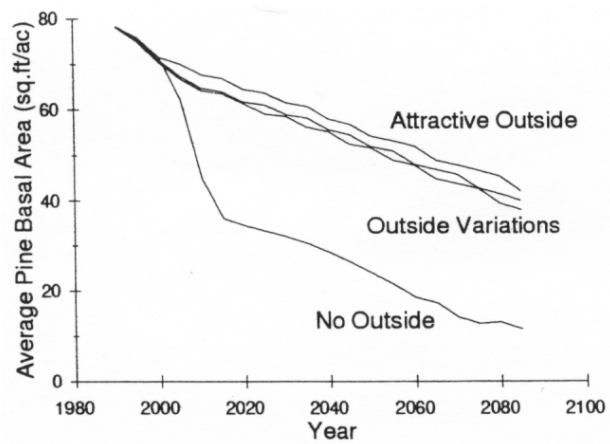


Figure 2—The influence of the "outside world" beyond the simulated landscape. The graph shows how the average pine basal area across the landscape changes overtime in the presence of beetles. The lower line shows the decline in pine basal area if the landscape is modeled in isolation (such as if there were no "outside world" beyond the landscape). The higher lines show the results of including the outside world in the simulation, and making that outside world more attractive to beetles by increasing the density of host pine from 50 to 70 percent (top line) of the initial landscape average.

when considering forest insects that can disperse overlarge distances. The dispersal of beetles within any one landscape—and to and from that landscape—is much influenced by the amount of host available elsewhere. Taking the "outside world" into account allows beetle epidemics to enter endemic phases prior to the eradication of preferred host trees in the simulation. It also helps to eliminate the artificial "edge effects" seen in some simulations, in which stands on the edge of the simulated landscape suffer greater loss of host during beetle outbreaks than do stands in the center.

Because of the importance of the outside world, however, assumptions about its condition can have a strong influence on the results of simulations. The outside world and other aspects of the model require careful calibration to ensure that simulation results will be reliable. The WPBM has thus far undergone only limited testing with landscape-level data sets. As is, the model is suitable for exploring the possible range of outcomes under a given scenario. The WPBM is, in fact, the only modeling tool available for considering beetle effects across a landscape. Ideally, however, the model will receive further calibration before it is used to evaluate alternative scenarios in a management context. Further development of the model awaits the availability of longterm data sets on beetle dynamics and impacts, with information from the stand-level up to the level of the watershed level or higher. The application of these data sets to model calibration would help to ensure the reliability of model projections.

The WPBM demonstrates how both large-scale spatial processes and detailed nonspatial processes may be successfully represented in a single ecological model. FVS and the PPE simulate forest growth and development within each stand in the landscape, while the WPBM accounts for contagion processes between the stands and between each stand and the outside world. The WPBM then calculates the resulting impacts on each stand. This modeling approach may be successfully transferred to simulation of the impacts of other forest insects.

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